A Look at 2016

Takeaway Points from the *State of the Climate* Supplement

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The following salient events and trends are reported in greater depth in the State of the Climate in 2016*, the supplement to this issue of* BAMS*. Figures shown here are drawn from the supplement and are not cited in the text below.*

GLOBAL CLIMATE. The dominant greenhouse gases released into Earth's atmosphere—carbon dioxide, methane, and nitrous oxide—all continued to increase and reach new record high abundances. Increases in the global annual mean atmospheric concentrations of methane and nitrogen dioxide from 2015 to 2016 were generally consistent with decadal trends, but the 3.5 ± 0.1 ppm rise in global annual mean carbon dioxide from 2015 to 2016 was the largest annual increase ever observed in the 58-year measurement record. The global average carbon dioxide concentration at Earth's surface for 2016 was 402.9 ± 0.1 ppm, surpassing 400 ppm for the first time in the modern atmospheric measurement record and in ice core records dating back as far as 800,000 years.

Owing to the combination of strong El Niño conditions early in the year and a long-term upward trend, Earth's surface observed record warmth for a third consecutive year, with the 2016 annual global surface temperature surpassing the previous record of 2015, albeit by a much slimmer margin than that by which the 2015 record was set. Above Earth's surface, the globally averaged lower troposphere temperature was also record high according to all datasets analyzed, while the lower stratospheric temperature was record low according to most of the in situ and satellite datasets.

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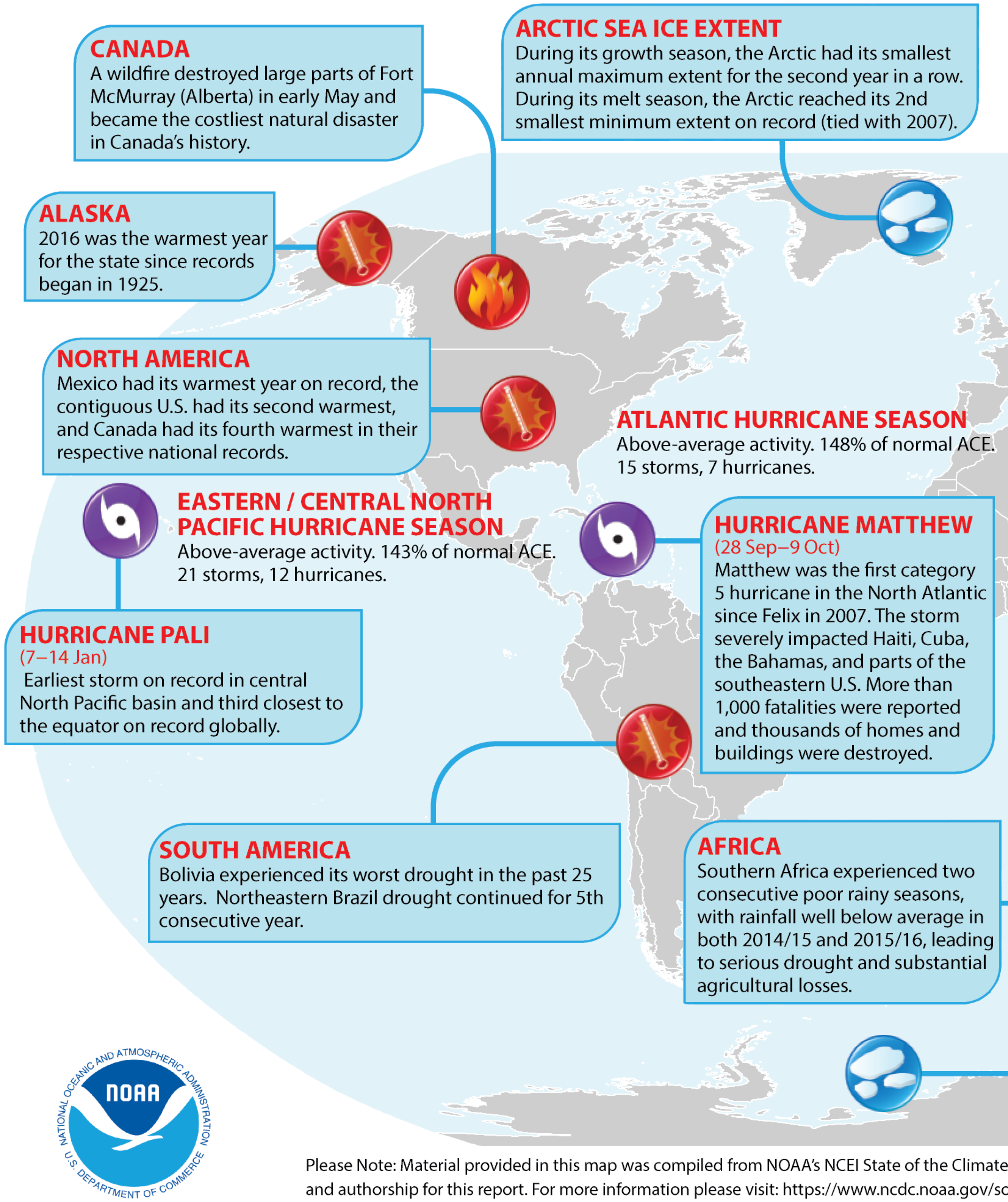
The global warmth was associated with extensive drought, surpassing most years in the post-1950 record and strongly influenced by the El Niño. For any given month during 2016, 12% or more of global land was experiencing at least severe drought conditions, the longest such stretch in the record.

GLOBAL OCEANS. The globally averaged annual sea surface temperature (SST) for 2016 was record high, just surpassing the previous record of 2015 by about 0.01°C. The global SST trend for the twenty-first century to date (2000–16) of +1.62°C century^{-1} is much higher than the longer-term (1950–2016) warming trend of +1.00°C century^{-1}.

