(http://www.noaa.gov)

Earth System Research Laboratory (https://www.esrl.noaa.gov)

Global Monitoring Division (/gmd/)

Global Greenhouse Gas Reference Network (/gmd/ccgg/)

(/gmd/webdata/ccgg/trends/rss.xml)

Trends in Atmospheric Carbon Dioxide

Mauna Loa, Hawaii (mlo.html) Global (global.html) CO_2 Animation (history.html)

CO_2 Emissions (ff.html)

Last Month (monthly.html)

Last 1 Year (weekly.html)

Full Record (mlo.html)

Growth Rate (gr.html)

Data (data.html)

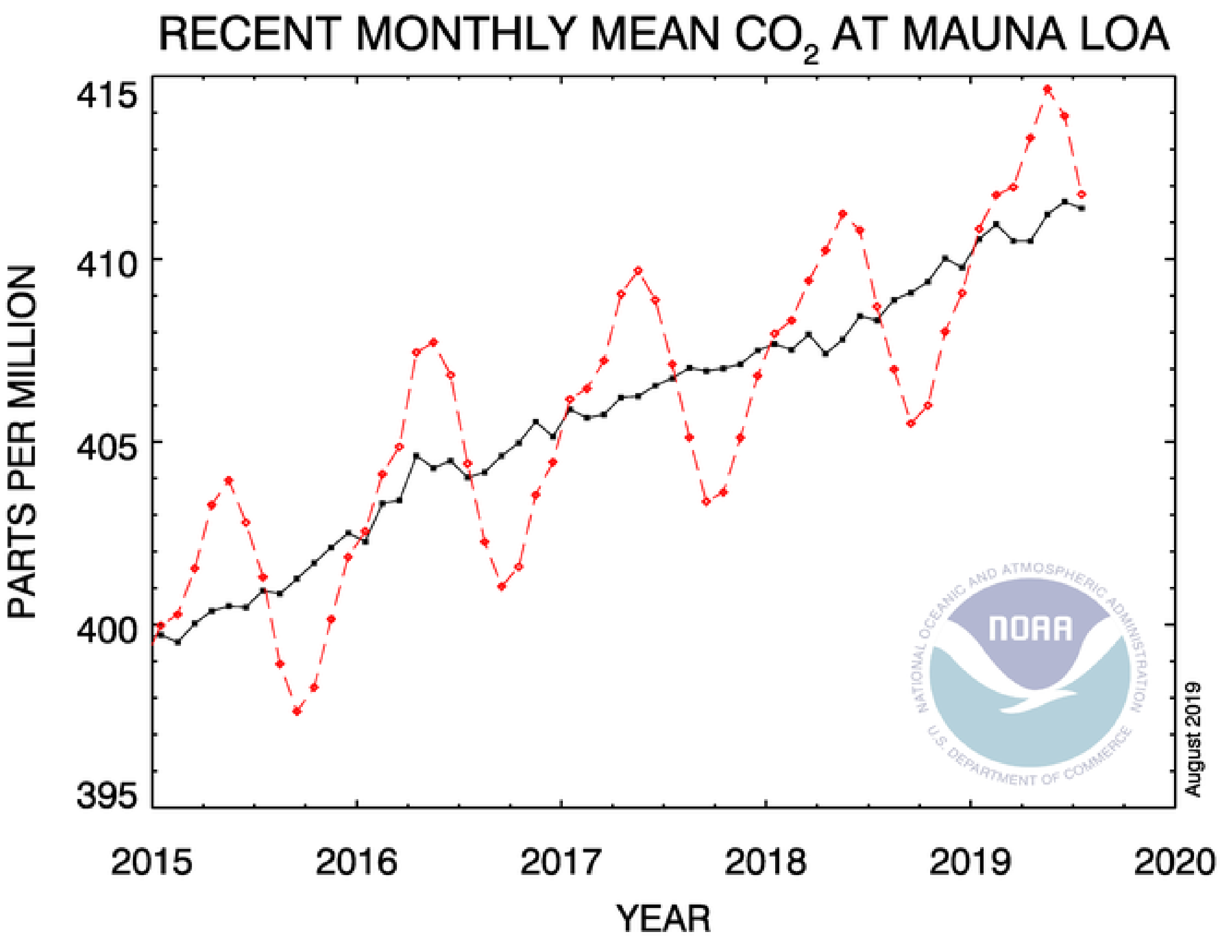
Interactive Plots (graph.html)

Monthly Average Mauna Loa CO_2

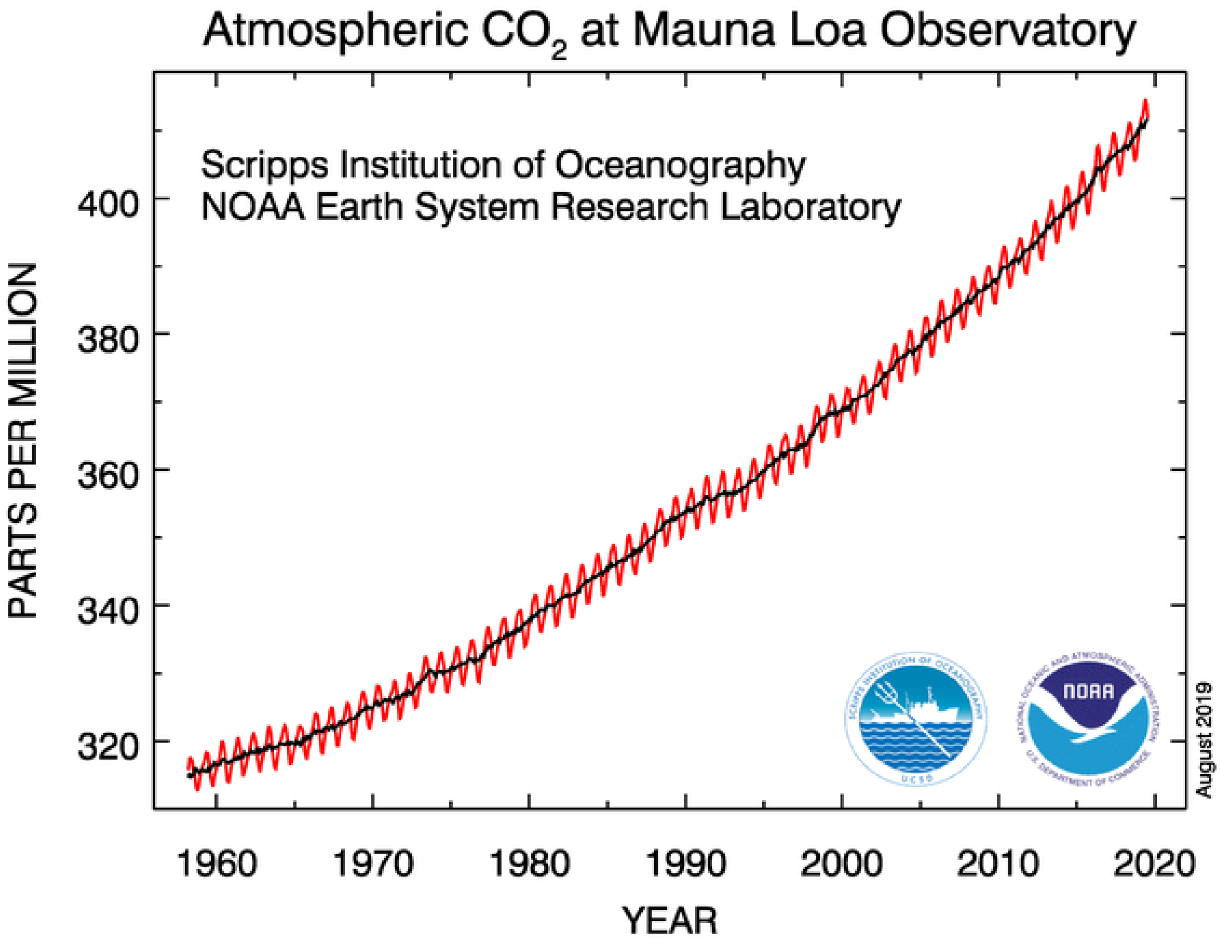
July 2019: 411.77 ppm

July 2018: 408.71 ppm

Last updated: August 5, 2019



PNG Version (/gmd/webdata/ccgg/trends/co2_trend_mlo.png) PDF Version (/gmd/webdata/ccgg/trends/co2_trend_mlo.pdf)



PNG Version (/gmd/webdata/ccgg/trends/co2_data_mlo.png) PDF Version (/gmd/webdata/ccgg/trends/co2_data_mlo.pdf)

The graphs show monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. The carbon dioxide data (red curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. They were started by C. David Keeling of the Scripps Institution of Oceanography in March of 1958 at a facility of the National Oceanic and Atmospheric Administration *[Keeling, 1976]*. NOAA started its own CO_2 measurements in May of 1974, and they have run in parallel with those made by Scripps since then *[Thoning, 1989]*.

The last four complete years of the Mauna Loa CO_2 record plus the current year are shown in the first graph. The full record of combined Scripps data and NOAA data are shown in the second graph. The dashed red lines with diamond symbols represent the monthly mean values, centered on the middle of each month. The **black lines** with the square symbols represent the same, after correction for the average seasonal cycle. The latter is determined as a moving average of SEVEN adjacent seasonal cycles centered on the month to be corrected, except for the first and last THREE and one-half years of the record, where the seasonal cycle has been averaged over the first and last SEVEN years, respectively.

The last year of data are still **preliminary**, pending recalibrations of reference gases and other quality control checks. Data are reported as a dry air mole fraction defined as the number of molecules of carbon dioxide divided by the number of all molecules in air, including CO_2 itself, after water vapor has been removed. The mole fraction is expressed as parts per million (ppm). Example: 0.000400 is expressed as 400 ppm. The Mauna Loa data are being obtained at an altitude of 3400 m in the northern subtropics, and may not be the same as the **globally averaged CO_2 concentration at the surface** (global.html#global).

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National Oceanic and Atmospheric Administration
U.S. Department of Commerce

June 2019 was hottest on record for the globe

Antarctic sea ice coverage shrank to new record low

Climate Satellites | climate analyses and statistics

July 18, 2019 —

Mother Earth worked up a major sweat last month. Scorching temperatures made June 2019 the hottest June on record for the globe. And for the second month in a row, warmth brought Antarctic sea-ice coverage to a new low for June.

Here's a closer look into NOAA's latest monthly global climate report:

Climate by the numbers

June 2019

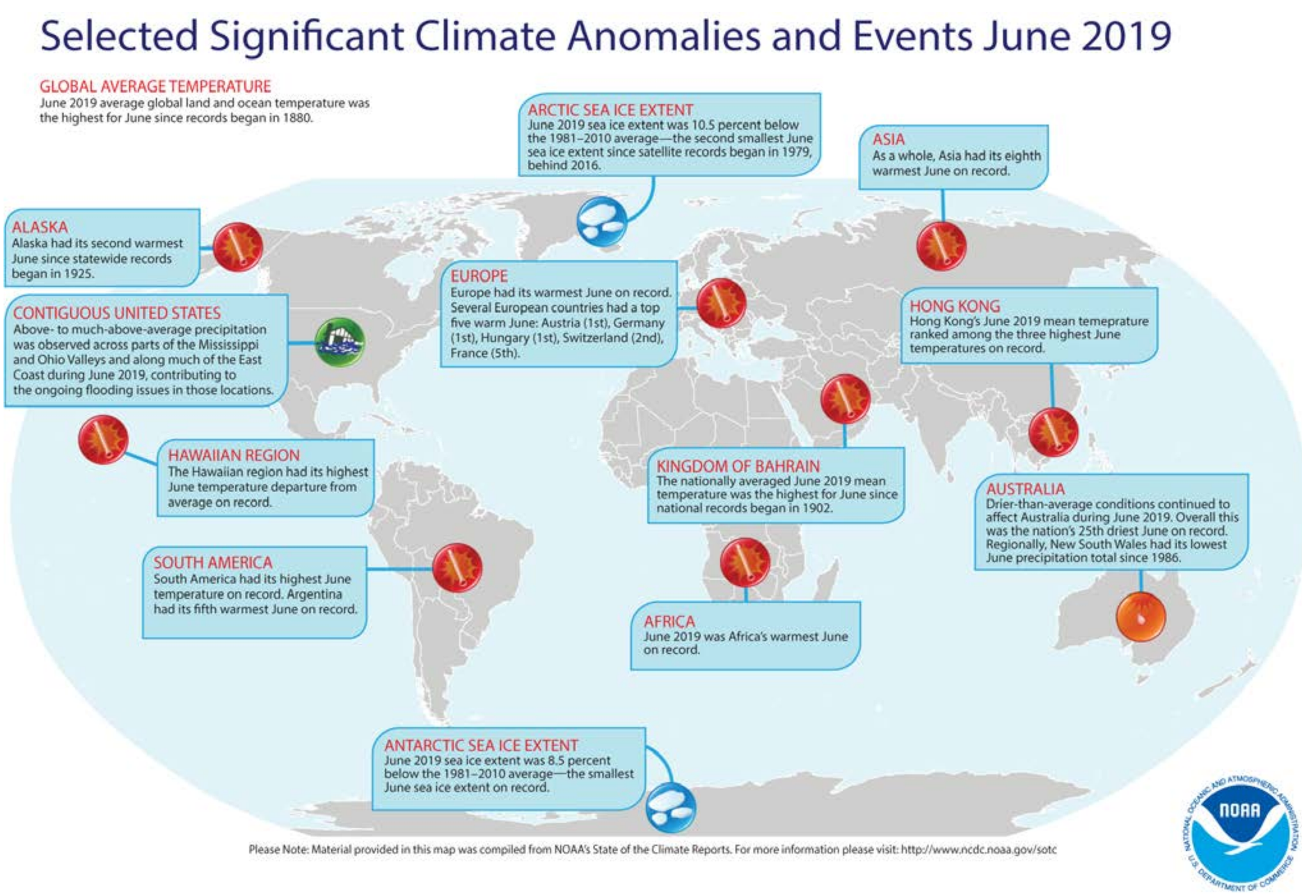
The average global temperature in June was 1.71 degrees F above the 20th-century average of 59.9 degrees, making it the hottest June in the 140-year record, according scientists to NOAA's National Centers for Environmental Information.

Nine of the 10 hottest Junes have occurred since 2010. Last month also was the 43rd consecutive June and 414th consecutive month with above-average global temperatures.

Year to date I January through June

The period from January through June produced a global temperature 1.71 degrees F above the 20th-century average of 56.3 degrees, tying with 2017, as the second-hottest year to date on record.

It was the hottest first half of the year for: South America, parts of the southern portion of Africa, Madagascar, New Zealand, Alaska, western Canada, Mexico, eastern Asia, the Atlantic and Indian oceans, and the Bering Sea.



An annotated map of the world showing notable climate events that occurred around the world in June 2019. For details, see the short bulleted list below in our story and at http://bit.ly/Global201906.

More notable stats and facts

- **Sea ice keeps melting**: Average Antarctic sea-ice coverage was 8.5% below the 1981-2010 average – the smallest on record for June. Average Arctic sea ice coverage was 10.5% below average – the second-smallest on record for June.
- **A slightly cooler year, so far, for some**: The contiguous U.S. and southern Canada had year-to-date temperatures at least 1.8 degrees F cooler than average.

More > Access NOAA's full climate report and download images from NCEI website.

Media contact

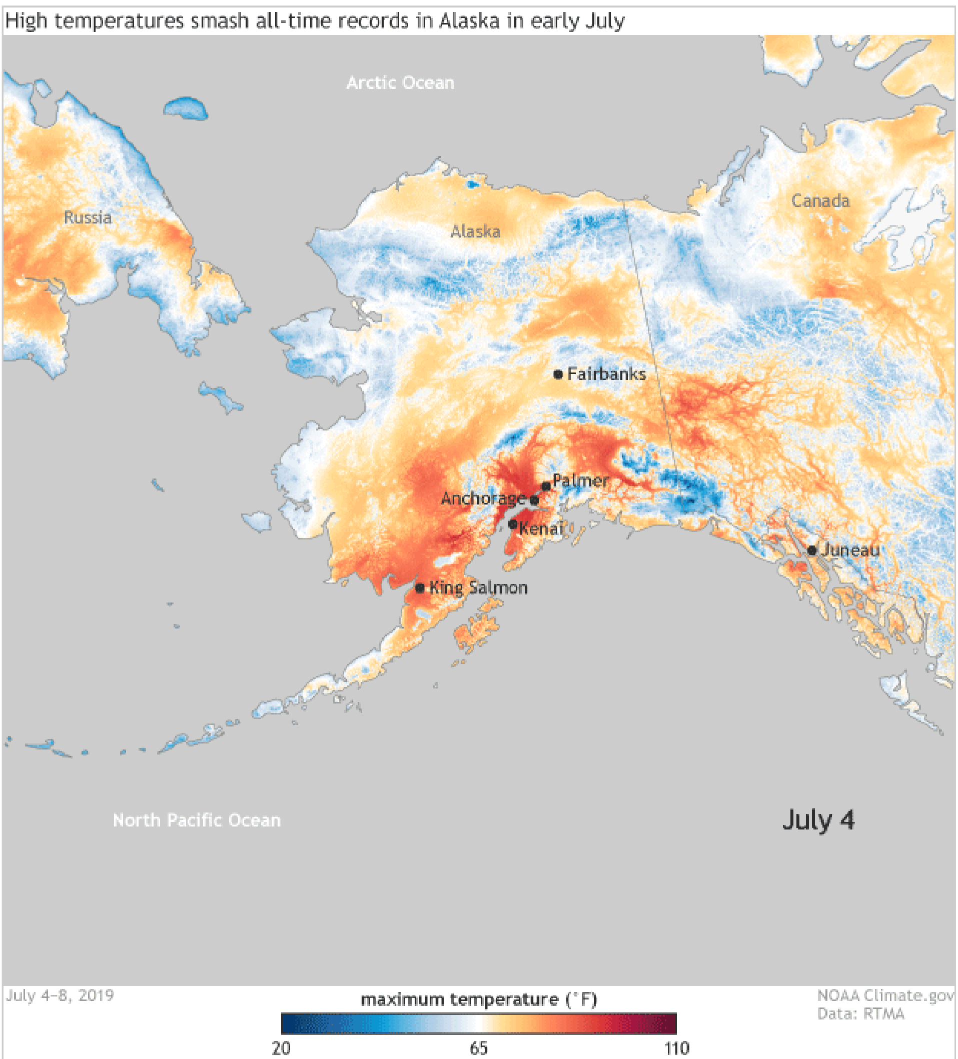
John Leslie, (301)-713-0214

Author:

Tom Di Liberto

Tuesday, July 16, 2019

Experiencing a summer heat wave with temperatures in the nineties is probably pretty normal for most people. But now imagine you live in Alaska. Not so normal anymore, is it? Alaska has just come to the end of a period of warmth that re-wrote the record books for multiple cities and communities across the state. And crazy enough, it was one of several jaw dropping climate events taking place across our largest state.



This animated gif shows the build-up of extremely high daytime high temperatures across Alaska from July 4–8, 2019. Temperatures cooler than 65°F are shades of blue; those warmer than 65°F are yellow, orange, and red. NOAA Climate.gov image, based on RTMA data.

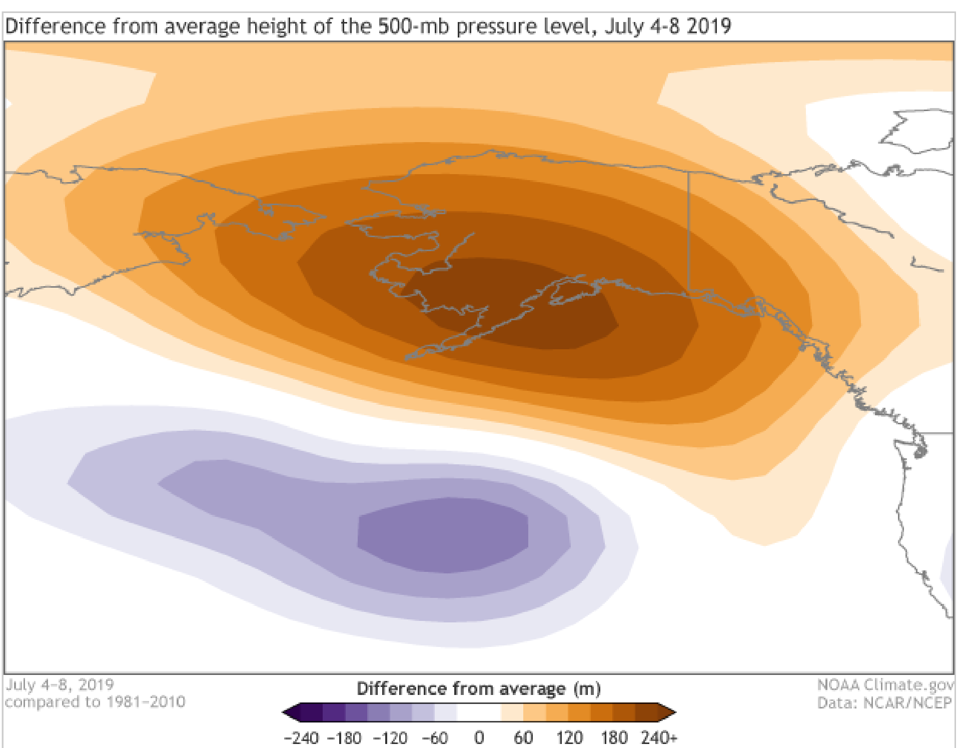
How hot? ALASKA hot.

Starting on the Fourth of July and lasting multiple days, temperatures across Alaska were 20 to 30 degrees above average in some locations. On July 4, all-time high temperature records were set in Kenai, Palmer, King Salmon, and Anchorage International Airport. The airport reached an astounding, for Alaska, 90°F, breaking the previous all-time record by 5°F! The average temperature in Anchorage during summer is normally in the mid-sixties. Anchorage, Talkeetna (which saw a July record daily high of 93°F), and King Salmon also observed their warmest week on record.

And the anomalous Arctic heat has not been short-lived. Through July 10, Juneau saw the high temperature reach at least 70°F for a record 17 consecutive days. In Anchorage, the highs have reached 80°F for a record six consecutiv days, doubling the previous record. And three of those days broke or tied the previous all-time record! The average high temperature from June 27 through July 8 was nearly 81°F, 5.5°F higher than the previous 12-day record. There's out of the ordinary, and then there is what has been happening in Alaska.

What was going on in the atmosphere?

A large dome of high pressure sat over the region for more than a week, keeping clouds away and allowing for muc warmer than average temperatures to persist. Over Anchorage, the average height of the 500mb pressure level in the atmosphere set a July record, and tied the July record in Fairbanks, according to Rick Thoman of Alaska Center for Climate Assessment and Policy. (Atmospheric pressure generally declines with altitude. A *pressure level* is the height above the surface at which the air pressure has fallen off to a given threshold, for example, 500 mb.)



A dome of high pressure squatted over Alaska July 4–8, 2019, keeping temperatures high and skies cloud-free. The 500-millibar pressure level—the altitude at which the air has thinned enough to drop the pressure to 500 millibars—was more than a hundred meters taller than average during the period. NOAA Climate.gov image, based on NCAR/NCEP Reanalysis data provided by ESRL Physical Sciences Division.

In a historical context, Alaska has a tendency for warmer than average conditions during the summer when El Niño conditions are present in the equatorial Pacific. However, this year's El Niño has been weak, making any connectioı to the current Alaskan heatwave an open question.

Of course, this heatwave is also occurring against the backdrop of human-caused climate change. And Alaska has often been on the forefront of impacts from climate change. In fact, since the 1950s, Alaska has been warming twic as fast as the global average, according to the Fourth National Climate Assessment. Since the late 1970s, the statewide annual average temperature has being increasing a rate of 0.7°F per decade. And starting in the 1990s, record-high temperature have occurred three times as often as record lows. Simply put, record-breaking high temperatures across Alaska are not uncommon nowadays.

You said this was one of several extreme events going on in Alaska? What are the others?

Where to begin? June was the second warmest on record for Alaska. The hot temperatures were accompanied by dr conditions, creating the perfect set-up for wildfires. Alaskan wildfires have burned well 1.6 million acres in 2019 through July 14, according to the Alaska Interagency Coordinate Center. Nearly 1,000,000 acres have burned just since July 3.

Numerous large fires billowed smoke across Alaska on July 8, 2019. Both Fairbanks, in central Alaska, and Anchorage, on the southern coast, were under the pall, creating unhealthy air quality. NOAA Climate.gov image, based on NOAA/NASA satellite data provided by Worldview.

The smoke from those wildfires has drifted towards the major population centers and choked the air across southern western and interior Alaska, leading to the first ever dense smoke advisory for Anchorage and some of the worst air quality in the world in Anchorage and Fairbanks. The smoke has made it difficult for the many people to cool off: air conditioning is rare, and opening the windows is a nonstarter.

Meanwhile, the well above average air temperatures have also coincided with, and were likely influenced by, well above average ocean temperatures around the state as well as record-low sea ice in the Bering and Chukchi seas. Overall, the total amount of sea ice in the Arctic is currently running neck and neck with 2012, the year which ended up with the lowest ice extent in the satellite record.

Climate change impacts and Alaskan resilience

These drastic changes to the environment in Alaska, tied to human-caused climate change, have cascading effects throughout the Arctic. The lack of sea ice can lead to increased storm surges, coastal flooding and erosion. The changing shorelines have already forced some communities to relocate.

Warm summers and ice-free seas can negatively impact marine mammals, fish, and crabs. For example, warm summers negatively impact the survival rates of young fish species like walleye pollock. Such conditions in the past have led to lowered catch limits for pollock—the nation's largest commercial fishery. The fish prefer a large summer cold pool of water at the bottom of the Bering Sea. Warm summers shrink this cold pool, jeopardizing young pollock's ability to survive through the following winter. The lack of ice allows the ocean and atmosphere to interact more, which can exacerbate ocean acidification; this drop in ocean pH due to the absorption of carbon dioxide which can affect marine mammal habitats, and the growth and survival of fish and crabs.

A warming climate also is likely to increase the number and size of wildfires across the state, degrading air quality and increasing smoke inhalation, both threats to human health. The cost of a warming climate for Alaska is projected to be between $3 to $6 billion between 2008 and 2030, according to the National Climate Assessment.

But Alaskans are not taking this threat sitting down. Instead, many communities are taking action to reduce their climate vulnerability. In Homer, a city driven by commercial fishing and summer tourism, government officials developed a climate action plan that included incorporating adaptation goals. In western Alaska, the Western Alaska Landscape Conservation Cooperative (LCC) helped develop a tool using satellite images to help residents, resource managers, and stewards of the land plan for the future by understanding how Alaska's coastline is changing now and will likely change in the future.

For more examples of how communities in Alaska are confronting climate change, head to the U.S. Climate Resilience Toolkit for many more case studies.

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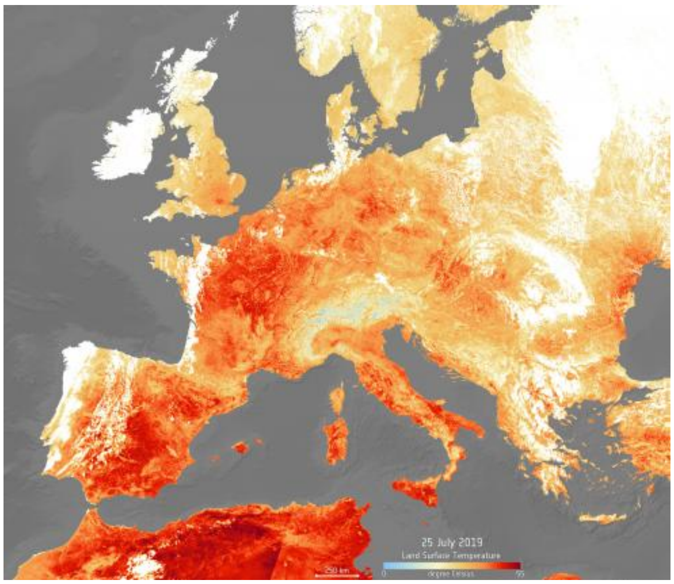


July matched, and maybe broke, the record for the hottest month since analysis began

Tags: Climate change Environment Public health

1 Published **1 August 2019**

According to new data from the World Meteorological Organization and the Copernicus Climate Change Programme, July matched, and maybe broke, the record for the hottest month since analysis began.

The data from the Copernicus Climate Change Programme, run by the European Centre for Medium-Range Weather Forecasts, is fed into the UN system by WMO. The figures show that July 2019 was on par with, and possibly marginally warmer than the previous warmest July, in 2016, which was also the warmest month ever.

The latest figures are particularly significant because July 2016 was during one of the strongest occurrence of the El Niño phenomenon, which contributes to heightened global temperatures. Unlike 2016, 2019 has not been marked by a strong El Niño.

“We have always lived through hot summers. But this is not the summer of our youth. This is not your grandfather’s summer,” said UN Secretary-General António Guterres, announcing the data in

Latest WMO News

IPCC climate change and land report marks critical contribution to global effort

8 August 2019

Monthly Weather Summary - July 2019 - Kingdom of Bahrain

6 August 2019

New York.

July 2019 was around 1.2°C warmer than the pre-industrial era, according to the data.

“All of this means that we are on track for the period from 2015 to 2019 to be the five hottest years on record. This year alone, we have seen temperature records shattered from New Delhi to Anchorage, from Paris to Santiago, from Adelaide and to the Arctic Circle. If we do not take action on climate change now, these extreme weather events are just the tip of the iceberg. And, indeed, the iceberg is also rapidly melting,” Mr Guterres said.

“Preventing irreversible climate disruption is the race of our lives, and for our lives. It is a race that we can and must win,” he underlined.

Heatwaves

Exceptional heat has been observed across the globe in recent week, with a string of European countries logging record highs temperatures that have caused disruption to transport and infrastructure and stress on people's health and the environment. As the heat dome spread northwards through Scandinavia and towards Greenland, it accelerated the already above average rate of ice melt.

“July has re-written climate history, with dozens of new temperature records at local, national and global level,” said WMO Secretary-General Petteri Taalas.

“The extraordinary heat was accompanied by dramatic ice melt in Greenland, in the Arctic and on European glaciers. Unprecedented wildfires raged in the Arctic for the second consecutive month, devastating once pristine forests which used to absorb carbon dioxide and instead turning them into fiery sources of greenhouse gases. This is not science fiction. It is the reality of climate change. It is happening now and it will worsen in the future without urgent climate action,” Mr Taalas said.

GEO-KOMPSAT-2A transition to operation - Korea Meteorological Administration

1 August 2019

The weather in Germany in June 2019 - Deutscher Wetterdienst

31 July 2019

Record-breaking temperatures in Israel July 2019

25 July 2019

What is trending

Climate change

Climate

Weather

WMO

Environment

Disaster risk reduction

Elsewhere on the WMO website

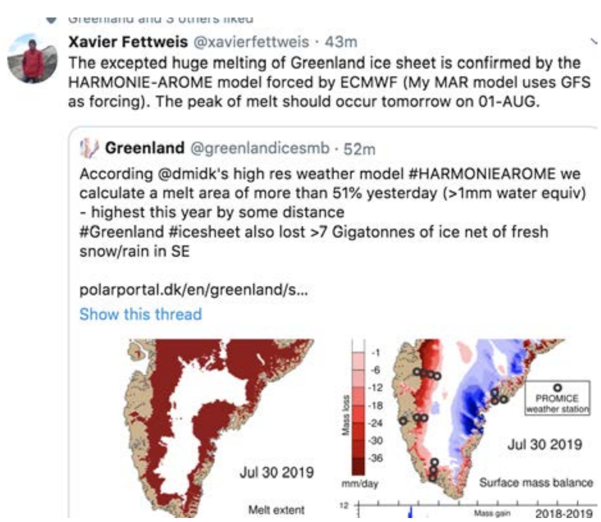
“WMO expects that 2019 will be in the five top warmest years on record, and that 2015-2019 will be the warmest of any equivalent five-year period on record. Time is running out to reign in dangerous temperature increases with multiple impacts on our planet,” he said.

Such heatwaves are consistent with what we expect from climate change and rising global temperatures.

“While July is usually the warmest month of the year for the globe, according to our data, it also was the warmest month recorded globally by a very small margin,” said Jean-Noël Thépaut, head of the Copernicus Climate Change Service. “With continued greenhouse gas emissions and the resulting impact on global temperatures, records will continue to be broken in the future.”

Belgium, Germany, Luxembourg, the Netherlands and the United Kingdom saw new national temperature records on 25 July, as weather maps were redrawn to include – for the first time – temperatures of above 40°C. In France, Paris recorded its hottest day on record, with a temperature of 42.6 °C at 16:32, an unprecedented value since the beginning of measurements.

The heatwave was caused by warm air coming up from North Africa and Spain and this was then transported from Central Europe to Scandinavia, Norway saw new station records on 27 July, and 28 locations had “tropical nights” above 20°C. The Finnish capital Helsinki set a new station record of 33.2°C on 28 July and in the south of Finland, Porvoo saw a temperature of 33.7°C.

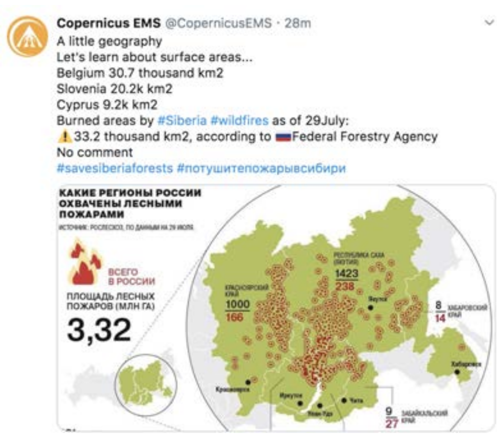


The anomalously high temperatures are expected to enhance melting of the Greenland ice sheet, which already saw an extensive melt episode between 11 and 20 June. The persistent high melt and runoff in the last few weeks means the season total is running near to the 2012 record high loss, according to Polar climate scientists monitoring the Greenland ice sheet.

The station Nord, situated 900 kilometres from the North Pole, measured a temperature of 16°C and in western Greenland, the station of Qaarsut (near 71°N) recorded a temperature of 20.6°C on 30 July. At Summit Camp station, at the peak of the ice sheet and at an altitude of 3200m, a temperature of 0.0°C was measured.

"It is important to remember that that any given day or year, Greenland ice sheet surface mass budget is a result largely of weather, though with the background climate trend affecting this," tweeted Ruth Mottram, a climate scientist with the Danish Meteorological Institute.

Over the weekend of 3-4 August, the ice melt continued, though the peak is over, the Danish Meteorological Institute tweeted, with 8.5 Gigatonnes lost on Saturday and 7.6 Gigatonnes on Sunday. An average day would see a loss of around 4 Gigatonnes, it said, noting that the levels do vary from day to day and year to year.


Copernicus EMS @CopernicusEMS · 28m
A little geography
Let's learn about surface areas...
Belgium 30.7 thousand km2
Slovenia 20.2k km2
Cyprus 9.2k km2
Burned areas by #Siberia #wildfires as of 29July:
⚠️33.2 thousand km2, according to 🇷🇺Federal Forestry Agency
No comment
#savesiberiaforests #потушитепожарывсибири

This will also impact Arctic sea ice, which where the loss of ice extent through the first half of July matched loss rates observed in 2012, the year which had the lowest September sea ice extent in the satellite record, according to the US National Snow and Ice Data Center.

The high temperatures also fanned wildfire activity in the Arctic, including in Greenland, Alaska and Siberia.

The Russian Federal Forestry Agency estimated that, as of 29 July, wildfires in Siberia had burned 33,200 square kilometres, with 745 active fires, causing massive ecological devastation and impacting air quality for hundreds of kilometres. The smoke was clearly visible from space.

first comprehensive scientific assessment of this key area.

It marks a critical contribution to efforts to curb greenhouse gas emissions and protect food security.

READ MORE: bit.ly/2MPcdI2 #SRCCL

1h

WMO | OMM
@WMO
On Monday 5 August, the first radiosonde was launched at the recently rehabilitated Nairobi Upper Air Station, through the contribution of the HIGHWAY Project.

To learn more about the HIGHWAY Project and the partners who have made it possible, see here: bit.ly/2yMUDw4

5h

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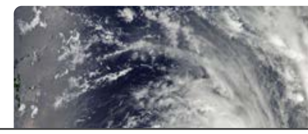
Investing in early

The European Centre for Medium-Range Weather Forecasts/Copernicus Atmosphere Monitoring Service estimated that July 2019 wildfire CO_2 emissions for the Arctic Circle totalled 75.5047 megatonnes, which is comparable to the 2017 annual fossil fuel emissions of Colombia. This was more than double July 2018 levels, and followed a record month in June.

“By burning vegetation, the fires also reduce the capacity of the biosphere to absorb carbon dioxide. Action against climate change necessitates rather that we should expand this capacity,” said Oksana Tarasova, Chief of WMO’s Atmosphere and Environment Research Division.



June-July heat

The July heatwave follows an unusually early and exceptionally intense heatwave in June, which set new temperature records in Europe and ensured that the month of June was the hottest on record for the continent, with the average temperature of 2°C above normal.

June was also the warmest June on record globally.

In parts of Europe, the heat was accompanied by below-average precipitation. On 31 July, WMO’s regional climate monitoring centre for Europe, operated by the German Weather Service, or Deutscher Wetterdienst, updated its Climate Watch advisory on drought. This provides guidance to national meteorological and hydrological services in issuing climate advisories for their territory.

“A continuation of drought conditions and below-normal precipitation in large parts of Central and Northeastern Europe. In these areas mostly only 60-80 % of normal precipitation was recorded in June, in some parts even less. There was also only scarce rainfall in July and forecasts show continued below-normal precipitation in most of the area with weekly deficits of partly 10-30mm for this week with a probability of 80% and higher,” it said.

In the wake of the heatwave, some European countries have faced very heavy precipitation, but it is not enough to undo the impact of drought conditions.

“Next week, above-normal precipitation will be expected over Central Europe, but this might not be sufficient to compensate for the rain deficits during the weeks before and therefore soils will be still dry. Northeastern Europe (Baltic countries and southern Finland) will still receive not more than below-normal to normal precipitation next week and therefore drought conditions are likely to continue. Drought conditions can result in harvest losses, forest fires, lack of animal food water restrictions, restrictions of ship traffic due to low water levels,“ said the Deutscher Wetterdienst.

During the heatwave, national meteorological and hydrological services issued heat alerts - including the top-level red alert - and, in some areas, fire warnings to minimize the risk to life and the environment. Heat-health action plans mobilized civil protection efforts across the region. Heat events kill thousands of people every year and often trigger secondary events such as wildfires and failures to electrical grids. Urbanization compounds the problem. Heat stroke, dehydration, cardiovascular and other temperature related diseases are major health risks.

The new absolute record of 42.6°C for Paris was recorded on 25 July at the centennial weather station in Paris-Montsouris, and broke the previous record dating back to 28 July 1947 with 40.4 °C. This temperature is typical of the average July temperature in Bagdad, Iraq. The night of 24/25 July was also exceptionally hot, with minimal temperatures above 25°C and even 28.3°C in a downtown Paris weather station. What is striking is the margin with which the records were beaten. Lille recorded 41.4°C, that’s nearly 4°C above the previous record. France set a new national temperature record of 46°C during the last heatwave on 28 June. It was only the second time Météo-France has ever issued red level warnings for a heatwave in France. The first time was during June's heatwave when several departments in the south were put on red alert. But it is unprecedented for Paris and the north of the country to be on a red alert for a heatwave. Thousands of hectares were burned by wildfires in northern France, where it is very unusual to see wildfires.

The Deutscher Wetterdienst described 25 July as "a day which will make weather history." Germany set a new national temperature record (provisional figure) of 42.6°C in Lingen, near the Dutch border, defeating the old record by 2.3 °C. There were 25 weather stations above 40 °C. The previous national temperature record was 40.3°C (5 July 2015).

The Netherlands broke a 75-year-old heat record (set in Aug 1944) with a temperature of 40.7°C at Gilye Rijen. Belgium also set a new national record of 41.8°C. Luxembourg set a new national record of 40.8°C.

On 25 July, temperatures in the United Kingdom reached 38.7°C at Cambridge Botanical Gardens, the highest ever officially recorded, breaking the previous record of 38.5°C recorded in Faversham, Kent, in August 2003, according to the Met Office.

Climate change and heatwaves

"Such intense and widespread heatwaves carry the signature of man-made climate change. This is consistent with the scientific finding showing evidence of more frequent, drawn out and intense heat events as greenhouse gas concentrations lead to a rise in global temperatures," according to Johannes Cullmann, Director of WMO's Climate and Water Department. WMO will submit a five year report on the state of the climate 2015-2019 to the UN Climate Action Summit in September.

Many scientific studies have been conducted on the links between climate change and heatwaves.

Human-influenced climate change is likely to have added 1.5-3 ºC to the extreme temperatures recorded during Europe's July 2019, according to a report by World Weather Attribution, which underlined the manifold risks.

"Heatwaves the height of summer pose a substantial risk to human health and are potentially lethal. This risk is aggravated by climate change, but also by other factors such as an aging population, urbanisation, changing social structures, and levels of preparedness. The full impact is only known after a few weeks when the mortality figures have been analysed. Effective heat emergency plans, together with accurate weather forecasts such as those issued before this heatwave, reduce impacts and are becoming even more important in light of the rising risks," it said.

"It is noteworthy that every heatwave analysed so far in Europe in recent years (2003, 2010, 2015, 2017, 2018, June 2019, this study) was found to be made much more likely and more intense due to human-induced climate change. How much more depends very strongly on the event definition: location, season, intensity and duration. The July 2019 heatwave was so extreme over continental Western Europe that the observed magnitudes would have been extremely unlikely without climate change," it added.

In its In its Fifth Assessment Report, released in 2014, the Intergovernmental Panel on Climate Change said that "it is very likely that human influence has contributed to the observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century. It is likely that human influence has more than doubled the probability of occurrence of heat waves in some locations."

In its 2018 report on Global Warming of 1.5°C, the IPCC said that climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5 °C and increase further with 2 °C.

Limiting warming to 1.5°C rather than 2°C could result in 420 million fewer people being exposed to severe heatwaves, it said.

Between 2000 and 2016, the number of people exposed to heatwaves was estimated to have increased by around 125 million persons, as the average length of individual heatwaves was 0.37 days longer, compared to the period between 1986 and 2008, according to the World Health Organization.

Many countries have issued national climate assessments and scenarios which underline the close connection between climate change and heat.

For instance, the UK State of the Climate report showed an increase

in higher maximum temperatures and longer warm spells. The hottest day of the year for the most recent decade (2008-2017) has increased by 0.8°C above the 1961-1990 average. Warm spells have also more than doubled in length – increasing from 5.3 days in 1961-90 to over 13 days in the most recent decade (2008-2017).
The summer of 2018 was the joint warmest on record for the UK as a whole and the hottest ever for England. The Met Office research showed that human-induced climate change made the 2018 record-breaking UK summer temperatures about 30 times more likely than it would have been naturally. By 2050 these are expected to happen every other year.

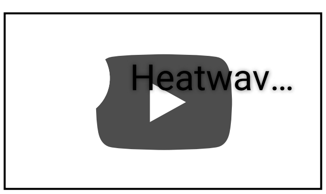
France has also reported an increase in the frequency and intensity of heatwaves over the past 30 years, according to Météo-France, in an observation echoed elsewhere in Europe .

Swiss climate change scenarios warn that if greenhouse gas emissions continue to increase, by the middle of this century, average summer temperatures may be up to 4.5 °C higher than now.

"The increases in the highest temperatures are even more pronounced than for the average seasonal temperatures. By 2060, the hottest days in an average summer could be up to 5.5 °C higher than they are today. This is explained in part by the fact that less water will be evaporating and cooling the ground because there will be less moisture in the soil," says the Swiss report.

"The regions of Europe that surround the Mediterranean Sea, including Switzerland, are affected by some of the most severe increases in temperature extremes worldwide. This trend has been apparent even over recent decades and is very likely to continue into the future," it says.

Multimedia



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The Washington Post

Capital Weather Gang

July was Earth's hottest month on record, beating or tying July 2016

A sizzling Europe and warm Arctic helped propel the global average temperature to new heights.

By Andrew Freedman
August 5

(This story has been updated with new data released on August 5)

July was Earth's hottest month ever recorded, coming in slightly higher than the previous warmest month, which was July 2016, according to data from the Copernicus Climate Change Service. This European climate agency said in a statement Monday that July 2019 was 1.01 degrees (0.56 Celsius) above the 1981 to 2010 average, "which is close to 1.2 Celsius above the preindustrial level as defined by the Intergovernmental Panel on Climate Change (IPCC)," the agency said in a statement.

The month beat July 2016 by about 0.07 degrees (0.04 Celsius).

On Thursday, U.N. Secretary General António Guterres cited preliminary Copernicus data at a news conference as an example of why more ambitious action to cut planet-warming greenhouse gases is needed.

"We have always lived through hot summers. But this is not the summer of our youth. This is not your grandfather's summer," Guterres said as he called upon countries to rapidly cut their carbon emissions.

Through the Paris climate agreement, world leaders have committed to preventing the planet from warming more than 3.6 degrees (2 Celsius), and are trying to keep global warming even more limited, to 2.4 degrees (1.5 Celsius), relative to preindustrial levels.

July's numbers clearly indicate that the planet is already lapping up against the lower threshold. It also means the world is headed for a top 3 warmest year, up from a top-5 warmest ranking earlier in the year. The period from 2015 to 2019 will go down in history as the warmest five-year period on record since the late 19th century and, probably, well before that.

A month of extremes

The temperature spike was driven largely by record warmth in Western Europe, noteworthy warmth stretching across the Arctic that culminated in one of the most significant melt events ever recorded in Greenland at the end of the month.

During the entire month of July, the Greenland ice sheet poured 197 billion tons of water into the North Atlantic in July alone, enough to raise global sea levels by 0.5 millimeters, or 0.02 inches.

Noteworthy extreme weather events during July include a widespread heat wave in Western Europe that set national temperature records in Britain, Germany, the Netherlands and Belgium. Paris soared to its highest temperature ever recorded, 108.7 degrees (42.6 Celsius).

Globally, Copernicus found that temperatures were well above average across Alaska, Baffin Island and Greenland, parts of Siberia, the central Asian Republics and Iran, as well as large parts of Antarctica. In addition, nearly the entire continents of Africa and Australia were warmer than average. Parts of western Canada and Asia saw cooler-than-average conditions.

A study released Friday from a group of researchers that study climate change's possible role in extreme weather and climate events found that climate change made this heat wave at least 10 times as likely to occur, compared with a climate without an increased amount of greenhouse gases, such as carbon dioxide.

The report, from World Weather Attribution, also found that by raising global average surface temperatures, climate change boosted the heat wave's temperatures by up to 5.4 degrees (3 Celsius).

"The July 2019 heat wave was so extreme over continental Western Europe that the observed magnitudes would have been extremely unlikely without climate change," the report, which has not been peer-reviewed by an academic journal, states.

Elsewhere during July, a record flare-up of simultaneous, large and persistent wildfires erupted from Siberia to northern Alaska. These fires have consumed millions of acres and emitted large amounts of greenhouse gases, constituting a positive feedback loop by worsening future global warming.

Arctic sea ice was at a record low for the month, and it's possible, though not assured, that 2019 will have a record low for sea ice extent in the Arctic. The previous record was set in 2012, and numerous scientific assessments show the Arctic will be seasonally ice-free as early as the 2040s under continued global warming, even if emissions of greenhouse gases are curtailed in the near-term.