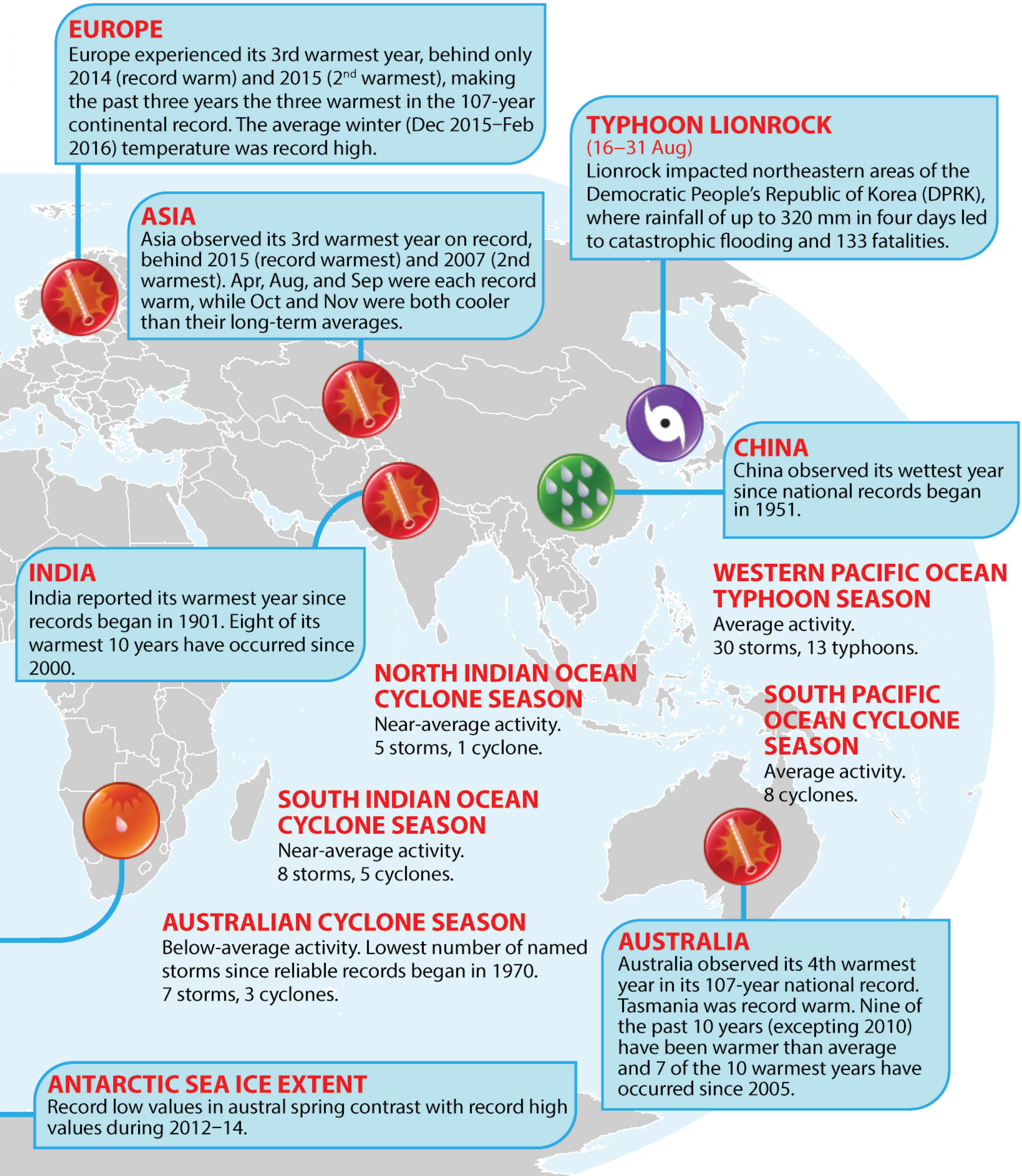
Global mean sea level also reached a new record high in 2016, marking the sixth consecutive year, and in 21 out of the last 23 years, it has increased compared to the previous year. The new high reflects the ongoing multidecadal trend during the satellite altimetry era, 3.4 (±0.4) mm yr^{-1}, as well as the continuation of El Niño into spring 2016.

Global annual ocean heat content (OHC) saw a slight drop compared to the record high of 2015. Over the period 1993–2016, there are statistically significant warming trends of OHC in the Southern Hemisphere, mostly north of the Antarctic Circumpolar Current, where much of Pacific Ocean carbon sequestration is observed. The overall ocean rate of uptake of carbon from the atmosphere has generally risen along with atmospheric carbon dioxide concentrations.

THE TROPICS. Globally, 93 named tropical storms were observed during 2016, above the 1981–2010 average of 82, but fewer than the 101 storms recorded in



Geographical distribution of selected notable climate anomalies and events in 2016.



Reports, the WMO Statement on the Status of the Global Climate in 2016 (WMO-No. 1189),
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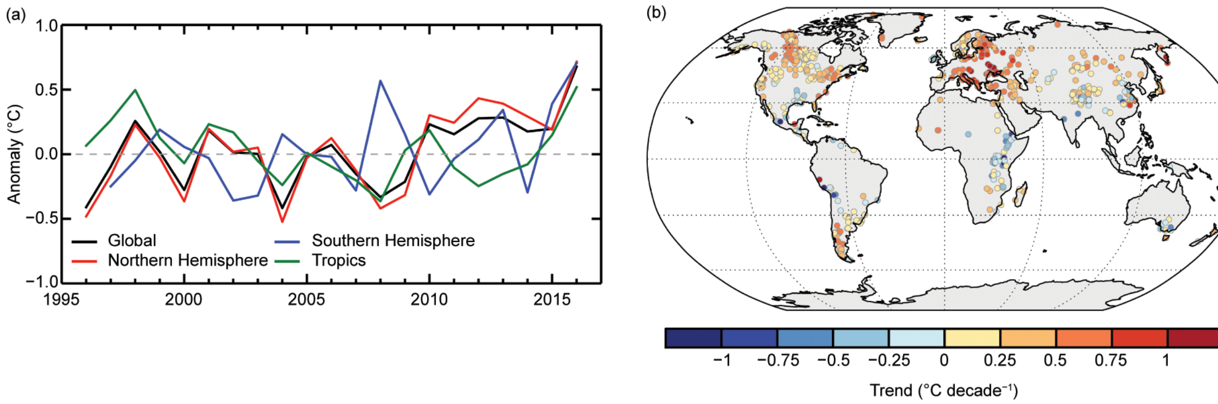
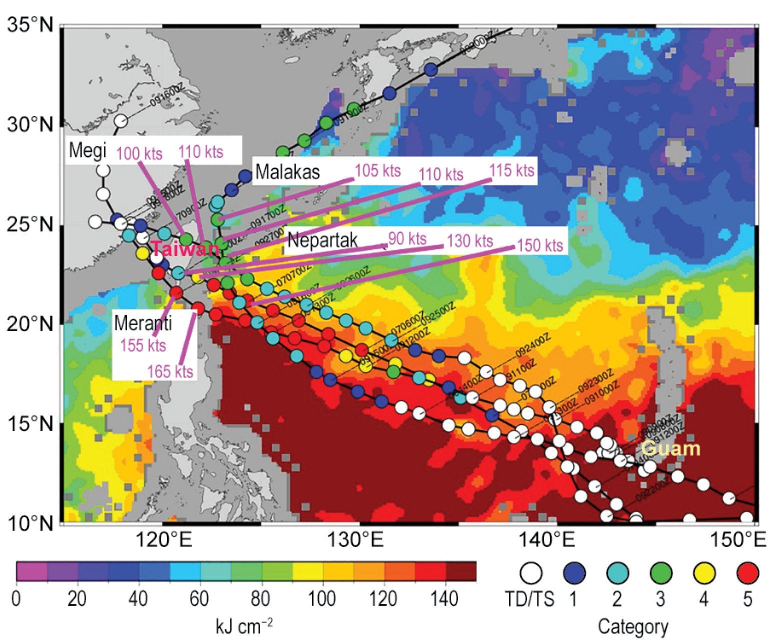
Warming Lakes



Warmth can encourage bacterial blooms and lower water quality. In 2016, lakes overall were the warmest they've been in the 21-year record. The global and equally weighted lake surface water temperature (LSWT) anomaly was +0.65°C, with warm conditions noted in both the Northern (NH) and Southern Hemispheres (SH). LSWT from 681 lakes show (a) global and regional annual average anomalies (°C), and (b) 1996–2016 LSWT trend (°C decade^{-1}). Annual LSWTs are calculated for the warm season (Jul–Sep in NH; Jan–Mar in SH), and LSWT trends are calculated on these anomalies. (Fig. 2.3 in *State of the Climate in 2016*; see discussion there in section 2b2.)

Typhoons for Taiwan



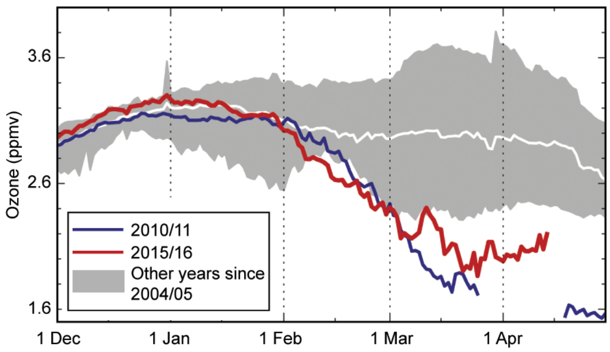
Even with a late start and a lull in August, few regions have ever recorded a more severe tropical season than Taiwan did in 2016. Four typhoons (Supertyphoons Nepartak and Meranti, category 4 Typhoon Malakas, and category 3 Typhoon Megi) approached Taiwan. Their peak intensity and intensity closest to Taiwan are depicted over a background based on daily composite of the four pre-typhoon tropical cyclone heat potential (i.e., integrated heat content from SST down to the 26°C isotherm depth) maps from 3 July, and 9, 12, and 22 September. (Fig. SB4.3 of the *State of the Climate in 2016*; see discussion there in sidebar 4.2.)

2015. Three basins—the North Atlantic and the eastern and western North Pacific—experienced above-normal activity in 2016. The Australian basin recorded its least active season since the beginning of the satellite era in 1970.

Overall, four tropical cyclones reached Saffir–Simpson category 5 intensity—one each in the North Atlantic, South Indian, western North Pacific, and southwest Pacific basins. This is half the number of category 5 storms recorded in 2015. In terms of accumulated cyclone energy (ACE), the North Atlantic basin recorded its first above-normal season since 2012, with more than 2.5 times the average ACE of the previous three seasons. Category 5 Hurricane Matthew alone produced 35% of the season's ACE. The western North Pacific's activity was similarly dominated by two typhoons (Lionrock and Meranti) accounting for about 25% of the total seasonal ACE.

THE ARCTIC. The 2016 average temperature of land surfaces north of 60°N was 2.0°C above the 1981–2010

Arctic Ozone Loss



Winter destruction of Arctic stratospheric ozone in 2015/16 initially proceeded faster than the record-setting loss of 2010/11. The ultimate decline was not a record, but exceeded nearly all years since 2004. The period of activated chlorine destroying ozone halted early due to March warmth. The averaged ozone mixing ratios (ppmv) plotted above are for the area bounded by the polar vortex at approximately 18 km altitude, measured by the *Aura* Microwave Limb Sounder. The solid white line is the average for 2004/05 to 2014/15 (minimum/maximum range in gray) with 2010/11 and 2015/16 excluded. Gaps in the blue line for 2010/11 are missing data. The 2015/16 record (red line) ends early because the vortex was not defined after mid-April. (Fig. 5.26 in *State of the Climate of 2016*; see discussion there in section 5j.)

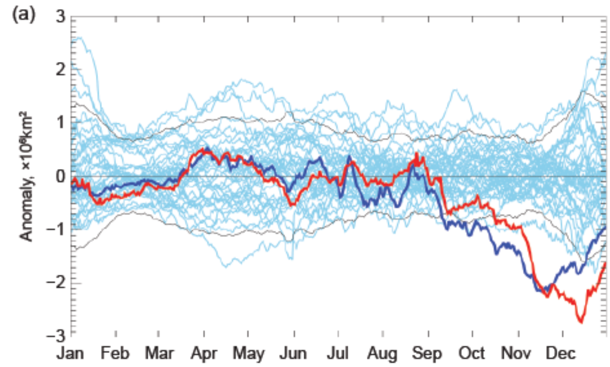
average, breaking the previous record of 2007, 2011, and 2015 by 0.8°C and representing a 3.5°C increase since the record began in 1900. This region is warming at more than twice the rate of lower latitudes.