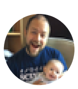
Key caveats

Copernicus, a climate services program from the European Union, reports its monthly temperature rankings earlier than other temperature tracking agencies such as NASA, and its rankings may differ slightly. This is because it uses a different source for its data.

The ranking was generated using what are called reanalysis records, which take data collected for weather forecasting and feed many different observational variables into a weather model for each hour of every month.

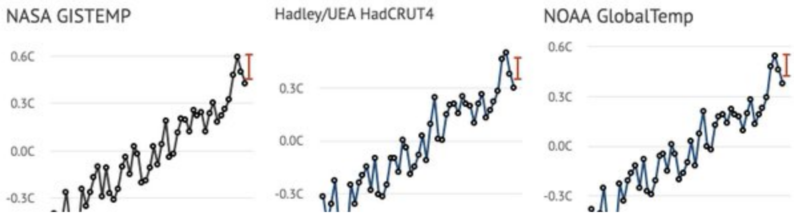
Reanalysis data tends to allow for faster reporting of monthly global temperatures, but it still must be checked against observational records gathered from networks of thousands of measuring sites worldwide.

Those readings will be reported by NASA, NOAA and other agencies in the coming weeks, but they're not likely to differ significantly from Copernicus. These agencies may, however, give the month a slightly different ranking.



Zeke Hausfather
@hausfath

July 2019 will be the warmest month ever recorded in the @CopernicusECMWF ERA5 dataset, and likely either the warmest or second warmest on record for other temperature datasets. 2019 as a whole is on-track to be the second warmest year on record after the 2016 super-El Nino event



24 5:20 PM - Aug 1, 2019

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The monthly temperature record comes without the added warming influence of a strong El Niño event in the tropical Pacific Ocean. Such events add heat to the oceans and atmosphere and help boost planetary temperatures. The 2016 record, for example, occurred during a year with a strong El Niño. The lack of a significant El Niño this July shows how much easier it is to set temperature records on a rapidly warming planet.

"The fact that summer 2019 is as warm (or warmer) than 2016 shows that in a few years the relentless march upward of temperatures driven by increasing atmospheric greenhouse gas concentrations can make what was an exceptionally warm El Niño event into a typical summer," said Zeke Hausfather, a climate scientist with Berkeley Earth, via email.

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The Greenland ice sheet poured 197 billion tons of water into the North Atlantic in July alone

Earth's temperatures are skewed hot. Expected cool weather in a few spots doesn't change that.

What exactly are heat domes and why are they so long-lasting and miserable?

July was the warmest month on record in Boston, Portland, Hartford, and Manchester

Andrew Freedman
Andrew Freedman edits and reports on weather, extreme weather and climate science for Capital Weather Gang. He has covered science, with a specialization in climate research and policy, for Axios, Mashable, Climate Central, E&E Daily and other publications. He was among the first contributors to Capital Weather Gang, starting in 2004. Follow

SCIENCE

July was the hottest month in history

Chelsea Harvey, E&E News reporter • Published: Tuesday, August 6, 2019

People cooling off in a pool in Rotterdam on July 23 as a heat wave blanketed the Netherlands and most of Europe. Robin Utrecht/Sipa USA/Newscom

In what may be the week's most unsurprising news, scientists have officially announced that this past July was the hottest month ever recorded on Earth.

According to data released yesterday by the Copernicus Climate Change Service, a program of the European Centre for Medium-Range Weather Forecasts, last month edged out July 2016, the previous record-holder, for the title.

Last month was 0.04 degree Celsius, or about 0.07 degree Fahrenheit, warmer than July 2016. And it was more than 1 F warmer than the average July between 1981 and 2010.

The news follows a spate of record-breaking temperatures across Europe and the Arctic, the product of a persistent heat wave that roasted European cities and spurred historic melting on the Greenland ice sheet (***Climatewire***, Aug. 2).

While these regions experienced some of the most striking extremes, many other parts of the world also saw above-average temperatures last month. Much of the United States, most of Africa and Australia, and parts of Central Asia were also hotter than normal. Even Antarctica was "less cold" than usual for July, the agency reported.

Scientists have already begun to link last month's extreme heat to the influence of climate change.

A **study** published last week by collaborative research group World Weather Attribution concluded that the influence of climate change probably made the most recent heat wave, which swept across Western Europe and Scandinavia during the last week of July, up to 3 C (5.4 F) hotter and 10 to 100 times more likely to occur, depending on the location.

It's a rapid study that has not yet been subject to peer review, although the research was conducted by some of the world's foremost experts in extreme event attribution science. It's also not the first such study they've released this summer.

A few weeks ago, the same research group conducted a rapid attribution **study** on an earlier heat wave, which struck parts of Europe at the end of June. Focusing on France, the study found that climate change has increased the probability of such an event by at least a factor of five, although it could be a factor of 100 or more.

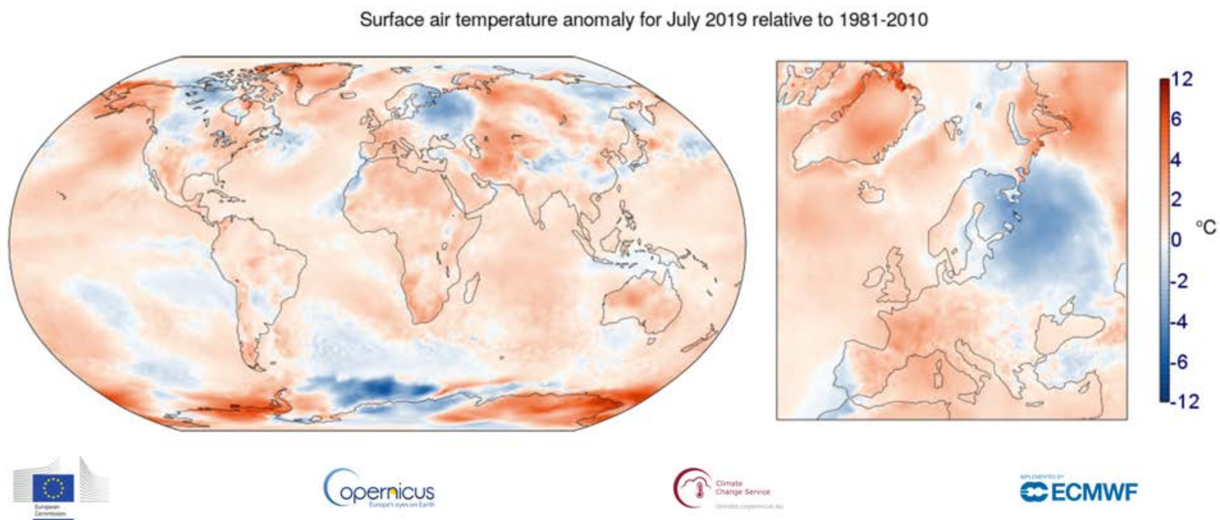
The group also noted, "Every heatwave occurring in Europe today is made more likely and more intense by human-induced climate change." It's just the amount that differs from one event to the next.

Scientists have already pegged 2019 for one of the top three hottest years on record. NOAA last month **pointed out** that 2019 was so far tied with 2017 for the second-hottest year on record.

Twitter: **@chelseaeharvey** | Email: **charvey@eenews.net**

Surface air temperature for July 2019

In Europe July temperatures were just above to the 1981-2010 average, with large differences across the continent. Western Europe was above average, largely due to the short, but very intense heatwave in the last week of the month. The eastern parts of the continent were generally below average, particularly so in the north-east. Globally temperatures were the most above the 1981-2010 average over Alaska, Baffin Island and Greenland, parts of Siberia, the central Asian Republics and Iran, as well as large parts of Antarctica. Africa and Australia were above average over almost all of each continent. Areas with temperatures below the 1981-2010 average include mid-western Canada and parts of Asia, and over the Weddell Sea and inland from there over Antarctica.



Surface air temperature anomaly for July 2019 relative to the July average for the period 1981-2010. Data source: ERA5. (Credit: ECMWF, Copernicus Climate Change Service)

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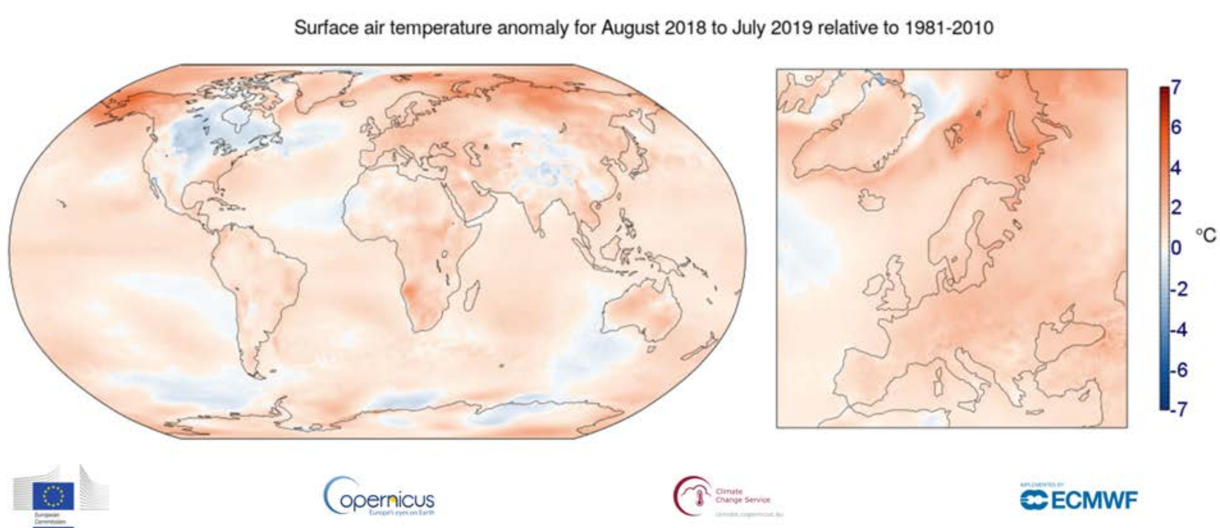
The average temperature over Europe in July 2019 was just above the 1981-2010 average for the month. It was warmer than normal over western Europe, except for south-western Iberia, but cooler than normal over the east of the continent, particularly the north-east. The first half of the month had a wider area of below-normal temperature but a short, very intense heatwave towards the end of the month over western Europe raised averages there for the month as a whole. Several countrywide and capital-city records for maximum temperature were broken during the heatwave, as detailed in the information that has been collated and made available by the World Meteorological Organization.

Elsewhere, temperatures were markedly above average over Alaska, where all-time temperature records were broken, over Baffin and Ellesmere Islands, where the record at the northernmost settlement Alert was broken, and most of Greenland, where monitoring indicated a high rate of ice-sheet mass loss due to melting. Much of Antarctica was less cold than usual for July. Other regions with temperatures substantially above normal include much of the USA and eastern Canada, Iran, the Central Asian Republics and a swathe of Siberia to the north, and most of Africa and Australia.

Following generally warm and dry conditions in June, a high level of wildfire activity has continued in eastern Russia and Alaska.

Temperatures were notably below average over mid-western Canada and parts of Asia, and over the Weddell Sea and inland from there over Antarctica. Other land regions tended to be moderately warmer than average, but some experienced conditions that were a little cooler than average.

Although regions of below-average temperature occurred over all major oceans, marine air temperatures were predominantly higher than average.



Surface air temperature anomaly for August 2018 to July 2019 relative to the average for 1981-2010. Data source: ERA5. (Credit: ECMWF, Copernicus Climate Change Service)

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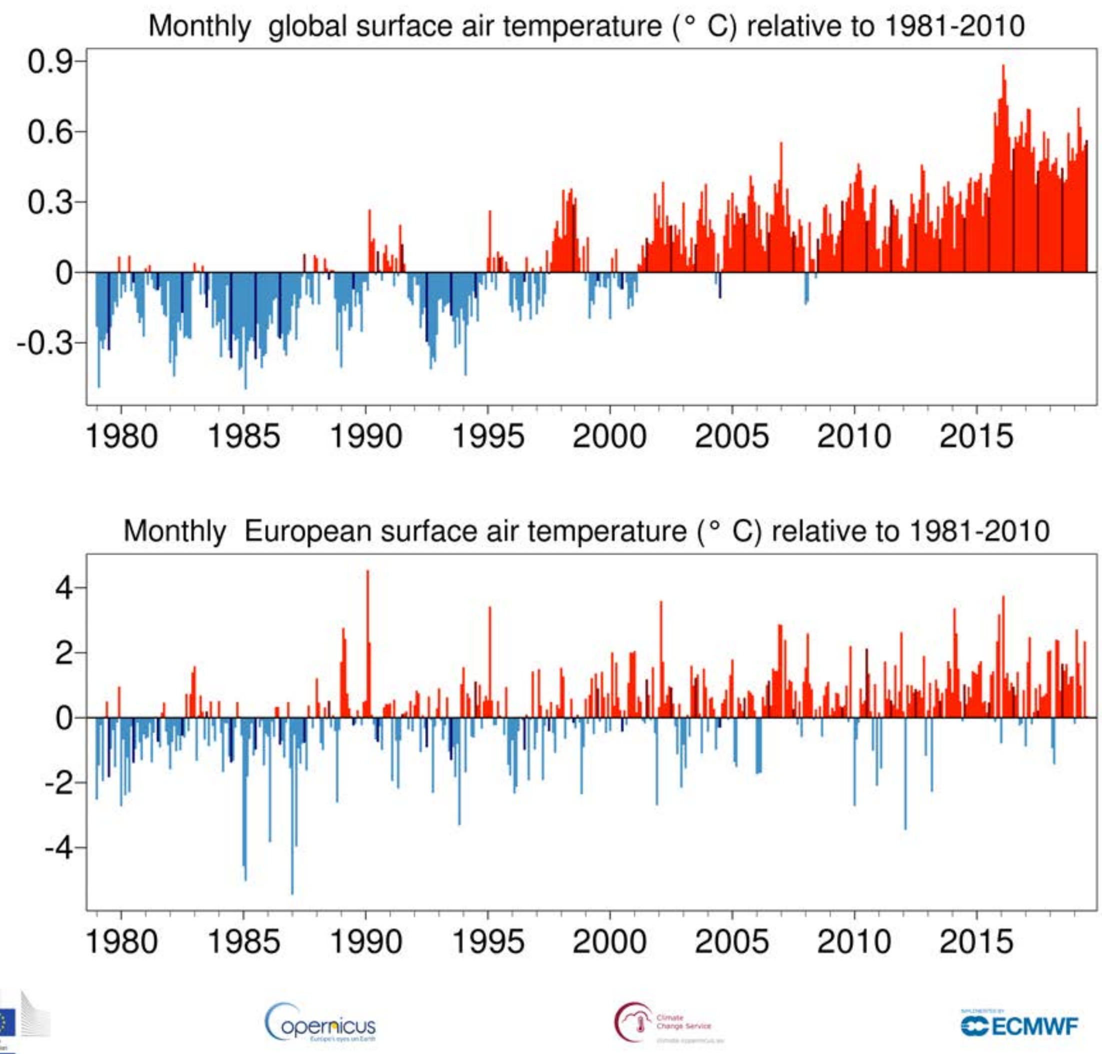
Temperatures averaged over the twelve-month period from August 2018 to July 2019 were:

- much above the 1981-2010 average over most of the Arctic, peaking over and near Alaska;
- above average over almost all of Europe;
- above average over other areas of land and ocean, especially so over central northern Siberia, north-eastern China, the Middle East, south-east Asia, Australia, central and southern Africa and some parts of the Antarctic;
- below average over several land and oceanic areas, including much of Canada, parts of the North Atlantic and South Pacific, and to the south-west of Australia.



Monthly global-mean and European-mean surface air temperature anomalies relative to 1981-2010, from January 1979 to July 2019. The *darker coloured bars denote the July values. Data source: ERA5. (Credit: ECMWF, Copernicus Climate Change Service)*

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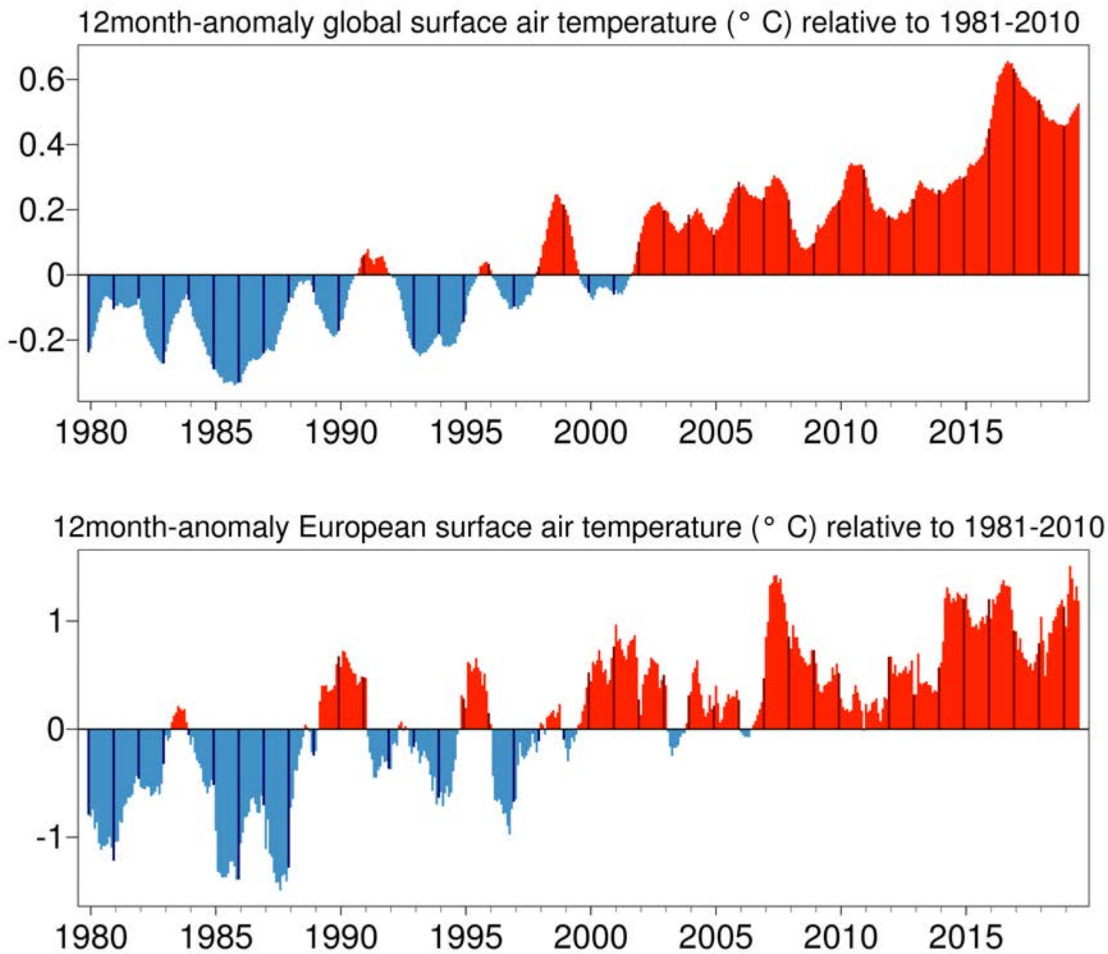
The global temperature was substantially above average in July 2019, sufficient for the month to become by a narrow margin the warmest July in this data record. July 2019 was:

- 0.56°C warmer than the average July from 1981-2010;
- about 0.04°C warmer than July 2016, the previous warmest July in this data record.

July is typically the warmest month of the year in the global average. July 2016 was previously the warmest of any month on record in absolute terms. It has now been surpassed by July 2019, albeit by a margin that is small compared with the typical differences between datasets for previous Julys. Further discussion and illustrations can be found here.

The largest anomalies in European-average temperatures occur in wintertime, when values can vary substantially from month to month. June 2019 was nevertheless substantially warmer than average, by more than 2.3ºC. In contrast, July 2019 had a European-average temperature less than 0.1ºC above the 1981-2010 norm.



Running twelve-month averages of global-mean and European-mean surface air temperature anomalies relative to 1981-2010, based on monthly values from January 1979 to July 2019. The darker coloured bars are the averages for each of the calendar years from 1979 to 2018. Data source: ERA5. (Credit: ECMWF, Copernicus Climate Change Service)

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Averaging over twelve-month periods smooths out the shorter-term variations. Globally, the twelve-month period from August 2018 to July 2019 was 0.53°C warmer than the 1981-2010 average. The warmest twelve-month period was from October 2015 to September 2016, with a temperature 0.66°C above average. 2016 is the warmest calendar year on record, with a global temperature 0.63°C above that for 1981-2010. The second warmest calendar year, 2017, had a temperature 0.54°C above average, while the third warmest year, 2018, was 0.46°C above the 1981-2010 average.

0.63°C should be added to these values to relate recent global temperatures to the pre-industrial level defined in the IPCC Special Report on "Global Warming of 1.5°C". Monthly temperatures over the past twelve months have been mostly in the range from 1.0 to 1.1°C above this pre-industrial level. The temperature for July 2019 is close to 1.2°C above the level.

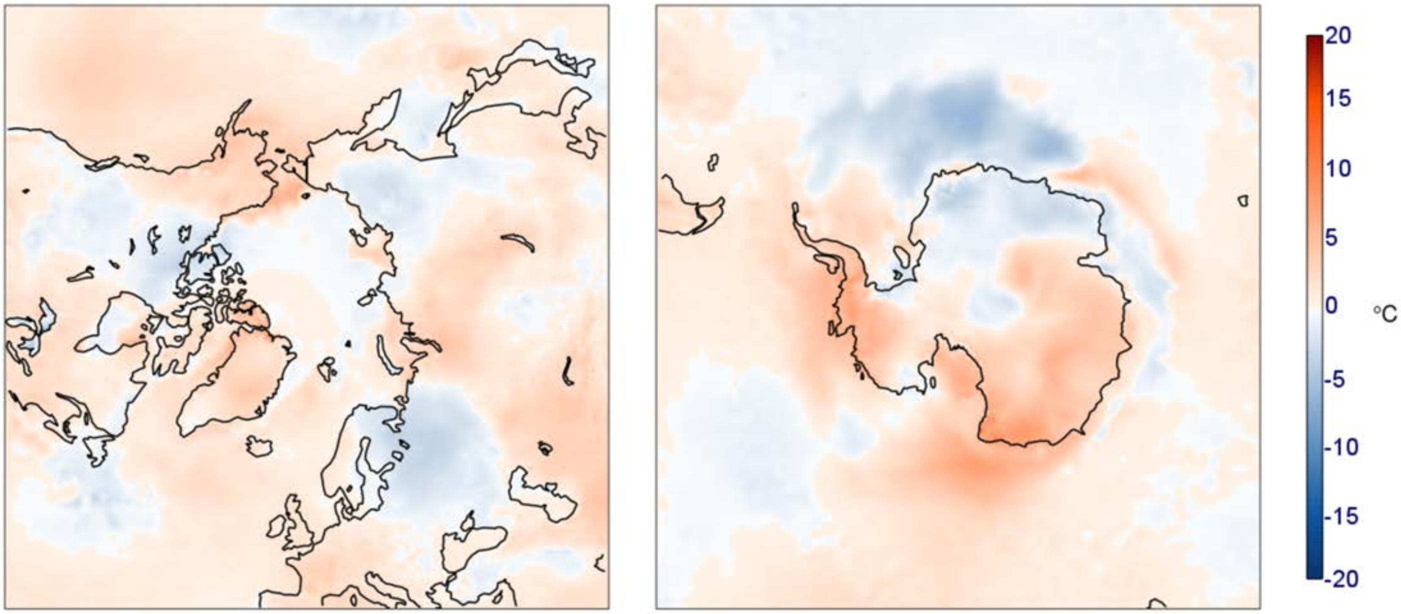
The spread in the global averages from various temperature datasets has been unusually large over the past two or more years. During this period the twelve-month average values presented here are higher than those from several independent datasets, by between 0.05°C and 0.15°C for the twelve months for which spread is largest. This is due partly to differences in the extent to which datasets represent the relatively warm conditions that have predominated over the Arctic and the seas around Antarctica. Differences in estimates both of sea-surface temperature elsewhere and of temperatures over land outside the Arctic have been further factors. There is nevertheless general agreement between datasets regarding:

- the exceptional warmth of 2016, and the warmth also of 2015, 2017 and 2018;
- the overall rate of warming since the late 1970s;
- the sustained period of above-average temperatures from 2001 onwards.

There is more variability in average European temperatures, but values are less uncertain because observational coverage of the continent is relatively dense. Twelve-month averages for Europe were at a high level from 2014 to 2016. They then fell, but remained 0.5°C or more above the 1981-2010 average. Twelve-month averages have risen since then. The latest average, for the period from August 2018 to July 2019, is close to 1.2°C above the 1981-2010 norm. The warmest such period, from April 2018 to March 2019, was 1.5°C above average.

The average surface air temperature analysis homepage explains more about the production and reliability of the values presented here.

Surface air temperature anomaly for July 2019 relative to 1981-2010



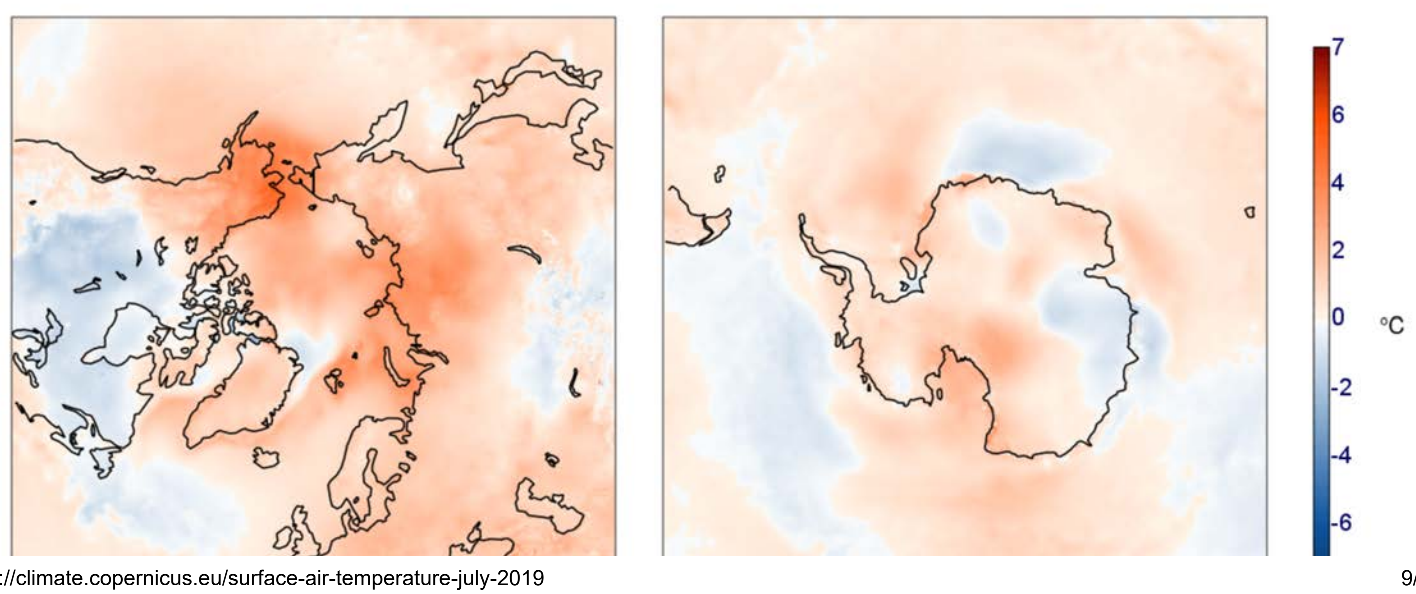
SURFACE AIR TEMPERATURE MAPS OF PREVIOUS MONTHS

YOU CAN FIND MORE INFORMATION ABOUT THE MAPS AND THE DATA ON OUR SURFACE AIR TEMPERATURE ANALYSIS PAGE.

MONTHLY CLIMATE UPDATE

FEATURED STORIES

Surface air temperature anomaly for August 2018 to July 2019 relative to 1981-2010



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Capital Weather Gang

Stifling heat to rule the weekend for two-thirds of the Lower 48, with records in jeopardy

By Andrew Freedman
July 20

Torrid levels of humidity combined with high temperatures in the upper 90s to low 100s are combining to form dangerous heat conditions across the United States. The weather map shows a stretch of magenta hues, denoting heat warnings, stretching from Texas northward to Chicago and east all the way to northern New England.

The heat index, which measures the combined effect of heat and humidity on the human body, is predicted to reach rare territory of 110 to 115 degrees or higher across highly populated areas on Saturday, including Washington, Baltimore, Philadelphia and New York. On Friday, some of the highest heat indexes were found in Iowa, where evapotranspiration from cornfields (also known as "corn sweat") led to heat indexes as high as 121 degrees.

The heat wave is prompting cities like New York to cancel outdoor events, open cooling shelters and warn residents that the hot weather can be deadly. A subway outage at rush hour on Friday evening compounded the misery in the Big Apple, as temperatures on crowded subway platforms climbed well into the 90s.

Extreme heat typically is the biggest weather killer, outnumbering hurricanes, tornadoes and flooding. It's a sneaky killer, too, as heat stroke can mimic other illnesses due to symptoms like confusion, nausea and rapid heartbeat.

[923a] Here are today's forecast high temps vs. record high temps. Boston, Hartford, and Worcester are all on track to set new records for July 20th. pic.twitter.com/by2KvaCTTr

— NWS Boston (@NWSBoston) July 20, 2019

The heat poses a particular risk to the elderly, children, athletes practicing outdoors, outdoor workers and anyone without air conditioning. Pets left in areas without air conditioning, including cars, can quickly succumb to the heat.

This heat wave has already proved deadly, taking the life of ex-Giants offensive lineman Mitch Petrus Thursday in Little Rock.

In many cities affected by the heat, public fountains have turned into oases of relief, zoos are taking precautions to keep their animals cool, and public swimming pools are staying open late.

Electric utilities are seeing energy demands spike as customers turn up their air conditioners. In New York, Con Edison has crews working longer shifts, and Mayor Bill de Blasio (D) has urged building owners to set thermostats to 78 degrees to ease the burden on the grid.

One of the hallmarks of this extreme weather event is the extremely warm overnight low temperatures because extraordinarily high dew points, plus urban heat islands that trap heat in cities, are preventing the temperature from falling back to comfortable levels. This is increasing the public health risks because people need several hours of respite in a 24-hour period to get through multiple days of heat stress.

On Friday, Rockford, Ill., tied its record for the warmest all-time overnight low temperature of 81 degrees. On Saturday morning in Washington, the temperature failed to fall below 81 degrees, missing the daily record by 1 degree.; the forecast low for Sunday morning is in the low 80s once again.

Providence, R.I., probably set a record minimum temperature for Saturday, according to meteorologist Jason Furtado, with a low of 77 degrees. New York City's Central Park also tied a record low on Saturday morning, as the temperature failed to drop below 82 degrees, with an overnight minimum heat index of 87.

Saturday forecast city by city

St. Louis — Forecast high: 97. Peak heat index: 109.
Chicago — Forecast high: 95. Peak heat index: 108.
Cincinnati — Forecast high: 96. Peak heat index: 106.
Detroit — Forecast high: 98. Peak heat index: 111.
Washington — Forecast high: 100. Peak heat index: 111.
Philadelphia — Forecast high: 98. Peak heat index: 111.
New York — Forecast high: 99. Peak heat index: 110.
Boston — Forecast high: 97. Peak heat index: 104.

Derecho tears across Minnesota

At the northern edge of the heat dome, across Minnesota, Wisconsin and Michigan, a record strong jet stream for this time of year helped to spark a long-lived complex of damaging thunderstorms known as a "derecho." Winds in this weather system likely exceeded 80 miles per hour, leaving a nearly 500-mile-long trail of downed trees and power lines.

#GOESR/#GOESEast imagery thus far of the monster MCS (likely derecho) moving across the Upper Midwest. First visible/infrared sandwich imagery through sunset, gravity waves galore as the cirrus canopy grows. #mnwx #wiwx pic.twitter.com/CZP8jQuujE

— William Churchill (@kudrios) July 20, 2019

On Saturday morning, more than 200,000 people were without power in these three states, cutting out access to air conditioning during the heat event.

Such complexes of storms tend to occur along the edges of hot air masses during exceptional heat events. Meteorologists refer to this phenomenon as the "ring of fire," taking inspiration from geologists who study the volcanoes that ring the Pacific Ocean.

More severe thunderstorms are possible in the Upper Midwest again today, particularly across eastern Wisconsin and central Michigan.

Climate change raises the odds of extreme heat events

Heat waves such as this one are becoming more likely to occur, more severe and longer-lasting as the climate warms due to human activities. One of the most robust conclusions of climate science, rooted in statistics and physics, is that, as you increase the global average temperature, the odds of hot extremes increase at a disproportionately high rate.

For example, the warm overnight low temperature records that are being tied or broken during the ongoing event are part of a long-term trend in the United States, in which warm summertime lows are increasing at nearly twice the rate as daytime high temperatures. This is playing out in multiple locations across the country.

Climate change attribution studies, which are the equivalent of global warming crime scene investigations that seek to identify the role that warming played, if any, in an extreme event, have shown that global warming has often increased the chances for exceptional heat events.

For example, one study published in 2019 found the record-breaking summer heat wave in Japan during 2018 “could not have happened without human-induced global warming.” A recent rapid attribution analysis, which has not yet been published in a peer reviewed science journal, showed that the early summer heat wave in France was made at least five times more likely than if human-caused warming had not occurred.

In addition, the 2018 National Climate Assessment found that heat waves are on the increase in the United States and have been since the 1960s, though the 1930s still stand out as having the most extreme heat events on record in the nation, due to weather variability and land use practices at the time.

Jason Samenow contributed to this story.

Andrew Freedman

Andrew Freedman edits and reports on weather, extreme weather and climate science for Capital Weather Gang. He has covered science, with a specialization in climate research a

‘It never stops’: US farmers now face extreme heat wave after floods and trade war

Published Sat, Jul 20 2019 8:00 AM EDTUpdated Sat, Jul 20 2019 10:01 PM EDT
Emma Newburger@emma_newburger

Key Points

- In the past year, torrential rains have dumped water on U.S. farmers’ lands, destroying acreage and delaying crops from getting planted on time.
- Now, farmers face yet another hurdle: a stifling heat wave that’s spreading across the United States, expected to be the worst in the farm states including Oklahoma, Kansas, Nebraska, Missouri, Iowa and Illinois.
- “Every time we think we catch a break, it’s just another issue we have to solve,” Adam Jones, a 28-year-old organic farmer from Central Illinois, tells CNBC.

Farmer walks through his soy fields in Harvard, Illinois.
Nova Safo | AFP | Getty Images

In the past year, torrential rains have dumped water on U.S. farmlands, destroying acreage and delaying crops from getting planted on time.

Now, farmers face another hurdle: a stifling heat wave that's spreading across the United States and is expected to be the worst in the farm regions, including Oklahoma, Kansas, Nebraska, Missouri, Iowa and Illinois.

"Every time we think we catch a break, it's just another issue we have to solve," Adam Jones, a 28-year-old organic farmer from Illinois, told CNBC. "It seems like it never stops."

"This year, there are farmers who are the first in their family for three generations to not grow crops on their fields," he continued.

"That's really hard on pride — to not be able to do the one thing you're set out to do in life."

Heat warnings and advisories are in effect across the country. Dangerously hot temperatures are expected to rise above 100 degrees, including 120 record-high minimum temperatures in some areas, according to the National Weather Service.

The moisture from former Hurricane Barry, which dumped rain in the Southeast last week, is also exacerbating humidity levels as the heat index is forecast to climb across the country.

High heat and humidity have farmers across the Midwest stressed about their already vulnerable corn and soybean crops.

One extreme to another

The record flooding in the Midwest and Great Plains has caused at least $3 billion in damage, left millions of acres unseeded and put crops that were planted late at high risk for damage from severe weather during the growing season.

As a result, crops are less able withstand extreme changes in weather. A heat wave would cause wet soil to crust and compact, stunting root development and ruining crops, according to Arlan Suderman, chief commodities economist with INTL FCStone in Kansas City, Missouri.

"There's a high level of stress right now," Suderman said. "We've never planted this late in the year, and the conditions in which the crops were planted make it more difficult for them to withstand heat and dryness."

VIDEO4:2104:21
Agricultural prices rise as heavy floods hit the Midwest
Squawk Box

Aaron Keilen, an organic farmer from Portland, Michigan, was unable to plant on 75% of his land this year due to flooding, and was delayed in planting his crops until the last week of June, over a month later than usual. The delay will hurt his yield; after May 15, each day a farmer doesn't plant crops means a roughly 1% reduction in corn yields. For soybeans, each day after June 1 means a 1% reduction in yields, Keilen said.

Now, Keilen said the heat wave is stunting the growth of his crops, which were planted later than usual in wet soil. While his crop insurance will be just enough to keep him in business, he worries about lost profit.

"We've never seen a year like this. It's been so hard," Keilen said. "But we see people coming together, churches offering prayer services for farmers and coming together to support each other."

Nationwide, farmers are expected to harvest the smallest corn crop in four years, according to the U.S. Department of Agriculture. The USDA in June lowered soybean and corn production estimates, and after widespread planting delays this spring, will release a report in August with updated plantings figures for corn and soybeans.

Puddles are seen in farm fields as heavy rains caused unprecedented delays in U.S. corn planting this spring, near Sheffield, Illinois, U.S., June 13, 2019. Picture taken June 13, 2019.
Tom Polansek | REUTERS

The extreme weather also heaps more pain on an industry that has suffered from years of low crop prices, and the U.S.-China trade war that slowed down agricultural exports. In May, tariff from China on $60 billion worth of U.S. goods targeted a wide range of agricultural products.

Charlie Johnson, a farmer from Madison, South Dakota, said farmers in his community were suffering from lower prices resulting from the trade war tariffs. The flooding, he said, will further erode profits. And with respect to the heat wave, Johnson said that stepping outside to his farm has felt like walking into a sauna.

“You’re mentally struggling with issues of flooding, and then it’s hard physically to be outside in this heat to get work done,” he said.

“It’s tough on farmers and the people in our rural community. We all worry about each other.”

Climate change implications

A study published Tuesday in Environmental Research Communications found that the frequency of extreme heat in the U.S. is projected to increase significantly, even if greenhouse gases are kept below standard levels.

While particular events cannot be causally linked to climate change, experts agree that global warming is making extreme heat events more common.

“Everything is probabilities,” said Martin Weitzman, a Harvard University economics professor. “Climate change increases the probability of heat waves, but it’s still difficult to link one event to climate change.”

The latest heat wave does follow a trend worldwide: The five hottest years in recorded history have been the last five, and 18 of the 19 warmest years have occurred since 2001, according to a recent NASA analysis.

“The weather conditions are bouncing from extreme to extreme — from excessive wetness to record setting heat waves,” said Brad Rippey, a USDA meteorologist. “There’s no in between.”

Alex Jones, climate division director at the U.N. Food and Agriculture Organization, attributed the heat wave to climate change and warned farmers to “get used to it” and build resilience into the system by planting more resistant crops, even if doing so results in lower yields.

“The one key message is this is the new normal — and it’s only going to get worse,” Jones said.

VIDEO4:0404:04
We’re at a loss of where to go with our products: ND farmer
The Exchange
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QUARTZ

UNDER WATER

As the climate crisis heats up, flooded farms in the Midwest can't plant corn

By Michael J. Coren • May 30, 2019

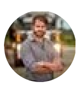
AP PHOTO/NATI HARNIK

Difficult to plant.

The angst on farmer Twitter is palpable. Across the Midwest, torrential rains have soaked the fields, leaving the sodden soil unsuitable for planting millions of acres with corn, soybeans, and other crops, presaging a terrible harvest. Seeds are usually in the ground this time of year. But thanks to floods, unrelenting rains, hail, and scores of tornadoes—nearly 200 more than average (paywall) by this point in the year—the season is off to one of the worst starts in history. #NoPlant19 is trending on Twitter.

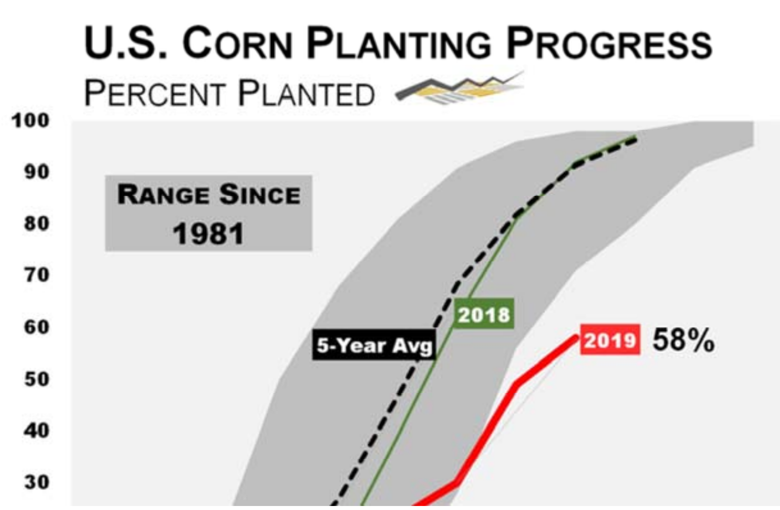
In Oklahoma, every county is in a state of emergency. The Midwest is having its wettest 12 months ever (paywall). These extremes follow on a blistering 2018, the fourth hottest year on Earth, just behind "2016 (warmest), 2015 (second warmest), and 2017 (third warmest)," according to the 139-year climate record of the US National Oceanographic and Atmospheric Administration.

Every day tractors don't enter the fields means a higher chance of crop failure (and less crop insurance on whatever makes it into the ground). On May 28, the USDA announced that US farmers have just 58% of their corn crop in the ground (versus a five-year average of 90% by this time) and 29% of the soybean crop (compared to 66%). Those are among the lowest rates in history. Other farmers may end up planting nothing and have declared a total crop loss.



Matthew Pot
@MatthewPot

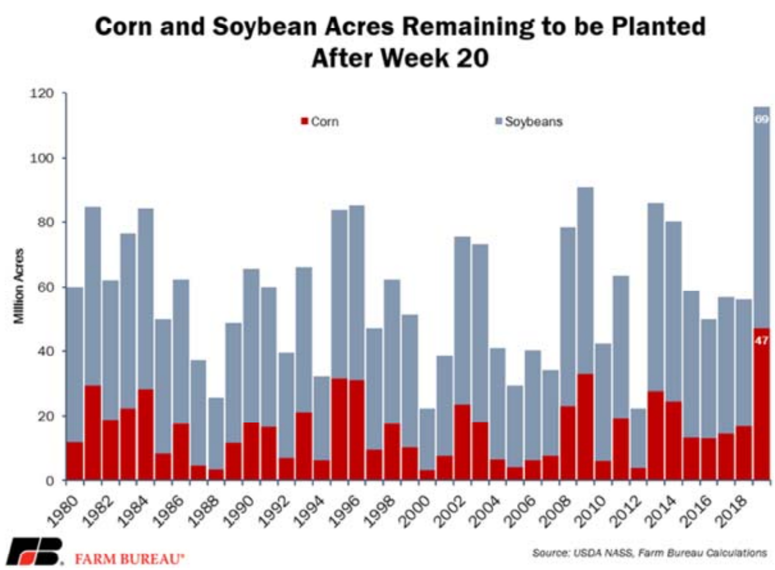
The USDA announced that 58% of the U.S. #corn crop has been planted as of May 26th, compared to the 5-year average pace of 90%. This is the slowest pace in recorded history. #NoPlant19 #Plant19



"The frequency of these disasters, I can't say we've experienced anything like this since I've been working in agriculture," John Newton, chief economist at the American Farm Bureau Federation, told the Washington Post (paywall).

John Newton
@New10_AgEcon

#CornBelt we have a problem
There are 116 million #corn and #soybean acres remaining to be planted as of May 19, the highest on record for both crops at 47 mil ac and 69 mil ac & topping the prior high by 26 mil acres! #NoPlant19 @FarmBureau



78 6:46 AM - May 21, 2019

85 people are talking about this

The stories across the Midwest are wrenching. Scrolling through the #NoPlant19 hashtag turns up dozens of posts about farmers staring out at soggy fields or farm equipment foundering in deep mud. It's likely many will see their harvests devastated this year, and global grain prices could spike.

Wentworth Farms
@WentworthFarms

Pretty much sums up #noplant19

566 2:10 PM - May 28, 2019

184 people are talking about this

Casey C.
@cattleNcrops83

I was getting worried, it hadn't rained in 15 min or so. #NoPlant19

Jeff M Brown
@JeffMBrown1

Trying to get more corn in today before the rain. Not the right way to farm but the only way to get plant 19 in the ground. I tell my sons “this is what not to do but we have to do it”. #plant19 vs #noplant19

56   7:10 AM - May 28, 2019

See Jeff M Brown's other Tweets

Pete Bouman
@PeteBouman

Quadtrac buried trying to do dirt work for new wind

David Ebert
@ebertgrainfarms

Rather scary how many people are here for a #PreventPlant meeting #plant19 #noplant19 #corn #soybeans

38 9:36 AM - May 22, 2019

27 people are talking about this

If this sounds like part of the climate crisis, it is. As the planet warms, extremes in heavy rain and drought are becoming the new normal, says Sean Sublette, a meteorologist at Climate Matters. It’s not that every weather event is the result of global warming. But the probability of extreme disaster rises as humans increase the levels of carbon dioxide, now at their highest point in the planet's atmosphere in 3 million years. Greenhouse gases trap heat and destabilize the climate system. Higher temperatures "supercharge" evaporation, leading to droughts and desertification. Water is dumped back on arid soil in torrential rains, creating flooding.

This year's crop trouble is a preview. A study by the Proceedings of the National Academy of Sciences this year predicted widespread crop failures as temperatures rise, including US corn production falling by almost half if temperatures rise by 4°C. That's the world's current trajectory without swift action, according to a World Bank study calling the scenario "cataclysmic." Were the world to act to keep temperature increases below 2°C, crop reductions would be about 18% lower.

The Washington Post

Capital Weather Gang

The Greenland ice sheet poured 197 billion tons of water into the North Atlantic in July alone

Extreme melt event led to greatest single day volume loss from the ice sheet since 1950

By Andrew Freedman and
Jason Samenow
August 3

(This story has been updated with new data from August 1.)

When one thinks of Greenland, images of an icebound, harsh and forbidding landscape probably come to mind, not a landscape of ice pocked with melt ponds and streams transformed into raging rivers. And almost certainly not one that features wildfires.

Yet the latter description is exactly what Greenland looked like this week, according to imagery shared on social media, scientists on the ground and data from satellites.

An extraordinary melt event that began earlier this week continued through August 1 on the Greenland ice sheet, and there are signs that about 60 percent of the expansive ice cover saw detectable surface melting, including at higher elevations that only rarely see temperatures climb above freezing.

On Thursday, the ice sheet saw its biggest single-day volume loss on record, with 12.5 billion tons of ice lost to the ocean from surface melt, according to computer model estimates based on satellite and other data. Records of daily mass loss date back to 1950.

“This model, which uses weather data and observations to build a record of ice and snowfall, and net change in mass of the ice sheet, is remarkably accurate,” says Ted Scambos, a senior researcher at the National Snow and Ice Data Center (NSIDC) in Colorado. “I would accept the result as fact. 12.5 billion tons [lost] in one day, and the highest single-day total since 1950,” Scambos said.

July 31 was the biggest surface melt day since at least 2012, with about 60 percent of the ice sheet seeing at least 1 millimeter of melt at the surface, and more than 10 billion tons of ice lost to the ocean from surface melt, according to data from the Polar Portal, a website run by Danish polar research institutions, and the NSIDC.

According to Ruth Mottram, a climate researcher with the Danish Meteorological Institute, the ice sheet sent 197 billion tons of water pouring into the Atlantic Ocean during July.

This is enough to raise sea levels by 0.5 millimeter, or 0.02 inches, in a one-month time frame, said Martin Stendel, a researcher with the institute.

For those keeping track, this means the #Greenland #icesheet ends July with a net mass loss of 197 Gigatonnes since the 1st of the month. https://t.co/Qgwj6WtUzF

— Ruth Mottram (@ruth_mottram) August 1, 2019

This might seem inconsequential, but every increment of sea-level rise provides a higher launchpad for storms to more easily flood coastal infrastructure, such as New York’s subway system, parts of which flooded during Hurricane Sandy in 2012. Think of a basketball game being played on a court whose floor is gradually rising, making it easier for even shorter players to dunk the ball.

As a result of both surface melting and a lack of snow on the ice sheet this summer, “this is the year Greenland is contributing most to sea-level rise,” said Marco Tedesco, a climate scientist at Columbia University.

Thanks to an expansive area of high pressure enveloping all of Greenland — the same weather system that brought extreme heat to Europe last week — temperatures in Greenland have been running up to 15 to 30 degrees above average this week.

At Summit Station, which at 10,551 feet is located at the highest point in Greenland and rarely sees temperatures above freezing, the thermometer exceeded this mark for about 11 hours Tuesday, according to Christopher Shuman, a glaciologist at the University of Maryland-Baltimore County and NASA Goddard Space Flight Center.

The 2019 extreme melt event is being compared to a record extreme heat and melt episode that occurred in Greenland in 2012. While the extent of surface melt during that event may have exceeded this one so far, Shuman found that Summit Station experienced warmth that was greater “in both magnitude and duration” during the current event. The temperature only remained above freezing about half as long in 2012, and the peak temperature reached 34.02 degrees this year, whereas it only hit 33.73 in 2012. During the 2012 extreme event, however, 97 percent of the ice surface experienced melting.

“Like 2012, this melt event reached the highest elevations of the ice sheet, which is highly unusual,” says Thomas Mote, a professor of geography at the University of Georgia. “Both our satellite observations and the ground-based observations from Summit indicated melt on Tuesday.”

“The event itself was unusual that the warm air mass came from the east, and appears to be a part of the air mass that caused the record-breaking heat wave in Europe. Most of our extreme melt days on the Greenland ice sheet are associated with warm air masses moving from the west and south. I cannot recall an instance where we saw such extensive melt associated with an air mass coming from Northern Europe,” Mote said.

The heat, along with below-average precipitation in parts of Greenland, has even sparked wildfires along the Greenland’s non-ice-covered western fringes. Satellite images and photos taken from the ground show fires burning in treeless areas, consuming mossy wetlands known as fen that can become vulnerable to fires when they dry out. These fires can burn into peatlands, releasing greenhouse gases buried long ago through decomposition of organic matter.

Studies have shown that ice melt periods like the one seen in 2012 typically occur about every 250 years, so the fact that another one is taking place only a few years later could be a sign of how climate change is upping the odds of such events.

According to DMI’s Mottram, the short-term, extreme melt event is a sign of climate change’s increasing influence on the Arctic.

“So yes it’s weather but it shows that in spite of internal variability the background signal of a warming climate is still “winning,” she said via a Twitter message. She said state-of-the-art climate computer models have been unable to simulate events like this, which hampers scientists’ ability to accurately predict Greenland ice melt and, therefore, future sea-level rise.

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The New York Times

Europe's Heat Wave, Fueled by Climate Change, Moves to Greenland

By Henry Fountain

Aug. 2, 2019

Climate change made the stifling heat that enveloped parts of Europe last week much more likely and hotter, researchers said Friday.

The heat wave, the second to hit Europe since late June, set temperature records in Paris, as well as in Germany, the Netherlands and other countries. Nuclear reactors in France and Germany were forced to reduce output or shut down because the water used to cool them was too warm.

The hot air, which was trapped over Europe after traveling from northern Africa, lingered for about four days. It has since moved north over Greenland, causing the surface of the island's vast ice sheet to melt at near-record levels.

World Weather Attribution, a group that conducts rapid analyses of weather events to see if they are influenced by climate change, said that for France and the Netherlands, the four days of extreme heat last week were a rare event even for a warming world. But it said climate change had made the heat wave at least 10 times more likely. In Germany, the heat wave was at least eight times more likely because of climate change, the group found, and in Britain, where the heat did not linger as long, it was at least two times more likely.

Looked at another way, the researchers said, the heat wave was hotter by about 2.5 to 5 degrees Fahrenheit, because of climate change.

More coverage of recent heat waves

Europe Suffers Heat Wave of Dangerous, Record-High Temperatures July 24, 2019

Heat Waves in the Age of Climate Change: Longer, More Frequent and More Dangerous July 18, 2019

As Extreme Heat Becomes New Normal in Europe, Governments Scramble to Respond July 26, 2019

“European summer heat waves are absolutely one of the hot spots of climate change,” said Friederike Otto, a member of the group and a climate researcher at the University of Oxford in England. “We’ve had two of these this summer alone, and the summer is only halfway through. We also had a massive heat wave last summer.”

World Weather Attribution, with researchers in Britain, France, the Netherlands and elsewhere, uses computer simulations of the climate as it is now and as it would be if human activity had not pumped hundreds of billions of tons of greenhouse gases into the atmosphere. The group’s goal is to bring legitimate scientific analysis to the public quickly after an event to help counter any potential misinformation.

The group said that every European heat wave that has been analyzed, dating back to 2003 and including the earlier one this summer, had been found to have been influenced by climate change, although the degree of impact has varied depending on location, intensity and other factors.

While they have analyzed other weather events, including floods, droughts, cold spells and extreme rainfall, Dr. Otto said, European heat waves have shown the greatest climate change influence.

Water sprinklers last week in Vienna, where temperatures reached the mid-90s Fahrenheit. Lisi Niesner/Reuters

With the hot air moving north this week, Greenland was experiencing its own version of a heat wave. On the southwestern coast, Nuuk, the capital, reported temperatures in the high 50s Fahrenheit, about 10 degrees higher than average for this time of year (55 Fahrenheit is the equivalent of roughly 13 Celsius).

The warmth increased the surface melting of Greenland's vast ice sheet, which covers about 80 percent of the island. Analysis of satellite data by the National Snow and Ice Data Center in Boulder, Colo., showed that melting on Wednesday extended across 380,000 square miles, or about 60 percent of the total ice area.

That is about four times the median extent for the end of July over the past four decades. But while the extent of melting has been higher than average this year — including a day in June that set an early-season record — it is less than the record 2012 melt season, when warm temperatures persisted for much of the summer and at one point nearly 100 percent of the ice sheet was melting.

Greenland's ice sheet is nearly two miles thick in places, and if all of it were to melt, global sea levels would rise about 24 feet. Melting has increased in recent decades because of climate change and has been outstripping accumulation from snow, resulting in a net loss of ice. Estimates vary, but a 2018 study found that the ice sheet has been losing an average of nearly 300 billion tons of ice per year this decade, contributing a total of about one-quarter of an inch to global sea level rise over that time.

For more news on climate and the environment, follow @NYTClimate on Twitter.

Henry Fountain covers climate change, with a focus on the innovations that will be needed to overcome it. He is the author of "The Great Quake," a book about the 1964 Alaskan earthquake. @henryfountain • Facebook

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ARTICLE

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Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements

Dmitry Yumashev[1,2], Chris Hope[3], Kevin Schaefer[4], Kathrin Riemann-Campe[5], Fernando Iglesias-Suarez[2,6], Elchin Jafarov[4,7], Eleanor J. Burke[8], Paul J. Young[1,2,9], Yasin Elshorbany[10] & Gail Whiteman[1]

Arctic feedbacks accelerate climate change through carbon releases from thawing permafrost and higher solar absorption from reductions in the surface albedo, following loss of sea ice and land snow. Here, we include dynamic emulators of complex physical models in the integrated assessment model PAGE-ICE to explore nonlinear transitions in the Arctic feedbacks and their subsequent impacts on the global climate and economy under the Paris Agreement scenarios. The permafrost feedback is increasingly positive in warmer climates, while the albedo feedback weakens as the ice and snow melt. Combined, these two factors lead to significant increases in the mean discounted economic effect of climate change: +4.0% ($24.8 trillion) under the 1.5 °C scenario, +5.5% ($33.8 trillion) under the 2 °C scenario, and +4.8% ($66.9 trillion) under mitigation levels consistent with the current national pledges. Considering the nonlinear Arctic feedbacks makes the 1.5 °C target marginally more economically attractive than the 2 °C target, although both are statistically equivalent.

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The Arctic region is warming twice as fast as the global average[1], manifested by a decrease in sea ice, snow and glaciers and permafrost degradation relative to their benchmark average states for the period between 1979 and 2005[2–6]. These changes can accelerate global warming further through a variety of climatic feedbacks. Carbon from thawing permafrost released into the atmosphere results in the permafrost carbon feedback (PCF)[7,8]. Decreasing sea ice and land snow covers increase solar absorption in high latitudes, causing the surface albedo feedback (SAF)[9,10]. Both feedbacks amplify the anthropogenic signal.

The PCF and SAF represent three of the thirteen main tipping elements the Earth's climate system identified in recent surveys[11–13]. Tipping elements are physical processes acting as positive nonlinear climate and biosphere feedbacks that, after passing a threshold, could irreversibly shift the planetary system to a new warmer state[13]. They could cause additional impacts on ecosystems, economies and societies throughout the world. The risk of triggering the tipping elements is one of the arguments for adopting the ambitious 1.5 °C and 2 °C targets in the Paris Agreement[14–16]. Therefore, a rigorous quantitative assessment of the climate tipping elements under different climatic and socio-economic scenarios is required to estimate their impacts and narrow down the uncertainties.

Despite significant advances documented by the IPCC 5th Assessment Report (AR5)[6], projections of future climate using general circulation models (GCMs) from the 5th climate model inter-comparison project (CMIP5) do not include the PCF[17,18], although several models are set to incorporate the PCF in their next versions as part of CMIP6. Consequently, most climate policy assessments based on results from the GCMs under-estimate the extent of global warming in response to anthropogenic emissions. The SAF, on the other hand, is present in GCM climate projections through the coupling of sea ice and land surface models to atmosphere and ocean models[17]. However, existing estimates of the total economic impact of climate change under different policy assumptions using integrated assessment models (IAMs) assume that radiative forcing from the SAF increases linearly with global mean temperature[19,20], which is inconsistent with predictions of the GCMs[21].

In this paper, we explore nonlinear transitions in the state-dependent PCF and SAF, and estimate the resulting climatic and economic impacts globally. To perform the analysis, we develop dynamic model emulators of the nonlinear PCF and SAF, which are comparatively simple statistical surrogates of the highly complex physical models. The emulators are integrated within PAGE-ICE, a new development of the PAGE09 IAM[19,20] that includes a number of updates to climate science and economics (Methods, Supplementary Note 1). The climatic impacts focus on changes in the global mean surface temperature (GMST) and the economic impacts focus on the net present value (NPV) of the total cost associated with future climate change. We consider a wide range of scenarios: zero emissions after 2020, the 1.5 °C and 2 °C targets for 2100 and the nationally determined contributions (NDCs) from the Paris Agreement, and a business as usual (BaU) scenario. We also introduce an intermediate 2.5 °C target, which requires more mitigation than is proposed by the NDCs, and an NDCs Partial scenario with a persistent under-delivery on pledges consistent with an estimated long-term effect of the US's withdrawal from the Paris Agreement. The scenarios extend out to 2300 to capture the effects of multiple slow physical processes including the PCF and the loss of the winter sea ice under high emissions pathways. While very long horizons like this may appear irrelevant from the point of view of the actual socio-economic processes, the well-established technological, demographic and resource constraints[22,23] imply that the range of scenarios is still plausible beyond the 21st century[24].

In addition to the PCF and SAF, Arctic feedbacks include carbon emissions from thawing sub-sea permafrost, boreal forest uptake and changes in ocean circulation from the melting of the Greenland ice sheet[13,25], which we do not explicitly simulate it in this study. Emissions from thawing sub-sea permafrost on Arctic shelf are poorly understood in comparison with land permafrost emissions[26]. The boreal forest and Greenland ice sheet feedbacks are beyond the scope of this study, along with the non-Arctic tipping elements and other major uncertain elements in the climate system such as the cloud feedback[27]. While not modelled directly, many of these effects are included implicitly in the PAGE-ICE IAM through a number of uncertain climate system parameters constrained according to the latest literature (Methods, Supplementary Note 1).

Our results show that the PCF gets progressively stronger in warmer climates, while the SAF weakens. Both feedbacks are characterised by nonlinear equilibrium responses to warming. The PCF also develops state-dependent lagged behaviour. Compared with zero PCF and constant SAF, which are the legacy values that have been used in climate policy modelling to date, the combined nonlinear PCF and SAF cause statistically significant extra warming globally under the low and medium emissions scenarios. For high emissions scenarios, the strength of the PCF saturates, and the weakening SAF gradually cancels the warming effect of the PCF; for BaU, this takes place from the second half of the 22nd century onwards. Nevertheless, under all scenarios, the predominantly warmer future climate associated with the nonlinear PCF and SAF relative to their legacy values translates into marginal increases in the total discounted economic effect of climate change. These increases, which are significant for all scenarios except for BaU, occur through additional temperature-driven impacts on economy, ecosystems and human health, additional impacts from sea level rise, as well as highly uncertain extra impacts from social discontinuities and climate tipping elements other than the PCF and SAF. Even with the legacy PCF and SAF, emissions pathways in the range between the 1.5 °C and 2 °C targets lead to the lowest total economic effects of climate change compared to all other scenarios. Considering the nonlinear PCF and SAF makes the pathways towards the lower end of the range covered by the Paris Agreement targets marginally more economically attractive.

Results

Nonlinear PCF and SAF. We base the PCF emulator on simulated emissions of thawed permafrost carbon from the two permafrost-enabled global land surface models (LSMs): SiBCASA (Simple Biosphere/Carnegie-Ames-Stanford Approach) and JULES (Joint UK Land Environment Simulator)[7,28,29] (Fig. 1). Permafrost carbon is organic matter buried and frozen in permafrost. The two LSMs have markedly different responses to future climate change: SiBCASA appears to be on the upper end and JULES on the lower end of the reference multi-models studies[8,29,30] (Supplementary Note 2, Supplementary Fig. 1). Their combined use here provides a suitable estimate of the range of permafrost responses arising from uncertainty in LSM parameterizations.

Our uncertainty estimate also depends on the range of global climate model (GCM) outputs used to force the LSMs, accounting for both the structural uncertainty arising from the different GCM's climate sensitivities, as well as the irreducible uncertainty arising from weather and climate variability. To capture this uncertainty in the PCF, both LSMs were forced with output from a range of GCMs, sampling the full range of expected Arctic

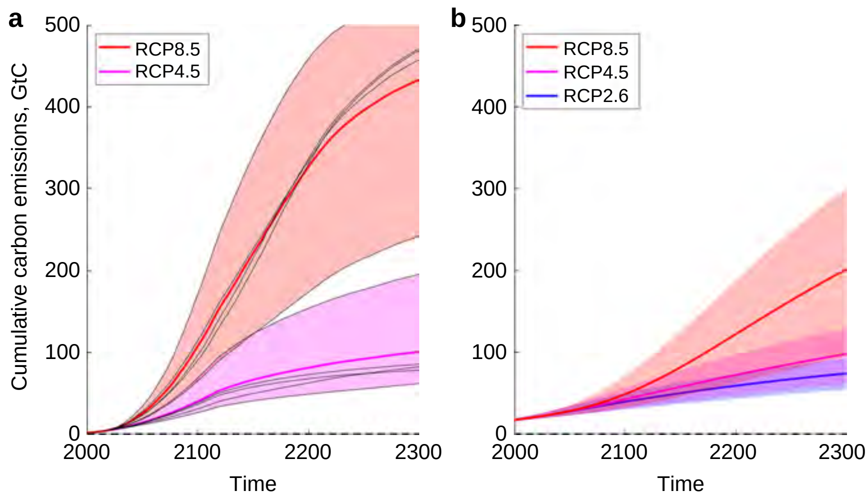

Fig. 1 Cumulative carbon emissions from thawing land permafrost simulated using specialised land surface models. CO_2 component of cumulative emissions of carbon from thawing land permafrost, obtained from **a** SiBCASA and **b** JULES LSMs forced by multiple climate models (GCMs) under a range of climate scenarios out to 2300. Thick lines: multi-GCM means; shaded areas: multi-GCM spread between the lowest and the highest values; thin black lines: SiBCASA runs with individual GCMs. Horizontal black dashed lines: legacy zero permafrost emissions currently assumed in IAMs. Units: GtC. Source data are provided as a Source Data file

responses under a given climate scenario to 2300. SiBCASA is an explicit LSM and was run to 2300 with output from five CMIP5 GCMs under two scenarios, whereas JULES was configured to run to 2300 with output from 22 CMIP3 GCMs under three climate scenarios (Fig. 1). Having information to 2300 is important to capture the nonlinear transitions in the permafrost emissions.

The dynamic PCF emulator uses a statistical fit to SiBCASA and JULES outputs for the land permafrost carbon emissions in the form of CO_2 and methane, capturing nonlinear effects seen in the LSM simulations. The PCF emulator only models the emitted permafrost carbon explicitly, while also accounting for the time lags between the temperature rise, thawed carbon and emitted carbon, as well as the uncertainty in the initial permafrost carbon stock[31]. The PAGE-ICE model adds the permafrost fluxes from the PCF emulator to the anthropogenic global CO_2 and methane emissions that follow a given climate scenario.

We base the SAF emulator on the ALL/CLR method of calculating the SAF using downward and upward atmospheric transmissivity and reflectivity inferred from climate models (GCMs)[32,33]. The method involves an atmospheric reflectivity parameterisation, which represents the effect of clouds and is based on clear sky and all sky shortwave fluxes diagnosed from the GCMs. It allows us to account for the localised changes to the cloud cover and its effect on the SAF in line with the physical interactions represented in the fully-coupled CMIP5 models (Supplementary Figure 2)[34–36]. We do not compute the global cloud feedback; instead, it is included implicitly in the ECS parameter in the PAGE-ICE model and is assumed to be state-independent (see the section on the robustness of the results below).

We use historic and RCP8.5 simulations of 16 CMIP5 GCMs that have the diagnostic variables required for the SAF calculation (Supplementary Table 1)[32]. While short of the complete CMIP5 ensemble, these models sample the full range of Arctic responses as seen in the whole ensemble. Eight of the models have simulations that extend out to 2300, which is necessary to capture the nonlinear transitions in the SAF. Each model has its own domains for Arctic sea ice and land snow covers based on their respective monthly maximum extents during the pre-industrial period. The SAF, therefore, is separated into the northern hemispheric sea ice, northern hemispheric land snow and rest of the world. The components are represented as functions of the GMST rise individually for each model, at which point the multi-model statistics is established (Fig. 2). The sea ice and land snow components of the SAF peak for the GMST anomalies between 0–1 °C and 1–3 °C, respectively, coinciding with the loss of the summer sea ice[2,37] and spring and summer land snow[38] covers coupled with high Arctic insolation. However, both components decrease for higher GMST as the sea ice and land snow covers continue to decline, and eventually approach zero when the covers disappear. The plateau in the sea ice SAF component between 5–7 °C coincides with the loss of the spring sea ice[39,40]. In contrast, the SAF for the rest of the world stays nearly constant until high GMST anomalies.

The SAF emulator models the global SAF as a function of the GMST (Methods), reproducing the nearly monotonic decline driven largely by the Arctic sea ice and land snow components. While IAMs other than PAGE-ICE have implied unrealistic constant SAF (dashed lines in Fig. 2), which is implicitly included in the $2 \times CO_2$ ECS parameter (Methods), the SAF emulator accounts for the difference between the nonlinear SAF and its constant legacy value. It alters the governing equation for the GMST change in PAGE-ICE by adding extra terms to the total anthropogenic radiative forcing (RF) for a given climate scenario (Supplementary Note 3).

GMST changes due to the nonlinear PCF and SAF. Figure 3 shows the medians and 25–75% ranges for the GMST projections relative to pre-industrial levels for the climate scenarios considered, obtained using PAGE-ICE with the legacy values of the PCF and SAF. For the PCF, the legacy value is zero emissions from permafrost since the PCF is not included in most climate projections using GCMs[18]. For the SAF, the legacy value is constant SAF of $0.35 \pm 0.05\ \mathrm{W\,m^{-2}\,K^{-1}}$, which corresponds to $2 \times CO_2$ equilibrium climate sensitivity (ECS) calibrated according to IPCC AR5. In subsequent sections, our main results report the difference between the climatic and economic impacts of the nonlinear PCF and SAF and their respective legacy values. Further details appear in Methods.

Figure 4 shows the means and ±1SD ranges of the absolute changes in GMST until 2300 due to the nonlinear PCF, SAF and PCF & SAF combined, measured relative to their respective

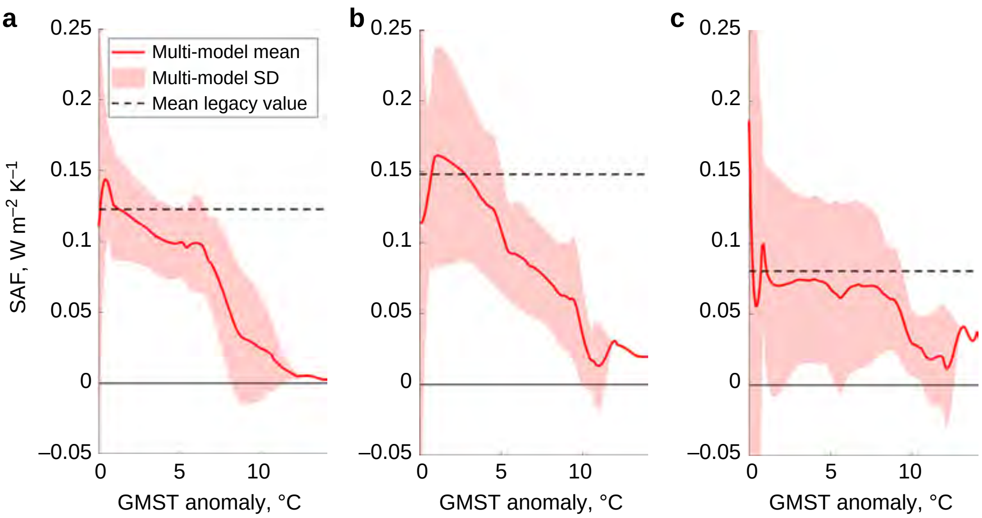

Fig. 2 Three components of the surface albedo feedback deduced from simulations of fully coupled climate models. SAF components (average global equivalent values) for **a** Arctic sea ice, **b** Northern Hemisphere land snow and **c** rest of the world, presented as functions of the GMST rise relative to pre-industrial conditions. Obtained from multiple CMIP5 GCMs using the ALL/CLR method. Solid red line: multi-model mean; shaded area: ±1 standard deviation (SD). Horizontal black dashed lines: legacy SAF forcing currently assumed in IAMs. Source data are provided as a Source Data file

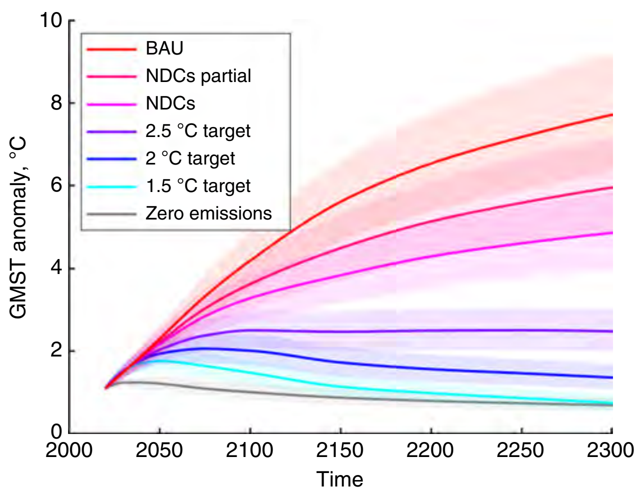

Fig. 3 Global mean temperature simulations under the range of climate scenarios considered. Median GMST projections relative to pre-industrial 1850–1900 levels (thick lines) and the relevant 25–75% ranges (shaded areas) obtained from 100,000 runs of PAGE-ICE for all the climate scenarios considered, assuming the following legacy values of the PCF and SAF: zero permafrost emissions, constant SAF of 0.35 ± 0.05 W m^{-2} K^{-1}. This serves as a base estimate for the subsequent analysis of the nonlinear PCF and SAF. Source data are provided as a Source Data file

legacy values. The GMST changes from the PCF and SAF are smaller than the underlying uncertainty in the base climate projections in PAGE-ICE with legacy constant SAF and zero PCF (Fig. 3; note the different vertical scale). However, with few exceptions, the values plotted in Fig. 4 represent statistically significant shifts in the state of the climate system due to the two feedbacks at the 95% confidence level (the exceptions are listed in the Fig. 4 caption).

Because the legacy value is zero, the PCF increases GMST for all scenarios (Fig. 4a). The slow response of permafrost to thaw means the change in GMST before 2100 due to the PCF is nearly the same for all scenarios except Zero Emissions. The difference between the scenarios only becomes apparent in the 22nd and 23rd centuries, with the GMST effect of the PCF becoming progressively stronger as emissions increase towards BaU. The GMST increases are virtually indistinguishable between NDCs, NDCs Partial and BaU because the marginal effect on GMST of additional CO_2 emissions from the PCF drops as total atmospheric CO_2 concentrations increase. In addition, the highest emissions scenarios exhaust the permafrost carbon stocks in some simulations, causing a drop in the annual CO_2 flux from permafrost beyond 2200. This results in carbon removal from the atmosphere through CO_2 ocean uptake (Supplementary Note 4, Supplementary Fig. 3) and causes a slight decline in the GMST effect of the PCF in the 23rd century for the BaU scenario.

The nonlinear SAF is dominated by the decrease of its sea ice and land snow components (Fig. 2), resulting in less warming and negative GMST changes compared to the constant legacy SAF (Fig. 4b). The NDCs, NDCs Partial and BaU scenarios have the largest temperature increases and greatest decreases in land snow and sea ice SAF components, and thus show the greatest negative differences in GMST. The differences are the highest for BaU with nearly ice-free oceans and snow-free land even in winter after 2200. For the Zero Emissions, 1.5 °C, 2.0 °C and 2.5 °C scenarios, there are small increases in GMST for the entire time period due to the small peaks in the sea ice and land snow SAF components within this temperature range (Fig. 2). Overall, the constant legacy SAF appears reasonable for low emission scenarios, but overestimates GMST for high emission scenarios according to the current generation of climate models (CMIP5), with no apparent tipping points (Supplementary Fig. 4).

The nonlinear SAF can partially compensate for the PCF (Fig. 4c). For the high emission NDC, NDC Partial, and BaU scenarios, reduced warming due to the nonlinear response of the SAF partially cancels out warming due to the PCF. The effect is strongest for the BaU scenario, where the change in GMST from the legacy value switches sign from positive to negative. The SAF slightly amplifies the PCF for the low emission scenarios where the constant SAF forcing assumption remains valid (Zero Emissions, 1.5 °C, 2.0 °C and 2.5 °C). This means IAMs that do not include the PCF and assume a constant SAF will underestimate GMST by between 0.1 and 0.2 C for all but the highest emissions scenarios. These findings stemming from the non-linearities both in the PCF and SAF have been overlooked in climate policy studies so far (Supplementary Note 5)[41–44].

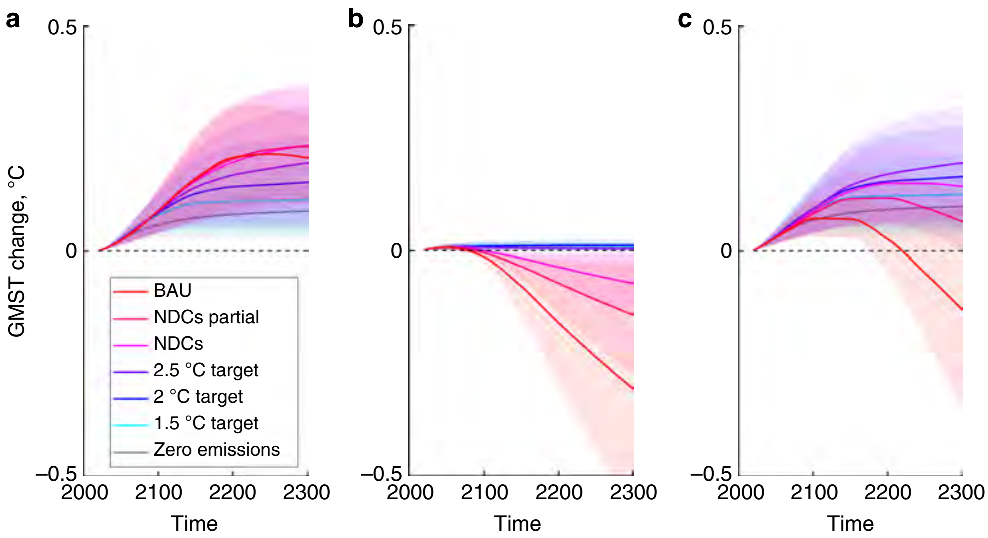

Fig. 4 Additional warming due to the nonlinear Arctic feedbacks relative to their legacy values. Differences between the GMST effects of the nonlinear PCF and SAF, and the GMST effects of their constant legacy values, obtained using the new PCF and SAF emulators in PAGE-ICE for **a** PCF, **b** SAF and **c** combined PCF & SAF. The legacy PCF value is zero and the legacy SAF value is the black dashed line in Fig. 2. Thick lines: ensemble mean; shaded areas: ±1SD. The cases when the GMST effect of the feedbacks is not significant at the 5% level: SAF under NDCs and NDCs Partial at the turn of the 22nd century, SAF under BaU in the second half of the 21st century, PCF & SAF combined under NDCs Partial in the second half of the 23rd century, and PCF & SAF combined under BaU from the second half of the 22nd century onwards. Source data are provided as a Source Data file

Implications for the total economic effect of climate change. The NPV of the total economic effect of climate change, denoted as C_{NPV}, consists of mitigation costs, adaptation costs and climate-related economic impacts aggregated until 2300 and discounted using equity weighting and a pure time preference rate[45]. We base the economic impacts due to changing temperatures on a recent macro-econometric analysis of historic temperature shocks on economic growth in multiple countries[46]. We project the economic impact function derived from this analysis onto the 8 global regions of the PAGE model[19] using gridded population-weighted ERA-Interim reanalysis data[47] for mean climatological temperatures in the base year, and adapt it to fit with the consumption-only approach for climate impacts in PAGE with no lasting effects on economic growth. Termed the level effects[46], this provides a likely lower end estimate for the economic impacts and also allows one to compare directly with the default PAGE09 impact functions[48–51], for which the original results for the PCF were derived[41]. We also carry out updates to the sea level rise driver, discontinuity impacts and mitigation costs according to the latest literature (Methods, Supplementary Note 1). The Zero Emissions scenario provides a hypothetical upper bound for the mitigation costs and includes residual impacts from historic emissions.

First, we calculated C_{NPV} for the global climate-economy system using the base PAGE-ICE model with the legacy Arctic feedbacks, and PAGE-ICE with the nonlinear PCF and SAF representations (Fig. 5a). In both settings, the mean total economic effects of the 1.5 °C, 2 °C and 2.5 °C scenarios are the lowest of the seven scenarios considered, while the NDC scenarios and, particularly, the BaU scenario have much higher mean total economic effects. All the distributions have long upper tails representing a possibility of large impacts relative to the means. The tails get elongated for higher emissions scenarios and when the nonlinear PCF and SAF representations are used.

We then calculated the additional economic effect of the nonlinear PCF and SAF relative to the legacy values (Fig. 5b). The nonlinear PCF leads to statistically significant increases in C_{NPV} at the 5% significance level for all the scenarios considered, especially the NDC and BaU. The nonlinear correction to the SAF leads to small but statistically significant increases in C_{NPV} for Zero Emissions and 1.5 °C, 2.0 °C and 2.5 °C target scenarios, statistically significant decreases in C_{NPV} for NDCs Partial and BaU, and is not significant for NDCs (all at the 5% level).

When the nonlinear PCF and SAF representations are combined, the statistical mean of the economic effect of climate change increases relative to the base estimate with the legacy PCF and SAF by $16.1 trillion (1 trillion = 10^{12}) for the counterfactual Zero Emissions scenario ($1288 trillion base estimate), $24.8 trillion for 1.5 °C target ($613 trillion base estimate), $33.8 trillion for 2.0 °C target ($613 trillion base estimate), $50.3 trillion for 2.5 °C target ($815 trillion base estimate), $66.9 trillion for NDCs ($1390 trillion base estimate), and by $59.8 trillion for NDCs Partial ($1702 trillion base estimate). These increases are statistically significant (5% level). We also found marginal but statistically insignificant increases for BaU ($2197 trillion base estimate), which remains the most expensive and least desirable scenario.

The mean economic impact of net additional warming from the nonlinear PCF & SAF peaks at just under $70 trillion (NPV until 2300) for NDCs. To put this number into context, it exceeds the estimated long-term gains from economic development in the Arctic region through transit shipping routes[52] and mineral resource extraction[53] under high emissions scenarios by around 10 times, and could also dwarf pan-Arctic damages to infrastructure from thawing permafrost[54,55]. The economic losses due to climate warming also tend to be higher in warmer poorer regions such as India and Africa[20], which are also less likely to benefit from the economic opportunities associated with a warmer Arctic[56].

Robustness of the estimates for the PCF and SAF effects. Other major feedbacks implemented in the fully-coupled GCMs such as clouds, water vapour and lapse rate contribute to overall uncertainty and state-dependency in the ECS parameter[35]. The combined magnitude of these feedbacks showed weak responses to GMST increases in CMIP3 GCMs[21]. CMIP5 GCMs, however, produced increases in the water vapour feedback in warmer climates associated with rising tropopause[57]. While the

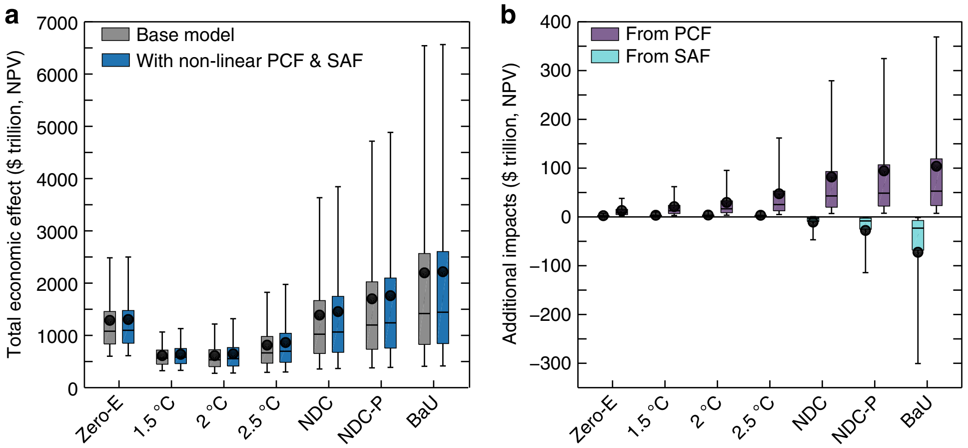

Fig. 5 Total economic effect of climate change with the nonlinear and legacy Arctic feedbacks. **a** NPVs of the total economic effect of climate change (until 2300, equity-weighted, PTP-discounted), plotted for the legacy Arctic feedbacks (Base model) and with the nonlinear PCF & SAF corrections included, and **b** NPVs of the additional economic impact separately from the nonlinear PCF and SAF, calculated relative to their legacy values under the climate scenarios considered. Whiskers: 5–95% range; boxes: 25–75% range; horizontal lines: median; dots: mean. 100,000 Monte-Carlo runs of PAGE-ICE. The effect of the imaginary Zero Emissions scenario is higher compared to the 1.5 °C, 2 °C and 2.5 °C scenarios due to the large mitigation costs. Source data are provided as a Source Data file

state-dependencies in the planetary feedbacks require further investigations as part of CMIP6, the evidence so far suggests that apart from the SAF effects presented here, the magnitudes of the feedbacks are less likely to decrease with GMST. This implies that our estimates for the impacts of the state-dependent PCF and SAF are likely to be on a conservative side.

The particularly large uncertainty in climate warming caused globally by clouds and aerosol parametrization is an established issue[58–61]. Of the two most recent studies on the cloud feedback that were based on observational constraints, one matched closely with the ECS parameterisation from IPCC AR5 adopted in PAGE-ICE, suggesting that our climate projections are robust. The uncertainties in the permafrost models used in this study, robustness of our PCF and SAF emulators, and uncertainties in other key parameterisations such as the carbon cycle, sea level rise, mitigation business as usual pathway and economic impacts of rising temperatures are discussed in Methods and Supplementary Notes 1–3.

Discussion

We have investigated the climatic and economic impacts of two major planetary feedbacks associated with the decline of Arctic land permafrost, snow and sea ice. PCF is caused by additional CO_2 and methane emissions from thawing permafrost, and SAF is mostly driven by increased solar absorption due to the decline of Arctic sea ice and land snow covers. These two feedbacks belong to the main tipping elements in the Earth's climate system identified by recent surveys[13]. Model simulations indicate that both feedbacks accelerate the warming and are nonlinear, with the PCF being the stronger of the two, while most climate policy studies to date have assumed constant positive SAF and zero PCF, which we refer to as the legacy values. All this warrants their rigorous quantitative assessment. To perform such an assessment, we developed novel statistical emulators of the two Arctic feedbacks calibrated according to simulations results from the specialised land surface and general circulation models. The emulators allow one to study the entire parameter space, which is not possible with complex physical models, and also help establish dynamic links between highly specialized climate and economic models. We implemented the emulators dynamically inside the new integrated assessment model (IAM) PAGE-ICE, allowing us to explore nonlinear interactions between the Arctic feedbacks and the global climate and socio-economic systems under a range of scenarios consistent with the Paris Agreement.

With the current parameterisations in PAGE-ICE, adding the significant corrections from the nonlinear Arctic feedbacks to the base estimates of the mean total economic effect of climate change makes the 1.5 °C target ($638 trillion) marginally more economically attractive than the 2 °C target ($646 trillion). While the total economic effects of the 1.5 °C and 2 °C scenarios are statistically equivalent (Fig. 6), we have several reasons to believe it would be prudent to aim for emissions towards the bottom end of the range covered by these scenarios. First, the PAGE-ICE model, in common with other aggregate IAMs, does not explicitly model other known climatic tipping elements such as Amazon rainforest, boreal forest, coral reefs and El Niño–Southern Oscillation (ENSO), as well as ocean acidification and climate-induced large-scale migration and conflict[62] (we cannot reject the null hypothesis that the total economic effects of climate change are the same for these scenarios either at the 5% or at the 10% significance level). Some of these effects are already included implicitly in the highly uncertain non-economic and discontinuity impact sectors in PAGE-ICE, contributing to the long upper tails in the distributions of the total economic effect of climate change in Fig. 5a; even with the current parameterisations, the upper tails in the distributions are at their lowest for the 1.5 °C scenario. It is possible that with an explicit modelling of the other climatic and societal tipping elements, as well as with comprehensive representation of the impacts of rising temperatures and increasing extreme weather events on economic growth[63], both the economic effect of climate change with legacy Arctic feedbacks, and the additional impacts due to the nonlinear PCF and SAF, would be higher compared to those reported here. The associated global risks are minimised at lower emissions. Second, it is possible that recent reduction trends in the costs of mitigation technologies such as solar power[64,65], which are captured by PAGE-ICE, could accelerate further if appropriate policy instruments such as carbon prices are implemented globally. Third, PAGE-ICE does not account for possible co-benefits of deep mitigation as part of a wider green growth transition in

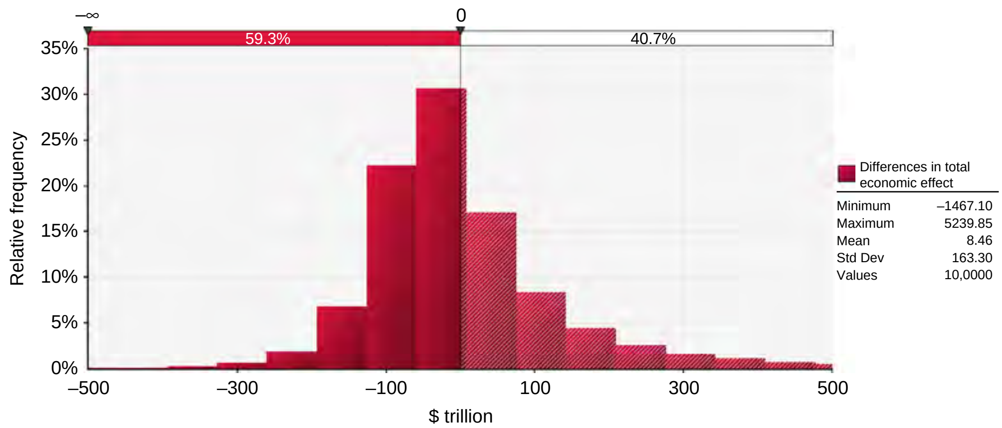

Fig. 6 Simulated difference between the total economic effects of climate change under the 2 °C and 1.5 °C scenarios. Probability density function (relative frequency) of the difference between the total economic effects of climate change for the 2 °C and 1.5 °C target scenarios with the nonlinear PCF & SAF. Horizontal axis units: $trillion, NPV until 2300, equity-weighted, PTP-discounted. 100,000 Monte-Carlo runs of PAGE-ICE. Source data are provided as a Source Data file

Table 1 Climate and socio-economic scenarios obtained by pairing RCPs with SSPs

Scenario	Description
Zero Emissions	GHG emissions stop immediately after 2020
1.5 °C Target	50% chance of staying below 1.5 °C relative to pre-industrial in 2100
2 °C Target	50% chance of staying below 2 °C relative to pre-industrial in 2100
2.5 °C Target	50% chance of staying below 2.5 °C relative to pre-industrial in 2100
NDCs	Current nationally determined contributions (pledges) to reducing GHG emissions
NDCs Partial	Around 30% of the NDCs are not met, consistent with long-term effects of the US's withdrawal
Business as usual (BaU)	Projections for GHG emissions without NDCs

economy[66,67]. All these factors advocate for pursuing the target well below 2 °C as the way of avoiding substantial ecological and socio-economic losses from climate change (see Supplementary Discussion for further details)[68].

The nonlinear transitions in the two feedbacks explored in this study demonstrate the pressing need for a better understanding of state-dependent processes in the Earth's climate system, both those associated with the Arctic and beyond. This is important because triggering these and other planetary feedbacks might accelerate the pace of climate change[13,69] and increase the risks of irreversible socio-economic losses[70]. The methodology introduced in this paper could be used to quantitatively assess the economic and climate policy implications of the other tipping elements in the Earth's climate system, including the Greenland and West Antarctic ice sheets, Amazon rainforest, boreal forest, Sahel and ENSO[13]. Such assessments could provide a more complete understanding of the socio-economic risks from climate change that in turn can help guide policymakers towards prudent decisions on emissions reduction targets.

Methods

Climate scenarios and model setup in PAGE-ICE. We defined the scenarios consistent with the Paris Agreement and current climate change projections by pairing representative concentration pathways (RCPs) and shared socio-economic pathways (SSPs) according to the feasible ranges of emissions for each of the five main SSPs[22,23]. Table 1 summarises the scenarios. The imaginary Zero Emissions scenario in which all global emissions stop in the base year 2020 characterises the effect of the historic emissions on the PCF and SAF.

First, we defined a new SSPM scenario by averaging SSP2, SSP3 and SSP4 with equal weights, and paired it with RCP4.5 to represent a likely world with medium levels of emissions. Second, we paired SSP1 with RCP2.6 and SSP5 with RCP8.5, which represents the likely lower and the upper ends of the emissions range and the associated socio-economic makeup of the world. Using these low, medium and high emissions pairs, we introduced a weighting scheme that covers the entire range as the weighting parameter w changes from -1 (lower end) to $+1$ (upper end):

$$\begin{Bmatrix} \text{SSPW} \\ \text{RCPW} \end{Bmatrix} = \left(\frac{1-w}{2}\right)^2 \cdot \begin{Bmatrix} \text{SSP1} \\ \text{RCP2.6} \end{Bmatrix} + \frac{1-w^2}{2} \cdot \begin{Bmatrix} \text{SSPM} \\ \text{RCP4.5} \end{Bmatrix} + \left(\frac{1+w}{2}\right)^2 \cdot \begin{Bmatrix} \text{SSP5} \\ \text{RCP8.5} \end{Bmatrix} \quad (1)$$

A statistical optimisation algorithm (Risk Optimiser) was then employed in PAGE-ICE to find the values of w in Equation 1 that result in a 50% probability for the GMST in 2100 to reach the levels consistent with: first, NDCs from the Paris Agreement extrapolated until 2100 (3.3 °C, $w = -0.14$);[71] second, partially implemented NDCs representing an estimated long-term effect of the US's withdrawal from the NDCs (3.6 °C, $w = 0.1$);[72] and third, business as usual projections without the Paris Agreement (4.2 °C, $w = 0.52$)[71]. We also added a 2.5 ° C target scenario ($w = -0.7$) which is more ambitious than the NDCs but falls short of the 2 °C target.

The 1.5 °C and 2 °C scenarios, defined as having a 50% chance of keeping the GMST rise in 2100 below the 1.5 °C and 2 °C targets based on PAGE-ICE simulations, require extra abatement relative to RCP2.6. They fall outside the range covered by the SSPW and RCPW pairs described above. We, therefore, introduced an additional abatement rate relative to RCP2.6, the same for all the major GHGs represented in PAGE-ICE, and employed Risk Optimiser to find that it is equal to 0.24% per year for the 2 °C target and 4.05% per year for the 2 °C target scenario. Both of these scenarios overshoot their respective targets during the second half of the 21st century and imply negative CO_2 emissions thereafter.

All the RCP scenarios in PAGE-ICE are emissions-driven[73], unlike the concentration-driven RCP scenarios that were used in most CMIP5 experiments[17]. We simulated each SSP-RCP pair out to 2300 assuming constant levels of annual emissions, constant GDP growth rates and zero population growth rates beyond 2100. Under each scenario, we ran 100,000 Monte-Carlo simulations in PAGE-ICE to perform sensitivity experiments for the climatic and economic effects of the PCF and SAF.

Emulator for the nonlinear PCF. The new dynamic emulator for CO_2 and methane emissions from thawing land permafrost is based on simulations from the SiBCASA and JULES LSMs[7,28], forced by multiple CMIP5 and CMIP3 general circulation models (GCMs) run under a range of climate scenarios out to 2300. The simulated CO_2 and methane fluxes from thawing permafrost as a function of time represent the strength and timing of the PCF.