On 24 March, the sea ice extent at the end of the growth season saw its lowest maximum in the 37-year satellite record, tying with 2015 at 7.2% below the 1981–2010 average. The September 2016 Arctic sea ice minimum extent tied with 2007 for the second-lowest value on record, 33% smaller than the 1981–2010 average. Arctic sea ice cover remains relatively young and thin, making it vulnerable to continued extensive melt.

The mass of the Greenland ice sheet, which has the capacity to contribute ~7 m to sea level rise, reached a record low value, with enhanced melting occurring in the southwest and northeast regions. The onset of the surface melt was the second earliest (after 2012) in the 37-year satellite record.

The spring snow cover extent (SCE) has also undergone significant reductions, particularly since 2005. In 2016, new record low April and May SCEs were reached for the North American Arctic. In addition to warming air temperatures, there is also evidence of decreasing pre-melt snow mass (an indication of shallower snow), which may further

Late-Season Southern Sea Ice Melt



Sea ice extent was close to the means around Antarctic in winter, but on 31 August reached its peak—a record early date (according to the satellite data). From then on SH ice extent (red line) and area (blue line) daily anomalies departed dramatically from the 1981–2010 mean. Thin blue lines represent the historical daily values of extent for 1979–2015, while the thin black lines represent ±2 std. dev. of extent. As recently as 2012–14 daily sea ice extent/area set record highs in the region. (Fig. 6.8a in the *State of the Climate in 2016*; see discussion there in section 6f.)

precondition the snowpack for earlier and more rapid springtime melt.

Continuing a pattern below the surface, record high temperatures at 20-m depth were measured at all permafrost observatories on the North Slope of Alaska and at the Canadian observatory on northernmost Ellesmere Island. Thawing permafrost has the potential to release significant amounts of greenhouse gases.

ANTARCTICA. Monthly low surface pressure records for March, June, and September were broken at many stations. New monthly high values (since 1957) of the southern annular mode index, a measure of the zonal mean pressure difference between 40° and 65°S, were set in March and June, +4.36 and +3.66, respectively.

Monthly high surface pressure records for August and November were set at several stations. During this period, record low daily and monthly sea ice extents were observed, with the November mean sea ice extent more than 5 standard deviations below the 1981–2010 average. These record low sea ice values in austral spring 2016 contrast sharply with the record high values observed during 2012–14.

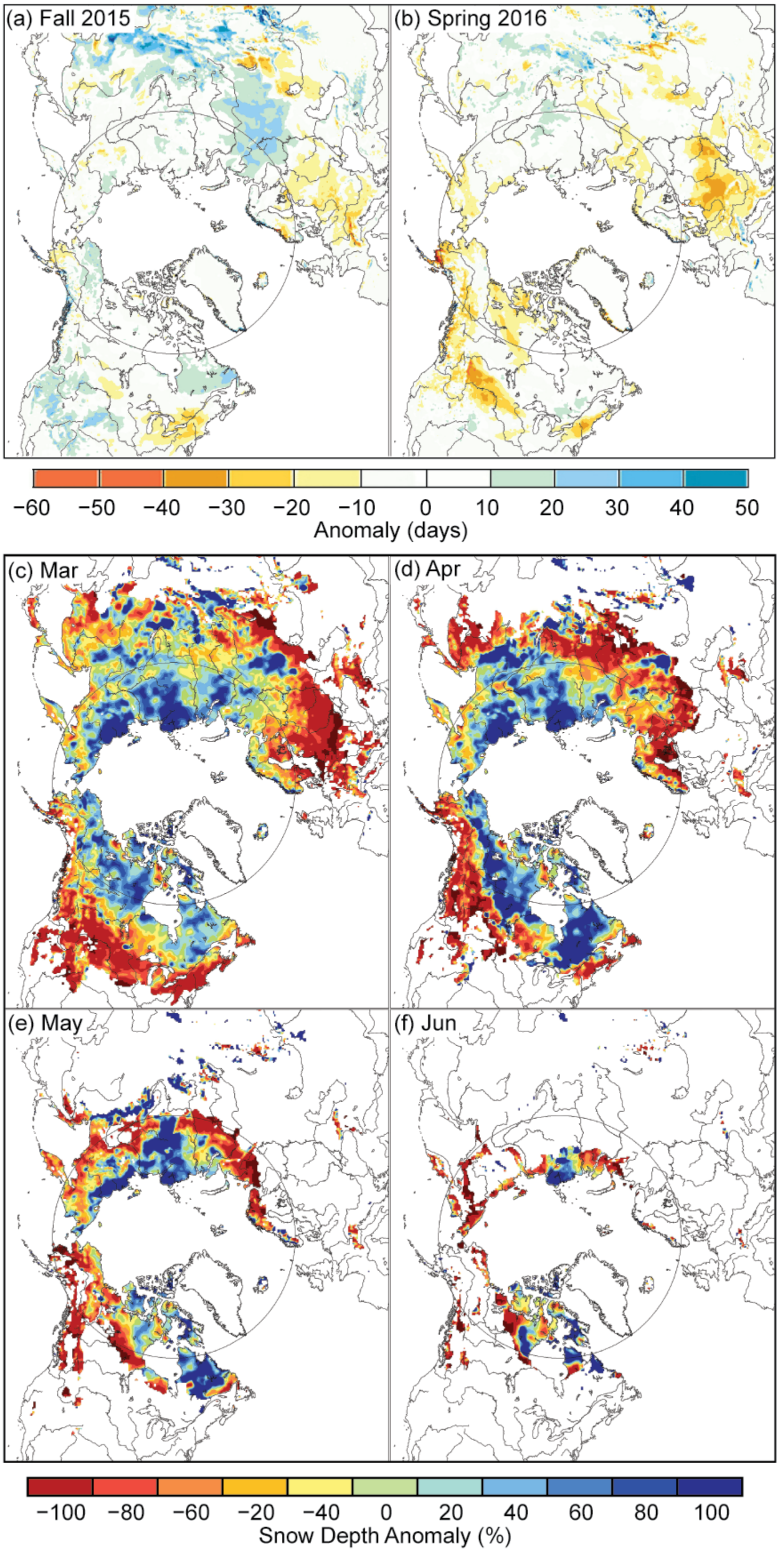
With cool surface temperatures prevailing during the 2015/16 melt season, most of the continent and ice shelves showed negative melt duration anomalies (compared to 1981–2010). However, the Ross Ice Shelf showed an unusual and widespread positive melt season relative to the 1981–2010 mean. Although the Antarctic Peninsula typically experiences the longest melt seasons relative to the rest of the continent, the Peninsula melt duration anomalies in 2015/16 were mostly negative.