SiBCASA has fully integrated water, energy, and carbon cycles, and a modified snow model to better simulate permafrost dynamics[74]. The soil model separately tracks liquid water, ice, and frozen organic matter at each time step as prognostic variables, accounting for the effects of latent heat[7,75]. SiBCASA separately tracks CO_2 and methane emissions. The model was used to make one of the first estimates of future permafrost degradation and global carbon emissions from thawing permafrost[7]. Here we ran multiple projections from 1901 to 2300 starting from the same initial conditions. We spun up the model until the release from permafrost carbon was negligible, ending up with 560 GtC of frozen permafrost carbon in the top three metres of soil[75,76] by initializing the model with the observed values from the Northern Circumpolar Soil Carbon Dataset version 2 (NCSCDv2)[77]. We used the Climatic Research Unit National Centre for Environmental Predictions (CRUNCEP) reanalysis[78] scaled by global climate projections from CMIP5[17]. We chose CMIP5 models that ran both RCP4.5 and RCP8.5 scenarios out to 2300 and that represent a broad range of warming above pre-industrial temperatures: CNRM-CM5, GISS-E2-H, HadGEM2-ES, IPSL-CM5A-LR and MPI-ESM-LR.

The version of JULES used here has an improved representation of physical and biogeochemical processes in the cold regions[79,80]. Competition of vegetation was enabled, allowing the models to determine both their initial vegetation distributions and litterfall, and the response of the vegetation distribution and litterfall to climate change. The profile of soil carbon was spun up until it was in equilibrium with the 1860's climate, giving 738 GtC in the top 3m of soil. Any soil carbon in the permafrost in 1860 was labelled as permafrost carbon and traced throughout the simulation. We assumed that any part of this permafrost carbon which is emitted to the atmosphere is emitted in the form of CO_2 only. JULES was forced by climate patterns from the full set of 22 CMIP3 climate model simulations under the RCP2.6, RCP4.5 and RCP8.5 scenarios, extended out to 2300 using the IMOGEN climate emulator[28].

The dynamic emulator of the permafrost carbon emissions is based on a nonlinear first order ODE:

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \frac{C_{\max}}{\tau\, \varphi_\tau(T)} \cdot \left(\frac{\max\left(C_{\mathrm{eq}}(T) - C, 0\right)}{C_{\max}}\right)^{(1+p)\, \varphi_{\mathrm{p}}(T)} \quad (2)$$

Here $T = \mathrm{AF_p} \cdot \mathrm{GMST}$ is mean annual permafrost temperature anomaly in year t, averaged spatially across the estimated pre-industrial permafrost regions (□C relative to pre-industrial levels); AFp is the permafrost amplification factor which links T with the GMST anomaly; C is cumulative permafrost carbon emitted since the pre-industrial period as of time t (GtC, either CO_2 or methane component); $C_{\mathrm{eq}}(T)$ is equilibrium cumulative carbon emitted for a constant permafrost temperature anomaly T, expressed as

$$C_{\mathrm{eq}}(T) = \min(\omega\, \varphi_\omega(T) \cdot T, C_{\max}); \quad (3)$$

$C_{\max}$ is a limit on the maximum possible cumulative emissions determined by the initial carbon stock estimates in SiBCASA (560 GtC) and JULES (738 GtC); ω (GtC K^{-1}) is equilibrium sensitivity of the carbon emissions to permafrost warming; τ (yr) is the time lag at $t = 0$ (pre-industrial) corresponding to the given $C_{\max}$; p is a fixed power that defines the dynamics of how the equilibrium is approached; φ_ω (Equation 3), φ_τ and φ_{p} (Equation 2) are temperature-driven corrections to the parameters ω,τ,p. All the parameters are assumed to be constant unless they are marked as functions. Equation 2 implies no regeneration of permafrost carbon stocks on the timescales considered[81].

The emulator is calibrated, separately, to the CO_2 components of the permafrost emissions simulated by SiBCASA and JULES, and the methane component simulated by SiBCASA. Each combination of a GCM (m) and climate scenario (s), either in SiBCASA or JULES simulations, produces its own set of optimal equilibrium carbon, lag and power parameters $(\omega,\tau, p)_{m,s}$ that achieves the best emulator fit. The resulting statistics for the ω,τ, p parameters is based on the assumptions of equal weights between the GCMs and the scenarios. The corrections φ_ω, φ_τ, φ_{p} (all non-negative) ensure quasi-independence of the $(\omega,\tau, p)_{m,s}$ set as a whole from the scenarios or climate models used. The latter allows us to use these sets of values to construct the corresponding probability distributions for ω,τ, p in PAGE-ICE, which are expected to work throughout the simulated range of temperatures. The full technical details of the calibration algorithm and the resulting numerical values for the SIBCASA and JULES emulators are provided in Supplementary Note 2, Supplementary Figs 5–17 and Supplementary Tables 2–6.

The type of a model described by Equation 2 and Equation 3 is often referred to as pursuit curve, and its simpler quasi-linear version ($p = 0$) has been employed for sea level rise emulators previously[82,83]. Even in its simpler form, such a model has never been applied to projected permafrost emissions from process-based simulations of LSMs. The pursuit curve model ensures that there is an equilibrium level of cumulative carbon emissions from permafrost for any given level of warming globally (providing $p > -1$). The dynamic model formulation employed here contains the following layers of nonlinearity: nonlinear response of the equilibrium cumulative carbon to GMST changes, represented by the $\omega\varphi_\omega(T)\cdot T$ term; evolution of the characteristic time lag for cumulative permafrost emissions with the difference between the equilibrium and realised cumulative carbon, represented by p (in the corresponding linear model $p = 0$ and the lag is simply equal to τ); temperature-dependence in the lag and power parameters, represented by φ_τ, φ_{p}; and, saturation of the cumulative carbon emissions due to the permafrost carbon stock exhaustion, represented by $C_{\max}$.

The cumulative carbon emissions from the emulators, calibrated separately to SiBCASA and JULES simulations, were averaged with equal weights, both for CO_2 and methane, and scaled according to the uncertainty in the observed permafrost carbon stocks[31]. As JULES does not model permafrost methane emissions explicitly, the latter were inferred from its CO_2 emissions using observational constraints[84]. The resulting cumulative CO_2 and methane emissions from permafrost simulated by PAGE-ICE are plotted in Fig. 7 under the range of scenarios considered.

Emulator for the nonlinear SAF. Our nonlinear SAF estimates are based on the ALL/CLR method with atmospheric reflectivity parameterisation[32,33], which uses CMIP5 GCM simulations for atmospheric shortwave radiation fluxes from pre-industrial conditions until either 2100 or 2300 under RCP8.5 scenario (Supplementary Note 3). None of the GCM variables were bias-corrected in order to preserve internal consistency of the sea ice and land snow physics in each model. The statistics of the nonlinear SAF assumes model democracy in the CMIP5 sample used (equal weights for all GCMs).

Applying the ALL/CLR method to the transient GCM simulations produced time series for the global RF associated with the surface albedo changes. These were differentiated with respect to GMST trends over 30-year climatological windows, separately for each model, using linear polynomial fitting to obtain climatologically-averaged SAF in each year. A Savitzky–Golay filter (base period = 31 years; polynomial order = 1) was applied to obtain smooth time series for GMST and SAF. The SAF (both global total and separately for the three main components) was then represented as a function of the GMST rise individually for each model, at which point the multi-model statistics was calculated.

We based the emulator of the global nonlinear SAF on a two-segment approximation described by the following expressions for the SAF, $f(T)$, and the associated RF, $F(T)$:

$$f(T) = \begin{cases} a_0 + a_1 T + a_2 T^2 + \sigma\varepsilon, & T < T_* \\ b_0 + \rho\varepsilon, & T \geq T_* \end{cases}$$

$$F(T) = \int_0^T f(T')\mathrm{d}T' = \begin{cases} (a_0 + \sigma\varepsilon)T + \frac{1}{2}a_1 T^2 + \frac{1}{3}a_2 T^3, & T < T_* \\ (a_0 + \sigma\varepsilon)T_* + \frac{1}{2}a_1 T_*^2 + \frac{1}{3}a_2 T_*^3 + (b_0 + \rho\varepsilon)\cdot(T - T_*), & T \geq T_* \end{cases} \quad (4)$$

Here T is the GMST anomaly (not to be confused with the permafrost temperature), $T_* = 10\,°\mathrm{C}$ is an empirically determined switch between the quadratic and constant SAF segments (Fig. 8), a_j are the coefficients of quadratic polynomial fitting to the multi-model mean global SAF over the $T < T_*$ segment, b_0 is average of the multi-model mean global SAF over the $T \geq T_*$ segment, $\sigma(\rho)$ is average of the multi-model SD of the global SAF over the $T < T_*$ ($T \geq T_*$) segment, and $\varepsilon = \mathcal{N}(0, 1)$. The full technical description of the implementation of the SAF emulator in PAGE-ICE is provided in Supplementary Note 3.

PAGE-ICE IAM. PAGE-ICE (v6.22) is based on the PAGE09 IAM[19,20]. It includes several updates both to climate science and economics from IPCC AR5 and literature that followed, as well as several novel developments presented in this paper. The updates are summarised below, with the full technical description provided in Supplementary Note 1, Supplementary Figs 18–23 and Supplementary Tables 7–17.

PAGE and similar IAMs do not model natural climate variability, and therefore each Monte-Carlo run is deterministic in time. This allows us to work with Monte-Carlo generated probability distributions of multiple climatic and economic parameters in any fixed analysis year like 2100, as opposed to taking averages over the 30-year climatological windows (a standard requirement for any climate model data with multiple natural variability cycles). The ranges for all the uncertain parameters in PAGE-ICE are listed in the Supplementary Table 17.

Generic updates in PAGE-ICE: first, adjusted analysis years starting with 2015 (base year), 2020, 2030, 2040, 2050, 2075, 2100, 2150, 2200, 2250 and 2300, allowing for a better representation of the essential long-term processes: permafrost emissions, winter sea ice and land snow decline and melting of the ice sheets; second, updated base year (2015) data for the emissions, temperature, population, GDP-PPP, cumulative permafrost emissions and surface albedo feedback, with uncertainty ranges for most parameters; third, updated set of emissions (RCP) and socio-economic (SSP) scenarios paired according to the RCP-SSP compatibility conditions[22], and modified to cover the range of scenarios in line with the Paris Agreement, as well as the possibility of a reversal of climate policies in the US and globally.

Climate science updates in PAGE-ICE: first, internal dynamic representation of the nonlinear PCF and SAF using emulators based on simulations from multiple CMIP5 and CMIP3 GCMs and SiBCASA and JULES LSMs run under the extended RCP8.5, 4.5 and 2.6 (only JULES) scenarios out to 2300 (see the relevant Methods sections above); second, adjusted transient climate response (TCR), feedback response time (FRT) and ECS parameter ranges according to IPCC AR5 based on CMIP5 models, paleo-records and climate models of intermediate complexity; third, revised CO_2 cycle in line with the latest multi-model assessment of the

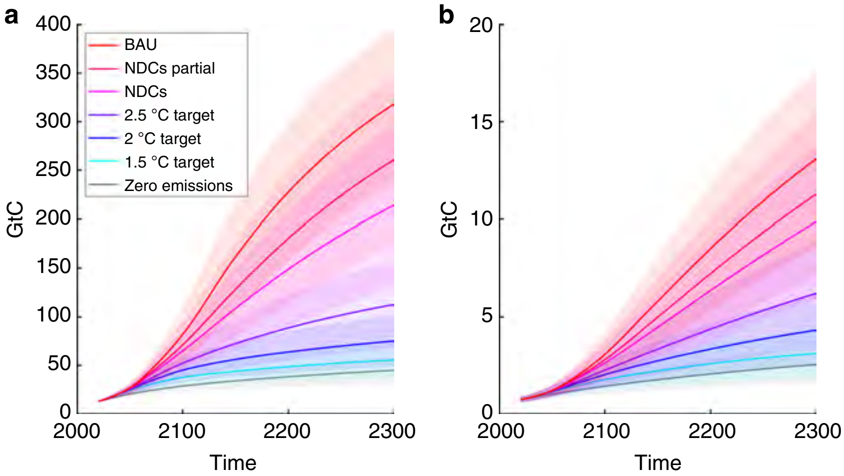

Fig. 7 Cumulative carbon emissions from the permafrost simulated using the dynamic emulator. Cumulative carbon emissions from thawing land permafrost for **a** CO_2 and **b** methane components simulated by the new statistical emulator of SiBCASA and JULES (equal weighting) under the chosen range of climate scenarios until the year 2300 (solid lines: mean; shaded areas: ±1SD). 100,000 Monte-Carlo runs of PAGE-ICE. Units: GtC. Note the difference in the Y-axis scale between the plots. Source data are provided as a Source Data file

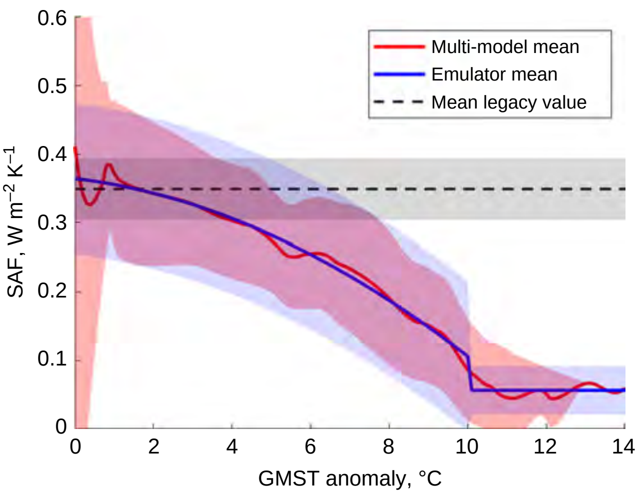

Fig. 8 Emulator of the global surface albedo feedback and its legacy value. Global SAF as a function of the GMST rise relative to pre-industrial conditions obtained from 16 CMIP5 GCMs using the ALL/CLR method. Red line: multi-model mean; shaded red area: ±1SD; blue line and shaded area: mean and ±1SD of the two-segment emulator. The dashed line and grey shaded area show statistical mean and ±1SD of the SAF averaged between pre-industrial conditions and the level of warming corresponding to the $2xCO_2$ ECS experiment (mean value of 2.8 °C, 5–95% range of 1.7 °C–4.2 °C according to IPCC AR5). Source data are provided as a Source Data file

atmospheric CO_2 response function;[85] fourth, improved GMST equation using a better numerical scheme for finite analysis periods; fifth, CMIP5-based amplification factors for the regional temperatures; sixth, changes in the implementation of the regional sulphate cooling: sulphates now add to the global forcing and affect the regional temperatures implicitly through the CMIP5-based amplification factors (their RF is not included in the regional temperature equation directly due to the complexity of climatic response to regional RFs, which requires regional climate sensitivities to be introduced;[86] seventh, approximately halved indirect sulphate cooling effect; eighth, fat-tailed distribution for the sea level rise (SLR) time lag (at the lower values end) to account for the possible acceleration in the discharge from the West Antarctica and Greenland ice sheets[87–90].

Economics updates in PAGE-ICE: first, new economic impact function based on the recent macro-econometric analysis of the effect of historic temperature shocks on economic growth in multiple countries by Burke et al.[46], projected onto the 8 major regions of the PAGE model using population-weighted temperatures, and adapted to fit with the single year consumption-only approach for climate impacts used in PAGE; second, considerably downscaled saturation limit for the impacts; third, modified uncertainty range for the BaU scenario, which is used as a reference point for calculating the abatement costs, covering the range roughly between RCP6.0 and a pathway exceeding RCP8.5;[23] fourth, revised present-day marginal abatement cost (MAC) curves[64], technological learning rate (CO_2 only)[65] and autonomous technological change based on energy efficiency improvements;[91] fifth, significantly downscaled discontinuity sector, which now accounts only for socio-economic tipping points such as pandemics, mass migration and wars, as well as possible other tipping points in the climate than permafrost, sea ice, land snow and lea level rise from ice sheets (the catastrophic loss of the ice sheets has been moved to the fat-tailed distribution in the sea level rise module); sixth, reduced tolerable temperature rise that gives no chance of a discontinuity; seventh, significantly decreased time constant of a discontinuity in line with its new interpretation; eighth, focus on autonomous adaptation as part of the Burke et al. economic impact function, with planned adaptation restricted to SLR impacts.

Climate model data. The complete lists of the CMIP5 and CMIP3 models used in the study are provided in Supplementary Tables 18 and 19.

Image processing. The Figures were plotted using Matlab R2018a, IDL (Fig. 5) and Palisade Risk 7.5 (Fig. 6). We used Matlab's Savitzky–Golay smoothing for the SAF results from CMIP5 (Fig. 2) and Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) interpolation for the time-series results from PAGE-ICE.

Data availability

All data generated or analysed during this study are included in this published article and its Supplementary Dataset files, with exception of the publically available CMIP datasets acknowledged below.

Code availability

The PAGE-ICE model (v6.22) and the associated pre- and post-processing computer codes are included in the Supplementary Code files. The SiBCASA and JULES models are managed, respectively, by expert teams at the National Snow and Ice Data Centre (US) and at the UK Met Office, and are not included in this publication due to their complexity.

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Author contributions

D.Y., G.W. and C.H. conceived the research; D.Y. and C.H. created the PAGE-ICE model and ran the simulations; D.Y. developed and calibrated the permafrost and albedo feedback emulators; K.S. and E.J. designed and ran SiBCASA simulations; E.B. designed and ran JULES simulations; K.R.C., F.I.S. and D.Y. adapted the ALL/CLR script for the albedo feedback; F.I.S., K.R.C., K.S., P.Y. and Y.E. processed climate model data; All authors provided input on the scientific and policy matters and contributed to the writing of the paper.

Additional information

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The New York Times

SIBERIA DISPATCH

Russian Land of Permafrost and Mammoths Is Thawing

Global warming is shrinking the permanently frozen ground across Siberia, disrupting everyday life in one of the coldest inhabited places on earth.

By Neil MacFarquhar Photographs by Emile Ducke

Aug. 4, 2019

YAKUTSK, Russia — The lab assistant reached into the freezer and lifted out a football-size object in a tattered plastic grocery bag, unwrapping its muddy covering and placing it on a wooden table. It was the severed head of a wolf.

The animal, with bared teeth and mottled fur, appeared ready to lunge. But it had been glowering for some 32,000 years — preserved in the permafrost, 65 feet underground in Yakutia in northeastern Siberia.

As the Arctic, including much of Siberia, warms at least twice as fast as the rest of the world, the permafrost — permanently frozen ground — is thawing. Oddities like the wolf's head have been emerging more frequently in a land already known for spitting out frozen woolly mammoths whole.

The thawing of the permafrost — along with other changes triggered by global warming — is reshaping this incredibly remote region sometimes called the Kingdom of Winter. It is one of the coldest inhabited places on earth, and huge; Yakutia, if independent, would be the world's eighth largest country.

The loss of permafrost deforms the landscape itself, knocking down houses and barns. The migration patterns of animals hunted for centuries are shifting, and severe floods wreak havoc almost every spring.

The water, washing out already limited dirt roads and rolling corpses from their graves, threatens entire villages with permanent inundation. Waves chew away the less frozen Arctic coastline.

Water has inundated the cemetery in Srednekolymsk, shifting the graves. Emile Ducke for The New York Times

Vasily P. Okoneshnikov, 54, the head of the village of Nalimsk, inspecting a pole used to tie horses. Due to frequent floods, the poles no longer stand straight, but some, considered sacred, cannot be righted.
Emile Ducke for The New York Times

Indigenous peoples are more threatened than ever. Residents joust constantly with nature in unpredictable ways, leaving them feeling baffled, unsettled, helpless, depressed and irritated.

“Everything is changing, people are trying to figure out how to adapt,” said Afanasiy V. Kudrin, 63, a farmer in Nalimsk, a village of 525 people above the Arctic Circle. “We need the cold to come back, but it just gets warmer and warmer and warmer.”

Climate change is a global phenomenon, but the shifts are especially pronounced in Russia, where permafrost covers some two-thirds of the country at depths ranging up to almost a mile.

“People don’t comprehend the scale of this change, and our government is not even thinking about it,” said Aleksandr N. Fedorov, deputy director of the Melnikov Permafrost Institute, a research body in Yakutsk, the regional capital.

Afanasiy V. Kudrin, 63, a farmer in Nalimsk, showing a permafrost cellar whose walls now drip water.
Emile Ducke for The New York Times

A 32,000-year-old wolf head, which had been frozen in permafrost 65 feet underground.
Emile Ducke for The New York Times

In Yakutia, almost 20 percent of Russia, distances are vast and transportation erratic. The population is just under one million. Natives joke that every resident could claim one lake.

Yakutia's 33 districts are the size of countries. In the far northeast, the Srednekolymsk district, which lies entirely above the Arctic Circle, is slightly smaller than Greece. Just 8,000 residents live in 10 villages, including 3,500 in the capital, also Srednekolymsk.

The region has been a synonym for remote for centuries. Empress Elizabeth exiled the first prominent political prisoner to Srednekolymsk in 1744, when it took a year to reach overland from St. Petersburg. There are just two main highways transiting Yakutia, with the one built mostly by Gulag prisoners under Communism still largely unpaved.

In Srednekolymsk, summer used to last from June 1 to Sept. 1, but now extends a couple weeks longer on both ends. Outsiders might not notice that the thermometer in January often hovers around -50 F, rather than -75 F. Residents call -50 “chilly.”

By The New York Times

In a regionwide pattern, the average annual temperature in Yakutsk has risen more than four degrees, to 18.5 F from 14 F, over several decades, said Mr. Fedorov of the permafrost institute.

Warmer winters and longer summers are steadily thawing the frozen earth that covers 90 percent of Yakutia. The top layer that thaws in summer and freezes in winter can extend down as far as 10 feet where three feet used to be the maximum.

Eroding cliffs on riverbanks expose other areas, like where the wolf head appeared, that had long been deeply buried.

A Soviet-era memorial to honor political prisoners exiled to Srednekolymsk under Tsarist rule.
Emile Ducke for The New York Times

Across Yakutia, farmers have replaced tens of thousands of cows with native horses who eat less hay, but produce less milk. The market for their meat is limited. Emile Ducke for The New York Times

The thawing permafrost, and increased precipitation, have made the land wetter. The snow and rain create a vicious circle, forming an insulating layer that speeds defrosting underground.

Water backing up behind ice floes now causes ravaging floods virtually every May.

In Srednekolymsk last year, floods swamped the dirt airstrip, with its separate outhouses for men and women. Often battered Soviet turboprops are the lifeline to the world, but the airstrip had to close for a week.

Nalimsk, 11 miles north of Srednekolymsk, has flooded five years in a row. Mosquitoes grown fat in the expanding bogs swarm like kamikaze pilots. “Free acupuncture!” joked Vasily P. Okoneshnikov, 54, the village headman.

Plump black Turpan ducks used to arrive regularly during the first week of June. This year migrating birds began to descend on May 1. There were far fewer Turpans, and suddenly geese, a novelty.

Fishermen hauling their boat off the Kolyma River in northeastern Yakutia around 9 p.m., during the summer nights when the sun never entirely sets. Emile Ducke for The New York Times

Appolinariy H. Popov, 55, built his small fisherman's hut in Vyatkino, north of Srednekolymsk, on a bluff overlooking the Kolyma River because floods swept away many similar structures closer to the water.
Emile Ducke for The New York Times

Elsewhere, the migration routes of wild reindeer have shifted, while unfamiliar insects and plants inhabit the woods.

Nalimsk hunters once stored their fish and game in a 22-foot deep cave dug out of the permafrost, a kind of natural freezer. Now its thawing walls drip water, and the meat rots.

"We buy meat and it is no good, too dry," Mr. Okoneshnikov said. "We have no choice, even if it's shameful" to shop, rather than hunt.

Farther north, residents refuse to abandon their waterlogged, riverfront villages, afraid of losing access to whitefish, their staple diet.

The village of Beryozovka has flooded virtually every spring for a decade, its 300 residents forced onto boats for weeks to run errands like buying bread. They finally accepted a five-year project to move the village 900 yards uphill.

In the district, Beryozovka has the only concentration of Even people, one of various dwindling indigenous tribes.

The Even, who are reindeer herders, were settled only in 1954 through a government drive. They speak a distinct language; individual clans inherit ancestral songs.

"At some point they talked about abandoning the village, but people did not want to move out," said Octyabrina R. Novoseltseva, chairwoman of the Northern Indigenous People's Association in the Srednekolymsk region. "They would lose everything, the culture would all disappear."

"At some point they talked about abandoning the village, but people did not want to move out," said Octyabrina R. Novoseltseva, the chairwoman of the Northern Indigenous People's Association in the Srednekolymsk region. Emile Ducke for The New York Times

An exhibition at the Museum of Archaelogy and Ethnography in Yakutsk displays ancient life of indigenous people in Yakutia. Various small, indigenous tribes, who have herded reindeer for centuries, are under threat as global warming thaws the permafrost. Emile Ducke for The New York Times

The government in distant Moscow is an abstract concept. Alaska is closer. Villagers throughout Yakutia bemoan relying on their own resources to adapt to climate change.

Even state-run institutions like the permafrost institute lack the means for the complicated field work needed to assess the full extent of permafrost loss. Nor can they gauge other fallout, like how much methane that microbes in the newly thawed ground produce, adding to global warming.

“We do not really monitor the situation, so we just have to see what it brings,” said Yevgeny M. Sleptsov, the head of the Srednekolymsk district, as he piloted a fishing boat along the Kolyma River at 10 p.m. in the muted light of the endless Arctic day.

The government is also unable to do much about other environmental problems, including wildfires surging through millions of acres of remote forest across Yakutia and the rest of Siberia. Reaching them is too costly.

The north side of Srednekolymsk regularly gets flooded during the spring. Emile Ducke for The New York Times

Ivan D. Trofimov, a 63-year-old farmer, inside his old house in the central village of Usun-Kyuyol. The house sank due to melting permafrost. Emile Ducke for The New York Times

In 1901, the first woolly mammoth discovered whole in the permafrost emerged from a riverbank near Srednekolymsk, an event immortalized with a stylized red mammoth on the town's shield.

But thawing permafrost is exposing more of the huge hairy beasts, which roamed a more temperate northern Siberia 10,000 years ago. And with agriculture and hunting unreliable, more locals are looking for them.

Digging for mammoths is illegal, so the hunters are secretive, but one ivory tusk sold to China can earn $16,000 — enough to live on for a year.

Tusk hunters unearthed the Pleistocene wolf head stored in the Department of Mammoth Studies at the Academy of Science in Yakutsk.

The loss of permafrost also afflicts the capital, Yakutsk. Subsiding ground has damaged about 1,000 buildings, said the mayor, Sardana Avksentieva, while roads and sidewalks require constant repair.

As the permafrost thaws across Yakutia, some land sinks, transforming the terrain into an obstacle course of hummocks and craters — called thermokarst. It can sink further to become swamps, then lakes. From the air, thermokarst looks as if giant warts are plaguing the earth. It makes plowing or grazing on formerly flat fields impossible.

In Srednekolymsk, after a local veteran of the war in eastern Ukraine went berserk, shooting dead a police officer and then himself, the police preserved his corpse in an old natural freezer carved out of the underground permafrost. Emile Ducke for The New York Times

The skeleton of a mammoth in the lobby that the Museum of Archaelogy and Ethnography shares with the Museum of Mammoths in Yakutsk. Emile Ducke for The New York Times

Thermokarsts besiege the Churapcha region, 120 miles east of Yakutsk.

Thirty-three families once inhabited the northern part of Usun-Kyuyol, a village of 750 people. After their cow barns and fences repeatedly collapsed, 10 families decamped. Those remaining feel beleaguered.

To find flat, dry land to grow hay, farmers work further and further away.

Across Yakutia, farmers have replaced tens of thousands of cows with native horses. Horses consume less hay, but produce less milk, and the market for their meat is limited. They also die in droves when their hooves cannot penetrate thicker snow and ice to forage.

Nikolai S. Makarkov, 62, is building a new house. He tired of jacking up his old one after it sank four times so that the doors would not open. Water also seeped underneath, rotting the floorboards and freezing in winter, chilling the interior.

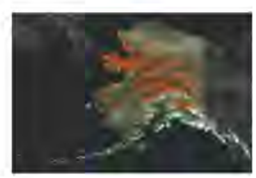
Years ago, the village road ran straight, with log cabins and cow barns arrayed along its length. Now the potholed muddy track meandering among the hummocks barely resembles a road. Abandoned houses tilt at odd angles.

“There might as well have been a war here,” said Mr. Makarkov, whose new house is raised off the ground on pillars sunk 16 feet, where there is still permafrost. “Soon there will be no flat land left in this village. I only have 30-40 years to live, so hopefully my new house will last that long.”

In Yakutsk more than 1,000 buildings have been destroyed as global warming melts the permafrost under the foundations of buildings. This structure is on stilts to try to prevent its heat from melting the permafrost. Emile Ducke for The New York Times

From Siberia, an Unlikely Cry: 'We Need Greenpeace Out Here!' April 26, 2018

Alaska's Permafrost Is Thawing Aug. 23, 2017



Weaning Itself From Elephant Ivory, China Turns to Mammoths Aug. 6, 2017

Neil MacFarquhar, the Moscow bureau chief, was previously the bureau chief at the United Nations and in Cairo, and held several assignments in the Middle East. @NeilMacFarquhar

A version of this article appears in print on Aug. 3, 2019, Section A, Page 6 of the New York edition with the headline: A Long-Frozen Place, Melting and Changing Right Under Their Feet

United States Government Accountability Office

Testimony

Before the Committee on the Budget, House of Representatives

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CLIMATE CHANGE

Opportunities to Reduce Federal Fiscal Exposure

Statement of J. Alfredo Gómez, Director, Natural Resources and Environment

GAO-19-625T

June 11, 2019

CLIMATE CHANGE

Opportunities to Reduce Federal Fiscal Exposure

GAO Highlights

Highlights of GAO-19-625T, a testimony before the Committee on the Budget, House of Representatives

Why GAO Did This Study

Since 2005, federal funding for disaster assistance is at least $450 billion, including approximately $19.1 billion in supplemental appropriations signed into law on June 6, 2019. In 2018 alone, there were 14 separate billion-dollar weather and climate disaster events across the United States, with a total cost of at least $91 billion, according to the National Oceanic and Atmospheric Administration. The U.S. Global Change Research Program projects that disaster costs will likely increase as certain extreme weather events become more frequent and intense due to climate change.

The costs of recent weather disasters have illustrated the need for planning for climate change risks and investing in resilience. Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events, according to the National Academies of Science, Engineering, and Medicine. Investing in resilience can reduce the need for far more costly steps in the decades to come.

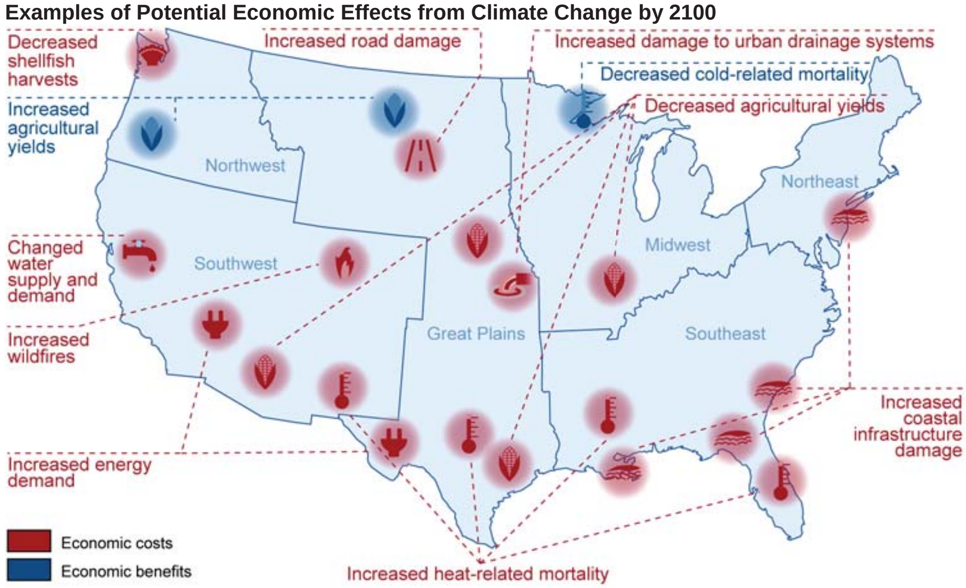
Since February 2013, GAO has included *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* on its list of federal program areas at high risk of vulnerabilities to fraud, waste, abuse, and mismanagement or most in need of transformation. GAO updates this list every 2 years. In March 2019, GAO reported that the federal government had not made measurable progress since 2017 to reduce fiscal exposure to climate change.

View GAO-19-625T. For more information, contact J. Alfredo Gómez at (202) 512-3841 or gomezj@gao.gov.

What GAO Found

The estimated economic effects of climate change, while imprecise, can convey useful insight about potential damages in the United States. In September 2017, GAO reported that the potential economic effects of climate change could be significant and unevenly distributed across sectors and regions (see figure). This is consistent with the recent findings of the U.S. Global Change Research Program's Fourth National Climate Assessment, which concluded, among other things, that the continued increase in the frequency and extent of high-tide flooding due to sea level rise threatens America's trillion-dollar coastal infrastructure.

Examples of Potential Economic Effects from Climate Change by 2100



Sources: GAO analysis of Environmental Protection Agency, *Climate Change Impacts in the United States: Benefits of Global Action* (Washington, D.C.: 2015), and Solomon Hsiang et al., "Estimating Economic Damage from Climate Change in the United States," *Science*, vol. 356 (2017); Map Resources (map). | GAO-19-625T

Information about the potential economic effects of climate change could inform decision makers about significant potential damages in different U.S. sectors or regions. According to prior GAO work, this information could help decision makers identify significant climate risks as an initial step toward managing them.

The federal government faces fiscal exposure from climate change risks in several areas, including:

- **Disaster aid:** due to the rising number of natural disasters and increasing reliance on federal assistance. GAO has previously reported that the federal government does not adequately plan for disaster resilience. GAO has also reported that, due to an artifically low indicator for determining a jursidiction's ability to respond to disasters that was set in 1986, the Federal Emergency

This testimony—based on reports GAO issued from October 2009 to March 2019—discusses (1) what is known about the potential economic effects of climate change in the United States and the extent to which this information could help federal decision makers manage climate risks across the federal government, (2) the potential impacts of climate change on the federal budget, (3) the extent to which the federal government has invested in resilience, and (4) how the federal government could reduce fiscal exposure to the effects of climate change.

GAO has made 62 recommendations related to the *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* high-risk area. As of December 2018, 25 of those recommendations remained open.

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Management Agency risks recommending federal assistance for juridisctions that could recover on their own.

- **Federal insurance for property and crops:** due, in part, to the vulnerability of insured property and crops to climate change impacts. Federal flood and crop insurance programs were not designed to generate sufficient funds to fully cover all losses and expenses. The flood insurance program, for example, was about $21 billion in debt to the Treasury as of April 2019. Further, the Congressional Budget Office estimated in May 2019 that federal crop insurance would cost the federal government an average of about $8 billion annually from 2019 through 2029.
- **Operation and management of federal property and lands:** due to the hundreds of thousands of federal facilities and millions of acres of land that could be affected by a changing climate and more frequent extreme events. For example, in 2018, Hurricane Michael devastated Tyndall Air Force Base in Florida, with a preliminary repair estimate of $3 billion.

The federal budget, however, does not generally account for disaster assistance provided by Congress or the long-term impacts of climate change on existing federal infrastructure and programs. GAO has reported that more complete information about fiscal exposure could help policymakers better understand the trade-offs when making spending decisions.

Further, federal investments in resilience to reduce fiscal exposures have been limited. As GAO has reported, enhancing resilience can reduce fiscal exposure by reducing or eliminating long-term risk to people and property from natural hazards. For example, a 2018 interim report by the National Institute of Building Sciences estimated approximate benefits to society in excess of costs for several types of resilience projects. While precise benefits are uncertain, the report estimated that for every dollar invested in designing new buildings to particular design standards, society could accrue benefits amounting to about $11 on average.

The federal government has invested in individual agency efforts that could help build resilience within existing programs or projects. For example, the National Climate Assessment reported that the U.S. military integrates climate risks into its analysis, plans, and programs. In additon, as GAO reported in March 2019, the Disaster Recovery Reform Act of 2018 could improve resilience by allowing the President to set aside a portion of certain grants for pre-disaster mitigation. However, the federal government has not undertaken strategic government-wide planning to manage climate risks.

GAO's March 2019 High-Risk report identified a number of recommendations GAO has made related to fiscal exposure to climate change. The federal government could reduce its fiscal exposure by implementing these recommendations. Among GAO's key government-wide recommendations are:

- Entities within the Executive Office of the President (EOP) should work with partners to establish federal strategic climate change priorities that reflect the full range of climate-related federal activities;
- Entities within EOP should use information on potential economic effects from climate change to help identify significant climate risks and craft appropriate federal responses;
- Entities within EOP should designate a federal entity to develop and update a set of authoritative climate observations and projections for use in federal decision making, and create a national climate information system with defined roles for federal agencies and certain nonfederal entities; and
- The Department of Commerce should convene federal agencies to provide the best-available forward-looking climate information to organizations that develop design standards and building codes to enhance infrastructure resilience.

Chairman Yarmuth, Ranking Member Womack, and Members of the Committee:

Thank you for the opportunity to discuss our work on how to limit the federal government's fiscal exposure by better managing climate change risks, an area that has been on our High-Risk List since February 2013.[1] Addressing climate change risks requires advanced planning and investment to reduce the need for far more costly steps in the decades to come, which, as we have previously reported, the federal government is not well organized to do. The costs associated with recent disasters have illustrated the need for such planning and investment. In 2018 alone, there were 14 separate billion-dollar weather and climate disaster events across the United States, with a total cost of at least $91 billion, according to the National Oceanic and Atmospheric Administration (NOAA).[2] Further, on June 6, 2019, a supplemental appropriation of approximately $19.1 billion was signed into law for recent disasters.

The U.S. Global Change Research Program (USGCRP), which coordinates and integrates the activities of 13 federal agencies that research changes in the global environment and their implications for society, reported in its November 2018 Fourth National Climate Assessment that climate change is playing a role in the increasing frequency of some types of extreme weather that lead to the billion-dollar disasters.[3] These changes include the rise in vulnerability to drought, lengthening wildfire seasons, and the potential for extremely heavy rainfall becoming more common in some regions. USGCRP reported in the prior assessment that the costs of many of these disasters will likely

[1]Our High-Risk List identifies federal program areas that are at high risk of vulnerabilities to fraud, waste, abuse, and mismanagement or most in need of transformation. See GAO, *High-Risk Series: An Update*, GAO-13-283 (Washington, D.C.: Feb. 14, 2013).

[2]NOAA National Centers for Environmental Information, U.S. Billion-Dollar Weather and Climate Disasters (2019). See: https://www.ncdc.noaa.gov/billions/time-series, accessed June 3, 2019.

[3]D.R. Reidmiller, C.W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart (eds.), *2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Washington, DC: U.S. Global Change Research Program, November 2018). Under the Global Change Research Act of 1990 (Pub. L. No. 101-606, § 103 (1990)), USGCRP is to periodically prepare a scientific assessment—known as the National Climate Assessment—which is an important resource for understanding and communicating climate change science and impacts in the United States. The Office of Science and Technology Policy within the Executive Office of the President oversees USGCRP.

increase as extreme weather events become more frequent and intense with climate change.[4]

In my testimony today, I will discuss (1) what is known about the potential economic effects of climate change in the United States and the extent to which this information could help federal decision makers manage climate risks across the federal government, (2) the potential impacts of climate change on the federal budget, (3) the extent to which the federal government has invested in resilience to climate change impacts,[5] and (4) how the federal government could reduce fiscal exposure to the effects of climate change. My testimony is based on reports we issued from October 2009 to March 2019. More detailed information on our objectives, scope, and methodology can be found in those reports.

The work upon which this statement is based was conducted in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[4]Jerry M. Melillo, Terese (T.C.) Richmond, and Gary W. Yohe, eds., *Climate Change Impacts in the United States: The Third National Climate Assessment*, U.S. Global Change Research Program (Washington, D.C.: May 2014).

[5]The National Academies of Sciences, Engineering, and Medicine (National Academies) define resilience as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. See the National Academies, Committee on Increasing National Resilience to Hazards and Disasters; Committee on Science, Engineering, and Public Policy; Disaster Resilience: A National Imperative (Washington, D.C.: 2012). We reported in May 2016 that two related sets of actions can enhance resilience by reducing risk. These include climate change adaptation and pre-disaster hazard mitigation. Adaptation is defined as adjustments to natural or human systems in response to actual or expected climate change. Pre-disaster hazard mitigation refers to actions taken to reduce the loss of life and property by lessening the impacts of adverse events and applies to all hazards, including terrorism and natural hazards, such as health pandemics or weather-related disasters. In this testimony, we use the term “resilience” for consistency and to encompass both of these sets of actions as they relate to addressing climate risks. GAO, *Climate Change: Selected Governments Have Approached Adaptation through Laws and Long-Term Plans,* GAO-16-454 (Washington, D.C.: May 12, 2016).

Information on the Potential Economic Effects of Climate Change in the United States Could Help Federal Decision Makers Better Manage Climate Risks

We reported in September 2017 that, while estimates of the economic effects of climate change are imprecise due to modeling and information limitations, they can convey useful insight into broad themes about potential damages in the United States.[6] We reported that, according to the two national-scale studies available at the time that examined the economic effects of climate change across U.S. sectors, potential economic effects could be significant and these effects will likely increase over time for most of the sectors analyzed.[7] For example, for 2020 through 2039, one of the studies estimated from $4 billion to $6 billion in annual coastal property damages from sea level rise and more frequent and intense storms.[8] In addition, the national-scale studies we reviewed and several experts we interviewed for the September 2017 report suggested that potential economic effects could be unevenly distributed across sectors and regions. For example, one of the studies estimated that the Southeast, Midwest, and Great Plains regions will likely experience greater combined economic effects than other regions, largely because of coastal property damage in the Southeast and changes in crop yields in the Midwest and Great Plains (see figure 1).[9] This is

[6]GAO, *Climate Change: Information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure,* GAO-17-720 (Washington, D.C.: Sept. 28, 2017).

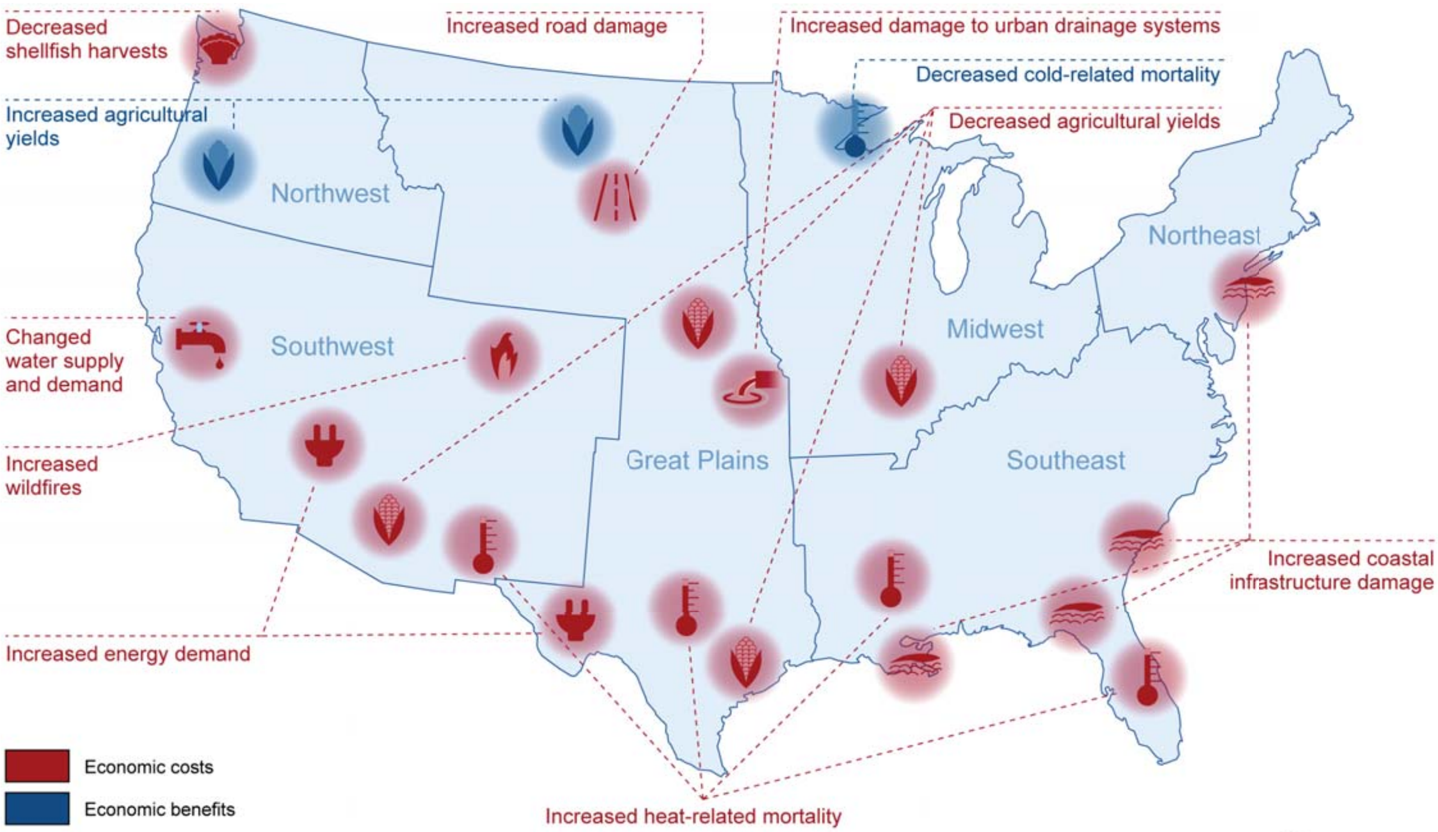
[7]These national-scale studies were the Environmental Protection Agency's *Climate Change Impacts and Risk Analysis*—a summary study of an ongoing EPA project—and the Rhodium Group's *American Climate Prospectus.* See Environmental Protection Agency, Office of Atmospheric Programs, *Climate Change in the United States: Benefits of Global Action*, EPA 430-R-15-001 (Washington, D.C.: 2015). The EPA project on which the summary study was based was coordinated by EPA's Office of Atmospheric Programs—Climate Change Division, with contributions from national laboratories and the academic and private sectors. The detailed methods and results of the project were published in a 2014 special issue of the peer-reviewed journal, *Climatic Change* entitled, "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." An update to this project was used in the 2018 Fourth National Climate Assessment. Also see Rhodium Group, LLC., *American Climate Prospectus: Economic Risks in the United States* (New York: October 2014). The *American Climate Prospectus* was funded by the Risky Business Project, a project funded by Bloomberg Philanthropies, the Paulsen Institute, and TomKat Charitable Trust; the Skoll Global Threats Fund; and the Rockefeller Family Fund. The Rhodium Group, LLC, a research consultancy and advisory company, coordinated the effort, which involved authors from universities and the private sector. This study was later published by the Columbia University Press in 2015: Trevor Houser et al., *Economic Risks of Climate Change: An American Prospectus* (New York: Columbia University Press, 2015). An update to this analysis was published in *Science* in June 2017: Solomon Hsiang et al "Estimating Economic Damage from Climate Change in the United States," *Science*, vol. 356 (2017).

[8]Rhodium Group, *American Climate Prospectus.*

[9]Rhodium Group, *American Climate Prospectus.*

consistent with the findings of the Fourth National Climate Assessment.[10] For example, according to that assessment, the continued increase in the frequency and extent of high-tide flooding due to sea level rise threatens America's trillion-dollar coastal property market and public infrastructure sector.