Over the region, springtime Antarctic stratospheric ozone depletion was less severe compared to the 1991–2006 average (a period of peak chlorine and bromine over Antarctica), but ozone levels were still low compared to pre-1990 levels.

REGIONAL CLIMATES. *North America.* Mexico was record warm for 2016 (since 1971), while the United States observed its second-warmest year on record (since 1895), behind 2012. After being plagued by heat and drought for several years, California had its first wetter-than-average year since 2012. To the north in western Canada, with abnormally warm and dry conditions prevailing for about a year, the Fort McMurray wildfire burned nearly 590,000 hectares and became the costliest disaster in Canadian history, with $3 billion (U.S. dollars) in insured losses.

Central America and the Caribbean. Most reporting stations in Central America had higher-than-average temperatures in 2016, primarily due to more frequent

Diminished Arctic Snow Pack



A shallow snowpack combined with spring warmth led to diminished snow cover extent (SCE) in the Arctic. Below-normal SCE anomalies (relative to 1981–2010) set records in March and April 2016 in the North American Arctic; spring SCE anomalies were also negative in Eurasia. Snow cover duration departures (days; with respect to 1998–2010) from the NOAA Interactive Multisensor Snow and Ice Mapping System (IMS) data record for the (a) 2015 fall season and (b) 2016 spring season. Snow depth anomaly (% of 1999–2010 average) from the Canadian Meteorological Centre (CMC) snow depth analysis for (c) March, (d) April, (e) May, and (f) June 2016. (Fig. 5.18 in *State of the Climate 2016*; see discussion there in section 5g.)

warmer-than-average days as opposed to extreme temperatures. In the Caribbean, Cuba reported its fourth-highest annual temperature in the 66-year national record. Several tropical cyclones impacted the region. Notably, Hurricane Matthew affected Cuba, Barbados, St. Lucia, the Dominican Republic, and Haiti. The storm caused Haiti's largest humanitarian emergency since the 2010 earthquake, with two million people affected and more than 540 fatalities reported for the country. In eastern Cuba approximately $2.5 billion U.S. dollars in damages were incurred. In late November Hurricane Otto—the strongest North Atlantic hurricane so late in the season and the latest on record in the Caribbean Sea—severely impacted Panama, Costa Rica, and Nicaragua, with 18 fatalities and more than 2,400 damaged or destroyed homes.

ABOUT THE REPORT

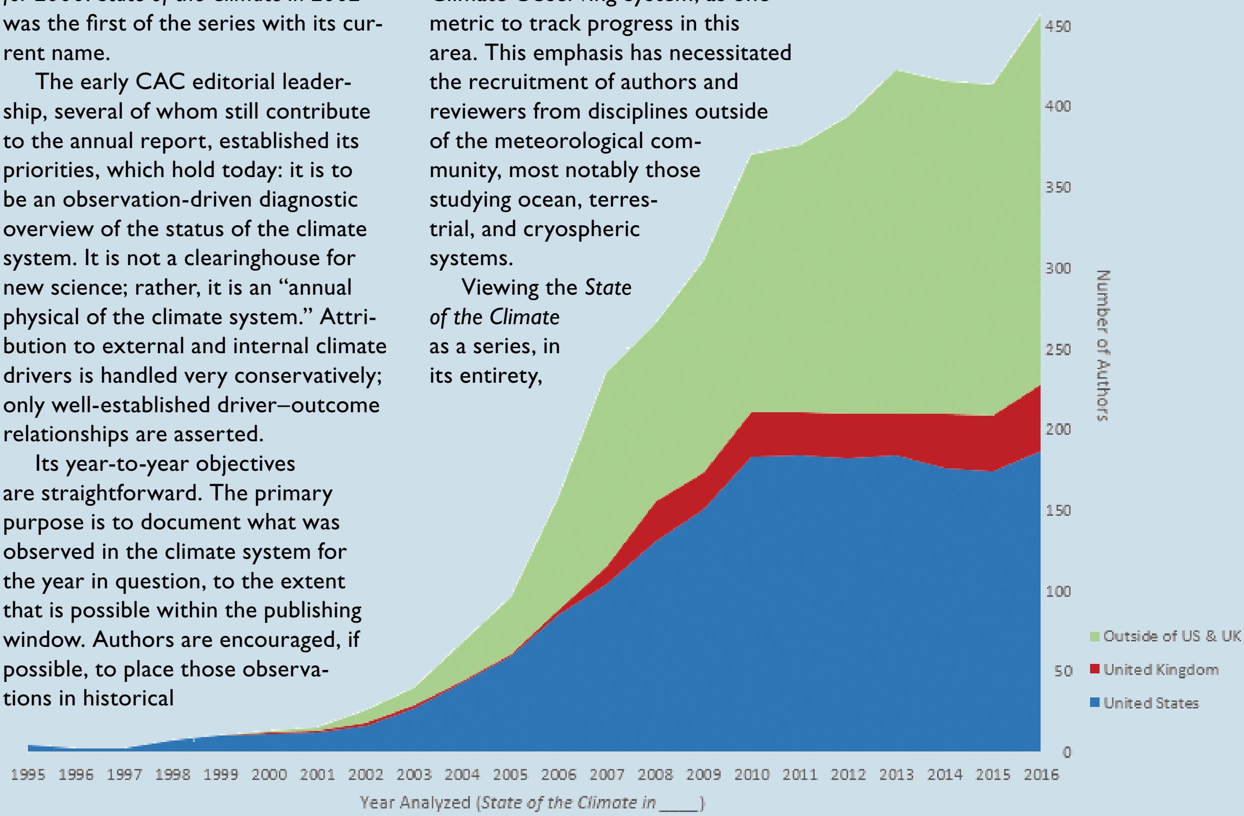
This is the twenty-seventh annual *State of the Climate* report. The series originated as an annual *Climate Assessment* published by NOAA's Climate Analysis Center (CAC), now the Climate Prediction Center. The first to be published in *BAMS* was the *Climate Assessment for 1995*. Editorial leadership transitioned to NOAA's National Climatic Data Center, now the National Centers for Environmental Information, with *Climate Assessment for 2000*. *State of the Climate in 2002* was the first of the series with its current name.