Figure 1: Examples of Potential Economic Effects from Climate Change by 2100



Sources: GAO analysis of Environmental Protection Agency, *Climate Change Impacts in the United States: Benefits of Global Action* (Washington, D.C.: 2015), and Solomon Hsiang et al., "Estimating Economic Damage from Climate Change in the United States," *Science*, vol. 356 (2017); Map Resources (map). | GAO-19-625T

As we reported in September 2017, information on the potential economic effects of climate change could help federal decision makers better manage climate risks, according to leading practices for climate risk management, economic analysis we reviewed, and the views of several

[10]D.R. Reidmiller e.t. al, *Fourth National Climate Assessment, Volume II.*

experts we interviewed.[11] For example, such information could inform decision makers about significant potential damages in different U.S. sectors or regions. According to several experts and our prior work, this information could help federal decision makers identify significant climate priorities as an initial step toward managing climate risks.[12] Such a first step is consistent with leading practices for climate risk management and federal standards for internal control.[13] For example, leading practices from the National Academies call for climate change risk management efforts that focus on where immediate attention is needed.[14] As noted in our September 2017 report, according to a 2010 National Academies report, other literature we reviewed, and several experts we interviewed, to make informed choices, decision makers need more comprehensive information on economic effects to better understand the potential costs of climate change to society and begin to develop an understanding of the benefits and costs of different options for managing climate risks.[15]

[11]In that report, we also found that additional economic information could help federal, state, local, and private sector decision makers manage climate risks that drive federal fiscal exposure. GAO-17-720.

[12]GAO-17-720.

[13]National Research Council of the National Academies, America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, *Adapting to the Impacts of Climate Change* and GAO, *Standards for Internal Control in the Federal Government*, GAO-14-704G (Washington, D.C.: September 2014).

[14]National Research Council of the National Academies, America's Climate Choices: Panel on Adapting to the Impacts of Climate Change, *Adapting to the Impacts of Climate Change* (Washington, D.C.: 2010).

[15]GAO-17-720.

The Federal Government Faces Fiscal Exposure from Climate Change Risks, but Does Not Have Certain Information Needed to Help Make Budget Decisions

The federal government faces fiscal exposure from climate change risks in a number of areas, and this exposure will likely increase over time, as we concluded in September 2017.[16] In the March 2019 update to our High-Risk List, we summarized our previous work that identified several of these areas across the federal government, including programs related to the following:[17]

- **Disaster aid.** The rising number of natural disasters and increasing reliance on federal assistance are a key source of federal fiscal exposure, and this exposure will likely continue to rise. Since 2005, federal funding for disaster assistance is at least $450 billion.[18] In September 2018, we reported that four hurricane and wildfire disasters in 2017 created an unprecedented demand for federal disaster resources and that hurricanes Harvey, Irma, and Maria ranked among the top five costliest hurricanes on record.[19] Subsequently, the fall of 2018 brought additional catastrophic

[16] GAO-17-720.

[17] We have identified other areas with potential links to climate and the federal budget in past reports, including global migration, state and local infrastructure, federal supply chains, and public health. See GAO, *Climate Change: Activities of Selected Agencies to Address Potential Impact on Global Migration,* GAO-19-166 (Washington, D.C.: Jan. 17, 2019); *Climate Information: A National System Could Help Federal, State, Local, and Private Sector Decision Makers Use Climate Information,* GAO-16-37 (Washington, D.C.: Nov. 23, 2015); *Federal Supply Chains: Opportunities to Improve the Management of Climate-Related Risks,* GAO-16-32 (Washington, D.C.: Oct. 13, 2015); and *Climate Change: HHS Could Take Further Steps to Enhance Understanding of Public Health Risks,* GAO-16-122 (Washington, D.C.: Oct. 5, 2015). We also have ongoing work in many areas related to federal fiscal exposure to climate change, examining issues such as how to identify and prioritize resilience projects to build resilience to climate change impacts, how to make water infrastructure more resilient to the impacts of climate change, and how to help communities voluntarily relocate to avoid climate change impacts.

[18] This total includes, for fiscal years 2005 through 2014, $278 billion that GAO found that the federal government had obligated for disaster assistance. See GAO, *Federal Disaster Assistance: Federal Departments and Agencies Obligated at Least $277.6 Billion during Fiscal Years 2005 through 2014,* GAO-16-797 (Washington, D.C.: Sept. 22, 2016). It also includes, for fiscal years 2015 through 2018, $124 billion in select supplemental appropriations to federal agencies for disaster assistance, approximately $7 billion in annual appropriations to the Disaster Relief Fund (a total of $28 billion for the 4-year period). For fiscal years 2015 through 2018, it does not include other annual appropriations to federal agencies for disaster assistance. Lastly, on June 6, 2019, the Additional Supplemental Appropriations for Disaster Relief Act of 2019 was signed into law, which provides approximately $19.1 billion for disaster assistance. H.R. 2157, 116th Cong. (2019) (enacted).

[19] GAO, *2017 Hurricanes and Wildfires: Initial Observations on the Federal Response and Key Recovery Challenges*, GAO-18-472 (Washington, D.C.: Sept. 4, 2018).

disasters such as Hurricanes Florence and Michael and devastating California wildfires, with further needs for federal disaster assistance. Disaster costs are projected to increase as certain extreme weather events become more frequent and intense due to climate change—as observed and projected by USGCRP.[20] In July 2015, we reported that the federal government does not adequately plan for disaster resilience and that most federal funding for hazard mitigation is available after a disaster.[21] In addition, our prior work found that the Federal Emergency Management Agency's (FEMA) indicator for determining whether to recommend that a jurisdiction receive disaster assistance—which was set in 1986—is artificially low because it does not accurately reflect the ability of state and local governments to respond to disasters.[22] Without an accurate assessment of a jurisdiction's capability to respond to a disaster without federal assistance, we found that FEMA runs the risk of recommending that the President award federal assistance to jurisdictions that have the capability to respond and recover on their own.

- **Federal insurance for property and crops.** The National Flood Insurance Program (NFIP) and the Federal Crop Insurance Corporation are sources of federal fiscal exposure due, in part, to the vulnerability of the insured property and crops to climate change.[23] These programs provide coverage where private markets for insurance do not exist, typically because the risk associated with the property or crops is too great to privately insure at a cost that buyers are willing to accept. From 2013 to 2017, losses paid under NFIP and

[20] Jerry M. Melillo, et. al., *Climate Change Impacts in the United States: The Third National Climate Assessment.*

[21] For example, from fiscal years 2011 to 2014, the Federal Emergency Management Agency obligated more than $3.2 billion for the Hazard Mitigation Grant Program for post-disaster hazard mitigation while obligating approximately $222 million for the Pre-Disaster Mitigation Grant Program. GAO, *Hurricane Sandy: An Investment Strategy Could Help the Federal Government Enhance National Resilience for Future Disasters*, GAO-15-515 (Washington, D.C.: July 30, 2015).

[22] GAO, *Federal Disaster Assistance: Improved Criteria Needed to Assess a Jurisdiction's Capability to Respond and Recover on Its Own,* GAO-12-838 (Washington, D.C.: Sept. 12, 2012).

[23] The NFIP is administered by FEMA within the U.S. Department of Homeland Security, and the Federal Crop Insurance Corporation is administered by the Risk Management Agency within the U.S. Department of Agriculture.

the federal crop insurance program totaled $51.3 billion.[24] Federal flood and crop insurance programs were not designed to generate sufficient funds to fully cover all losses and expenses, which means the programs need budget authority from Congress to operate. The NFIP, for example, was about $21 billion in debt to the Treasury as of April 2019.[25] Further, the Congressional Budget Office estimated in May 2019 that federal crop insurance would cost the federal government an average of about $8 billion annually from 2019 through 2029.[26]

- **Operation and management of federal property and lands.** The federal government owns and operates hundreds of thousands of facilities and manages millions of acres of land that could be affected by a changing climate and represent a significant federal fiscal exposure. For example, the Department of Defense (DOD) owns and operates domestic and overseas infrastructure with an estimated replacement value of about $1 trillion. In September 2018, Hurricane Florence damaged Camp Lejeune and other Marine Corps facilities in North Carolina, resulting in a preliminary Marine Corps repair estimate of $3.6 billion. One month later, Hurricane Michael devastated Tyndall Air Force Base in Florida, resulting in a preliminary Air Force repair estimate of $3 billion and upwards of 5 years to complete the work. In addition, we recently reported that the federal government manages about 650 million acres of land in the United States that could be vulnerable to climate change, including the possibility of more frequent and severe droughts and wildfires.[27] Appropriations for federal wildland fire management activities have increased

[24]FEMA and Risk Management Agency published data. This does not include the costs of running these programs or the premiums collected to partially offset the costs. Losses for the crop insurance program are losses associated with crops harvested in that year, also known as crop year.

[25]U. S. Department of The Treasury, Bureau of the Fiscal Service. *Monthly Treasury Statement. Table 6. Schedule C* (Washington, D.C.: April 2019).

[26]Congressional Budget Office, *CBO's May 2019 Baseline for Farm Programs* (Washington, D.C.: May 2, 2019).

[27]GAO, *Climate Change: Various Adaptation Efforts Are Under Way at Key Natural Resource Management Agencies,* GAO-13-253 (Washington, D.C.: May 31, 2013).

considerably since the 1990s, as we and the Congressional Research Service have reported.[28]

Although the federal government faces fiscal exposure from climate change across the nation, it does not have certain information needed by policymakers to help understand the budgetary impacts of such exposure.[29] We have previously reported that the federal budget generally does not account for disaster assistance provided by Congress—which can reach tens of billions of dollars for some disasters—or the long-term impacts of climate change on existing federal infrastructure and programs.[30] For Example, as we reported in April 2018, the Office of Management and Budget's (OMB) climate change funding reports we reviewed did not include funding information on federal programs with significant fiscal exposures to climate change identified by OMB and others—such as domestic disaster assistance, flood insurance, and crop insurance.[31] A more complete understanding of climate change fiscal exposures can help policymakers anticipate changes in future spending and enhance control and oversight over federal resources, as we reported in October 2013.[32] For budget decisions for federal programs with fiscal exposure to climate change, we found in the April 2018 report that information that could help provide a more complete understanding would include: (1) costs to repair, replace, and improve the weather-related resilience of federally-funded property and resources; (2) costs for

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[28]*GAO, Budget Issues: Opportunities to Reduce Federal Fiscal Exposures Through Greater Resilience to Climate Change and Extreme Weather,* GAO-14-504T (Washington, D.C.: July 29, 2014) and Congressional Research Service, *Wildfire Suppression Spending: Background, Issues, and Legislation in the 115th Congress,* R44966 (Washington, D.C.: November 8, 2017).

[29]In our past work, we identified broad principles for an effective budget process, including that it should (1) provide information about the long-term effects of decisions; (2) provide information necessary to make important trade-offs between spending with long-term benefits and spending with short-term benefits, and (3) provide for accountability and be transparent, among other principles. Further, in October 2013, we reported that incorporating more complete information on fiscal exposures could help meet these principles for an effective budget process. See GAO, *Budget Process: Enforcing Fiscal Choices,* GAO-11-626T (Washington, D.C.: May 4, 2011) and GAO, *Fiscal Exposures: Improving Cost Recognition in the Federal Budget,* GAO-14-28 (Washington, D.C.: Oct. 29, 2013).

[30]GAO-14-505T.

[31]GAO, *Climate Change: Analysis of Reported Federal Funding,* GAO-18-223 (Washington, D.C.: Apr. 30, 2018).

[32]GAO-14-28.

federal flood and crop insurance programs; and (3) costs for disaster assistance programs, among other identified areas of fiscal exposure to climate change.[33] To help policymakers better understand the trade-offs when making spending decisions, we recommended in the April 2018 report that OMB provide information on fiscal exposures related to climate change in conjunction with future reports on climate change funding.[34]

Federal Investments in Resilience to Climate Change Impacts Have Been Limited

Although the federal government faces fiscal exposure to climate change, its investments in resilience to climate change impacts have been limited. One way to reduce federal fiscal exposure is to enhance resilience by reducing or eliminating long-term risk to people and property from natural hazards. For example, in September 2018 we reported that elevating homes and strengthened building codes in Texas and Florida prevented greater damages during the 2017 hurricane season.[35] In addition, one company participating in a 2014 forum we held on preparing for climate-related risks noted that for every dollar it invested in resilience efforts, the company could prevent $5 in potential losses.[36] Finally, a 2018 interim report by the National Institute of Building Sciences examined a sample of federal grants for hazard mitigation. The report estimated approximate benefits to society (i.e., homeowners, communities, etc.) in excess of costs for several types of resilience projects through the protection of lives and property, and prevention of other losses.[37] For example, while

[33]GAO-18-223.

[34]OMB disagreed with this recommendation and has not implemented it, but we continue to believe that the recommendation is valid. GAO-18-223.

[35]Specifically, FEMA officials said Hurricane Harvey demonstrated how prior hazard mitigation projects prevented greater damages (e.g., elevated homes and equipment sustained less damages). FEMA officials said Florida strengthened its building codes for resilience as a result of Hurricanes Andrew in 1992, and Matthew in 2016. GAO-18-472.

[36]GAO, *Highlights of a Forum: Preparing for Climate-Related Risks: Lessons from the Private Sector,* GAO-16-126SP (Washington, D.C.: Nov. 19, 2015).

[37]This report examined a narrow sample of hazard mitigation grants awarded by FEMA, the Economic Development Administration, and the Department of Housing and Urban Development from 1993 to 2016 to address various hazards. Extrapolation to a broader set of grants needs to be interpreted in the context of the selected sample. These hazards included fires at the wildland-urban interface (i.e., fires in areas where homes are built near or among lands prone to wildland fire), hurricane- and tornado-force winds, and riverine floods (i.e., floods that occur when river flows exceed the capacity of the river channel). See Multihazard Mitigation Council, a council of the National Institute of Building Sciences, *Natural Hazard Mitigation Saves: 2018 Interim Report (Washington, D.C.: December 2018)*.

precise benefits are uncertain, the report estimated that for every grant dollar the federal government spent on resilience projects, over time, society could accrue benefits amounting to the following:

- About $3 on average from projects addressing fire at the wildland urban interface, with most benefits (69 percent) coming from the protection of property (i.e., avoiding property losses).
- About $5 on average from projects to address hurricane and tornado force winds, with most benefits (89 percent) coming from the protection of lives. This includes avoiding deaths, nonfatal injuries, and causes of post-traumatic stress.
- About $7 on average from projects that buy out buildings prone to riverine flooding, with most benefits (65 percent) coming from the protection of property.

The interim report also estimated that society could accrue benefits amounting to about $11 on average for every dollar invested in designing new buildings to meet the 2018 International Building Code and the 2018 International Residential Code—the model building codes developed by the International Code Council—with most benefits (46 percent) coming from the protection of property.[38]

We reported in October 2009 that the federal government's activities to build resilience to climate change were carried out in an ad hoc manner and were not well coordinated across federal agencies.[39] Federal agencies have included some of these activities within existing programs and operations—a concept known as mainstreaming. For example, the Fourth National Climate Assessment reported that the U.S. military integrates climate risks into its analysis, plans and programs, with particular attention paid to climate effects on force readiness, military

[38]The International Code Council is a member-focused association with over 64,000 members dedicated to developing model codes and standards used in the design, build, and compliance process to construct safe, sustainable, affordable and resilient structures. The report used a baseline of buildings constructed to a prior generation of codes represented by 1990s-era design and National Flood Insurance Program requirements.

[39]GAO, *Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions,* GAO-10-113 (Washington, D.C.: Oct. 7, 2009).

bases, and training ranges.[40] However, according to the Fourth National Climate Assessment, while a significant portion of climate risk can be addressed by mainstreaming, the practice may reduce the visibility of climate resilience relative to dedicated, stand-alone approaches and may prove insufficient to address the full range of climate risks.[41]

In addition, as we reported in March 2019, the Disaster Recovery Reform Act of 2018 (DRRA) was enacted in October 2018, which could improve state and local resilience to disasters. DRRA, among other things, allows the President to set aside, with respect to each major disaster, a percentage of the estimated aggregate amount of certain grants to use for pre-disaster hazard mitigation and makes federal assistance available to state and local governments for building code administration and enforcement.[42] However, it is too early to tell what impact the implementation of the act will have on state and local resilience.

The federal government has made some limited investments in resilience and DRRA could enable additional improvements at the state and local level. However, we reported in September 2017 that the federal government had not undertaken strategic government-wide planning to manage significant climate risks before they become fiscal exposures.[43] We also reported in July 2015 that the federal government had no comprehensive strategic approach for identifying, prioritizing, and

[40]Lempert, R., J. Arnold, R. Pulwarty, K. Gordon, K. Greig, C. Hawkins Hoffman, D. Sands, and C. Werrell. 2018. Reducing Risks Through Adaptation Actions. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Washington, D.C.: U.S. Global Change Research Program, 2018). We also reported in May 2014 that officials from the Office of the Secretary of Defense and the military departments stated that their goal is to address potential climate change impacts and vulnerabilities through existing infrastructure planning processes so that the effects of climate change are considered in the same way other impacts and vulnerabilities—such as force protection—are currently considered. GAO, *Climate Change Adaptation: DOD Can Improve Infrastructure Planning and Processes to Better Account for Potential Impacts,* GAO-14-446 (Washington, D.C.: May 30, 2014).

[41]Lempert, R., J. Arnold, R. Pulwarty, K. Gordon, K. Greig, C. Hawkins Hoffman, D. Sands, and C. Werrell, 2018: Reducing Risks Through Adaptation Actions. *In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Washington, D.C.: U.S. Global Change Research Program, 2018).

[42]FAA Reauthorization Act of 2018, Pub. L. No. 115-254, div. D, §§ 1206(a)(3), 1234(a)(2)(C), 1234(a)(5), 132 Stat. 3186, 3440, 3462 (2018). The FAA Reauthorization Act of 2018, which included the DRRA, became law on October 5th, 2018.

[43]GAO-17-720.

implementing investments for disaster resilience.[44] As an initial step in managing climate risks, most of the experts we interviewed for the September 2017 report told us that federal decision makers should prioritize risk management efforts on significant climate risks that create the greatest fiscal exposure.[45] However, as we reported in our March 2019 High-Risk List, the federal government had not made measurable progress since 2017 to reduce fiscal exposure in several key areas that we have identified.[46] The High-Risk List identified *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* as an area needing significant attention because the federal government has regressed in progress toward one of our criterion for removal from the list.[47]

[44]In our 2015 report, we recommended that the Mitigation Framework Leadership group—an interagency body chaired by FEMA—create a National Mitigation Investment Strategy to help federal, state, and local officials plan for and prioritize disaster resilience. In response, the Mitigation Framework Leadership Group developed a draft, high-level strategy. FEMA officials expect to publish the final version of the strategy by July 2019. However, the draft strategy does not explicitly address future climate change risks. GAO-15-515.

[45]GAO-17-720.

[46]GAO-19-157SP.

[47]We update our High-Risk List every 2 years. To determine which federal government programs and functions should be designated high-risk, we consider qualitative factors such as whether the risk could result in significantly impaired service, or significantly reduced economy, efficiency, or effectiveness; the exposure to loss in monetary or other quantitative terms; and corrective measures planned or under way. We have issued the following five criteria for an area to be removed from the list: leadership commitment, capacity, action plan, monitoring, and demonstrated progress. In the March 2019 report, the federal government regressed in progress toward meeting the monitoring criterion for the *Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks* high-risk area. Criteria for removing this area from the High-Risk List include demonstrating leadership commitment that is sustained and enhanced to address all aspects of the federal fiscal exposure to climate change cohesively.

The Federal Government Could Reduce Its Fiscal Exposure by Focusing and Coordinating Federal Efforts

As we reported in March 2019, the federal government could reduce its fiscal exposure to climate change by focusing and coordinating federal efforts.[48] However, the federal government is currently not well organized to address the fiscal exposure presented by climate change, partly because of the inherently complicated and crosscutting nature of the issue. We have made a total of 62 recommendations related to limiting the federal government's fiscal exposure to climate change over the years, 12 of which have been made since February 2017. As of December 2018, 25 of these recommendations remained open. In describing what needs to be done to reduce federal fiscal exposure to climate change, our March 2019 High-Risk report discusses many of the open recommendations.[49] Implementing these recommendations could help reduce federal fiscal exposure. Several of them, including those highlighted below, identify key government-wide efforts needed to help plan for and manage climate risks and direct federal efforts toward common goals, such as improving resilience:

- **Develop a national strategic plan:** In May 2011, we recommended that appropriate entities within the Executive Office of the President (EOP), including OMB, work with agencies and interagency coordinating bodies to establish federal strategic climate change priorities that reflect the full range of climate-related federal activities, including roles and responsibilities of key federal entities.[50]
- **Use economic information to identify and respond to significant climate risks:** In September 2017, we recommended that the appropriate entities within EOP use information on the potential economic effects of climate change to help identify significant climate risks facing the federal government and craft appropriate federal responses.[51] Such federal responses could include establishing a strategy to identify, prioritize, and guide federal investments to enhance resilience against future disasters.

[48] GAO-19-157SP.

[49] GAO-19-157SP.

[50] EOP neither agreed nor disagreed with our recommendation and as of March 2019, had not implemented it. GAO, *Climate Change: Improvements Needed to Clarify National Priorities and Better Align Them with Federal Funding Decisions,* GAO-11-317 (Washington, D.C.: May 20, 2011).

[51] EOP neither agreed nor disagreed with this recommendation and as of March 2019, had not implemented it. GAO-17-720.

- **Provide decision makers with the best available climate information:** In November 2015, we reported that federal efforts to provide information about climate change impacts did not fully meet the climate information needs of federal, state, local, and private sector decision makers, which hindered their efforts to plan for climate change risks.[52] We reported that these decision makers would benefit from a national climate information system that would develop and update authoritative climate observations and projections specifically for use in decision-making. As a result, we recommended that EOP (1) designate a federal entity to develop and periodically update a set of authoritative climate observations and projections for use in federal decision-making, which other decision makers could also access; and (2) designate a federal entity to create a national climate information system with defined roles for federal agencies and nonfederal entities with existing statutory authority.[53]
- **Consider climate information in design standards:** In November 2016, we reported that design standards, building codes, and voluntary certifications established by standards-developing organizations play a role in ensuring the resilience of infrastructure to the effects of natural disasters. However, we reported that these organizations faced challenges to using forward-looking climate information that could help enhance the resilience of infrastructure. As a result, we recommended in the November 2016 report that the Department of Commerce, acting through the National Institute of Standards and Technology—which is responsible for coordinating federal participation in standards organizations—convene federal agencies for an ongoing government-wide effort to provide the best available forward-looking climate information to standards-developing organizations for their consideration in the development of design standards, building codes, and voluntary certifications.[54]

In conclusion, the effects of climate change have already and will continue to pose risks that can create fiscal exposure across the federal government and this exposure will continue to increase. The federal

[52]GAO-16-37.

[53]EOP neither agreed nor disagreed with these recommendations and as of March 2019, had not implemented them.

[54]Commerce neither agreed nor disagreed with this recommendation and as of May 2018, had not implemented it. GAO, *Climate Change: Improved Federal Coordination Could Facilitate Use of Forward-Looking Climate Information in Design Standards, Building Codes, and Certifications,* GAO-17-3 (Washington, D.C.: Nov. 30, 2016).

government does not generally account for such fiscal exposure to programs in the budget process nor has it undertaken strategic efforts to manage significant climate risks that could reduce the need for far more costly steps in the decades to come. To reduce its fiscal exposure, the federal government needs a cohesive strategic approach with strong leadership and the authority to manage risks across the entire range of related federal activities. The federal government could make further progress toward reducing fiscal exposure by implementing the recommendations we have made.

Chairman Yarmuth, Ranking Member Womack, and Members of the Committee, this completes my prepared statement. I would be pleased to respond to any questions that you may have at this time.

GAO Contact and Staff Acknowledgments

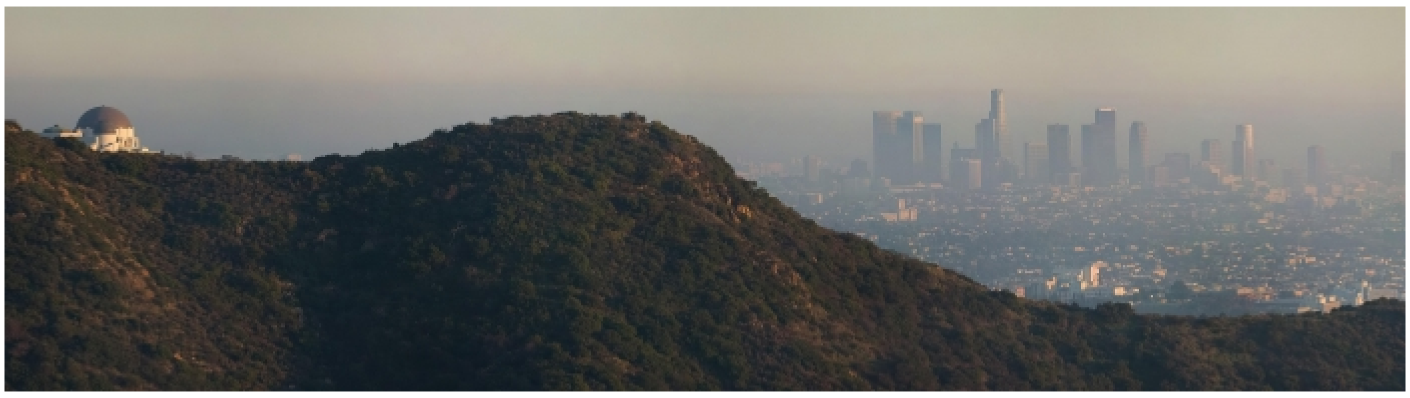
If you or your staff have any questions about this testimony, please contact me at (202) 512-3841or gomezj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this statement. GAO staff who made key contributions to this testimony are J. Alfredo Gómez (Director), Joseph Dean Thompson (Assistant Director), Anne Hobson (Analyst in Charge), Celia Mendive, Kiki Theodoropoulos, Reed Van Beveren, and Michelle R. Wong.

CLIMATE CENTRAL

Researching and reporting the science and impacts of climate change

Climate Change is Threatening Air Quality across the Country

Published: *July 30th, 2019*



Research brief by Climate Central

As summers heat up, the air we breathe is increasingly at risk of becoming unhealthy, despite decades of air quality improvements.

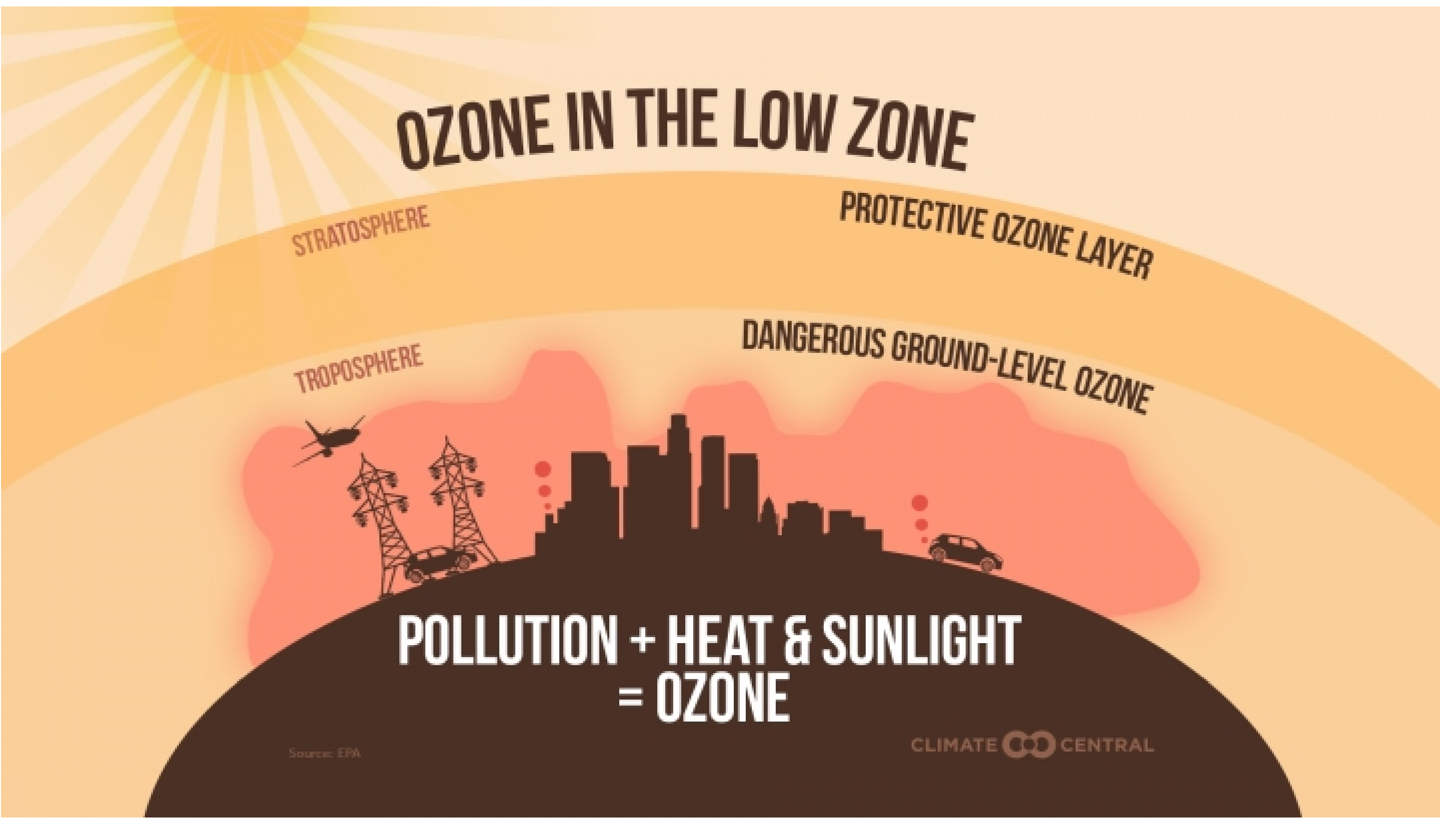
Download this report as a PDF.

Hotter summers come with an increase in "stagnation events"—stationary domes of hot air that can cause air pollutants to get trapped and persist in the lower atmosphere. Climate Central found a positive correlation between summer maximum temperatures and the number of summer stagnant days in 98% of the contiguous U.S. cities analyzed. Further, the data showed that stagnation events are becoming more prevalent, with the number of annual stagnant days increasing in 83% of the cities.

These stagnant days set up the perfect conditions for ground-level ozone, a dangerous air pollutant, to develop. "Ozone season," the period when states and communities monitor local air quality for unhealthy levels of ozone, is now year-long in eight states and in dozens of urban areas across the country.

Looking at ozone levels in 244 locations, Climate Central identified 54 cities with an "ozone problem," defined as either having a high number of unhealthy ozone days or experiencing a recent increase in unhealthy ozone days, potentially posing a threat to the long-term trend of air quality improvement.

Exposure to high levels of ozone has long been known to have serious health consequences, especially for children, the elderly, people with cardiovascular or lung diseases, and for those who work outside. Recent research also shows that low levels of ozone exposure can be hazardous for anyone spending time outdoors. As our climate heats up, increasing numbers of the U.S. population could be exposed to unhealthy ozone days, leading to more hospital and emergency room visits, missed school and work, and long-term health risks.



Ozone: The Good, the Bad, the Dirty

High-altitude ozone is a gas made up of three oxygen atoms that forms naturally in the upper atmosphere. This stratospheric ozone is essential to our existence, protecting our planet from harmful ultraviolet radiation from the sun, like a benevolent layer of SPF for the Earth.

Ground-level ozone is chemically equivalent to high-altitude ozone, but is not formed naturally. Rather, it is a byproduct of two pollutants (nitrogen oxides and volatile organic compounds) that react in the presence of heat and sunlight. Emissions from chemical and industrial plants, electric utilities, refineries, exhaust from cars and trucks, and increasingly wildfire smoke and oil and gas extraction are sources of these pollutants. Ground-level ozone doesn't rise into the stratosphere, but builds up at the Earth's surface where we live and breathe. Ozone is colorless on its own—an invisible pollutant—although it has a distinctive smell and is a primary component of smog. A slow-moving high pressure system, with no wind or rain to wash the pollution away, can contribute to increased concentrations of ground-level ozone that not only make it uncomfortable to breathe, but can be unhealthy or even dangerous for vulnerable populations including children, the elderly, and people with asthma or other lung diseases.

Urban areas tend to be most impacted by ground-level ozone, but winds can transport ozone hundreds of miles away to rural regions as well. Both the formation and transport of ozone are greatly influenced by weather conditions and topography.

Millions of Americans Live in Areas With an "Ozone Problem"

Using county-level data collected by the U.S. Environmental Protection Agency (EPA), Climate Central looked at the annual number of unhealthy ozone days—those exceeding the current EPA standard —for 244 U.S. cities since 2000. We studied the average annual number of unhealthy ozone days over the period 2000 to 2014, as well as for each of the past four years. This 19-year timeframe allowed us to observe the historical average of unhealthy ozone days in the wake of emission controls implemented to meet requirements of the Clean Air Act of 1970, as well as during the last four years when episodes of high heat occurred.

Overwhelmingly, the data showed that air quality has improved in most cities since the early part of this century. Yet 40 cities had at least 20 unhealthy ozone days since 2015—including four cities that had more than 300. Another 14 cities had fewer unhealthy days overall, but experienced an uptick in unhealthy ozone days in recent years, a potential sign that progress is stagnating or slowing.

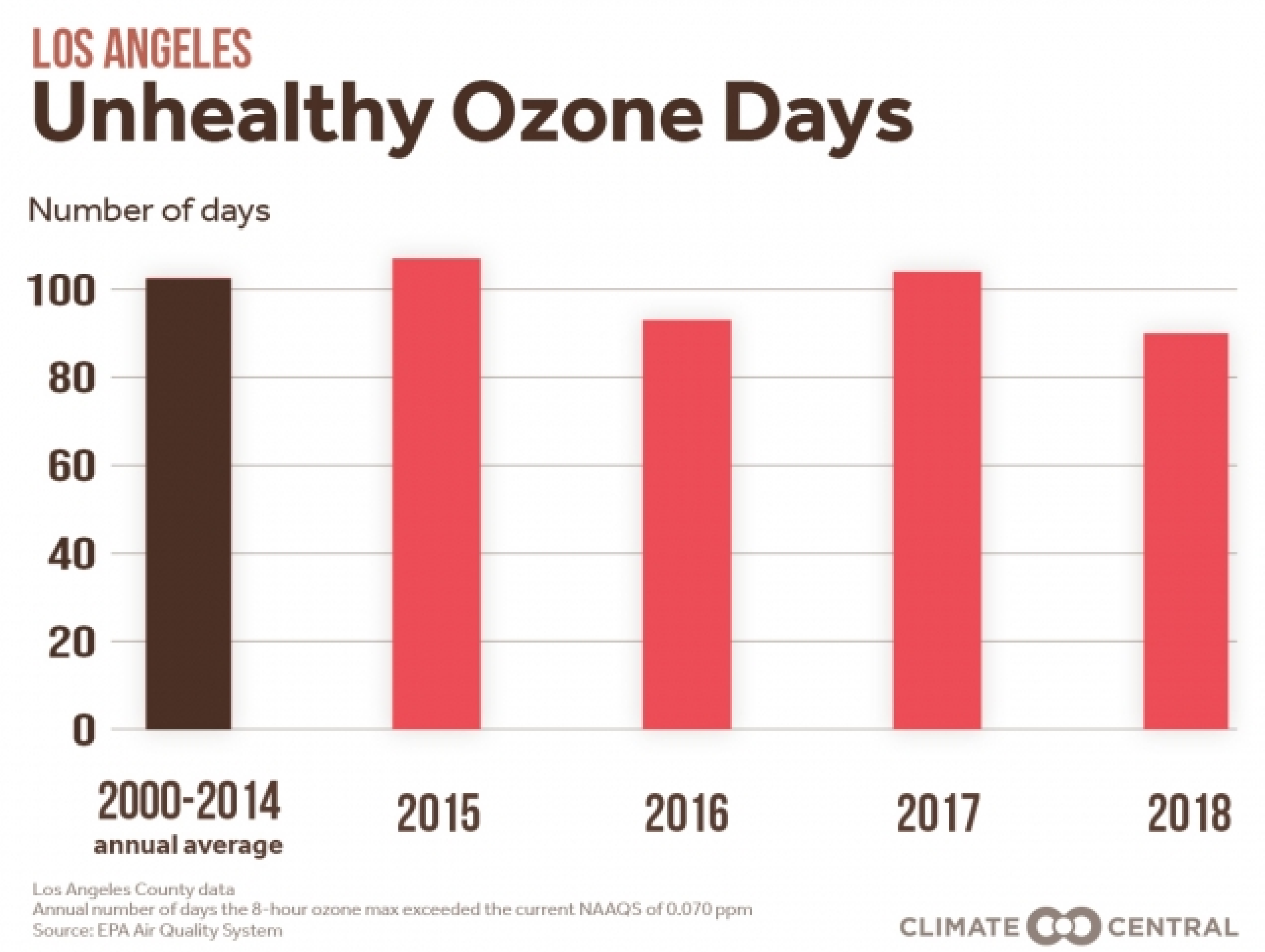
And while the United States overall experienced a 16 percent decrease in unhealthy ozone levels since 2000, there are currently 124 million people living in 201 counties that are not in attainment with national air quality standards for ozone. As the climate continues to warm, bringing hot and sunny conditions that create more ground-level ozone, these areas (and many others) will likely have a difficult time meeting federal health-based standards for ozone.

Highlights of Cities with Ozone Problems

WEST AND SOUTHWEST

The West and Southwest have seen a decline in unhealthy days over the last 19 years, but a number of cities in these regions are experiencing the highest number of unhealthy ozone days in the country overall. The high ozone levels could result from several interacting factors, including but not limited to higher temperatures, topography, increased emissions of ozone-forming chemicals from more frequent wildfires, high levels of automobile emissions, and an increase in gas and oil extraction operations.

> California has some of the worst air quality in the nation. Palm Springs had the highest 2000-2014 average of 130 unhealthy ozone days per year and also had 450 days occur since the start of 2015. Los Angeles experienced 103 unhealthy days per year on average from 2000-2014, but recently saw unhealthy days happen even more frequently, with 107 days in 2015 and 104 days in 2017.
>
> Oil and gas extraction is likely having an effect on increased ozone levels in Colorado, according to a 2017 CIRES study. Denver's ozone levels improved down to 0 unhealthy days in 2017, but spiked back up to 7 days in 2018, which was higher than the average during the 2000-2014 period. Colorado Springs similarly saw an increase to 7 days in 2018 from just 1 unhealthy ozone day in 2015.



In Nevada, lingering wildfire smoke and high temperatures increased unhealthy ozone days last year. Las Vegas' average of about 45 days a year of unhealthy ozone between 2000 and 2014 was nearly cut in half from 2015 to 2017. But last year the unhealthy days skyrocketed back to 46. Reno also had an unhealthy 2018, with nearly 20 high ozone days, compared to an average of about 7 from 2000-2014.

Houston has the worst ozone record in Texas, with an average of 46 annual unhealthy days from 2000-2014 and 97 days total over the last 4 years. Dallas saw a drop to just 3 unhealthy days in 2016 compared to 31 days on average in the 2000-2014 period—but the number of unhealthy days rose to 7 in 2017 and 14 in 2018. El Paso had 14 unhealthy days in 2018, nearing its average of 18 days from 2000-2014. Austin recorded a similar pattern, with just 1 unhealthy ozone day in 2016, down from 14 on average, but an increase to 3 in 2017 and 6 days in 2018.

Phoenix, which was the nation's fastest growing city last year (with a population over 50,000), averaged 37 unhealthy ozone days over the last 4 years, and had an average of 55 per year from 2000-2014.

Salt Lake City had significantly more unhealthy ozone days in 2017 and 2018 than on average during the 2000-2014 period. Last year, Salt Lake City had 31 unhealthy ozone days compared to an average of about 22 per year in 2000-2014. A number of factors may be contributing, including its increasing population and its bowl-like topography which can act as a trap for pollutants.

PACIFIC NORTHWEST

Our analysis shows that a number of cities in the Pacific Northwest have an ozone problem. Despite their relatively few unhealthy ozone days, such days have increased over the last few years. Overall, the region experienced an 8% increase in unhealthy ozone levels over the last 19 years—the only NOAA/NCEI region that did not improve during that time period.

In 2017, Seattle had 12 days of unhealthy ozone—a year in which the city went for a record 56 days without rain—and 6 days in 2018. This is an increase from about 4 days on average between 2000 and 2014.

Portland, Oregon had just 2 unhealthy ozone days in each of the last 2 years, but this is up from about a half day on average per year from 2000-2014. Similarly, Medford, Oregon went from fewer than 2 days per year from 2000 to 2014 to 6 days in 2018.

MIDWEST

Midwestern cities have also shown marked improvements in bad ozone days, but there are signs that this progress is plateauing as heat indexes climb.

Chicago's unhealthy ozone days have been consistent in the last three years, similar to its annual average of 19 unhealthy days from 2000 to 2014.

Louisville, Kentucky has seen a drop from an average of 21 unhealthy days from 2000-2014 to just 7 in 2015, but has averaged 9 unhealthy days over the last 3 years.

After an average of 14 unhealthy ozone days in Detroit from 2000-2014, the city had only 3 unhealthy ozone days in 2015. But the improvements plateaued at about 7 days each year between 2016 and 2018.

Memphis notched similar vast improvements in the number of unhealthy ozone days, from 25 annually on average between 2000 and 2014 to just 3 in 2015. But the numbers showed an uptick to 6 in 2016 and 8 in 2018.

NORTHEAST AND SOUTHEAST

Most communities across the Eastern seaboard saw a decrease in unhealthy ozone days in recent decades hold steady, although our analysis revealed a number of cities with an increase in unhealthy days over the last 4 years. The EPA has acknowledged that its air quality programs have helped to reduce interstate transport of ozone in the eastern United States, in which air pollution from upwind states crosses state lines and affects air quality in downwind states. These air quality improvements are also likely being supported by a major decline in coal consumption since 2007 and recent closures of older coal-fired power plants throughout the Midwest.

Our nation's capital improved from 21 days of unhealthy ozone on average between 2000 and 2014, but Washington, D.C. still had 5 days of unhealthy ozone levels on average over the last 4 years.

In 2018, New York City reported a rise to 10 days of unhealthy ozone levels, compared to 4 days or fewer in the previous three years and compared to about 7 days on average in the 15 years prior.

Providence saw improvement from nearly 11 annual days of unhealthy ozone on average from 2000-2014 to just 4 days each in 2015 through 2017, but an uptick to 8 days in 2018.

Philadelphia had 24 unhealthy days on average from 2000 to 2014, and while the number of unhealthy ozone days has fallen, the city experienced 45 unhealthy days over the last 4 years, the highest number among the East Coast cities on our list. Similarly, Pittsburgh improved from 25 days on average between 2000-2014 to under 10 days in each of the past 4 years, but still experienced 33 unhealthy days since 2014.

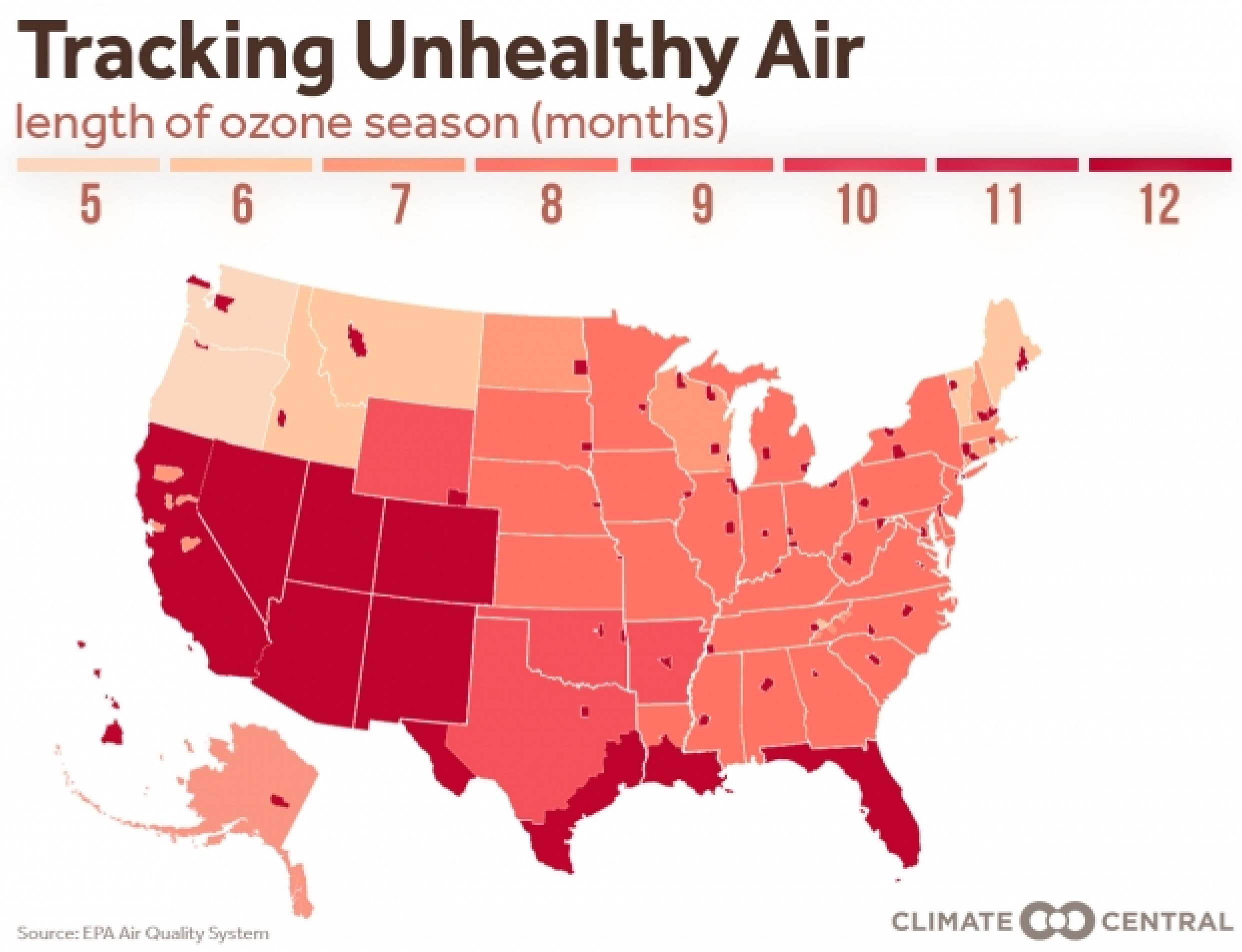
Atlanta has experienced local unhealthy ozone days decline from 26 on average between 2000 and 2014, to fewer than 5 in 2018. Still, the city had 32 unhealthy days over the last 4 years.

Tampa improved from 16 high ozone days on average between 2000-2014 to just 1 unhealthy ozone day in 2015. However, unhealthy days have ticked back up to 4 days in 2018.

Ozone Season Isn't Just For Summer Anymore

"Ozone seasons" are designated time periods when ground-level ozone typically reaches its highest levels and requires monitoring. Intensely sunny, hot days are most conducive for chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOC) to create ground-level ozone. Ozone season is generally associated with summer months, but the length of the season is set to match the times of year when ozone is most likely to approach unhealthy levels, so it varies from state to state and tends to be longer in highly populated areas.

Ozone levels are typically elevated in urban areas, partly due to the urban heat island effect. In cities, vast amounts of pavement and traditional asphalt or shingled roofs soak up more heat than do fields and forests; this heat is then trapped more efficiently overnight, keeping the city hotter than rural and suburban environments that have more trees and vegetation. Further, cities often have more vehicles, manufacturing, power plants, and other sources of emissions that are the precursors to ozone.



In 2015, the U.S. Environmental Protection Agency lowered the standard for ozone from .075 ppm (parts per million) to 0.070 ppm to improve public health outcomes. They also extended the ozone season in 32 states, as a review showed that ozone levels that either exceeded or approached the new standard were occurring outside the previous seasons when states were required to monitor it.

The ozone season is now monitored year-round in 8 states: Florida, Nevada, Hawaii, Arizona, New Mexico, Utah, Colorado, and California (save for a few counties). Many counties across southern Texas and the lower half of Louisiana also monitor for ozone 12 months a year. Only two states have ozone seasons shorter than a half year—Washington and Oregon—but both have counties with year-round ozone seasons. And the EPA lists 192 sites in counties around the country that currently monitor year-long ozone seasons, generally corresponding with highly populated urban areas.

Climate Change, Stagnation, and Air Quality Are All Linked

Heat and stagnation are closely linked. Climate Central analyzed summer high temperatures and used data from the NOAA/NCEI Air Stagnation Index, which incorporates upper atmospheric winds, surface winds, and precipitation to identify the number of stagnant days in a month. Looking back to 1973 when the index began, 98% of the cities analyzed show a positive correlation between summer maximum temperatures and the number of summer stagnant days.

Stagnation is happening more frequently. Since the NOAA/NCEI Air Stagnation Index began in 1973, annual stagnant days have increased in 83% of the contiguous U.S. cities analyzed. McAllen, Texas tops the list with 36 more days per year on average, followed by Los Angeles and San Francisco (where stagnation is less correlated with the heat). The largest increases have occurred across the South and West Coast as well as the East, while most of the decreases have occurred in the Mountain West. As the climate warms, stagnant days are projected to increase further, with up to 40 more days per year by late-century.

And stagnation impacts air quality. When the air is stagnant, pollutants react together in the heat and sun, and high concentrations of ground-level ozone can build up.

To protect human health under the Clean Air Act, the U.S. Environmental Protection Agency requires states to adopt plans to achieve and maintain National Ambient Air Quality Standards (NAAQS) for pollutants like ozone and particle pollution.

EPA's regulations have had a pronounced effect, with many communities across the United States experiencing improved air quality and lower ozone levels while the population and economy have continued to grow. However, air quality is localized and very sensitive to weather, and consequently to climate change. As shown by the Climate Central analysis, ozone levels are recently plateauing or are on the rise in some localities as the climate heats up. Emissions of human-made ozone precursors have been on the decline in the United States, due to better air quality policies and cleaner technologies, and this trend is expected to continue. But as the climate continues to warm, unhealthy ozone days are projected to worsen in some areas in the years ahead. This effect is known as the "climate penalty," though higher levels of atmospheric water vapor (another effect of climate change) may help ameliorate the effect in some places. With hotter temperatures projected, more air stagnation days, and increases in natural emissions from wildfire smoke, the climate penalty will make it difficult for many areas of the country to achieve mandated air quality standards.

Ozone and your Health

Even just a few unhealthy ozone days a year pose health concerns, as an increasing number of health risks are being linked to exposure to ozone and other air pollutants. According to the American Lung Association, ozone pollution is associated with asthma attacks; pneumonia; coughing and shortness of breath; cardiovascular damage; increased susceptibility to infections; and decreased lung functions. Ozone can cause developmental issues in children, and increase the risk of reproductive harm in adults. Studies have shown that hospital admissions and visits to the emergency room for asthma are increased due to elevated ozone levels.

Additionally, a number of vulnerable populations are at higher risk when exposed to ozone. School-age children with still-developing lungs are at increased risk for long-term damage, including developing asthma. Compared to adults, children tend to be more active outside and breathe in more air per pound of body weight, therefore taking in a "higher dose" of ozone. In times of extreme heat or cold, the effects of short-term ozone exposure have been shown to increase rates of mortality, especially for women and the elderly.

What You Can Do

Protect your health:

Enter your zip code into EPA's Air Quality Index to find out conditions in your area. The color-coded charts provide guidance on health risks and which activities are safe for various populations.

Avoid exercise or working outside on high ozone days.

Prevent more ozone from forming on hot, dry days:

Limit your driving as much as possible—carpool, take public transportation.

Don't let your engine idle.

Electric vehicles don't emit pollutants and have been found to be better for air quality and climate change, even if their electricity is derived from fossil fuels.

Refrain from barbecuing or using your fire pit.

Postpone any painting projects unless the paints are VOC-free. Solvent gases from many paints include VOCs that can contribute to ground-level ozone formation.

Fuel your vehicle in the early morning or later evening, since sunlight triggers ozone formation.

Mow your lawn late in the evening or if possible, use electric lawn equipment instead of gasoline-powered equipment.

METHODOLOGY

Ozone Analysis:
Climate Central analyzed daily ozone data for the counties of 244 cities from 2000-2018, as obtained from the EPA Air Quality System. Annual unhealthy ozone days were calculated for each county as well as a 2000-2014 annual average. An "unhealthy" ozone day is defined as one where the 8-hour max exceeds the most current NAAQS standard of 0.070 ppm (equivalent to an AQI value greater than 100). To highlight areas with an ozone problem, locations were identified that had either:

A large number of ozone days over the past four years in terms of pure count (greater than 20 days over the past four years)

An increase in recent years (a continuous increase in days over at least 3 of the past 4 years)

More ozone days in a single recent year (2015-2018) than their 2000-2014 average

Stagnation Analysis:
Climate Central analyzed gridded stagnation data from the NOAA/NCEI Air Stagnation Index, calculating annual trends since the dataset began in 1973. Correlation plots were created using annual average summer (June, July, and August) maximum temperature data obtained from the Applied Climate Information System and summer stagnation data from NOAA/NCEI. Although winter stagnation can greatly reduce the air quality in places like Salt Lake City, it is not fundamentally driven by increasing hot days which is the focus of this Climate Central analysis.

Comments

Name

Email

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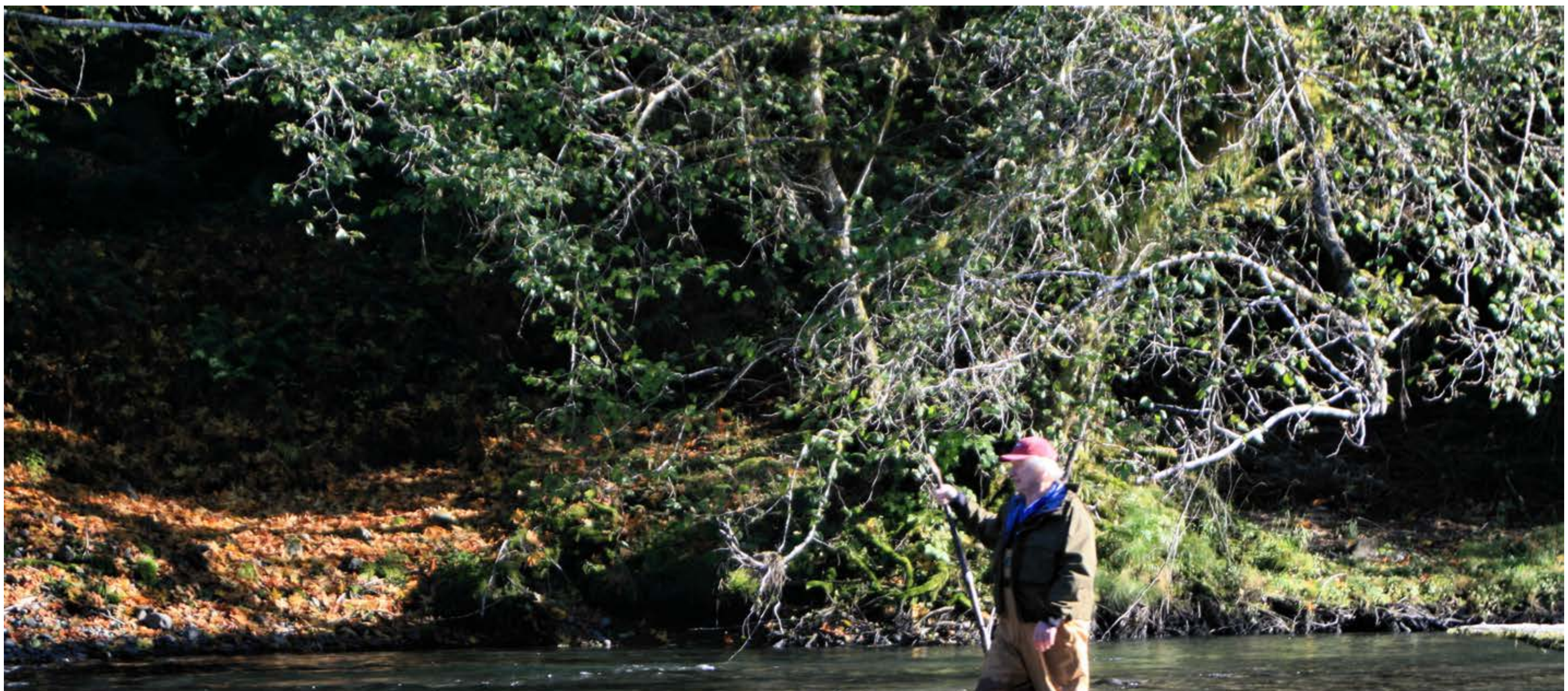

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INTERGOVERNMENTAL PANEL ON climate change

Climate Change and Land

An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

Summary for Policymakers

WG I WG II WG III

WMO UNEP

INTERGOVERNMENTAL PANEL ON climate change

IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems

Summary for Policymakers
Approved Draft

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Introduction

This Special Report on Climate Change and Land[1] responds to the Panel decision in 2016 to prepare three Special Reports[2] during the Sixth Assessment cycle, taking account of proposals from governments and observer organizations[3]. This report addresses greenhouse gas (GHG) fluxes in land-based ecosystems , land use and sustainable land management[4] in relation to climate change adaptation and mitigation, desertification[5], land degradation[6] and food security[7]. This report follows the publication of other recent reports, including the IPCC *Special Report on Global Warming of 1.5°C* (SR15), the thematic assessment of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) on Land Degradation and Restoration, the IPBES Global Assessment Report on Biodiversity and Ecosystem Services, and the Global Land Outlook of the UN Convention to Combat Desertification (UNCCD). This report provides an updated assessment of the current state of knowledge[8] while striving for coherence and complementarity with other recent reports.

This Summary for Policymakers (SPM) is structured in four parts: *A) People, land and climate in a warming world; B) Adaptation and mitigation response options; C) Enabling response options; and D) Action in the near-term.*

Confidence in key findings is indicated using the IPCC calibrated language[9]; the underlying scientific basis of each key finding is indicated by references to the main report.

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[1] The terrestrial portion of the biosphere that comprises the natural resources (soil, near-surface air, vegetation and other biota, and water), the ecological processes, topography, and human settlements and infrastructure that operate within that system.

[2] The three Special reports are: "Global Warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty."; "Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems"; "The Ocean and Cryosphere in a Changing Climate"

[3] related proposals were: climate change and desertification; desertification with regional aspects; land degradation – an assessment of the interlinkages and integrated strategies for mitigation and adaptation; agriculture, foresty and other landuse; food and agriculture; and food security and climate change.

[4] Sustainable Land Management is defined in this report as "the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions".

[5] Desertification is defined in this report as 'land degradation in arid, semi-arid, and dry sub-humid areas resulting from many factors, including climatic variations and human activities'.

[6] Land degradation is defined in this report as 'a negative trend in land condition, caused by direct or indirect human induced processes, including anthropogenic climate change, expressed as long-term reduction and as loss of at least one of the following: biological productivity, ecological integrity, or value to humans'.

[7] Food security is defined in this report as 'a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life'.

[8] The assessment covers literature accepted for publication by 7th April 2019.

[9] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, medium

A. People, land and climate in a warming world

A 1. Land provides the principal basis for human livelihoods and well-being including the supply of food, freshwater and multiple other ecosystem services, as well as biodiversity. Human use directly affects more than 70% (*likely* 69-76%) of the global, ice-free land surface (*high confidence*). Land also plays an important role in the climate system. {1.1, 1.2, 2.3, 2.4, Figure SPM.1}

A1.1. People currently use one quarter to one third of land's potential net primary production[10] for food, feed, fibre, timber and energy. Land provides the basis for many other ecosystem functions and services[11], including cultural and regulating services, that are essential for humanity (*high confidence*). In one economic approach, the world's terrestrial ecosystem services have been valued on an annual basis to be approximately equivalent to the annual global Gross Domestic Product[12] (*medium confidence*). {1.1, 1.2, 3.2, 4.1, 5.1, 5.5, Figure SPM.1}

A1.2. Land is both a source and a sink of greenhouse gases (GHGs) and plays a key role in the exchange of energy, water and aerosols between the land surface and atmosphere. Land ecosystems and biodiversity are vulnerable to ongoing climate change and weather and climate extremes, to different extents. Sustainable land management can contribute to reducing the negative impacts of multiple stressors, including climate change, on ecosystems and societies (*high confidence*). {1.1, 1.2, 3.2, 4.1, 5.1, 5.5, Figure SPM.1}

A1.3. Data available since 1961[13] show that global population growth and changes in per capita consumption of food, feed, fibre, timber and energy have caused unprecedented rates of land and freshwater use (*very high confidence*) with agriculture currently accounting for ca. 70% of global fresh-water use (*medium confidence*). Expansion of areas under agriculture and forestry, including commercial production, and enhanced agriculture and forestry productivity have supported consumption and food availability for a growing population *(high confidence).* With

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confidence. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, very likely. This is consistent with IPCC AR5.

[10] Land's potential net primary production (NPP) is defined in this report as the amount of carbon accumulated through photosynthesis minus the amount lost by plant respiration over a specified time period that would prevail in the absence of land use.

[11] In its conceptual framework, IPBES uses "nature's contribution to people" in which it includes ecosystem goods and services.

[12] i.e. estimated at $75 trillion for 2011, based on US dollars for 2007.

[13] This statement is based on the most comprehensive data from national statistics available within FAOSTAT, which starts in 1961. This does not imply that the changes started in 1961. Land use changes have been taking place from well before the pre-industrial period to the present.

large regional variation, these changes have contributed to increasing net GHG emissions (*very high confidence*), loss of natural ecosystems (e.g. forests, savannahs, natural grasslands and wetlands) and declining biodiversity (*high confidence*). {1.1, 1.3, 5.1, 5.5, Figure SPM.1}

A1.4. Data available since 1961 shows the per capita supply of vegetable oils and meat has more than doubled and the supply of food calories per capita has increased by about one third (*high confidence*). Currently, 25-30% of total food produced is lost or wasted (*medium confidence*). These factors are associated with additional GHG emissions (*high confidence*). Changes in consumption patterns have contributed to about 2 billion adults now being overweight or obese (*high confidence*). An estimated 821 million people are still undernourished (*high confidence*). {1.1, 1.3, 5.1, 5.5, Figure SPM.1}

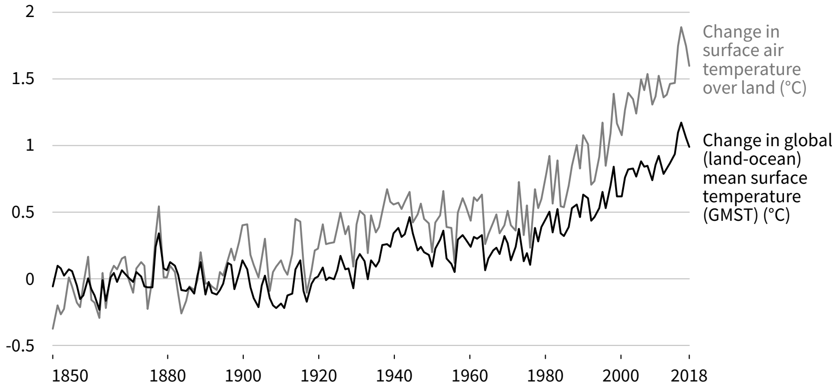
A1.5. About a quarter of the Earth's ice-free land area is subject to human-induced degradation (*medium confidence*). Soil erosion from agricultural fields is estimated to be currently 10 to 20 times (no tillage) to more than 100 times (conventional tillage) higher than the soil formation rate (*medium confidence*). Climate change exacerbates land degradation, particularly in low-lying coastal areas, river deltas, drylands and in permafrost areas (*high confidence*). Over the period 1961-2013, the annual area of drylands in drought has increased, on average by slightly more than 1% per year, with large inter-annual variability. In 2015, about 500 (380-620) million people lived within areas which experienced desertification between the 1980s and 2000s. The highest numbers of people affected are in South and East Asia, the circum Sahara region including North Africa, and the Middle East including the Arabian peninsula (*low confidence*). Other dryland regions have also experienced desertification. People living in already degraded or desertified areas are increasingly negatively affected by climate change (*high confidence*). {1.1, 1.2, 3.1, 3.2, 4.1, 4.2, 4.3, Figure SPM.1}

Land use and observed climate change

A. Observed temperature change relative to 1850-1900

Since the pre-industrial period (1850-1900) the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST).

CHANGE in TEMPERATURE rel. to 1850-1900 (°C)

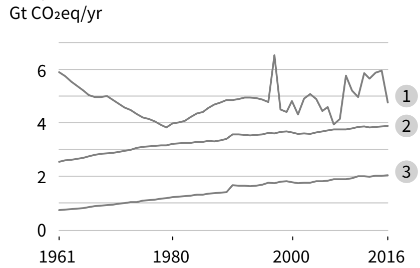


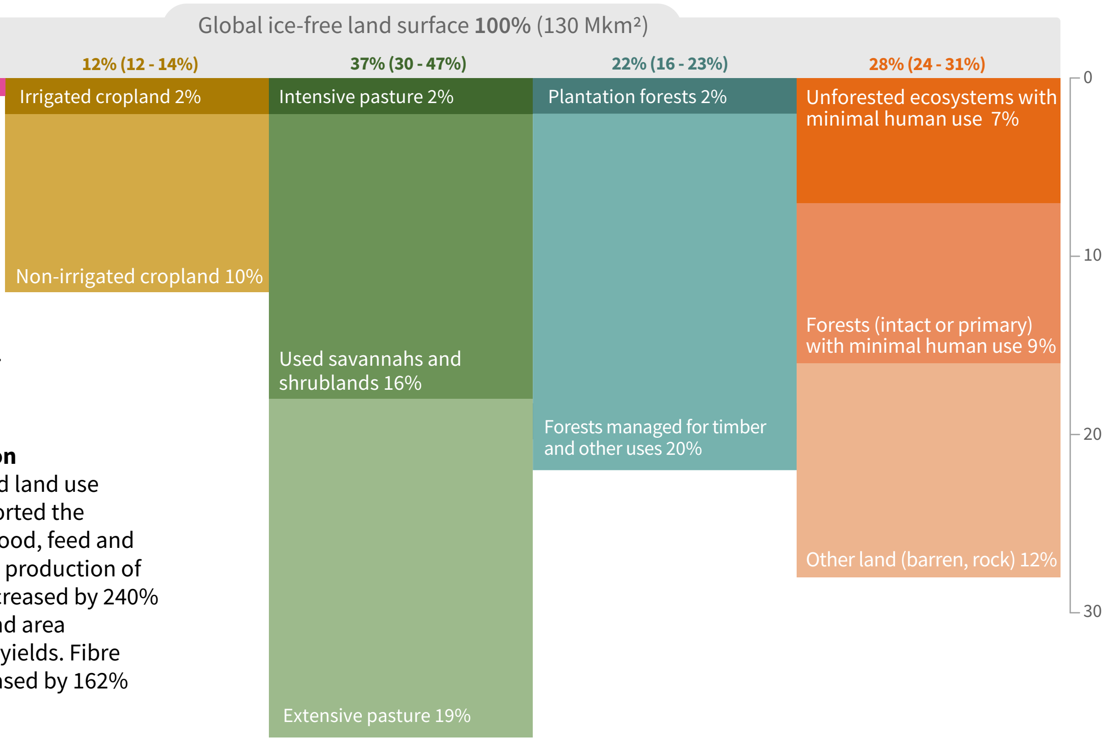
B. GHG emissions

An estimated 23% of total anthropogenic greenhouse gas emissions (2007-2016) derive from Agriculture, Forestry and Other Land Use (AFOLU).

CHANGE in emissions rel. to 1961

1. Net CO_2 emissions from FOLU (Gt CO_2/yr)
2. CH_4 emissions from Agriculture (Gt CO_2eq/yr)
3. N_2O emissions from Agriculture (Gt CO_2eq/yr)





C. Global land use in circa 2015

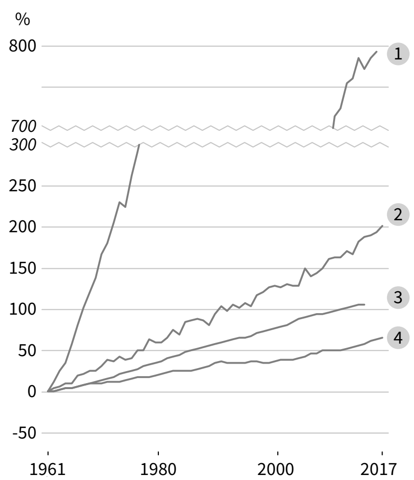
The barchart depicts shares of different uses of the global, ice-free land area. Bars are ordered along a gradient of decreasing land-use intensity from left to right.

D. Agricultural production

Land use change and rapid land use intensification have supported the increasing production of food, feed and fibre. Since 1961, the total production of food (cereal crops) has increased by 240% (until 2017) because of land area expansion and increasing yields. Fibre production (cotton) increased by 162% (until 2013).

CHANGE in % rel. to 1961

1. Inorganic N fertiliser use
2. Cereal yields
3. Irrigation water volume
4. Total number of ruminant livestock

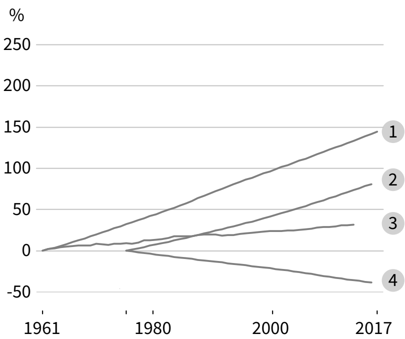


E. Food demand

Increases in production are linked to consumption changes.

CHANGE in % rel. to 1961 and 1975

1. Population
2. Prevalence of overweight + obese
3. Total calories per capita
4. Prevalence of underweight



F. Desertification and land degradation

Land-use change, land-use intensification and climate change have contributed to desertification and land degradation.

CHANGE in % rel. to 1961 and 1970

1. Population in areas experiencing desertification
2. Dryland areas in drought annually
3. Inland wetland extent

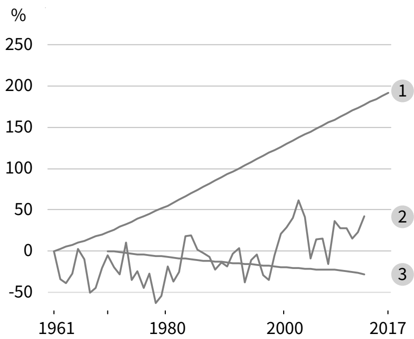


Figure SPM.1: Land use and observed climate change

A representation of the land use and observed climate change covered in this assessment report. Panels A-F show the status and trends in selected land use and climate variables that represent many of the core topics covered in this report. The annual time series in B and D-F are based on the most comprehensive, available data from national statistics, in most cases from FAOSTAT which starts in 1961. Y-axes in panels D-F are expressed relative to the starting year of the time series (rebased to zero). Data sources and notes: **A:** The warming curves are averages of four datasets {2.1; Figure 2.2; Table 2.1} **B:** N_2O and CH_4 from agriculture are from FAOSTAT; Net CO_2 emissions from FOLU using the mean of two bookkeeping models (including emissions from peatland fires since 1997). All values expressed in units of CO_2-eq are based on AR5 100 year Global Warming Potential values without climate-carbon feedbacks (N_2O=265; CH_4=28). {see Table SPM.1, 1.1, 2.3} **C:** Depicts shares of different uses of the global, ice-free land area for approximately the year 2015, ordered along a gradient of decreasing land-use intensity from left to right. Each bar represents a broad land cover category; the numbers on top are the total % of the ice-free area covered, with uncertainty ranges in brackets. Intensive pasture is defined as having a livestock density greater than 100 animals/km². The area of 'forest managed for timber and other uses' was calculated as total forest area minus 'primary/intact' forest area. {1.2, Table 1.1, Figure 1.3} **D:** Note that fertiliser use is shown on a split axis. The large percentage change in fertiliser use reflects the low level of use in 1961 and relates to both increasing fertiliser input per area as well as the expansion of fertilised cropland and grassland to increase food production. {1.1, Figure 1.3} **E:** Overweight population is defined as having a body mass index (BMI) > 25 kg m^{-2}; underweight is defined as BMI < 18.5 kg m^{-2}. {5.1, 5.2} **F:** Dryland areas were estimated using TerraClimate precipitation and potential evapotranspiration (1980-2015) to identify areas where the Aridity Index is below 0.65. Population data are from the HYDE3.2 database. Areas in drought are based on the 12-month accumulation Global Precipitation Climatology Centre Drought Index. The inland wetland extent (including peatlands) is based on aggregated data from more than 2000 time series that report changes in local wetland area over time. {3.1, 4.2, 4.6}

A 2. Since the pre-industrial period, the land surface air temperature has risen nearly twice as much as the global average temperature *(high confidence)*. Climate change, including increases in frequency and intensity of extremes, has adversely impacted food security and terrestrial ecosystems as well as contributed to desertification and land degradation in many regions (*high confidence*). {2.2, 3.2, 4.2, 4.3, 4.4, 5.1, 5.2, Executive Summary Chapter 7, 7.2}

A2.1. Since the pre-industrial period (1850-1900) the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST) (high confidence). From 1850-1900 to 2006-2015 mean land surface air temperature has increased by 1.53°C (very likely range from 1.38°C to 1.68°C) while GMST increased by 0.87°C (likely range from 0.75°C to 0.99°C). {2.2.1, Figure SPM.1}

A2.2. Warming has resulted in an increased frequency, intensity and duration of heat-related events, including heat waves[14] in most land regions (*high confidence*). Frequency and intensity of droughts has increased in some regions (including the Mediterranean, west Asia, many parts of South America, much of Africa, and north-eastern Asia) (*medium confidence*) and there

[14] A heatwave is defined in this report as 'a period of abnormally hot weather. Heatwaves and warm spells have various and in some cases overlapping definitions'.

has been an increase in the intensity of heavy precipitation events at a global scale (*medium confidence*). {2.2.5, 4.2.3, 5.2}

A2.3. Satellite observations[15] have shown vegetation greening[16] over the last three decades in parts of Asia, Europe, South America, central North America, and southeast Australia. Causes of greening include combinations of an extended growing season, nitrogen deposition, CO_2 fertilisation[17], and land management (*high confidence*). Vegetation browning[18] has been observed in some regions including northern Eurasia, parts of North America, Central Asia and the Congo Basin, largely as a result of water stress (*medium confidence*). Globally, vegetation greening has occurred over a larger area than vegetation browning (*high confidence*). {2.2.3, Box 2.3, 2.2.4, 3.2.1, 3.2.2, 4.3.1, 4.3.2, 4.6.2, 5.2.2}

A2.4. The frequency and intensity of dust storms have increased over the last few decades due to land use and land cover changes and climate-related factors in many dryland areas resulting in increasing negative impacts on human health, in regions such as the Arabian Peninsula and broader Middle East, Central Asia (*high confidence*)[19]. {2.4.1, 3.4.2}

A2.5. In some dryland areas, increased land surface air temperature and evapotranspiration and decreased precipitation amount, in interaction with climate variability and human activities, have contributed to desertification. These areas include Sub-Saharan Africa, parts of East and Central Asia, and Australia. (medium confidence) {2.2, 3.2.2, 4.4.1}

A2.6. Global warming has led to shifts of climate zones in many world regions, including expansion of arid climate zones and contraction of polar climate zones (*high confidence*). As a consequence, many plant and animal species have experienced changes in their ranges, abundances, and shifts in their seasonal activities (*high confidence*). {2.2, 3.2.2, 4.4.1}

A2.7. Climate change can exacerbate land degradation processes (*high confidence*) including through increases in rainfall intensity, flooding, drought frequency and severity, heat stress, dry spells, wind, sea-level rise and wave action, permafrost thaw with outcomes being

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[15] The interpretation of satellite observations can be affected by insufficient ground validation and sensor calibration. In addition their spatial resolution can make it difficult to resolve small-scale changes.
[16] Vegetation greening is defined in this report as an increase in photosynthetically active plant biomass which is inferred from satellite observations.
[17] CO2 fertilization is defined in this report as the enhancement of plant growth as a result of increased atmospheric carbon dioxide (CO2) concentration. The magnitude of CO2 fertilization depends on nutrients and water availability.
[18] Vegetation browning is defined in this report as a decrease in photosynthetically active plant biomass which is inferred from satellite observations.
[19] Evidence relative to such trends in dust storms and health impacts in other regions is limited in the literature assessed in this report.

modulated by land management. Ongoing coastal erosion is intensifying and impinging on more regions with sea level rise adding to land use pressure in some regions (*medium confidence*). {4.2.1, 4.2.2, 4.2.3, 4.4.1, 4.4.2, 4.9.6, Table 4.1, 7.2.1, 7.2.2}

A2.8. Climate change has already affected food security due to warming, changing precipitation patterns, and greater frequency of some extreme events (*high confidence*). In many lower-latitude regions, yields of some crops (e.g., maize and wheat) have declined, while in many higher-latitude regions, yields of some crops (e.g., maize, wheat and sugar beets) have increased over recent decades *(high confidence)*. Climate change has resulted in lower animal growth rates and productivity in pastoral systems in Africa (*high confidence)*. There is robust evidence that agricultural pests and diseases have already responded to climate change resulting in both increases and decreases of infestations (*high confidence*). Based on indigenous and local knowledge, climate change is affecting food security in drylands, particularly those in Africa, and high mountain regions of Asia and South America[20]. {5.2.1, 5.2.2, 7.2.2}

A 3. Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for around 13% of CO_2, 44% of methane (CH_4), and 82% of nitrous oxide (N_2O) emissions from human activities globally during 2007-2016, representing 23% (12.0 +/- 3.0 $GtCO_2e\ yr^{-1}$) of total net anthropogenic emissions of GHGs[21] (*medium confidence*). The natural response of land to human-induced environmental change caused a net sink of around 11.2 $GtCO_2\ yr^{-1}$ during 2007-2016 (equivalent to 29% of total CO_2 emissions) (*medium confidence*); the persistence of the sink is uncertain due to climate change (*high confidence*). If emissions associated with pre- and post-production activities in the global food system[22] are included, the emissions are estimated to be 21-37% of total net anthropogenic GHG emissions (*medium confidence*). {2.3, Table 2.2, 5.4}.

A3.1. Land is simultaneously a source and a sink of CO_2 due to both anthropogenic and natural drivers, making it hard to separate anthropogenic from natural fluxes (*very high confidence*). Global models estimate net CO_2 emissions of 5.2 ± 2.6 $GtCO_2\ yr^{-1}$ (*likely* range) from land use and land-use change during 2007-16. These net emissions are mostly due to deforestation, partly offset by afforestation/reforestation, and emissions and removals by other land use activities

[20] The assessment covered literature whose methodologies included interviews and surveys with indigenous peoples and local communities.
[21] This assessment only includes CO2, CH4 and N2O.
[22] Global food system in this report is defined as 'all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socioeconomic and environmental outcomes at the global level'. These emissions data are not directly comparable to the national inventories prepared according to the 2006 IPCC Guidelines for National Greenhouse Gas.

(*very high confidence*) (Table SPM.1)[23]. There is no clear trend in annual emissions since 1990 (*medium confidence*) (Figure SPM.1). {1.1, 2.3, Table 2.2, Table 2.3}

A3.2. The natural response of land to human-induced environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change, resulted in global net removals of 11.2 +/– 2.6 Gt CO_2 yr^{-1} (*likely* range) during 2007-2016 (Table SPM.1). The sum of the net removals due to this response and the AFOLU net emissions gives a total net land-atmosphere flux that removed 6.0+/-2.6 $GtCO_2$ yr^{-1} during 2007-2016 (*likely* range). Future net increases in CO_2 emissions from vegetation and soils due to climate change are projected to counteract increased removals due to CO_2 fertilisation and longer growing seasons (*high confidence*). The balance between these processes is a key source of uncertainty for determining the future of the land carbon sink. Projected thawing of permafrost is expected to increase the loss of soil carbon (*high confidence*). During the 21st century, vegetation growth in those areas may compensate in part for this loss (*low confidence*). {Box 2.3, 2.3.1, 2.5.3, 2.7; Table 2.3}

A3.3. Global models and national GHG inventories use different methods to estimate anthropogenic CO_2 emissions and removals for the land sector. Both produce estimates that are in close agreement for land-use change involving forest (e.g., deforestation, afforestation), and differ for managed forest. Global models consider as managed forest those lands that were subject to harvest whereas, consistent with IPCC guidelines, national GHG inventories define managed forest more broadly. On this larger area, inventories can also consider the natural response of land to human-induced environmental changes as anthropogenic, while the global model approach {Table SPM.1} treats this response as part of the non-anthropogenic sink. For illustration, from 2005 to 2014, the sum of the national GHG inventories net emission estimates is 0.1±1.0 $GtCO_2yr^{-1}$, while the mean of two global bookkeeping models is 5.1±2.6 $GtCO_2yr^{-1}$ (*likely* range). Consideration of differences in methods can enhance understanding of land sector net emission estimates and their applications.

[23] The net anthropogenic flux of CO2 from "bookkeeping" or "carbon accounting" models is composed of two opposing gross fluxes: gross emissions (about 20 GtCO2 yr-1) are from deforestation, cultivation of soils, and oxidation of wood products; gross removals (about 14 GtCO2 yr-1) are largely from forest growth following wood harvest and agricultural abandonment (medium confidence).

Table SPM1. Net anthropogenic emissions due to Agriculture, Forestry, and other Land Use (AFOLU) and non-AFOLU (Panel 1) and global food systems (average for 2007-2016)[1] (Panel 2). Positive value represents emissions; negative value represents removals.

		Direct Anthropogenic							
		Net anthropogenic emissions due to Agriculture, Forestry, and Other Land Use (AFOLU)			Non-AFOLU anthropogenic GHG emissions[6]	Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas	AFOLU as a % of total net anthropogenic emissions, by gas	Natural response of land to human-induced environmental change[7]	Net land – atmosphere flux from all lands
Panel 1: Contribution of AFOLU									
		FOLU	Agriculture	Total					
		A	B	C = B + A	D	**E = C + D**	F = (C/E)*100	G	A + G
CO_2[2]	Gt CO_2 y^{-1}	5.2 ± 2.6	--[11]	5.2 ± 2.6	33.9 ± 1.8	**39.1 ± 3.2**	~13%	-11.2 ± 2.6	-6.0 ± 2.0
CH_4[3,8]	Mt CH_4 y^{-1}	19 ± 6	142 ± 43	162 ± 48.6	201 ± 100	**363 ± 111**			
	Gt CO_2e y^{-1}	0.5 ± 0.2	4.0 ± 1.2	4.5 ± 1.4	5.6 ± 2.8	**10.1 ± 3.1**	~44%		
N_2O[3,8]	Mt N_2O y^{-1}	0.3 ± 0.1	8 ±2	8.3 ± 2.5	2.0 ± 1.0	**10.4 ± 2.7**			
	Gt CO_2e y^{-1}	0.09 ± 0.03	2.2 ± 0.7	2.3 ± 0.7	0.5 ± 0.3	**2.8 ± 0.7**	~82%		
Total (GHG)	**Gt CO_2e y^{-1}**	**5.8 ± 2.6**	**6.2 ± 1.4**	**12.0 ± 3.0**	**40.0 ± 3.4**	**52.0 ± 4.5**	**~23%**		
Panel 2: Contribution of global food system									
		Land-use change	Agriculture		Non-AFOLU[5] other sectors pre- to post-production	Total global food system emissions			
CO_2[4] Land-use change	Gt CO_2 y^{-1}	4.9 ± 2.5							
CH_4[3,8,9] Agriculture	Gt CO_2e y^{-1}		4.0 ± 1.2						
N_2O[3,8,9] Agriculture	Gt CO_2e y^{-1}		2.2 ± 0.7						
CO_2 other sectors	Gt CO_2 y^{-1}				2.4 – 4.8				
Total (CO2e)[10]	**Gt CO_2e y^{-1}**	**4.9 ± 2.5**	**6.2 ± 1.4**		**2.4 – 4.8**	**10.7 – 19.1**			

Data sources and notes:

[1] Estimates are only given until 2016 as this is the latest date when data are available for all gases.

[2] Net anthropogenic flux of CO_2 due to land cover change such as deforestation and afforestation, and land management including wood harvest and regrowth, as well as peatland burning, based on two bookkeeping models as used in the Global Carbon Budget and for AR5. Agricultural soil carbon stock change under the same land use is not considered in these models. {2.3.1.2.1, Table 2.2, Box 2.2}

[3] Estimates show the mean and assessed uncertainty of two databases, FAOSTAT and USEPA 2012 {2.3; Table 2.2}

[4] Based on FAOSTAT. Categories included in this value are "net forest conversion" (net deforestation), drainage of organic soils (cropland and grassland), biomass burning (humid tropical forests, other forests, organic soils). It excludes "forest land" (forest management plus net forest expansion), which is primarily a sink due to afforestation. Note: total FOLU emissions from FAOSTAT are 2.8 (±1.4) Gt CO_2 yr^{-1} for the period 2007-2016. {Table 2.2, Table 5.4}

[5] CO_2 emissions induced by activities not included in the AFOLU sector, mainly from energy (e.g. grain drying), transport (e.g. international trade), and industry (e.g. synthesis of inorganic fertilizers) part of food systems, including agricultural production activities (e.g. heating in greenhouses), pre-production (e.g. manufacturing of farm inputs) and post-production (e.g. agri-food processing) activities. This estimate is land based and hence excludes emissions from fisheries. It includes emissions from fibre and other non-food agricultural products since these are not separated from food use in data bases. The CO_2 emissions related to food system in other sectors than AFOLU are 6-13% of total anthropogenic CO_2 emissions. These emissions are typically low in smallholder subsistence farming. When added to AFOLU emissions, the estimated share of food systems in global anthropogenic emissions is 21-37%. {5.4.5, Table 5.4}

[6] Total non-AFOLU emissions were calculated as the sum of total CO_2e emissions values for energy, industrial sources, waste and other emissions with data from the Global Carbon Project for CO_2, including international aviation and shipping and from the PRIMAP database for CH_4 and N_2O averaged over 2007-2014 only as that was the period for which data were available {2.3; Table 2.2}.

[7] The natural response of land to human-induced environmental changes is the response of vegetation and soils to environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change. The estimate shown represents the average from Dynamic Global Vegetation Models {2.3.1.2.4, Box 2.2, Table 2.3}

[8] All values expressed in units of CO_2e are based on AR5 100 year Global Warming Potential (GWP) values without climate-carbon feedbacks (N_2O = 265; CH_4 = 28). Note that the GWP has been used across fossil fuel and biogenic sources of methane. If a higher GWP for fossil fuel CH4 (30 per AR5), then total anthropogenic CH4 emissions expressed in CO2e would be 2% greater.

[9] This estimate is land based and hence excludes emissions from fisheries and emissions from aquaculture (except emissions from feed produced on land and used in aquaculture), and also includes non-food use (e.g. fibre and bioenergy) since these are not separated from food use in databases. It excludes non-CO_2 emissions associated with land use change (FOLU category) since these are from fires in forests and peatlands.

[10] Emissions associated with food loss and waste are included implicitly, since emissions from food system are related to food produced, including food consumed for nutrition and to food loss and waste. The latter is estimated at 8-10% of total anthropogenic emissions in CO2e. {5.5.2.5}

[11] No global data are available for agricultural CO_2 emissions

A3.4. Global AFOLU emissions of methane in the period 2007-2016 were 162 ± 49 Mt CH_4 yr-1 (4.5 ± 1.4 $GtCO_2eq$ yr-1) (*medium confidence*). The globally averaged atmospheric concentration of methane shows a steady increase between the mid-1980s and early 1990s, slower growth thereafter until 1999, a period of no growth between 1999-2006, followed by a resumption of growth in 2007 (*high confidence*). Biogenic sources make up a larger proportion of emissions than they did before 2000 (*high confidence*). Ruminants and the expansion of rice cultivation are important contributors to the rising concentration (*high confidence*). {Table 2.2, 2.3.2, 5.4.2, 5.4.3, Figure SPM.1}.

A3.5. Anthropogenic AFOLU N_2O emissions are rising, and were 8.3 ± 2.5 MtN_2O yr^{-1} (2.3 ± 0.7 GtCO_2eq yr^{-1}) during the period 2007-2016. Anthropogenic N_2O emissions (Figure SPM.1, Table SPM.1) from soils are primarily due to nitrogen application including inefficiencies (over-application or poorly synchronised with crop demand timings) (*high confidence*). Cropland soils emitted around 3 Mt N_2O yr^{-1} (around 795 MtCO_2-eq yr^{-1}) during the period 2007-2016 (*medium confidence*). There has been a major growth in emissions from managed pastures due to increased manure deposition (*medium confidence*). Livestock on managed pastures and rangelands accounted for more than one half of total anthropogenic N_2O emissions from agriculture in 2014 (*medium confidence*). {Table 2.1, 2.3.3, 5.4.2, 5.4.3}

A3.6. Total net GHG emissions from agriculture, forestry, and other land use (AFOLU) emissions represent 12.0 +/- 3.0 GtCO_2eq yr^{-1} during 2007-2016. This represents 23% of total net anthropogenic emissions[24] (Table SPM.1). Other approaches, such as global food system, include agricultural emissions and land use change (i.e., deforestation and peatland degradation), as well as outside farm gate emissions from energy, transport and industry sectors for food production. Emissions within farm gate and from agricultural land expansion contributing to the global food system represent 16-27% of total anthropogenic emissions (*medium confidence*). Emissions outside the farm gate represent 5-10% of total anthropogenic emissions (*medium confidence*). Given the diversity of food systems, there are large regional differences in the contributions from different components of the food system (*very high confidence*). Emissions from agricultural production are projected to increase (*high confidence*), driven by population and income growth and changes in consumption patterns (*medium confidence*). {5.5, Table 5.4}

A 4. Changes in land conditions[25], either from land-use or climate change, affect global and regional climate (*high confidence*). At the regional scale, changing land conditions can reduce or accentuate warming and affect the intensity, frequency and duration of extreme events. The magnitude and direction of these changes vary with location and season (*high confidence*). {Executive Summary Chapter 2, 2.3, 2.4, 2.5, 3.3}

A4.1. Since the pre-industrial period, changes in land cover due to human activities have led to both a net release of CO_2 contributing to global warming (*high confidence*), and an increase in global land albedo[26] causing surface cooling (*medium confidence*). Over the historical period, the resulting net effect on globally averaged surface temperature is estimated to be small (*medium confidence*). {2.4, 2.6.1, 2.6.2}

[24] This assessment only includes CO2, CH4 and N2O.
[25] Land conditions encompass changes in land cover (e.g. deforestation, afforestation, urbanisation), in land use (e.g. irrigation), and in land state (e.g. degree of wetness, degree of greening, amount of snow, amount of permafrost)
[26] Land with high albedo reflects more incoming solar radiation than land with low albedo.

A4.2. The likelihood, intensity and duration of many extreme events can be significantly modified by changes in land conditions, including heat related events such as heat waves (*high confidence*) and heavy precipitation events (*medium confidence*). Changes in land conditions can affect temperature and rainfall in regions as far as hundreds of kilometres away (*high confidence*). {2.5.1, 2.5.2, 2.5.4, 3.3; Cross-Chapter Box 4 in Chapter 2}

A4.3. Climate change is projected to alter land conditions with feedbacks on regional climate. In those boreal regions where the treeline migrates northward and/or the growing season lengthens, winter warming will be enhanced due to decreased snow cover and albedo while warming will be reduced during the growing season because of increased evapotranspiration (*high confidence*). In those tropical areas where increased rainfall is projected, increased vegetation growth will reduce regional warming (*medium confidence*). Drier soil conditions resulting from climate change can increase the severity of heat waves, while wetter soil conditions have the opposite effect (*high confidence*). {2.5.2, 2.5.3}

A4.4. Desertification amplifies global warming through the release of CO_2 linked with the decrease in vegetation cover (*high confidence*). This decrease in vegetation cover tends to increase local albedo, leading to surface cooling (*high confidence*). {3.3}

A4.5. Changes in forest cover for example from afforestation, reforestation and deforestation, directly affect regional surface temperature through exchanges of water and energy[27] (*high confidence*). Where forest cover increases in tropical regions cooling results from enhanced evapotranspiration (*high confidence*). Increased evapotranspiration can result in cooler days during the growing season (*high confidence*) and can reduce the amplitude of heat related events (*medium confidence*). In regions with seasonal snow cover, such as boreal and some temperate, increased tree and shrub cover also has a wintertime warming influence due to reduced surface albedo[28] (*high confidence*). {2.3, 2.4.3, 2.5.1, 2.5.2, 2.5.4}

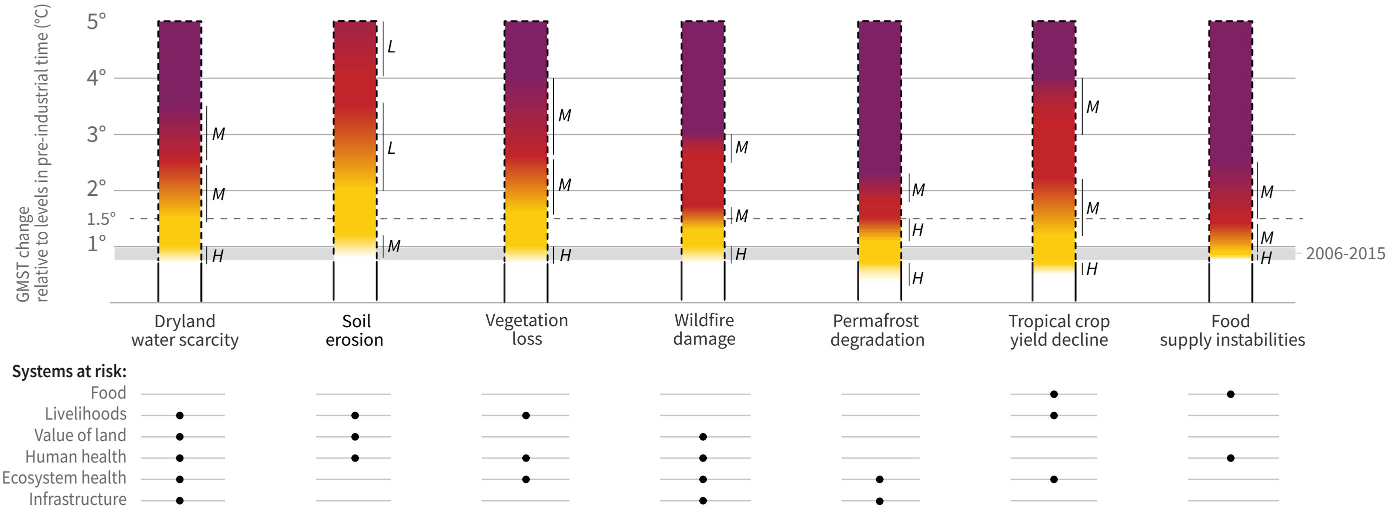
A4.6. Both global warming and urbanisation can enhance warming in cities and their surroundings (heat island effect), especially during heat related events, including heat waves (*high confidence*). Night-time temperatures are more affected by this effect than daytime temperatures (*high confidence*). Increased urbanisation can also intensify extreme rainfall events over the city or downwind of urban areas (*medium confidence*). {2.5.1, 2.5.2, 2.5.3, 4.9.1, Cross-Chapter Box 4 in Chapter 2}

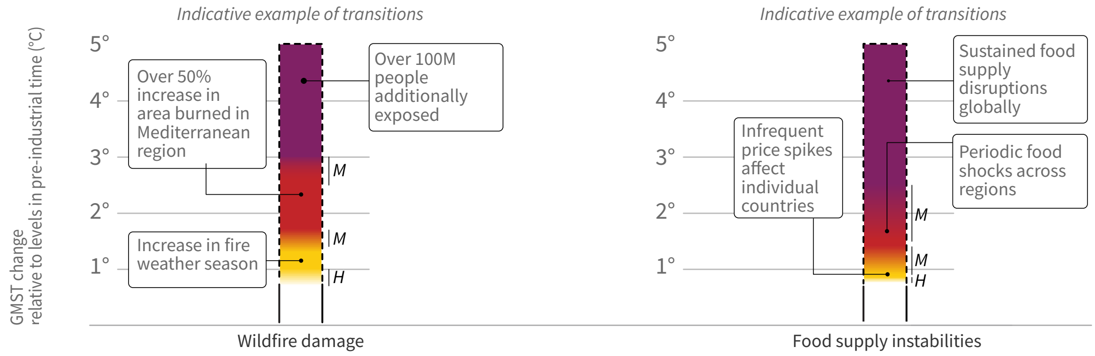
[27] The literature indicates that forest cover changes can also affect climate through changes in emissions of reactive gases and aerosols {2.4, 2.5}.