The early CAC editorial leadership, several of whom still contribute to the annual report, established its priorities, which hold today: it is to be an observation-driven diagnostic overview of the status of the climate system. It is not a clearinghouse for new science; rather, it is an "annual physical of the climate system." Attribution to external and internal climate drivers is handled very conservatively; only well-established driver–outcome relationships are asserted.

Its year-to-year objectives are straightforward. The primary purpose is to document what was observed in the climate system for the year in question, to the extent that is possible within the publishing window. Authors are encouraged, if possible, to place those observations in historical perspective, using standard climate monitoring tools such as anomalies, departures from a baseline, or measures of unusualness. To the extent that data allow it, assessments of longer-term trends are of value.

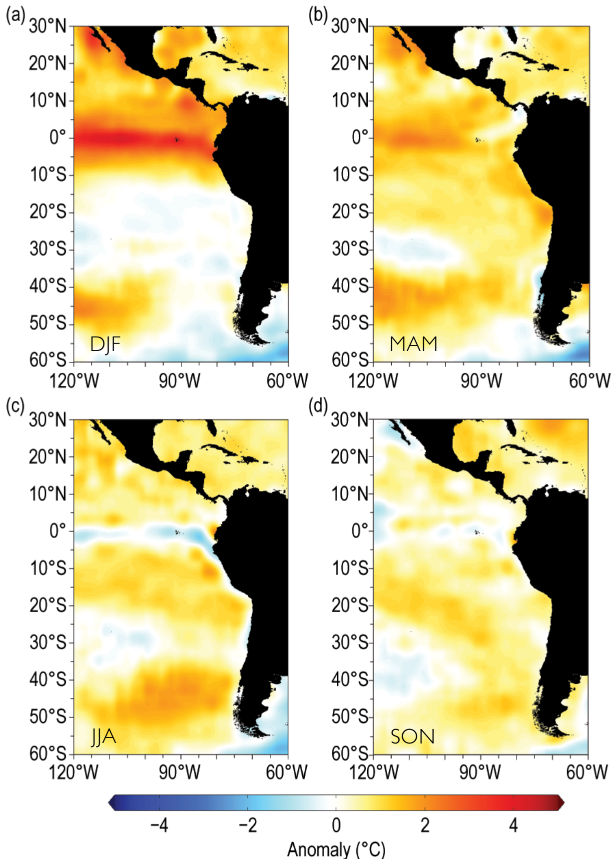
In the last decade, the *State of the Climate* has pursued a strategy of a more comprehensive assessment of the climate system (Rosenfeld 2015). It has used Essential Climate Variables, as defined by the Global Climate Observing System, as one metric to track progress in this area. This emphasis has necessitated the recruitment of authors and reviewers from disciplines outside of the meteorological community, most notably those studying ocean, terrestrial, and cryospheric systems.

Viewing the *State of the Climate* as a series, in its entirety, provides insights from something of a history-of-science perspective. As the document has grown, its authorship and leadership—not just its scope—have become more diverse. *State of the Climate* is now much more international, with authors from more than 60 countries this year. And, as a set, it tracks our capacity for, our commitment to, and our collaboration in observing the climate system.



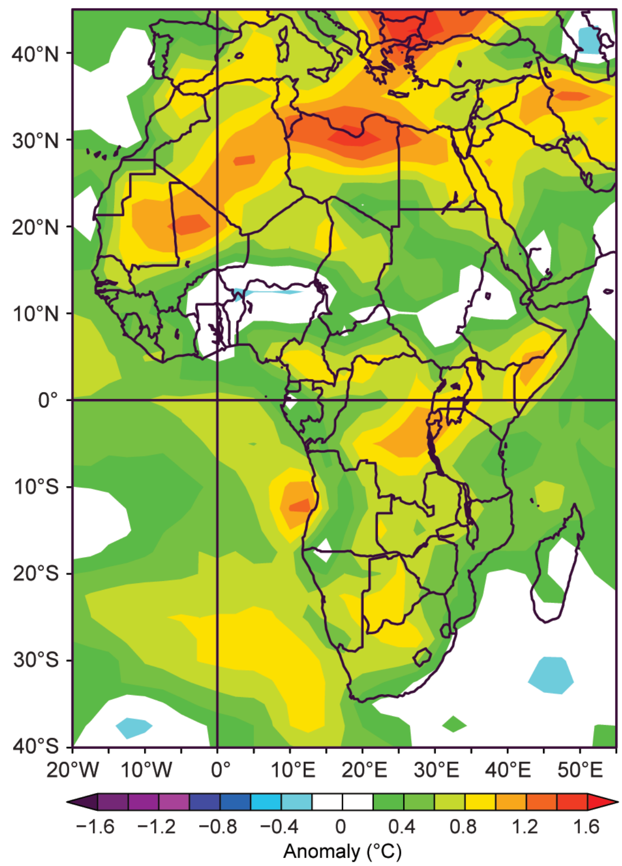
The number of authors, by national affiliation, for each edition of *State of the Climate* published by *BAMS*, from *Climate Assessment for 1995* through *State of the Climate in 2016*. Because a small number of authors in any given edition may be affiliated with institutions in multiple nations, this is not an exact author count.