[28] Emerging literature shows that boreal forest-related aerosols may counteract at least partly the warming effect of surface albedo {2.4.3}.

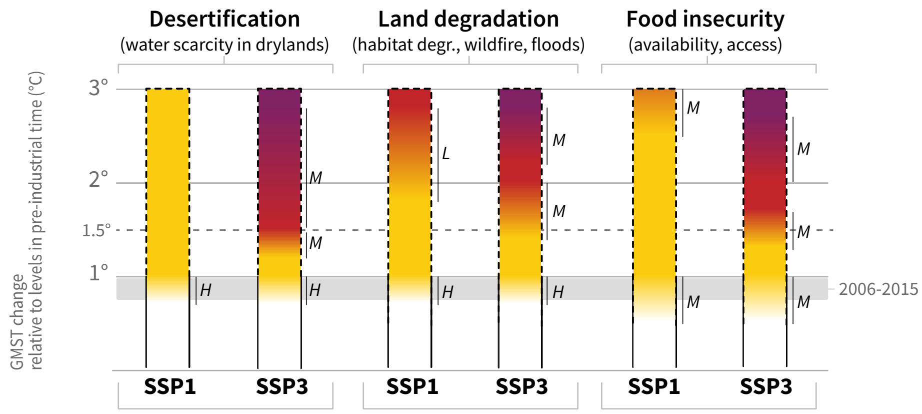
A. Risks to humans and ecosystems from changes in land-based processes as a result of climate change

Increases in global mean surface temperature (GMST), relative to pre-industrial levels, affect processes involved in **desertification** (water scarcity), **land degradation** (soil erosion, vegetation loss, wildfire, permafrost thaw) and **food security** (crop yield and food supply instabilities). Changes in these processes drive risks to food systems, livelihoods, infrastructure, the value of land, and human and ecosystem health. Changes in one process (e.g. wildfire or water scarcity) may result in compound risks. Risks are location-specific and differ by region.





B. Different socioeconomic pathways affect levels of climate related risks



Socio-economic choices can reduce or exacerbate climate related risks as well as influence the rate of temperature increase. The **SSP1** pathway illustrates a world with low population growth, high income and reduced inequalities, food produced in low GHG emission systems, effective land use regulation and high adaptive capacity. The **SSP3** pathway has the opposite trends. Risks are lower in SSP1 compared with SSP3 given the same level of GMST increase.

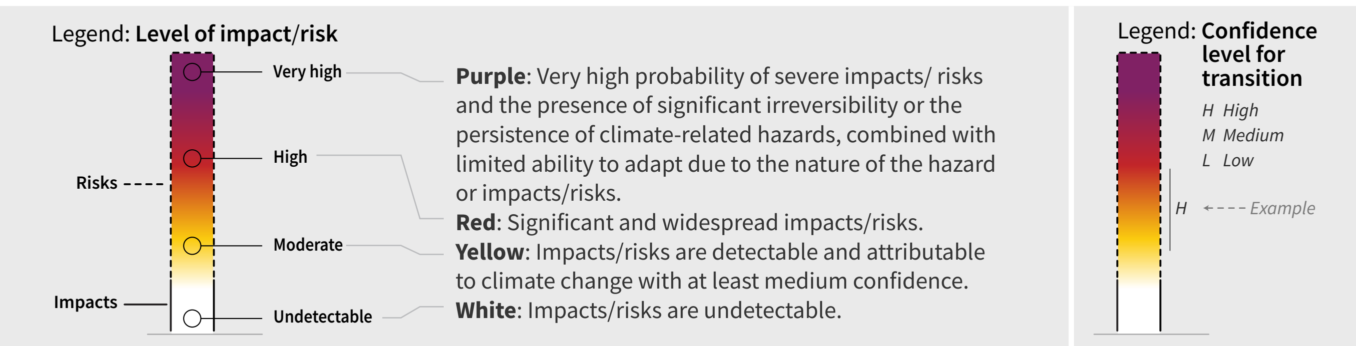


Figure SPM. 2 Risks to land-related human systems and ecosystems from global climate change, socio-economic development and mitigation choices in terrestrial ecosystems.

As in previous IPCC reports the literature was used to make expert judgements to assess the levels of global warming at which levels of risk are undetectable, moderate, high or very high, as described further in Chapter 7 and other parts of the underlying report. The figure indicates assessed risks at approximate warming levels which may be influenced by a variety of factors, including adaptation responses. The assessment considers adaptive capacity consistent with the SSP pathways as described below. **Panel A:** Risks to selected elements of the land system as a function of global mean surface temperature {2.1; Box 2.1; 3.5; 3.7.1.1; 4.4.1.1; 4.4.1.2; 4.4.1.3; 5.2.2; 5.2.3; 5.2.4; 5.2.5; 7.2;7.3, Table SM7.1}. Links to broader systems are illustrative and not intended to be comprehensive. Risk levels are estimated assuming medium exposure and vulnerability driven by moderate trends in socioeconomic conditions broadly consistent with an SSP2 pathway. {Table SM7.4}. **Panel B:** Risks associated with desertification, land degradation and food security due to climate change and patterns of socio-economic development. Increasing risks associated with desertification include population exposed and vulnerable to water scarcity in drylands. Risks related to land degradation include increased habitat degradation, population exposed to wildfire and floods and costs of floods. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable due to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3 {SPM Box 1}) excluding the effects of targeted mitigation policies {3.5; 4.2.1.2; 5.2.2; 5.2.3; 5.2.4; 5.2.5; 6.1.4; 7.2, Table SM7.5}. Risks are not indicated beyond 3°C because SSP1 does not exceed this level of temperature change. **All panels**: As part of the assessment, literature was compiled and data extracted into a summary table. A formal expert elicitation protocol (based on modified-Delphi technique and the Sheffield Elicitation Framework), was followed to identify risk transition thresholds. This included a multi-round elicitation process with two rounds of independent anonymous threshold judgement, and a final consensus discussion. Further information on methods and underlying literature can be found in Chapter 7 Supplementary Material.

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BOX SPM.1: Shared Socioeconomic Pathways (SSPs)

In this report the implications of future socio-economic development on climate change mitigation, adaptation and land-use are explored using shared socio-economic pathways (SSPs). The SSPs span a range of challenges to climate change mitigation and adaptation.

- SSP1 includes a peak and decline in population (~7 billion in 2100), high income and reduced inequalities, effective land-use regulation, less resource intensive consumption, including food produced in low-GHG emission systems and lower food waste, free trade and environmentally-friendly technologies and lifestyles. Relative to other pathways, SSP1 has low challenges to mitigation and low challenges to adaptation (i.e., high adaptive capacity).
- SSP2 includes medium population growth (~9 billion in 2100), medium income; technological progress, production and consumption patterns are a continuation of past trends, and only gradual reduction in inequality occurs. Relative to other pathways, SSP2 has medium challenges to mitigation and medium challenges to adaptation (i.e., medium adaptive capacity).

- SSP3 includes high population (~13 billion in 2100), low income and continued inequalities, material-intensive consumption and production, barriers to trade, and slow rates of technological change. Relative to other pathways, SSP3 has high challenges to mitigation and high challenges to adaptation (i.e., low adaptive capacity).
- SSP4 includes medium population growth (~9 billion in 2100), medium income, but significant inequality within and across regions. Relative to other pathways, SSP4 has low challenges to mitigation, but high challenges to adaptation (i.e., low adaptive capacity).
- SSP5 includes a peak and decline in population (~7 billion in 2100), high income, reduced inequalities, and free trade. This pathway includes resource-intensive production, consumption and lifestyles. Relative to other pathways, SSP5 has high challenges to mitigation, but low challenges to adaptation (i.e., high adaptive capacity).

The SSPs can be combined with Representative Concentration Pathways (RCPs) which imply different levels of mitigation, with implications for adaptation. Therefore, SSPs can be consistent with different levels of global mean surface temperature rise as projected by different SSP-RCP combinations. However, some SSP-RCP combinations are not possible; for instance RCP2.6 and lower levels of future global mean surface temperature rise (e.g., 1.5ºC) are not possible in SSP3 in modelled pathways. {1.2.2, Cross-Chapter Box 1 in Chapter 1, 6.1.4, Cross-Chapter Box 9 in Chapter 6}

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A 5. Climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (*high confidence*). Increasing impacts on land are projected under all future GHG emission scenarios (*high confidence*). Some regions will face higher risks, while some regions will face risks previously not anticipated (*high confidence*). Cascading risks with impacts on multiple systems and sectors also vary across regions (*high confidence*). {2.2, 3.5, 4.2, 4.4, 4.7, 5.1, 5.2, 5.8, 6.1, 7.2, 7.3, Cross-Chapter Box 9 in Chapter 6, Figure SPM.2}

A5.1. With increasing warming, the frequency, intensity and duration of heat related events including heat waves are projected to continue to increase through the 21st century (*high confidence*). The frequency and intensity of droughts are projected to increase particularly in the Mediterranean region and southern Africa (*medium confidence*). The frequency and intensity of extreme rainfall events are projected to increase in many regions (*high confidence*). {2.2.5, 3.5.1, 4.2.3, 5.2}

A5.2. With increasing warming, climate zones are projected to further shift poleward in the middle and high latitudes (*high confidence*). In high-latitude regions, warming is projected to increase disturbance in boreal forests, including drought, wildfire, and pest outbreaks (*high confidence*). In tropical regions, under medium and high GHG emissions scenarios, warming is projected to result in the emergence of unprecedented[29] climatic conditions by the mid to late 21st century (*medium confidence*). {2.2.4, 2.2.5, 2.5.3, 4.3.2}

A5.3. Current levels of global warming are associated with moderate risks from increased dryland water scarcity, soil erosion, vegetation loss, wildfire damage, permafrost thawing, coastal degradation and tropical crop yield decline (*high confidence*). Risks, including cascading risks, are projected to become increasingly severe with increasing temperatures. At around 1.5°C of global warming the risks from dryland water scarcity, wildfire damage, permafrost degradation and food supply instabilities are projected to be high (*medium confidence*). At around 2°C of global warming the risk from permafrost degradation and food supply instabilities are projected to be very high (*medium confidence*). Additionally, at around 3°C of global warming risk from vegetation loss, wildfire damage, and dryland water scarcity are also projected to be very high (*medium confidence*). Risks from droughts, water stress, heat related events such as heatwaves and habitat degradation simultaneously increase between 1.5°C and 3°C warming (*low confidence*). {Figure SPM.2, 7.2.2, Cross-Chapter Box 9 in Chapter 6, Chapter 7 supplementary material}

A5.4. The stability of food supply[30] is projected to decrease as the magnitude and frequency of extreme weather events that disrupt food chains increases (*high confidence*). Increased atmospheric CO_2 levels can also lower the nutritional quality of crops (*high confidence*). In SSP2, global crop and economic models project a median increase of 7.6% (range of 1 to 23%) in cereal prices in 2050 due to climate change (RCP6.0), leading to higher food prices and increased risk of food insecurity and hunger (*medium confidence*). The most vulnerable people will be more severely affected (*high confidence*). {5.2.3, 5.2.4, 5.2.5, 5.8.1, 7.2.2.2, 7.3.1}

A5.5. In drylands, climate change and desertification are projected to cause reductions in crop and livestock productivity (*high confidence*), modify the plant species mix and reduce biodiversity (*medium confidence*). Under SSP2, the dryland population vulnerable to water stress, drought intensity and habitat degradation is projected to reach 178 million people by 2050 at 1.5°C warming, increasing to 220 million people at 2°C warming, and 277 million people at 3°C warming (*low confidence*). {3.5.1, 3.5.2, 3.7.3}

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[29] Unprecedented climatic conditions are defined in this report as not having occurred anywhere during the 20th century. They are characterized by high temperature with strong seasonality and shifts in precipitation. In the literature assessed, the effect of climatic variables other than temperature and precipitation were not considered.

[30] The supply of food is defined in this report as encompassing availability and access (including price). Food supply instability refers to variability that influences food security through reducing access.

A5.6. Asia and Africa[31] are projected to have the highest number of people vulnerable to increased desertification. North America, South America, Mediterranean, southern Africa and central Asia may be increasingly affected by wildfire. The tropics and subtropics are projected to be most vulnerable to crop yield decline. Land degradation resulting from the combination of sea level rise and more intense cyclones is projected to jeopardise lives and livelihoods in cyclone prone areas (*very high confidence*). Within populations, women, the very young, elderly and poor are most at risk (*high confidence*). {3.5.1, 3.5.2, 4.4, Table 4.1, 5.2.2, 7.2.2, Cross-Chapter Box 3 in Chapter 2}

A5.7. Changes in climate can amplify environmentally induced migration both within countries and across borders (*medium confidence*), reflecting multiple drivers of mobility and available adaptation measures (*high confidence*). Extreme weather and climate or slow-onset events may lead to increased displacement, disrupted food chains, threatened livelihoods (*high confidence*), and contribute to exacerbated stresses for conflict (*medium confidence*). {3.4.2, 4.7.3, 5.2.3, 5.2.4, 5.2.5, 5.8.2, 7.2.2, 7.3.1}

A5.8 Unsustainable land management has led to negative economic impacts (*high confidence*). Climate change is projected to exacerbate these negative economic impacts (*high confidence*). {4.3.1, 4.4.1, 4.7, 4.8.5, 4.8.6, 4.9.6, 4.9.7, 4.9.8, 5.2, 5.8.1, 7.3.4, 7.6.1, Cross-Chapter Box 10 in Chapter 7}

A6. The level of risk posed by climate change depends both on the level of warming and on how population, consumption, production, technological development, and land management patterns evolve (*high confidence*). Pathways with higher demand for food, feed, and water, more resource-intensive consumption and production, and more limited technological improvements in agriculture yields result in higher risks from water scarcity in drylands, land degradation, and food insecurity (*high confidence*). {5.1.4, 5.2.3, 6.1.4, 7.2, Cross-Chapter Box 9 in Chapter 6, Figure SPM.2b}

A6.1. Projected increases in population and income, combined with changes in consumption patterns, result in increased demand for food, feed, and water in 2050 in all SSPs (*high confidence*). These changes, combined with land management practices, have implications for land-use change, food insecurity, water scarcity, terrestrial GHG emissions, carbon sequestration potential, and biodiversity (*high confidence*). Development pathways in which incomes increase and the demand for land conversion is reduced, either through reduced

[31] West Africa has a high number of people vulnerable to increased desertification and yield decline. North Africa is vulnerable to water scarcity.

agricultural demand or improved productivity, can lead to reductions in food insecurity (*high confidence*). All assessed future socio-economic pathways result in increases in water demand and water scarcity (*high confidence*). SSPs with greater cropland expansion result in larger declines in biodiversity (*high confidence*). {6.1.4}

A6.2. Risks related to water scarcity in drylands are lower in pathways with low population growth, less increase in water demand, and high adaptive capacity, as in Shared Socio-economic Pathway 1 (SSP1) (See BOX SPM.1). In these scenarios the risk from water scarcity in drylands is moderate even at global warming of 3°C (*low confidence*). By contrast, risks related to water scarcity in drylands are greater for pathways with high population growth, high vulnerability, higher water demand, and low adaptive capacity, such as SSP3. In SSP3 the transition from moderate to high risk occurs between 1.2°C and 1.5°C (*medium confidence*). {7.2, Figure SPM.2b, BOX SPM.1}

A6.3. Risks related to climate change driven land degradation are higher in pathways with a higher population, increased land-use change, low adaptive capacity and other barriers to adaptation (e.g., SSP3). These scenarios result in more people exposed to ecosystem degradation, fire, and coastal flooding (*medium confidence*). For land degradation, the projected transition from moderate to high risk occurs for global warming between 1.8°C and 2.8°C in SSP1 (*low confidence*) and between 1.4°C and 2°C in SSP3 (*medium confidence*). The projected transition from high to very high risk occurs between 2.2°C and 2.8°C for SSP3 (*medium confidence*). {4.4, 7.2, Figure SPM.2b}

A6.4. Risks related to food security are greater in pathways with lower income, increased food demand, increased food prices resulting from competition for land, more limited trade, and other challenges to adaptation (e.g., SSP3) (*high confidence*). For food security, the transition from moderate to high risk occurs for global warming between 2.5°C and 3.5°C in SSP1 (*medium confidence*) and between 1.3°C and 1.7°C in SSP3 (*medium confidence*). The transition from high to very high risk occurs between 2°C and 2.7°C for SSP3 (*medium confidence*). {7.2, Figure SPM.2b}

A6.5 Urban expansion is projected to lead to conversion of cropland leading to losses in food production (*high confidence*). This can result in additional risks to the food system. Strategies for reducing these impacts can include urban and peri-urban food production and management of urban expansion, as well as urban green infrastructure that can reduce climate risks in cities[32] (*high confidence*). {4.9.1, 5.5, 5.6, 6.3, 6.4, 7.5.6} (Figure SPM3)

[32] The land systems considered in this report do not include urban ecosystem dynamics in detail. Urban areas, urban expansion, and other urban processes and their relation to land-related processes are extensive, dynamic, and complex.

B. Adaptation and mitigation response options

B 1. Many land-related responses that contribute to climate change adaptation and mitigation can also combat desertification and land degradation and enhance food security. The potential for land-related responses and the relative emphasis on adaptation and mitigation is context specific, including the adaptive capacities of communities and regions. While land-related response options can make important contributions to adaptation and mitigation, there are some barriers to adaptation and limits to their contribution to global mitigation. (*very high confidence*) {2.6, 4.8, 5.6, 6.1, 6.3, 6.4, Figure SPM.3}

B1.1. Some land-related actions are already being taken that contribute to climate change adaptation, mitigation and sustainable development. The response options were assessed across adaptation, mitigation, combating desertification and land degradation, food security and sustainable development, and a select set of options deliver across all of these challenges. These options include, but are not limited to, sustainable food production, improved and sustainable forest management, soil organic carbon management, ecosystem conservation and land restoration, reduced deforestation and degradation, and reduced food loss and waste (*high confidence*). These response options require integration of biophysical, socioeconomic and other enabling factors. {6.3, 6.4.5; Cross-Chapter Box 10 in Chapter 7}

B1.2. While some response options have immediate impact, others take decades to deliver measurable results. Examples of response options with immediate impacts include the conservation of high-carbon ecosystems such as peatlands, wetlands, rangelands, mangroves and forests. Examples that provide multiple ecosystem services and functions, but take more time to deliver, include afforestation and reforestation as well as the restoration of high-carbon ecosystems, agroforestry, and the reclamation of degraded soils (*high confidence*). {6.4.5; Cross-Chapter Box 10 in Chapter 7}

B1.3. The successful implementation of response options depends on consideration of local environmental and socio-economic conditions. Some options such as soil carbon management are potentially applicable across a broad range of land use types, whereas the efficacy of land management practices relating to organic soils, peatlands and wetlands, and those linked to freshwater resources, depends on specific agro-ecological conditions (*high confidence*). Given

Several issues addressed in this report such as population, growth, incomes, food production and consumption, food security, and diets have close relationships with these urban processes. Urban areas are also the setting of many processes related to land-use change dynamics, including loss of ecosystem functions and services, that can lead to increased disaster risk. Some specific urban issues are assessed in this report.

the site-specific nature of climate change impacts on food system components and wide variations in agroecosystems, adaptation and mitigation options and their barriers are linked to environmental and cultural context at regional and local levels *(high confidence).* Achieving land degradation neutrality depends on the integration of multiple responses across local, regional and national scales, multiple sectors including agriculture, pasture, forest and water (*high confidence*). {4.8, 6.2, 6.3, 6.4.4}

B1.4. Land based options that deliver carbon sequestration in soil or vegetation, such as afforestation, reforestation, agroforestry, soil carbon management on mineral soils, or carbon storage in harvested wood products do not continue to sequester carbon indefinitely (*high confidence*). Peatlands, however, can continue to sequester carbon for centuries (*high confidence*). When vegetation matures or when vegetation and soil carbon reservoirs reach saturation, the annual removal of CO_2 from the atmosphere declines towards zero, while carbon stocks can be maintained (*high confidence*). However, accumulated carbon in vegetation and soils is at risk from future loss (or sink reversal) triggered by disturbances such as flood, drought, fire, or pest outbreaks, or future poor management (*high confidence*). {6.4.1}

B 2. Most of the response options assessed contribute positively to sustainable development and other societal goals (*high confidence*). Many response options can be applied without competing for land and have the potential to provide multiple co-benefits (*high confidence*). A further set of response options has the potential to reduce demand for land, thereby enhancing the potential for other response options to deliver across each of climate change adaptation and mitigation, combating desertification and land degradation, and enhancing food security (*high confidence*). {4.8, 6.2, 6.3.6, 6.4.3; Figure SPM.3}

B2.1. A number of land management options, such as improved management of cropland and grazing lands, improved and sustainable forest management, and increased soil organic carbon content, do not require land use change and do not create demand for more land conversion (*high confidence*). Further, a number of response options such as increased food productivity, dietary choices and food losses and waste reduction, can reduce demand for land conversion, thereby potentially freeing land and creating opportunities for enhanced implementation of other response options (*high confidence*). Response options that reduce competition for land are possible and are applicable at different scales, from farm to regional (*high confidence*). {4.8, 6.3.6, 6.4; Figure SPM.3}

B2.2. A wide range of adaptation and mitigation responses, e.g. preserving and restoring natural ecosystems such as peatland, coastal lands and forests, biodiversity conservation, reducing competition for land, fire management, soil management, and most risk management options (e.g. use of local seeds, disaster risk management, risk sharing instruments) have the potential to make positive contributions to sustainable development, enhancement of ecosystem functions and services and other societal goals (*medium confidence*). Ecosystem-based adaptation can, in some contexts, promote nature conservation while alleviating poverty and even provide co-benefits by removing greenhouse gases and protecting livelihoods (e.g. mangroves) (*medium confidence*). {6.4.3, 7.4.6.2}

B2.3. Most of the land management-based response options that do not increase competition for land, and almost all options based on value chain management (e.g. dietary choices, reduced post-harvest losses, reduced food waste) and risk management, can contribute to eradicating poverty and eliminating hunger while promoting good health and wellbeing, clean water and sanitation, climate action, and life on land (*medium confidence*). {6.4.3}

B 3. Although most response options can be applied without competing for available land, some can increase demand for land conversion (*high confidence*). At the deployment scale of several $GtCO_2yr^{-1}$, this increased demand for land conversion could lead to adverse side effects for adaptation, desertification, land degradation and food security (*high confidence*). If applied on a limited share of total land and integrated into sustainably managed landscapes, there will be fewer adverse side-effects and some positive co-benefits can be realised (*high confidence*). {4.5, 6.2, 6.4; Cross-Chapter Box 7 in Chapter 6; Figure SPM.3}

B3.1. If applied at scales necessary to remove CO_2 from the atmosphere at the level of several $GtCO_2yr^{-1}$, afforestation, reforestation and the use of land to provide feedstock for bioenergy with or without carbon capture and storage, or for biochar, could greatly increase demand for land conversion (*high confidence*). Integration into sustainably managed landscapes at appropriate scale can ameliorate adverse impacts (*medium confidence*). Reduced grassland conversion to croplands, restoration and reduced conversion of peatlands, and restoration and reduced conversion of coastal wetlands affect smaller land areas globally, and the impacts on land use change of these options are smaller or more variable (*high confidence*). {Cross-Chapter Box 7 in Chapter 6; 6.4; Figure SPM.3}

B3.2. While land can make a valuable contribution to climate change mitigation, there are limits to the deployment of land-based mitigation measures such as bioenergy crops or afforestation. Widespread use at the scale of several millions of km^2 globally could increase risks for desertification, land degradation, food security and sustainable development (*medium confidence*). Applied on a limited share of total land, land-based mitigation measures that displace other land uses have fewer adverse side-effects and can have positive co-benefits for adaptation, desertification, land degradation or food security. (*high confidence*) {4.2, 4.5, 6.4; Cross-Chapter Box 7 in Chapter 6, Figure SPM3}

B3.3 The production and use of biomass for bioenergy can have co-benefits, adverse side effects, and risks for land degradation, food insecurity, GHG emissions and other environmental and sustainable development goals (*high confidence*). These impacts are context specific and depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime, and other land-demanding response options can have a similar range of consequences (*high confidence*). The use of residues and organic waste as bioenergy feedstock can mitigate land use change pressures associated with bioenergy deployment, but residues are limited and the removal of residues that would otherwise be left on the soil could lead to soil degradation (*high confidence*). {2.6.1.5; Cross-Chapter Box 7 in Chapter 6; Figure SPM3}

B3.4. For projected socioeconomic pathways with low population, effective land-use regulation, food produced in low-GHG emission systems and lower food loss and waste (SSP1), the transition from low to moderate risk to food security, land degradation and water scarcity in dry lands occur between 1 and 4 million km^2 of bioenergy or BECCS (*medium confidence*). By contrast, in pathways with high population, low income and slow rates of technological change (SSP3), the transition from low to moderate risk occurs between 0.1 and 1 million km^2 (*medium confidence*). {6.4; Cross-Chapter Box 7 in Chapter 6; Table SM7.6; Box SPM1}

B 4. Many activities for combating desertification can contribute to climate change adaptation with mitigation co-benefits, as well as to halting biodiversity loss with sustainable development co-benefits to society (*high confidence*). Avoiding, reducing and reversing desertification would enhance soil fertility, increase carbon storage in soils and biomass, while benefitting agricultural productivity and food security (*high confidence*). Preventing desertification is preferable to attempting to restore degraded land due to the potential for residual risks and maladaptive outcomes (*high confidence*). {3.6.1, 3.6.2, 3.6.3, 3.6.4, 3.7.1, 3.7.2}

B4.1. Solutions that help adapt to and mitigate climate change while contributing to combating desertification are site and regionally specific and include *inter alia*: water harvesting and micro-irrigation, restoring degraded lands using drought-resilient ecologically appropriate plants; agroforestry and other agroecological and ecosystem-based adaptation practices (*high confidence*). {3.3, 3.6.1, 3.7.2, 3.7.5, 5.2, 5.6}

B4.2. Reducing dust and sand storms and sand dune movement can lessen the negative effects of wind erosion and improve air quality and health (*high confidence*). Depending on water availability and soil conditions, afforestation, tree planting and ecosystem restoration programs, which aim for the creation of windbreaks in the form of "green walls", and "green dams" using native and other climate resilient tree species with low water needs, can reduce sand storms, avert wind erosion, and contribute to carbon sinks, while improving micro-climates, soil nutrients and water retention (*high confidence*). {3.3, 3.6.1, 3.7.2, 3.7.5}

B4.3. Measures to combat desertification can promote soil carbon sequestration (*high confidence*). Natural vegetation restoration and tree planting on degraded land enriches, in the long term, carbon in the topsoil and subsoil (*medium confidence*). Modelled rates of carbon sequestration following the adoption of conservation agriculture practices in drylands depend on local conditions (*medium confidence*). If soil carbon is lost, it may take a prolonged period of time for carbon stocks to recover. {3.1.4, 3.3, 3.6.1, 3.6.3, 3.7.1, 3.7.2}

B4.4 Eradicating poverty and ensuring food security can benefit from applying measures promoting land degradation neutrality (including avoiding, reducing and reversing land degradation) in rangelands, croplands and forests, which contribute to combating desertification, while mitigating and adapting to climate change within the framework of sustainable development. Such measures include avoiding deforestation and locally suitable practices including management of rangeland and forest fires (*high confidence*). {3.4.2, 3.6.1, 3.6.2, 3.6.3, 4.8.5}.

B4.5 Currently there is a lack of knowledge of adaptation limits and potential maladaptation to combined effects of climate change and desertification. In the absence of new or enhanced adaptation options, the potential for residual risks and maladaptive outcomes is high (*high confidence*). Even when solutions are available, social, economic and institutional constraints could pose barriers to their implementation (*medium confidence*). Some adaptation options can become maladaptive due to their environmental impacts, such as irrigation causing soil salinisation or over extraction leading to ground-water depletion (*medium confidence*). Extreme forms of desertification can lead to the complete loss of land productivity, limiting adaptation options or reaching the limits to adaptation (*high confidence*). {Executive Summary Chapter 3, 3.6.4, 3.7.5, 7.4.9}

B4.6. Developing, enabling and promoting access to cleaner energy sources and technologies can contribute to adaptation and mitigating climate change and combating desertification and forest degradation through decreasing the use of traditional biomass for energy while increasing the diversity of energy supply (*medium confidence*). This can have socioeconomic and health benefits, especially for women and children. (*high confidence*). The efficiency of wind and solar energy infrastructures is recognized; the efficiency can be affected in some regions by dust and sand storms (*high confidence*). {3.5.3, 3.5.4, 4.4.4, 7.5.2, Cross-Chapter Box 12 in Chapter 7}

B 5. Sustainable land management[33], including sustainable forest management[34], can prevent and reduce land degradation, maintain land productivity, and sometimes reverse the adverse impacts of climate change on land degradation (*very high confidence*). It can also contribute to mitigation and adaptation (*high confidence*). Reducing and reversing land degradation, at scales from individual farms to entire watersheds, can provide cost effective, immediate, and long-term benefits to communities and support several Sustainable Development Goals (SDGs) with co-benefits for adaptation (*very high confidence*) and mitigation (*high confidence*). Even with implementation of sustainable land management, limits to adaptation can be exceeded in some situations (*medium confidence*). {1.3.2, 4.1.5, 4.8, Table 4.2}

B5.1. Land degradation in agriculture systems can be addressed through sustainable land management, with an ecological and socioeconomic focus, with co-benefits for climate change adaptation. Management options that reduce vulnerability to soil erosion and nutrient loss include growing green manure crops and cover crops, crop residue retention, reduced/zero tillage, and maintenance of ground cover through improved grazing management (*very high confidence*). {4.8}

B5.2. The following options also have mitigation co-benefits. Farming systems such as agroforestry, perennial pasture phases and use of perennial grains, can substantially reduce erosion and nutrient leaching while building soil carbon (*high confidence*). The global sequestration potential of cover crops would be about 0.44 +/- 0.11 $GtCO_2$ yr^{-1} if applied to 25% of global cropland (*high confidence*). The application of certain biochars can sequester carbon (*high confidence*), and improve soil conditions in some soil types/climates (*medium confidence*). {4.8.1.1, 4.8.1.3, 4.9.2, 4.9.5, 5.5.1, 5.5.4; Cross-Chapter Box 6 in Chapter 5}

B5.3. Reducing deforestation and forest degradation lowers GHG emissions (*high confidence*), with an estimated technical mitigation potential of 0.4–5.8 $GtCO_2$ yr^{-1}. By providing long-term livelihoods for communities, sustainable forest management can reduce the extent of

[33] Sustainable land management is defined in this report as the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions. Examples of options include inter alia agroecology (including agroforestry), conservation agriculture and forestry practices, crop and forest species diversity, appropriate crop and forest rotations, organic farming, integrated pest management, the conservation of pollinators, rain water harvesting, range and pasture management, and precision agriculture systems.

[34] Sustainable forest management is defined in this report as the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality, and their potential to fulfill now and in the future, relevant ecological, economic and social functions at local, national and global levels and that does not cause damage to other ecosystems.

forest conversion to non-forest uses (e.g., cropland or settlements) (*high confidence*). Sustainable forest management aimed at providing timber, fibre, biomass, non-timber resources and other ecosystem functions and services, can lower GHG emissions and can contribute to adaptation. (*high confidence*). {2.6.1.2, 4.1.5, 4.3.2, 4.5.3, 4.8.1.3, 4.8.3, 4.8.4}

B5.4. Sustainable forest management can maintain or enhance forest carbon stocks, and can maintain forest carbon sinks, including by transferring carbon to wood products, thus addressing the issue of sink saturation (*high confidence*). Where wood carbon is transferred to harvested wood products, these can store carbon over the long-term and can substitute for emissions-intensive materials reducing emissions in other sectors (*high confidence*). Where biomass is used for energy, e.g., as a mitigation strategy, the carbon is released back into the atmosphere more quickly (*high confidence*). {2.6.1, 2.7, 4.1.5, 4.8.4, 6.4.1, Figure SPM.3, Cross-Chapter Box 7 in Chapter 6}

B5.5. Climate change can lead to land degradation, even with the implementation of measures intended to avoid, reduce or reverse land degradation (*high confidence*). Such limits to adaptation are dynamic, site specific and are determined through the interaction of biophysical changes with social and institutional conditions (*very high confidence*). In some situations, exceeding the limits of adaptation can trigger escalating losses or result inundesirable transformational changes (*medium confidence)*, such as forced migration (*low confidence*), conflicts (*low confidence*) or poverty (*medium confidence*). Examples of climate change induced land degradation that may exceed limits to adaptation include coastal erosion exacerbated by sea level rise where land disappears (*high confidence*), thawing of permafrost affecting infrastructure and livelihoods (*medium confidence*), and extreme soil erosion causing loss of productive capacity (*medium confidence*). {4.7, 4.8.5, 4.8.6, 4.9.6, 4.9.7, 4.9.8}

B 6. Response options throughout the food system, from production to consumption, including food loss and waste, can be deployed and scaled up to advance adaptation and mitigation (*high confidence*). The total technical mitigation potential from crop and livestock activities, and agroforestry is estimated as 2.3-9.6 $GtCO_2e.yr^{-1}$ by 2050 (*medium confidence)*. The total technical mitigation potential of dietary changes is estimated as 0.7-8 $GtCO_2$e.yr-1 by 2050 (*medium confidence*). {5.3, 5.5, 5.6}

B6.1. Practices that contribute to climate change adaptation and mitigation in cropland include increasing soil organic matter, erosion control, improved fertiliser management, improved crop management, for example, paddy rice management, and use ofvarieties and genetic improvements for heat and drought tolerance. For livestock, options include better grazing land management, improved manure management, higher-quality feed, and use of breeds and genetic improvement. Different farming and pastoral systems can achieve reductions in the emissions intensity of livestock products. Depending on the farming and pastoral systems and level of development, reductions in the emissions intensity of livestock products may lead to absolute reductions in GHG emissions (*medium confidence*). Many livestock related options can enhance the adaptive capacity of rural communities, in particular, of smallholders and pastoralists. Significant synergies exist between adaptation and mitigation, for example through sustainable land management approaches (*high confidence*). {4.8, 5.3.3, 5.5.1, 5.6}

B6.2. Diversification in the food system (e.g., implementation of integrated production systems, broad-based genetic resources, and diets) can reduce risks from climate change (*medium confidence*). Balanced diets, featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, present major opportunities for adaptation and mitigation while generating significant co-benefits in terms of human health (*high confidence*). By 2050, dietary changes could free several Mkm^2 (*medium confidence*) of land and provide a technical mitigation potential of 0.7 to 8.0 $GtCO_2e\ yr^{-1}$, relative to business as usual projections (*high confidence*). Transitions towards low-GHG emission diets may be influenced by local production practices, technical and financial barriers and associated livelihoods and cultural habits (*high confidence*). {5.3, 5.5.2, 5.5, 5.6}

B6.3. Reduction of food loss and waste can lower GHG emissions and contribute to adaptation through reduction in the land area needed for food production (*medium confidence*). During 2010-2016, global food loss and waste contributed 8-10% of total anthropogenic GHG emissions (*medium confidence*). Currently, 25-30% of total food produced is lost or wasted (*medium confidence*). Technical options such as improved harvesting techniques, on-farm storage, infrastructure, transport, packaging, retail and education can reduce food loss and waste across the supply chain. Causes of food loss and waste differ substantially between developed and developing countries, as well as between regions (*medium confidence*). {5.5.2} By 2050, reduced food loss and waste can free several Mkm^2 of land (*low confidence).* {6.3.6}

B 7. Future land use depends, in part, on the desired climate outcome and the portfolio of response options deployed (*high confidence*). All assessed modelled pathways that limit warming to 1.5ºC or well below 2°C require land-based mitigation and land-use change, with most including different combinations of reforestation, afforestation, reduced deforestation, and bioenergy (*high confidence*). A small number of modelled pathways achieve 1.5ºC with reduced land conversion (*high confidence*) and, thus, reduced consequences for desertification, land degradation, and food security (*medium confidence*). {2.6, 6.4, 7.4, 7.6; Cross-Chapter Box 9 in Chapter 6; Figure SPM.4}

B7.1. Modelled pathways limiting global warming to 1.5ºC[35] include more land-based mitigation than higher warming level pathways (*high confidence*), but the impacts of climate change on land systems in these pathways are less severe (*medium confidence*). {2.6, 6.4, 7.4, Cross-Chapter Box 9 in Chapter 6, Figure SPM.2, Figure SPM.4}

B7.2. Modelled pathways limiting global warming to 1.5°C and 2ºC project a 2 million km^2 reduction to a 12 million km^2 increase in forest area in 2050 relative to 2010 (*medium confidence*). 3ºC pathways project lower forest areas, ranging from a 4 million km^2 reduction to a 6 million km^2 increase (*medium confidence*). {2.5, 6.3, 7.3, 7.5; Cross-Chapter Box 9 in Chapter 6; Figure SPM.3, Figure SPM.4}

B7.3. The land area needed for bioenergy in modelled pathways varies significantly depending on the socioeconomic pathway, the warming level, and the feedstock and production system used (*high confidence*). Modelled pathways limiting global warming to 1.5°C use up to 7 million km^2 for bioenergy in 2050; bioenergy land area is smaller in 2°C (0.4 to 5 million km^2) and 3°C pathways (0.1 to 3 million km^2) (*medium confidence*). Pathways with large levels of land conversion may imply adverse side-effects impacting water scarcity, biodiversity, land degradation, desertification, and food security, if not adequately and carefully managed, whereas best practice implementation at appropriate scales can have co-benefits, such as management of dryland salinity, enhanced biocontrol and biodiversity and enhancing soil carbon sequestration (*high confidence*). {2.6, 6.1, 6.4, 7.2; Cross-Chapter Box 7 in Chapter 6, Figure SPM.3}

B7.4. Most mitigation pathways include substantial deployment of bioenergy technologies. A small number of modelled pathways limit warming to 1.5ºC with reduced dependence on bioenergy and BECCS (land area below <1 million km^2 in 2050) and other carbon dioxide removal (CDR) options (*high confidence*). These pathways have even more reliance on rapid and far-reaching transitions in energy, land, urban systems and infrastructure, and on behavioural and lifestyle changes compared to other 1.5°C pathways. {2.6.2, 5.5.1, 6.4, Cross-Chapter Box 7 in Chapter 6

B7.5. These modelled pathways do not consider the effects of climate change on land or CO_2 fertilisation. In addition, these pathways include only a subset of the response options assessed in this report (*high confidence*); the inclusion of additional response options in models could reduce the projected need for bioenergy or CDR that increases the demand for land. {6.4.4, Cross-Chapter Box 9 in Chapter 6}

[35] In this report references to pathways limiting global warming to a particular level are based on a 66% probability of staying below that temperature level in 2100 using the MAGICC model.

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel A shows response options that can be implemented without or with limited competition for land, including some that have the potential to reduce the demand for land. Co-benefits and adverse side effects are shown quantitatively based on the high end of the range of potentials assessed. Magnitudes of contributions are categorised using thresholds for positive or negative impacts. Letters within the cells indicate confidence in the magnitude of the impact relative to the thresholds used (see legend). Confidence in the direction of change is generally higher.

	Response options based on land management	Mitigation	Adaptation	Desertification	Land Degradation	Food Security	Cost
Agriculture	Increased food productivity	Large (L)	Large (M)	Large (L)	Large (M)	Large (H)	no data
Agriculture	Agro-forestry	Large (M)	Large (M)	Large (M)	Large (M)	Large (L)	Low cost
Agriculture	Improved cropland management	Moderate (M)	Large (L)	Large (L)	Large (L)	Large (L)	Medium cost
Agriculture	Improved livestock management	Moderate (M)	Moderate (L)	Moderate (L)	Large (L)	Large (L)	High cost
Agriculture	Agricultural diversification	Small (L)	Large (L)	Moderate (L)	Large (M)	Large (L)	Low cost
Agriculture	Improved grazing land management	Moderate (M)	Moderate (L)	Moderate (L)	Large (L)	Large (L)	no data
Agriculture	Integrated water management	Moderate (L)	Large (L)	Small (L)	Small (L)	Large (L)	Medium cost
Agriculture	Reduced grassland conversion to cropland	Moderate (L)	no data	Small (L)	Small (L)	- Negative moderate (L)	Low cost
Forests	Forest management	Moderate (M)	Large (L)	Large (L)	Large (L)	Moderate (L)	Medium cost
Forests	Reduced deforestation and forest degradation	Large (H)	Large (L)	Large (L)	Large (L)	Small (L)	Medium cost
Soils	Increased soil organic carbon content	Large (H)	Large (L)	Large (M)	Large (M)	Large (L)	Medium cost
Soils	Reduced soil erosion	Variable (L)	Large (L)	Large (M)	Large (M)	Large (L)	Medium cost
Soils	Reduced soil salinization	no data	Moderate (L)	Moderate (L)	Moderate (L)	Moderate (L)	Medium cost
Soils	Reduced soil compaction	no data	Small (L)	no data	Large (L)	Moderate (L)	Low cost
Other ecosystems	Fire management	Large (M)	Moderate (M)	Large (M)	Large (M)	Moderate (L)	Low cost
Other ecosystems	Reduced landslides and natural hazards	Small (L)	Large (L)	Small (L)	Large (L)	Moderate (L)	no data
Other ecosystems	Reduced pollution including acidification	Variable (M)	Moderate (M)	Moderate (L)	Moderate (L)	Large (L)	no data
Other ecosystems	Restoration & reduced conversion of coastal wetlands	Large (M)	Large (L)	Negligible (M)	Small (M)	Variable (L)	no data
Other ecosystems	Restoration & reduced conversion of peatlands	Moderate (M)	no data	na	Moderate (M)	- Negative moderate (L)	Low cost
	Response options based on value chain management						
Demand	Reduced post-harvest losses	Large (H)	Large (M)	Moderate (L)	Moderate (L)	Large (H)	no data
Demand	Dietary change	Large (H)	no data	Moderate (L)	Large (H)	Large (H)	no data
Demand	Reduced food waste (consumer or retailer)	Large (H)	no data	Moderate (L)	Large (M)	Large (M)	no data
Supply	Sustainable sourcing	no data	Moderate (L)	no data	Large (L)	Moderate (L)	no data
Supply	Improved food processing and retailing	Moderate (L)	Large (L)	no data	no data	Large (L)	no data
Supply	Improved energy use in food systems	Moderate (L)	Large (L)	no data	no data	Large (L)	no data
	Response options based on risk management						
Risk	Livelihood diversification	no data	Large (L)	no data	Small (L)	Large (L)	no data
Risk	Management of urban sprawl	no data	Moderate (L)	Small (L)	Small (M)	Moderate (L)	no data
Risk	Risk sharing instruments	Variable (L)	Moderate (L)	no data	Variable (L)	Moderate (L)	Medium cost

Options shown are those for which data are available to assess global potential for three or more land challenges.
The magnitudes are assessed independently for each option and are not additive.

Key for criteria used to define magnitude of impact of each integrated response option

		Mitigation *Gt CO_2-eq yr^{-1}*	Adaptation *Million people*	Desertification *Million km²*	Land Degradation *Million km²*	Food Security *Million people*
Positive	Large	More than 3	Positive for more than 25	Positive for more than 3	Positive for more than 3	Positive for more than 100
Positive	Moderate	0.3 to 3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
Positive	Small	Less than 0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
	Negligible	No effect	No effect	No effect	No effect	No effect
Negative	Small	Less than -0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
Negative	Moderate	-0.3 to -3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
Negative	Large	More than -3	Negative for more than 25	Negative for more than 3	Negative for more than 3	Negative for more than 100

⟷ **Variable**: Can be positive or negative — no data — na not applicable

Confidence level

Indicates confidence in the estimate of magnitude category.

H High confidence
M Medium confidence
L Low confidence

Cost range

See technical caption for cost ranges in US$ tCO_2e^{-1} or US$ ha^{-1}.

- ●●● High cost
- ●● Medium cost
- ● Low cost
- — no data

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel B shows response options that rely on additional land-use change and could have implications across three or more land challenges under different implementation contexts. For each option, the first row (high level implementation) shows a quantitative assessment (as in Panel A) of implications for global implementation at scales delivering CO_2 removals of more than 3 $GtCO_2$ yr^{-1} using the magnitude thresholds shown in Panel A. The red hatched cells indicate an increasing pressure but unquantified impact. For each option, the second row (best practice implementation) shows qualitative estimates of impact if implemented using best practices in appropriately managed landscape systems that allow for efficient and sustainable resource use and supported by appropriate governance mechanisms. In these qualitative assessments, green indicates a positive impact, grey indicates a neutral interaction.

Bioenergy and BECCS

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
H	L			L	● / ●●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts, assuming carbon dioxide removal by BECCS at a scale of 11.3 $GtCO_2$ yr^{-1} in 2050, and noting that bioenergy without CCS can also achieve emissions reductions of up to several $GtCO_2$ yr^{-1} when it is a low carbon energy source {2.7.1.5; 6.4.1.1.5}. Studies linking bioenergy to food security estimate an increase in the population at risk of hunger to up to 150 million people at this level of implementation {6.4.5.1.5}. The red hatched cells for desertification and land degradation indicate that while up to 15 million km_2 of additional land is required in 2100 in 2°C scenarios which will increase pressure for desertification and land degradation, the actual area affected by this additional pressure is not easily quantified {6.4.3.1.5; 6.4.4.1.5}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: The sign and magnitude of the effects of bioenergy and BECCS depends on the scale of deployment, the type of bioenergy feedstock, which other response options are included, and where bioenergy is grown (including prior land use and indirect land use change emissions). For example, limiting bioenergy production to marginal lands or abandoned cropland would have negligible effects on biodiversity, food security, and potentially co-benefits for land degradation; however, the benefits for mitigation could also be smaller. {Table 6.58}

Reforestation and forest restoration

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	M	M	M	M	●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of reforestation and forest restoration (partly overlapping with afforestation) at a scale of 10.1 $GtCO_2$ yr^{-1} removal {6.4.1.1.2}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people; the impact of reforestation is lower {6.4.5.1.2}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: There are co-benefits of reforestation and forest restoration in previously forested areas, assuming small scale deployment using native species and involving local stakeholders to provide a safety net for food security. Examples of sustainable implementation include, but are not limited to, reducing illegal logging and halting illegal forest loss in protected areas, reforesting and restoring forests in degraded and desertified lands {Box6.1C; Table 6.6}.

Afforestation

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	M	M	L	M	●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of afforestation (partly overlapping with reforestation and forest restoration) at a scale of 8.9 $GtCO_2$ yr^{-1} removal {6.4.1.1.2}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people {6.4.5.1.2}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: Afforestation is used to prevent desertification and to tackle land degradation. Forested land also offers benefits in terms of food supply, especially when forest is established on degraded land, mangroves, and other land that cannot be used for agriculture. For example, food from forests represents a safety-net during times of food and income insecurity {6.4.5.1.2}.

Biochar addition to soil

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	—	—	L	L	●●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of afforestation at a scale of 6.6 $GtCO_2$ yr^{-1} removal {6.4.1.1.3}. Dedicated energy crops required for feedstock production could occupy 0.4–2.6 Mkm^2 of land, equivalent to around 20% of the global cropland area, which could potentially have a large effect on food security for up to 100 million people {6.4.5.1.3}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: When applied to land, biochar could provide moderate benefits for food security by improving yields by 25% in the tropics, but with more limited impacts in temperate regions, or through improved water holding capacity and nutrient use efficiency. Abandoned cropland could be used to supply biomass for biochar, thus avoiding competition with food production; 5-9 Mkm^2 of land is estimated to be available for biomass production without compromising food security and biodiversity, considering marginal and degraded land and land released by pasture intensification {6.4.5.1.3}.

Figure SPM.3 Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security.

This Figure is based on an aggregation of information from studies with a wide variety of assumptions about how response options are implemented and the contexts in which they occur. Response options implemented differently at local to global scales could lead to different outcomes. **Magnitude of potential:** For panel A, magnitudes are for the technical potential of response options globally. For each land challenge, magnitudes are set relative to a marker level as follows. For mitigation, potentials are set relative to the approximate potentials for the response options with the largest individual impacts (~3 $GtCO_2$-eq yr^{-1}). The threshold for the “large” magnitude category is set at this level. For adaptation, magnitudes are set relative to the 100 million lives estimated to be affected by climate change and a carbon-based economy between 2010 and 2030. The threshold for the “large” magnitude category represents 25% of this total. For desertification and land degradation, magnitudes are set relative to the lower end of current estimates of degraded land, 10-60 million km^2. The threshold for the “large” magnitude category represents 30% of the lower estimate. For food security, magnitudes are set relative to the approximately 800 million people who are currently undernourished. The threshold for the “large” magnitude category represents 12.5% of this total. For panel B, for the first row (high level implementation) for each response option, the magnitude and thresholds are as defined for panel A. In the second row (best practice implementation) for each response option, the qualitative assessments that are green denote potential positive impacts, and those shown in grey indicate neutral interactions. Increased food production is assumed to be achieved through sustainable intensification rather than through injudicious application of additional external inputs such as agrochemicals. **Levels of confidence:** Confidence in the magnitude category (high, medium or low) into which each option falls for mitigation, adaptation, combating desertification and land degradation, and enhancing food security. *High confidence* means that there is a high level of agreement and evidence in the literature to support the categorisation as high, medium or low magnitude. *Low confidence* denotes that the categorisation of magnitude is based on few studies. *Medium confidence* reflects medium evidence and agreement in the magnitude of response. **Cost ranges:** Cost estimates are based on aggregation of often regional studies and vary in the components of costs that are included. In panel B, cost estimates are not provided for best practice implementation. One coin indicates low cost (<USD10 tCO_2-eq^{-1} or <USD20 ha^{-1}), two coins indicate medium cost (USD10-USD100 tCO_2-eq^{-1} or USD20-USD200 ha^{-1}), and three coins indicate high cost (>USD100 tCO_2-eq^{-1} or USD200 ha^{-1}). Thresholds in USD ha^{-1} are chosen to be comparable, but precise conversions will depend on the response option. **Supporting evidence:** Supporting evidence for the magnitude of the quantitative potential for land management-based response options can be found as follows: for mitigation tables 6.13 to 6.20, with further evidence in Section 2.7.1; for adaptation tables 6.21 to 6.28; for combating desertification tables 6.29 to 6.36, with further evidence in Chapter 3; for combating degradation tables 6.37 to 6.44, with further evidence in Chapter 4; for enhancing food security tables 6.45 to 6.52, with further evidence in Chapter 5. Other synergies and trade-offs not shown here are discussed in Chapter 6. Additional supporting evidence for the qualitative assessments in the second row for each option in panel B can be found in the tables 6.6, 6.55, 6.56 and 6.58, section 6.3.5.1.3, and Box 6.1c.

C. Enabling response options

C 1. Appropriate design of policies, institutions and governance systems at all scales can contribute to land-related adaptation and mitigation while facilitating the pursuit of climate-adaptive development pathways (*high confidence*). Mutually supportive climate and land policies have the potential to save resources, amplify social resilience, support ecological restoration, and foster engagement and collaboration between multiple stakeholders (*high confidence*). {Figure SPM.1, Figure SPM.2, Figure SPM.3; 3.6.2, 3.6.3, 4.8, 4.9.4, 5.7, 6.3, 6.4, 7.2.2, 7.3, 7.4, 7.4.7, 7.4.8, 7.5, 7.5.5, 7.5.6, 7.6.6; Cross-Chapter Box 10 in Chapter 7}

C1.1. Land-use zoning, spatial planning, integrated landscape planning, regulations, incentives (such as payment for ecosystem services), and voluntary or persuasive instruments (such as environmental farm planning, standards and certification for sustainable production, use of scientific, local and indigenous knowledge and collective action), can achieve positive adaptation and mitigation outcomes (*medium confidence*). They can also contribute revenue and provide incentive to rehabilitate degraded lands and adapt to and mitigate climate change in certain contexts (*medium confidence*). Policies promoting the target of land degradation neutrality can also support food security, human wellbeing and climate change adaptation and mitigation (*high confidence*). {Figure SPM.2; 3.4.2, 4.1.6, 4.7, 4.8.5, 5.1.2, 5.7.3, 7.3, 7.4.6, 7.4.7, 7.5}

C1.2. Insecure land tenure affects the ability of people, communities and organisations to make changes to land that can advance adaptation and mitigation (*medium confidence*). Limited recognition of customary access to land and ownership of land can result in increased vulnerability and decreased adaptive capacity (*medium confidence*). Land policies (including recognition of customary tenure, community mapping, redistribution, decentralisation, co-management, regulation of rental markets) can provide both security and flexibility response to climate change (*medium confidence*). {3.6.1, 3.6.2, 5.3, 7.2.4, 7.6.4, Cross-Chapter Box 6 in Chapter 5}

C1.3. Achieving land degradation neutrality will involve a balance of measures that avoid and reduce land degradation, through adoption of sustainable land management, and measures to reverse degradation through rehabilitation and restoration of degraded land. Many interventions to achieve land degradation neutrality commonly also deliver climate change adaptation and mitigation benefits. The pursuit of land degradation neutrality provides impetus to address land degradation and climate change simultaneously (*high confidence*). {4.5.3, 4.8.5, 4.8.7, 7.4.5}

C1.4. Due to the complexity of challenges and the diversity of actors involved in addressing land challenges, a mix of policies, rather than single policy approaches, can deliver improved results in addressing the complex challenges of sustainable land management and climate change (*high confidence*). Policy mixes can strongly reduce the vulnerability and exposure of human and natural systems to climate change (*high confidence*). Elements of such policy mixes may include weather and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, universal access to early warning systems combined with effective contingency plans (*high confidence*). {1.2, 4.8, 4.9.2, 5.3.2, 5.6, 5.6.6, 5.7.2, 7.3.2, 7.4, 7.4.2, 7.4.6, 7.4.7, 7.4.8, 7.5.5, 7.5.6, 7.6.4, Figure SPM.4}

C2. Policies that operate across the food system, including those that reduce food loss and waste and influence dietary choices, enable more sustainable land-use management, enhanced food security and low emissions trajectories (*high confidence*). Such policies can contribute to climate change adaptation and mitigation, reduce land degradation, desertification and poverty as well as improve public health (*high confidence*). The adoption of sustainable land management and poverty eradication can be enabled by improving access to markets, securing land tenure, factoring environmental costs into food, making payments for ecosystem services, and enhancing local and community collective action *(high confidence)*. {1.1.2, 1.2.1, 3.6.3, 4.7.1, 4.7.2, 4.8, 5.5, 6.4, 7.4.6, 7.6.5}

C2.1. Policies that enable and incentivise sustainable land management for climate change adaptation and mitigation include improved access to markets for inputs, outputs and financial services, empowering women and indigenous peoples, enhancing local and community collective action, reforming subsidies and promoting an enabling trade system (*high confidence*). Land restoration and rehabilitation efforts can be more effective when policies support local management of natural resources, while strengthening cooperation between actors and institutions, including at the international level. {3.6.3, 4.1.6, 4.5.4, 4.8.2, 4.8.4, 5.7, 7.2}

C2.2. Reflecting the environmental costs of land-degrading agricultural practices can incentivise more sustainable land management *(high confidence)*. Barriers to the reflection of environmental costs arise from technical difficulties in estimating these costs and those embodied in foods. {3.6.3, 5.5.1, 5.5.2, 5.6.6, 5.7, 7.4.4, Cross-Chapter Box 10 in Chapter 7}

C2.3. Adaptation and enhanced resilience to extreme events impacting food systems can be facilitated by comprehensive risk management, including risk sharing and transfer mechanisms *(high confidence)*. Agricultural diversification, expansion of market access, and preparation for increasing supply chain disruption can support the scaling up of adaptation in food systems (*high confidence)*. {5.3.2, 5.3.3, 5.3.5}

C2.4. Public health policies to improve nutrition, such as increasing the diversity of food sources in public procurement, health insurance, financial incentives, and awareness-raising campaigns, can potentially influence food demand, reduce healthcare costs, contribute to lower GHG emissions and enhance adaptive capacity *(high confidence)*. Influencing demand for food, through promoting diets based on public health guidelines, can enable more sustainable land management and contribute to achieving multiple SDGs *(high confidence)*. {3.4.2, 4.7.2, 5.1, 5.7, 6.3, 6.4}

C 3. Acknowledging co-benefits and trade-offs when designing land and food policies can overcome barriers to implementation (*medium confidence*). Strengthened multilevel, hybrid and cross-sectoral governance, as well as policies developed and adopted in an iterative, coherent, adaptive and flexible manner can maximise co-benefits and minimise trade-offs, given that land management decisions are made from farm level to national scales, and both climate and land policies often range across multiple sectors, departments and agencies (*high confidence*). {Figure SPM.3; 4.8.5, 4.9, 5.6, 6.4, 7.3, 7.4.6, 7.4.8, 7.4.9, 7.5.6, 7.6.2}

C3.1. Addressing desertification, land degradation, and food security in an integrated, coordinated and coherent manner can assist climate resilient development and provides numerous potential co-benefits (*high confidence*). {3.7.5, 4.8, 5.6, 5.7, 6.4, 7.2.2, 7.3.1, 7.3.4, 7.4.7, 7.4.8, 7.5.6, 7.5.5}

C3.2. Technological, biophysical, socio-economic, financial and cultural barriers can limit the adoption of many land-based response options, as can uncertainty about benefits (*high confidence*). Many sustainable land management practices are not widely adopted due to insecure land tenure, lack of access to resources and agricultural advisory services, insufficient and unequal private and public incentives, and lack of knowledge and practical experience (*high confidence*). Public discourse, carefully designed policy interventions, incorporating social learning and market changes can together help reduce barriers to implementation (*medium confidence*). {3.6.1, 3.6.2, 5.3.5, 5.5.2, 5.6, 6.2, 6.4, 7.4, 7.5, 7.6}

C3.3. The land and food sectors face particular challenges of institutional fragmentation and often suffer from a lack of engagement between stakeholders at different scales and narrowly focused policy objectives (*medium confidence*). Coordination with other sectors, such as public health, transportation, environment, water, energy and infrastructure, can increase co-benefits, such as risk reduction and improved health (*medium confidence*). {5.6.3, 5.7, 6.2, 6.4.4, 7.1, 7.3, 7.4.8, 7.6.2, 7.6.3}

C3.4. Some response options and policies may result in trade-offs, including social impacts, ecosystem functions and services damage, water depletion, or high costs, that cannot be well-managed, even with institutional best practices (*medium confidence*). Addressing such trade-offs helps avoid maladaptation (*medium confidence).* Anticipation and evaluation of potential trade-offs and knowledge gaps supports evidence-based policymaking to weigh the costs and benefits of specific responses for different stakeholders (*medium confidence*). Successful management of trade-offs often includes maximising stakeholder input with structured feedback processes, particularly in community-based models, use of innovative fora like facilitated dialogues or spatially explicit mapping, and iterative adaptive management that allows for continuous readjustments in policy as new evidence comes to light (*medium confidence*). {5.3.5, 6.4.2, 6.4.4, 6.4.5, 7.5.6; Cross-Chapter Box 13 in Chapter 7}

C 4. The effectiveness of decision-making and governance is enhanced by the involvement of local stakeholders (particularly those most vulnerable to climate change including indigenous peoples and local communities, women, and the poor and marginalised) in the selection, evaluation, implementation and monitoring of policy instruments for land-based climate change adaptation and mitigation (*high confidence*). Integration across sectors and scales increases the chance of maximising co-benefits and minimising trade-offs (*medium confidence*). {1.4, 3.1, 3.6, 3.7, 4.8, 4.9, 5.1.3, Box 5.1, 7.4, 7.6}

C4.1. Successful implementation of sustainable land management practices requires accounting for local environmental and socio-economic conditions (*very high confidence*). Sustainable land management in the context of climate change is typically advanced by involving all relevant stakeholders in identifying land-use pressures and impacts (such as biodiversity decline, soil loss, over-extraction of groundwater, habitat loss, land-use change in agriculture, food production and forestry) as well as preventing, reducing and restoring degraded land (*medium confidence*). {1.4.1, 4.1.6, 4.8.7, 5.2.5, 7.2.4, 7.6.2, 7.6.4}

C4.2. Inclusiveness in the measurement, reporting and verification of the performance of policy instruments can support sustainable land management (*medium confidence*). Involving stakeholders in the selection of indicators, collection of climate data, land modelling and land-use planning, mediates and facilitates integrated landscape planning and choice of policy (*medium confidence*). {3.7.5, 5.7.4, 7.4.1, 7.4.4, 7.5.3, 7.5.4, 7.5.5, 7.6.4, 7.6.6}

C4.3. Agricultural practices that include indigenous and local knowledge can contribute to overcoming the combined challenges of climate change, food security, biodiversity conservation, and combating desertification and land degradation (*high confidence*). Coordinated action across a range of actors including businesses, producers, consumers, land managers and policymakers in partnership with indigenous peoples and local communities enable conditions for the adoption of response options (*high confidence*) {3.1.3, 3.6.1, 3.6.2, 4.8.2, 5.5.1, 5.6.4, 5.7.1, 5.7.4, 6.2, 7.3, 7.4.6, 7.6.4}

C4.4. Empowering women can bring synergies and co-benefits to household food security and sustainable land management (*high confidence*). Due to women's disproportionate vulnerability to climate change impacts, their inclusion in land management and tenure is constrained. Policies that can address land rights and barriers to women's participation in sustainable land management include financial transfers to women under the auspices of anti-poverty programmes, spending on health, education, training and capacity building for women, subsidised credit and program dissemination through existing women's community-based organisations (*medium confidence*). {1.4.1, 4.8.2, 5.1.3, Box 5.1, Cross-Chapter Box 11 in Chapter 7}.

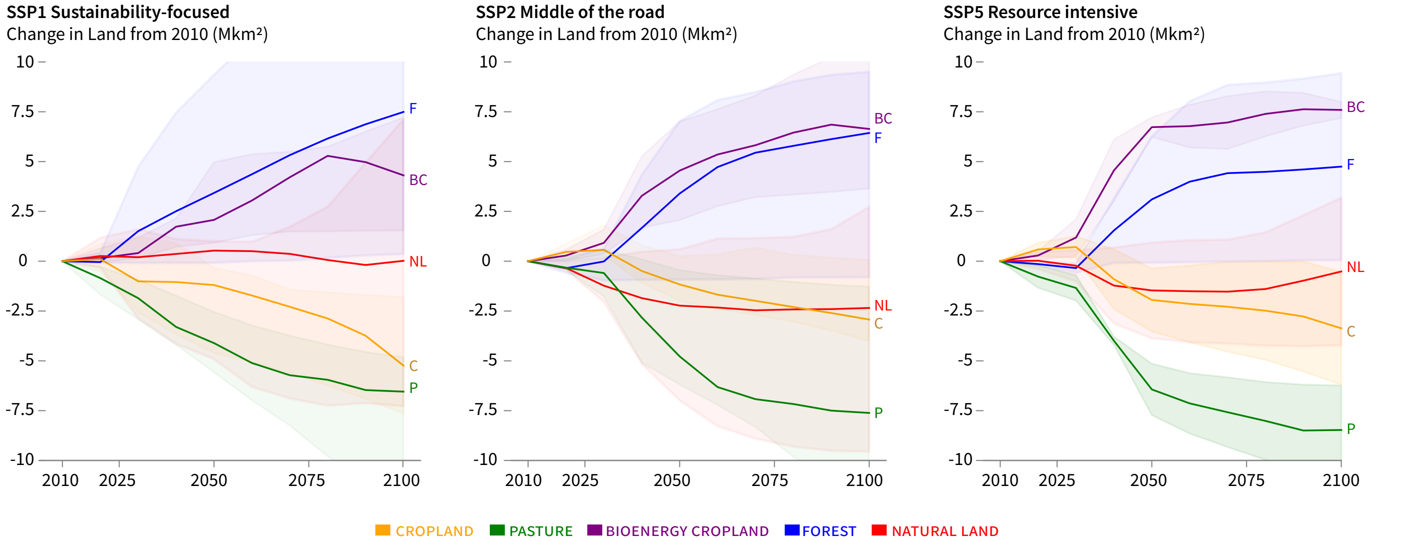
A. Pathways linking socioeconomic development, mitigation responses and land

Socioeconomic development and land management influence the evolution of the land system including the relative amount of land allocated to **CROPLAND**, **PASTURE**, **BIOENERGY CROPLAND**, **FOREST**, and **NATURAL LAND**. The lines show the median across Integrated Assessment Models (IAMs) for three alternative shared socioeconomic pathways (**SSP1**, **SSP2** and **SSP5** at **RCP1.9**); shaded areas show the range across models. Note that pathways illustrate the effects of climate change mitigation but not those of climate change impacts or adaptation.

A. Sustainability-focused (SSP1)
Sustainability in land management, agricultural intensification, production and consumption patterns result in reduced need for agricultural land, despite increases in per capita food consumption. This land can instead be used for reforestation, afforestation, and bioenergy.

B. Middle of the road (SSP2)
Societal as well as technological development follows historical patterns. Increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation decreases availability of agricultural land for food, feed and fibre.

C. Resource intensive (SSP5)
Resource-intensive production and consumption patterns, results in high baseline emissions. Mitigation focuses on technological solutions including substantial bioenergy and BECCS . Intensification and competing land uses contribute to declines in agricultural land.



B. Land use and land cover change in the SSPs

	Quantitative indicators for the SSPs	Count of models included*	Change in Natural Land from 2010 Mkm²	Change in Bioenergy Cropland from 2010 Mkm²	Change in Cropland from 2010 Mkm²	Change in Forest from 2010 Mkm²	Change in Pasture from 2010 Mkm²
SSP1	**RCP1.9** in 2050	5/5	0.5 (-4.9, 1)	2.1 (0.9, 5)	-1.2 (-4.6, -0.3)	3.4 (-0.1, 9.4)	-4.1 (-5.6, -2.5)
	↳ 2100		0 (-7.3, 7.1)	4.3 (1.5, 7.2)	-5.2 (-7.6, -1.8)	7.5 (0.4, 15.8)	-6.5 (-12.2, -4.8)
	RCP2.6 in 2050	5/5	-0.9 (-2.2, 1.5)	1.3 (0.4, 1.9)	-1 (-4.7, 1)	2.6 (-0.1, 8.4)	-3 (-4, -2.4)
	↳ 2100		0.2 (-3.5, 1.1)	5.1 (1.6, 6.3)	-3.2 (-7.7, -1.8)	6.6 (-0.1, 10.5)	-5.5 (-9.9, -4.2)
	RCP4.5 in 2050	5/5	0.5 (-1, 1.7)	0.8 (0.5, 1.3)	0.1 (-3.2, 1.5)	0.6 (-0.7, 4.2)	-2.4 (-3.3, -0.9)
	↳ 2100		1.8 (-1.7, 6)	1.9 (1.4, 3.7)	-2.3 (-6.4, -1.6)	3.9 (0.2, 8.8)	-4.6 (-7.3, -2.7)
	Baseline in 2050	5/5	0.3 (-1.1, 1.8)	0.5 (0.2, 1.4)	0.2 (-1.6, 1.9)	-0.1 (-0.8, 1.1)	-1.5 (-2.9, -0.2)
	↳ 2100		3.3 (-0.3, 5.9)	1.8 (1.4, 2.4)	-1.5 (-5.7, -0.9)	0.9 (0.3, 3)	-2.1 (-7, 0)
SSP2	**RCP1.9** in 2050	4/5	-2.2 (-7, 0.6)	4.5 (2.1, 7)	-1.2 (-2, 0.3)	3.4 (-0.9, 7)	-4.8 (-6.2, -0.4)
	↳ 2100		-2.3 (-9.6, 2.7)	6.6 (3.6, 11)	-2.9 (-4, 0.1)	6.4 (-0.8, 9.5)	-7.6 (-11.7, -1.3)
	RCP2.6 in 2050	5/5	-3.2 (-4.2, 0.1)	2.2 (1.7, 4.7)	0.6 (-1.9, 1.9)	1.6 (-0.9, 4.2)	-1.4 (-3.7, 0.4)
	↳ 2100		-5.2 (-7.2, 0.5)	6.9 (2.3, 10.8)	-1.4 (-4, 0.8)	5.6 (-0.9, 5.9)	-7.2 (-8, 0.5)
	RCP4.5 in 2050	5/5	-2.2 (-2.2, 0.7)	1.5 (0.1, 2.1)	1.2 (-0.9, 2.7)	-0.9 (-2.5, 2.9)	-0.1 (-2.5, 1.6)
	↳ 2100		-3.4 (-4.7, 1.5)	4.1 (0.4, 6.3)	0.7 (-2.6, 3.1)	-0.5 (-3.1, 5.9)	-2.8 (-5.3, 1.9)
	Baseline in 2050	5/5	-1.5 (-2.6, -0.2)	0.7 (0, 1.5)	1.3 (1, 2.7)	-1.3 (-2.5, -0.4)	-0.1 (-1.2, 1.6)
	↳ 2100		-2.1 (-5.9, 0.3)	1.2 (0.1, 2.4)	1.9 (0.8, 2.8)	-1.3 (-2.7, -0.2)	-0.2 (-1.9, 2.1)
SSP3	**RCP1.9** in 2050	Infeasible in all assessed models		-	-	-	-
	↳ 2100			-	-	-	-
	RCP2.6 in 2050	Infeasible in all assessed models		-	-	-	-
	↳ 2100			-	-	-	-
	RCP4.5 in 2050	3/3	-3.4 (-4.4, -2)	1.3 (1.3, 2)	2.3 (1.2, 3)	-2.4 (-4, -1)	2.1 (-0.1, 3.8)
	↳ 2100		-6.2 (-6.8, -5.4)	4.6 (1.5, 7.1)	3.4 (1.9, 4.5)	-3.1 (-5.5, -0.3)	2 (-2.5, 4.4)
	Baseline in 2050	4/4	-3 (-4.6, -1.7)	1 (0.2, 1.5)	2.5 (1.5, 3)	-2.5 (-4, -1.5)	2.4 (0.6, 3.8)
	↳ 2100		-5 (-7.1, -4.2)	1.1 (0.9, 2.5)	5.1 (3.8, 6.1)	-5.3 (-6, -2.6)	3.4 (0.9, 6.4)
SSP4	**RCP1.9** in 2050	Infeasible in all assessed models**		-	-	-	-
	↳ 2100			-	-	-	-
	RCP2.6 in 2050	3/3	-4.5 (-6, -2.1)	3.3 (1.5, 4.5)	0.5 (-0.1, 0.9)	0.7 (-0.3, 2.2)	-0.6 (-0.7, 0.1)
	↳ 2100		-5.8 (-10.2, -4.7)	2.5 (2.3, 15.2)	-0.8 (-0.8, 1.8)	1.4 (-1.7, 4.1)	-1.2 (-2.5, -0.2)
	RCP4.5 in 2050	3/3	-2.7 (-4.4, -0.4)	1.7 (1, 1.9)	1.1 (-0.1, 1.7)	-1.8 (-2.3, 2.1)	0.8 (-0.5, 1.5)
	↳ 2100		-2.8 (-7.8, -2)	2.7 (2.3, 4.7)	1.1 (0.2, 1.2)	-0.7 (-2.6, 1)	1.4 (-1, 1.8)
	Baseline in 2050	3/3	-2.8 (-2.9, -0.2)	1.1 (0.7, 2)	1.1 (0.7, 1.8)	-1.8 (-2.3, -1)	1.5 (-0.5, 2.1)
	↳ 2100		-2.4 (-5, -1)	1.7 (1.4, 2.6)	1.2 (1.2, 1.9)	-2.4 (-2.5, -2)	1.3 (-1, 4.4)
SSP5	**RCP1.9** in 2050	2/4	-1.5 (-3.9, 0.9)	6.7 (6.2, 7.2)	-1.9 (-3.5, -0.4)	3.1 (-0.1, 6.3)	-6.4 (-7.7, -5.1)
	↳ 2100		-0.5 (-4.2, 3.2)	7.6 (7.2, 8)	-3.4 (-6.2, -0.5)	4.7 (0.1, 9.4)	-8.5 (-10.7, -6.2)
	RCP2.6 in 2050	4/4	-3.4 (-6.9, 0.3)	4.8 (3.8, 5.1)	-2.1 (-4, 1)	3.9 (-0.1, 6.7)	-4.4 (-5, 0.2)
	↳ 2100		-4.3 (-8.4, 0.5)	9.1 (7.7, 9.2)	-3.3 (-6.5, -0.5)	3.9 (-0.1, 9.3)	-6.3 (-9.1, -1.4)
	RCP4.5 in 2050	4/4	-2.5 (-3.7, 0.2)	1.7 (0.6, 2.9)	0.6 (-3.3, 1.9)	-0.1 (-1.7, 6)	-1.2 (-2.6, 2.3)
	↳ 2100		-4.1 (-4.6, 0.7)	4.8 (2, 8)	-1 (-5.5, 1)	-0.2 (-1.4, 9.1)	-3 (-5.2, 2.1)
	Baseline in 2050	4/4	-0.6 (-3.8, 0.4)	0.8 (0, 2.1)	1.5 (-0.7, 3.3)	-1.9 (-3.4, 0.5)	-0.1 (-1.5, 2.9)
	↳ 2100		-0.2 (-2.4, 1.8)	1 (0.2, 2.3)	1 (-2, 2.5)	-2.1 (-3.4, 1.1)	-0.4 (-2.4, 2.8)

** Count of models included / Count of models attempted. One model did not provide land data and is excluded from all entries.*

*** One model could reach RCP1.9 with SSP4, but did not provide land data*

Figure SPM.4 Pathways linking socioeconomic development, mitigation responses and land

Future scenarios provide a framework for understanding the implications of mitigation and socioeconomics on land. The Shared Socioeconomic Pathways (SSPs) span a range of different socioeconomic assumptions (Box SPM.1). They are combined with Representative Concentration Pathways (RCPs)[36]which imply different levels of mitigation. The changes in cropland, pasture, bioenergy cropland, forest, and natural land from 2010 are shown. For this figure: Cropland includes all land in food, feed, and fodder crops, as well as other arable land (cultivated area). This category includes 1st generation non-forest bioenergy crops (e.g. corn for ethanol, sugar cane for ethanol, soybeans for biodiesel), but excludes 2nd generation bioenergy crops. Pasture includes categories of pasture land, not only high quality rangeland, and is based on FAO definition of "permanent meadows and pastures". Bioenergy cropland includes land dedicated to 2nd generation energy crops (e.g., switchgrass, miscanthus, fast-growing wood species). Forest includes managed and unmanaged forest. Natural land includes other grassland, savannah, and shrubland. **Panel A:** This panel shows integrated assessment model (IAM)[37] results for SSP1, SSP2 and SSP5 at RCP1.9[38]. For each pathway, the shaded areas show the range across all IAMs; the line indicates the median across models. For RCP1.9, SSP1, SSP2 and SSP5 include results from five, four and two IAMs respectively. **Panel B**: Land use and land cover change are indicated for various SSP-RCP combinations, showing multi-model median and range (min, max). {Box SPM.1, 1.3.2, Cross-Chapter Box 1 in Chapter 1, 2.7.2, Cross-Chapter Box 9 in Chapter 6, 6.1, 6.4.4, 7.4.2, 7.4.4, 7.4.5, 7.4.6, 7.4.7, 7.4.8, 7.5.3, 7.5.6; Cross-Chapter Box 9 in Chapter 6}

D. Action in the near-term

D 1. Actions can be taken in the near-term, based on existing knowledge, to address desertification, land degradation and food security while supporting longer-term responses that enable adaptation and mitigation to climate change. These include actions to build individual and institutional capacity, accelerate knowledge transfer, enhance technology transfer and deployment, enable financial mechanisms, implement early warning systems, undertake risk management and address gaps in implementation and upscaling (*high confidence*). {3.6.1, 3.6.2, 3.7.2, 4.8, 5.3.3, 5.5, 5.6.4, 5.7, 6.2, 6.4, 7.3, 7.4.9, 7.6; Cross-Chapter Box 10 in Chapter 7}

D1.1. Near-term capacity-building, technology transfer and deployment, and enabling financial mechanisms can strengthen adaptation and mitigation in the land sector. Knowledge and technology transfer can help enhance the sustainable use of natural resources for food security under a changing climate (*medium confidence*). Raising awareness, capacity building and education about sustainable land management practices, agricultural extension and advisory

[36] Representative Concentration Pathways (RCPs) are scenarios that include timeseries of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover".

[37] Integrated Assessment Models (IAMs) integrate knowledge from two or more domains into a single framework. In this figure, IAMs are used to assess linkages between economic, social and technological development and the evolution of the climate system.

[38] The RCP1.9 pathways assessed in this report have a 66% chance of limiting warming to 1.5C in 2100, but some of these pathways overshoot 1.5C of warming during the 21st century by >0.1C.

services, and expansion of access to agricultural services to producers and land users can effectively address land degradation (*medium confidence*). {3.1, 5.7.4, 7.2, 7.3.4, 7.5.4}

D1.2. Measuring and monitoring land use change including land degradation and desertification is supported by the expanded use of new information and communication technologies (cellphone based applications, cloud-based services, ground sensors, drone imagery), use of climate services, and remotely sensed land and climate information on land resources (*medium confidence*). Early warning systems for extreme weather and climate events are critical for protecting lives and property and enhancing disaster risk reduction and management (*high confidence*). Seasonal forecasts and early warning systems are critical for food security (famine) and biodiversity monitoring including pests and diseases and adaptive climate risk management (*high confidence*). There are high returns on investments in human and institutional capacities. These investments include access to observation and early warning systems, and other services derived from in-situ hydro-meteorological and remote sensing-based monitoring systems and data, field observation, inventory and survey, and expanded use of digital technologies (*high confidence*). {1.2, 3.6.2, 4.2.2, 4.2.4, 5.3.1, 5.3.6, 6.4, 7.3.4, 7.4.3, 7.5.4, 7.5.5, 7.6.4; Cross-Chapter Box 5 in Chapter 3}

D1.3. Framing land management in terms of risk management, specific to land, can play an important role in adaptation through landscape approaches, biological control of outbreaks of pests and diseases, and improving risk sharing and transfer mechanisms (*high confidence*). Providing information on climate-related risk can improve the capacity of land managers and enable timely decision making (*high confidence*). {5.3.2, 5.3.5, 5.6.2, 5.6.3; Cross-Chapter Box 6 in Chapter 5; 5.6.5, 5.7.1, 5.7.2, 7.2.4}

D1.4. Sustainable land management can be improved by increasing the availability and accessibility of data and information relating to the effectiveness, co-benefits and risks of emerging response options and increasing the efficiency of land use (*high confidence*). Some response options (e.g., improved soil carbon management) have been implemented only at small-scale demonstration facilities and knowledge, financial, and institutional gaps and challenges exist with upscaling and the widespread deployment of these options (*medium confidence*). {4.8, 5.5.1, 5.5.2, 5.6.1, 5.6.5, 5.7.5, 6.2, 6.4,}

D 2. Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits (*high confidence*). Co-benefits can contribute to poverty eradication and more resilient livelihoods for those who are vulnerable (*high confidence*). {3.4.2, 5.7, 7.5}

D2.1. Near-term actions to promote sustainable land management will help reduce land and food-related vulnerabilities, and can create more resilient livelihoods, reduce land degradation and desertification, and loss of biodiversity (*high confidence*). There are synergies between sustainable land management, poverty eradication efforts, access to market, non-market mechanisms and the elimination of low-productivity practices. Maximising these synergies can lead to adaptation, mitigation, and development co-benefits through preserving ecosystem functions and services (*medium confidence*). {3.4.2, 3.6.3, Table 4.2, 4.7, 4.9, 4.10, 5.6, 5.7, 7.3, 7.4, 7.5, 7.6; Cross-Chapter Box 12 in Chapter 7}

D2.2. Investments in land restoration can result in global benefits and in drylands can have benefit-cost ratios of between three and six in terms of the estimated economic value of restored ecosystem services (*medium confidence*). Many sustainable land management technologies and practices are profitable within three to 10 years (*medium confidence*). While they can require upfront investment, actions to ensure sustainable land management can improve crop yields and the economic value of pasture. Land restoration and rehabilitation measures improve livelihood systems and provide both short-term positive economic returns and longer-term benefits in terms of climate change adaptation and mitigation, biodiversity and enhanced ecosystem functions and services (*high confidence*). {3.6.1, 3.6.3, 4.8.1, 7.2.4, 7.2.3, 7.3.1, 7.4.6, Cross-Chapter Box 10 in Chapter 7}

D2.3. Upfront investments in sustainable land management practices and technologies can range from about USD 20 ha^{-1} to USD 5000 ha^{-1}, with a median estimated to be around USD 500 ha^{-1}. Government support and improved access to credit can help overcome barriers to adoption, especially those faced by poor smallholder farmers (*high confidence*). Near-term change to balanced diets (see B6.2) can reduce the pressure on land and provide significant health co-benefits through improving nutrition (*medium confidence)*. {3.6.3, 4.8, 5.3, 5.5, 5.6, 5.7, 6.4, 7.4.7, 7.5.5; Cross-Chapter Box 9 in Chapter 6}

D 3. Rapid reductions in anthropogenic GHG emissions across all sectors following ambitious mitigation pathways reduce negative impacts of climate change on land ecosystems and food systems (*medium confidence*). Delaying climate mitigation and adaptation responses across sectors would lead to increasingly negative impacts on land and reduce the prospect of sustainable development (*medium confidence*). {Box SPM.1, Figure SPM.2, 2.5, 2.7, 5.2, 6.2, 6.4, 7.2, 7.3.1, 7.4.7, 7.4.8, 7.5.6; Cross-Chapter Box 9 in Chapter 6, Cross-Chapter Box 10 in Chapter 7}

D3.1. Delayed action across sectors leads to an increasing need for widespread deployment of land-based adaptation and mitigation options and can result in a decreasing potential for the array of these options in most regions of the world and limit their current and future effectiveness (*high confidence*). Acting now may avert or reduce risks and losses, and generate benefits to society (*medium confidence*). Prompt action on climate mitigation and adaptation aligned with sustainable land management and sustainable development depending on the region could reduce the risk to millions of people from climate extremes, desertification, land degradation and food and livelihood insecurity (*high confidence*). {1.3.5, 3.4.2, 3.5.2, 4.1.6, 4.7.1, 4.7.2, 5.2.3, 5.3.1, 6.3, 6.5, 7.3.1}

D3.2. In future scenarios, deferral of GHG emissions reductions implies trade-offs leading to significantly higher costs and risks associated with rising temperatures (*medium confidence*). The potential for some response options, such as increasing soil organic carbon, decreases as climate change intensifies, as soils have reduced capacity to act as sinks for carbon sequestration at higher temperatures (*high confidence*). Delays in avoiding or reducing land degradation and promoting positive ecosystem restoration risk long-term impacts including rapid declines in productivity of agriculture and rangelands, permafrost degradation and difficulties in peatland rewetting (*medium confidence*). {1.3.1, 3.6.2, 4.8, 4.9, 4.9.1, 5.5.2, 6.3, 6.4, 7.2, 7.3; Cross-Chapter Box 10 in Chapter 7}

D3.3. Deferral of GHG emissions reductions from all sectors implies trade-offs including irreversible loss in land ecosystem functions and services required for food, health, habitable settlements and production, leading to increasingly significant economic impacts on many countries in many regions of the world (*high confidence*). Delaying action as is assumed in high emissions scenarios could result in some irreversible impacts on some ecosystems, which in the longer-term has the potential to lead to substantial additional GHG emissions from ecosystems that would accelerate global warming (*medium confidence*). {1.3.1, 2.5.3, 2.7, 3.6.2, 4.9, 4.10.1, 5.4.2.4, 6.3, 6.4, 7.2, 7.3; Cross-Chapter Box 9 in Chapter 6, Cross-Chapter Box 10 in Chapter 7}

The New York Times

Climate Change Threatens the World's Food Supply, United Nations Warns

By Christopher Flavelle

Aug. 8, 2019

Want climate news in your inbox? Sign up here for ***Climate Fwd:****, our email newsletter.*

The world's land and water resources are being exploited at "unprecedented rates," a new United Nations report warns, which combined with climate change is putting dire pressure on the ability of humanity to feed itself.

The report, prepared by more than 100 experts from 52 countries and released in summary form in Geneva on Thursday, found that the window to address the threat is closing rapidly. A half-billion people already live in places turning into desert, and soil is being lost between 10 and 100 times faster than it is forming, according to the report.

Climate change will make those threats even worse, as floods, drought, storms and other types of extreme weather threaten to disrupt, and over time shrink, the global food supply. Already, more than 10 percent of the world's population remains undernourished, and some authors of the report warned in interviews that food shortages could lead to an increase in cross-border migration.

A particular danger is that food crises could develop on several continents at once, said Cynthia Rosenzweig, a senior research scientist at the NASA Goddard Institute for Space Studies and one of the lead authors of the report. "The potential risk of multi-breadbasket failure is increasing," she said. "All of these things are happening at the same time."

The report also offered a measure of hope, laying out pathways to addressing the looming food crisis, though they would require a major re-evaluation of land use and agriculture worldwide as well as consumer behavior. Proposals include increasing the productivity of land, wasting less food and persuading more people to shift their diets away from cattle and other types of meat.

"One of the important findings of our work is that there are a lot of actions that we can take now. They're available to us," Dr. McElwee said. "What some of these solutions do require is attention, financial support, enabling environments."

The summary was released Thursday by the Intergovernmental Panel on Climate Change, an international group of scientists convened by the United Nations that pulls together a wide range of existing research to help governments understand climate change and make policy decisions. The I.P.C.C. is writing a series of climate reports, including one last year on the disastrous consequences if the planet's temperature rises just 1.5 degrees Celsius above its preindustrial levels, as well as an upcoming report on the state of the world's oceans.

Some authors also suggested that food shortages are likely to affect poorer parts of the world far more than richer ones. That could increase a flow of immigration that is already redefining politics in North America, Europe and other parts of the world.

"People's lives will be affected by a massive pressure for migration," said Pete Smith, a professor of plant and soil science at the University of Aberdeen and one of the report's lead authors. "People don't stay and die where they are. People migrate."

Between 2010 and 2015 the number of migrants from El Salvador, Guatemala and Honduras showing up at the United States' border with Mexico increased fivefold, coinciding with a dry period that left many with not enough food and was so unusual that scientists suggested it bears the signal of climate change.

Winnowing wheat at a grain market in Amritsar, India. Raminder Pal Singh/EPA, via Shutterstock

Harvesting in Xinjiang, northwest China. China Daily/Reuters

Barring action on a sweeping scale, the report said, climate change will accelerate the danger of severe food shortages. As a warming atmosphere intensifies the world's droughts, flooding, heat waves, wildfires and other weather patterns, it is speeding up the rate of soil loss and land degradation, the report concludes.

Higher concentrations of carbon dioxide in the atmosphere — a greenhouse gas put there mainly by the burning of fossil fuels — will also reduce food's nutritional quality, even as rising temperatures cut crop yields and harm livestock.

Those changes threaten to exceed the ability of the agriculture industry to adapt.

In some cases, the report says, a changing climate is boosting food production because, for example, warmer temperatures will mean greater yields of some crops at higher latitudes. But on the whole, the report finds that climate change is already hurting the availability of food because of decreased yields and lost land from erosion, desertification and rising seas, among other things.

Overall if emissions of greenhouse gases continue to rise, so will food costs, according to the report, affecting people around the world.

"You're sort of reaching a breaking point with land itself and its ability to grow food and sustain us," said Aditi Sen, a senior policy adviser on climate change at Oxfam America, an antipoverty advocacy organization.

In addition, the researchers said, even as climate change makes agriculture more difficult, agriculture itself is also exacerbating climate change.

The report said that activities such as draining wetlands — as has happened in Indonesia and Malaysia to create palm oil plantations, for example — is particularly damaging. When drained, peatlands, which store between 530 and 694 billion tons of carbon dioxide globally, release that carbon dioxide back into the atmosphere. Carbon dioxide is a major greenhouse gas, trapping the sun’s heat and warming the planet. Every 2.5 acres of peatlands release the carbon dioxide equivalent of burning 6,000 gallons of gasoline.

And the emission of carbon dioxide continues long after the peatlands are drained. Of the five gigatons of greenhouse gas emissions that are released each year from deforestation and other land-use changes, “One gigaton comes from the ongoing degradation of peatlands that are already drained,” said Tim Searchinger, a senior fellow at the World Resources Institute, an environmental think tank, who is familiar with the report. (By comparison, the fossil fuel industry emitted about 37 gigatons of carbon dioxide last year, according to the institute.)

An ethanol refinery in Tianjin, China. China Stringer Network/Reuters

A cattle market in Lagos, Nigeria. Florian Plaucheur/Agence France-Presse — Getty Images

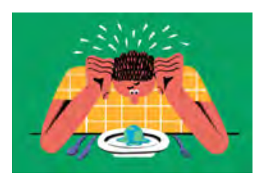
Similarly, cattle are significant producers of methane, another powerful greenhouse gas, and an increase in global demand for beef and other meats has fueled their numbers and increased deforestation in critical forest systems like the Amazon.

Since 1961 methane emissions from ruminant livestock, which includes cows as well as sheep, buffalo and goats, have significantly increased, according to the report. And each year, the amount of forested land that is cleared — much of that propelled by demand for pasture land for cattle — releases the emissions equivalent of driving 600 million cars.

Overall, the report says there is still time to address the threats by making the food system more efficient. The authors urge changes in how food is produced and distributed, including better soil management, crop diversification and fewer restrictions on trade. They also call for shifts in consumer behavior, noting that at least one-quarter of all food worldwide is wasted.

Read more about food and climate change

Your Questions About Food and Climate Change, Answered April 30, 2019



From Apples to Popcorn, Climate Change Is Altering the Foods America Grows
April 30, 2019

Central American Farmers Head to the U.S., Fleeing Climate Change April 13, 2019

But protecting the food supply and cutting greenhouse emissions can also come into conflict with each other, forcing hard choices.

For instance, the widespread use of strategies such as bioenergy — like growing corn to produce ethanol — could lead to the creation of new deserts or other land degradation, the authors said. The same is true for planting large numbers of trees (something often cited as a powerful strategy to pull carbon dioxide out of the atmosphere), which can push crops and livestock onto less productive land.

Planting as many trees as possible would reduce the amount of greenhouse gases in the atmosphere by about nine gigatons each year, according to Pamela McElwee, a professor of human ecology at Rutgers University and one of the report's lead authors. But it would also increase food prices as much as 80 percent by 2050.

"We cannot plant trees to get ourselves out of the problem that we're in," Dr. McElwee said. "The trade-offs that would keep us below 1.5 degrees, we're not talking about them. We're not ready to confront them yet."

Rice cultivation outside Prayagraj, India. Rajesh Kumar Singh/Associated Press

Flooded farms near Craig, Mo. Scott Olson/Getty Images

Preventing global temperatures from rising more than 1.5 degrees Celsius is likely to require both the widespread planting of trees as well as "substantial" bioenergy to help reduce the use of fossil fuels, the report finds. And if temperatures increase more than that, the pressure on food production will increase as well, creating a vicious circle.

"Above 2 degrees of global warming there could be an increase of 100 million or more of the population at risk of hunger," Edouard Davin, a researcher at ETH Zurich and an author of the report, said by email. "We need to act quickly."

Humans Are Speeding Extinction and Altering the Natural World at an 'Unprecedented' Pace May 6, 2019

The report also calls for institutional changes, including better access to credit for farmers in developing countries and stronger property rights. And for the first time, the I.P.C.C. cited indigenous people and their knowledge of land stewardship as resources to be tapped. "Agricultural practices that include indigenous and local knowledge can contribute to overcoming the combined challenges of climate change, food security, biodiversity conservation, and combating desertification and land degradation," the report's authors wrote.

It comes at a time when indigenous people are currently under threat. According to a report released this year by the nonprofit organization Global Witness, which looks at the links between conflicts and environmental resources, an average of three people were killed per week defending their land in 2018, with more than half of them killed in Latin America.

Overall, the report said that the longer policymakers wait, the harder it will be to prevent a global crisis. "Acting now may avert or reduce risks and losses, and generate benefits to society," the authors wrote. Waiting to cut emissions, on the other hand, risks "irreversible loss in land ecosystem functions and services required for food, health, habitable settlements and production."

For more news on climate and the environment, follow @NYTClimate on Twitter.

Correction: *Aug. 9, 2019*

An earlier version of this article misquoted and misattributed comments about proposals to address a possible food crisis. Those comments were made by Pamela McElwee, not Cynthia Rosenzweig. In addition, part of the quote was rendered incorrectly. Dr. McElwee said, "What some of these solutions do require is attention, financial support, enabling environments." She did not say, "But what some of these solutions do require is attention, financial support, enabling environments."

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