Influential El Niño



Higher-than-normal Pacific equatorial SSTs contributed to Amazonian drought and wildfires, but also to record-setting rains in April in Argentina and Uruguay. El Niño eventually gave way to cooler or near-neutral equatorial conditions, but waters generally remained warm along the South American coast. SST anomalies here were calculated with 1971–2000 base period. (Fig. 7.12 in *State of the Climate in 2016*; see discussion there in section 7d.)

African Temperatures

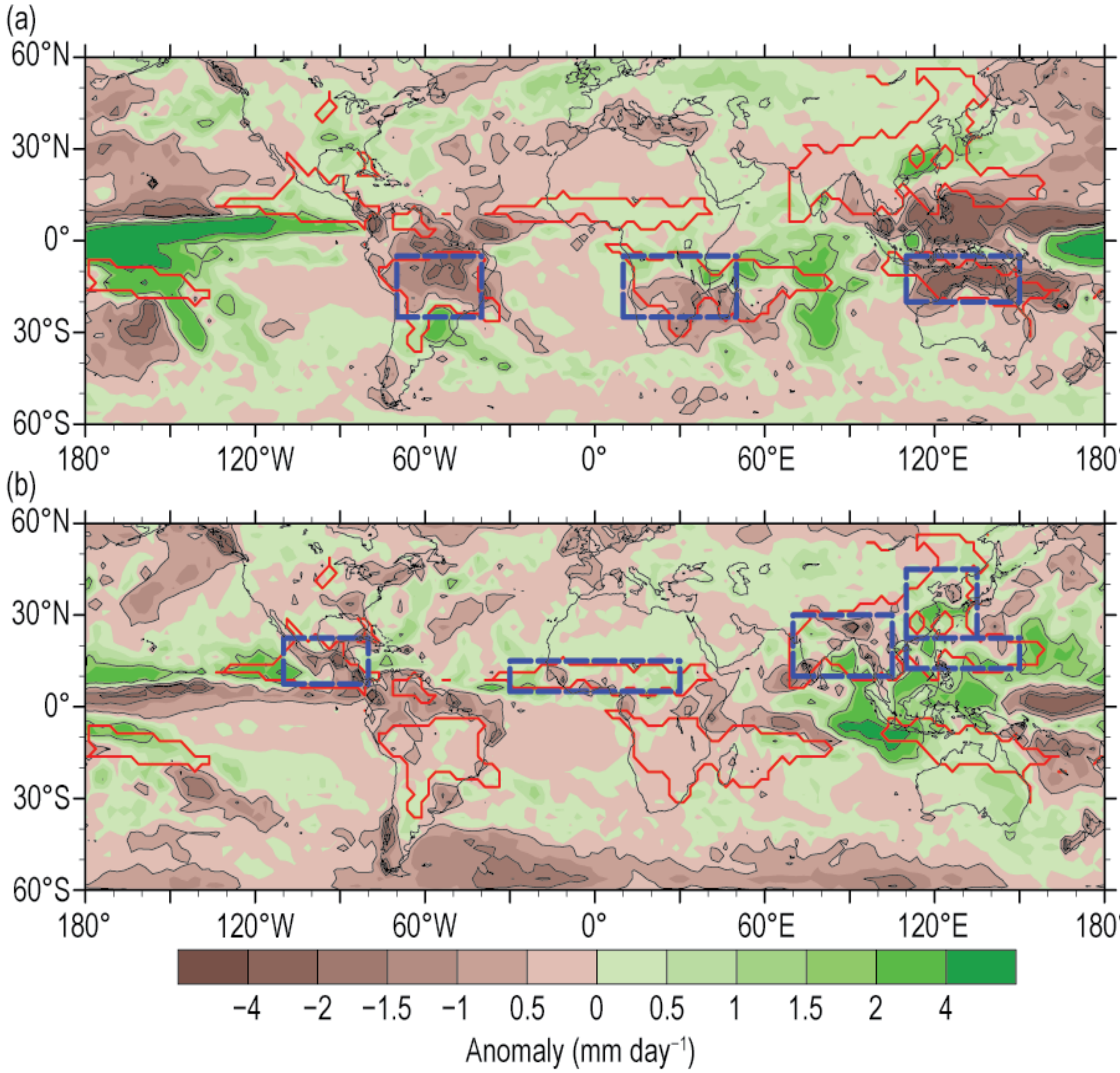


The above-average surface air temperature anomalies for 2016 in Africa included the second-highest annual mean (of a 66-year record) in South Africa and persistent summer heat waves in the north. Meanwhile, December brought an unusually severe cold snap to Ethiopia and Sudan. (Fig. 7.16 in the *State of the Climate in 2016*; see discussion there in section 7e.)

South America. The 2016 annual temperature was above normal across much of South America, including 2°–3°C above average in most of central South America, but cooler-than-average conditions were observed across southeastern Bolivia, Paraguay, southeastern Brazil, Uruguay, and central and northern Argentina. During 27–30 April, most of Paraguay was affected by its most intense cold wave in 57 years. It was dry in several areas. In northeastern Brazil, strong anomalous negative soil moisture and drought conditions were observed for the fifth consecutive year, making this the longest drought on record in this region. Dry conditions were also observed in western Bolivia and Peru, causing severe wildfires and water supply shortages. It was Bolivia's worst drought in the past 25 years. Wet conditions were observed throughout the year across southern South America, causing repeated heavy flooding in Argentina, Paraguay, and Uruguay.

Africa. In 2016, most of Africa experienced above-average temperatures. Several stations in Morocco reported temperatures among their highest since the start of their records in 1960. In Egypt, maximum temperatures reached 48°C on 27 and 28 May at Luxor. Record high temperatures were observed over Guinea, southern Mali, and Sierra Leone in August. South Africa reported the second-warmest year in its 66-year record. In the western Indian Ocean, Mauritius was record warm for 2016, while Mayotte and Comoros Islands each reported their second-warmest year. Generally, rainfall over the region covering 7.5°–15°N was above average, whereas it was below average over most of equatorial Africa and south of the equator. The strong El Niño at

A Tale of Two Monsoon Seasons



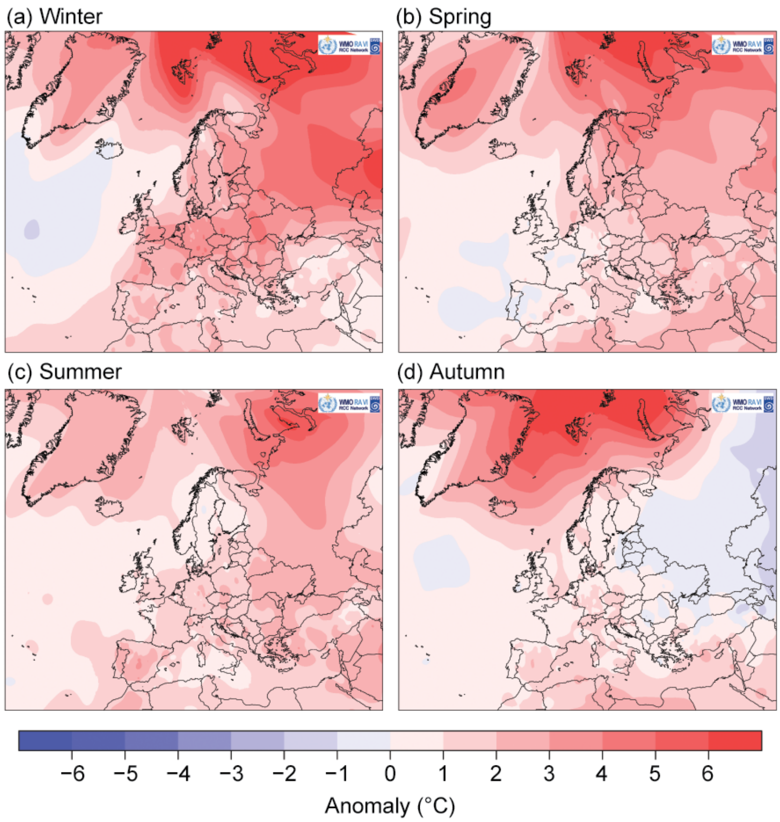
Global land monsoon precipitation is strongly influenced by ENSO, which evolved from the peak of a strong El Niño at the start of the SH monsoon season to a weak La Niña by the end of the following NH monsoon season.

The SH precipitation anomalies averaged for (a) November 2015–April 2016 were notably negative in many regions. In (b) May–October 2016 the anomalies were reversed in the NH monsoon season. The red lines outline the global monsoon precipitation domain that is defined by 1) the annual range (local summer minus winter) precipitation exceeding 300 mm and 2) the summer mean precipitation exceeding 55% of the total annual precipitation amount. Here the local summer denotes May–September for the NH and November–March for the SH. The precipitation indices for each regional monsoon are defined by the areal mean precipitation in the corresponding rectangular regions (dashed blue). (Fig. 4.18 in *State of the Climate in 2016*; see discussion there in section 4e.)

the beginning of 2016 contributed to drought in the first months of the year in southern Africa.

Europe and the Middle East. The annual land surface temperature for Europe was the third highest in the record dating to 1851, with a +1.41°C departure from the 1961–90 average. A long list of record temperatures in 2016 in European Russia including its warmest winter [December–February (DJF) 2015/16] since national records began in 1891; seasonal departures ranged up to +6°C. In June, daily maximum temperature records were set in Israel, surpassing 44°C, more than +1°C higher than any previous record in the 67-year history. In early autumn Switzerland had its warmest

Warmth in Europe



Europe and the Middle East were largely warmer than normal in 2016, as seen in near-surface air temperature anomalies (°C) for Europe and the Middle East using interpolated CLIMAT data from the German Weather Service (Deutscher Wetterdienst; 1961–90 base period) for (a) DJF (winter), (b) March–May (MAM; spring), (c) June–August (JJA; summer), and (d) September–November (SON; autumn). (Fig. 7.37 in *State of the Climate in 2016*; see discussion there in section 7f.)

September in its 153-year record, Germany reported 95 sites with new monthly records, and France observed temperatures up to 7°C above average. Several strong storms were reported across the continent. Norway was hit by several storms in January alone, and a new record wind speed of 48.9 m s^{-1} was measured on 29 January at Krakenes, north of Bergen. On 23 June, the Netherlands reported hailstones up to 10 cm in its province of Brabant, causing approximately $530 million U.S. dollars in damages.

Asia. Annual mean surface temperatures were above normal across most of Asia and Siberia in 2016, especially north of 60°N. India, South Korea, and Singapore each observed their warmest year on record, as did eastern Japan. China reported its third-warmest year since national records began in 1951. However, there was anomalous cold over parts of the continent: in January, −55.0°C was observed at Otgon station in western Mongolia, the second-lowest absolute minimum temperature for the country since records began in 1961. Wetter-than-usual conditions in central Asia alleviated the 2014/15 drought in southern Russia. The summer monsoon (June–September) typically contributes about 75% of South Asia's annual precipitation. The monsoon set in over Kerala, in southwestern India, on 8 June, seven days later than average; it covered the entire country by 13 July, two days earlier than normal. Monsoon seasonal rainfall over India was 97% of its 1951–2000 average. Hong Kong observed its wettest autumn on record.

Oceania. New Zealand observed its warmest year since its national records began in 1909, while Australia reported its fourth-warmest in its 107-year record. In February, Severe Tropical Cyclone Winston (category 5) became one of the strongest tropical cyclones to make landfall in the southwest Pacific in recorded history. Winston killed 44 people and damaged or destroyed about 40,000 homes in Fiji on 20 February, with about 40% of the nation's population significantly impacted by the storm. Damage in Fiji alone was estimated to be $1.4 billion U.S. dollars. Across Micronesia, annual rainfall totals were mostly below average, setting some new all-time dry records, particularly in October 2015–March 2016. In the southwest Pacific the El Niño likely had its greatest impact in Vanuatu, where annual rainfall was the lowest on record at Lamap (1,197 mm) and Port Vila (956 mm), since 1961 and 1953, respectively, and was in the lowest 10% of observations at the other five observation stations on the island. From May through the end of the year, a strong negative Indian Ocean dipole event developed, contributing to Australia's wettest May–October in the 117-year record.

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