

Executive Summary

Global mean surface temperatures have risen by $0.74^{\circ}\text{C} \pm 0.18^{\circ}\text{C}$ when estimated by a linear trend over the last 100 years (1906–2005). The rate of warming over the last 50 years is almost double that over the last 100 years ($0.13^{\circ}\text{C} \pm 0.03^{\circ}\text{C}$ vs. $0.07^{\circ}\text{C} \pm 0.02^{\circ}\text{C}$ per decade). Global mean temperatures averaged over land and ocean surfaces, from three different estimates, each of which has been independently adjusted for various homogeneity issues, are consistent within uncertainty estimates over the period 1901 to 2005 and show similar rates of increase in recent decades. The trend is not linear, and the warming from the first 50 years of instrumental record (1850–1899) to the last 5 years (2001–2005) is $0.76^{\circ}\text{C} \pm 0.19^{\circ}\text{C}$.

2005 was one of the two warmest years on record. The warmest years in the instrumental record of global surface temperatures are 1998 and 2005, with 1998 ranking first in one estimate, but with 2005 slightly higher in the other two estimates. 2002 to 2004 are the 3rd, 4th and 5th warmest years in the series since 1850. Eleven of the last 12 years (1995 to 2006) – the exception being 1996 – rank among the 12 warmest years on record since 1850. Surface temperatures in 1998 were enhanced by the major 1997–1998 El Niño but no such strong anomaly was present in 2005. Temperatures in 2006 were similar to the average of the past 5 years.

Land regions have warmed at a faster rate than the oceans. Warming has occurred in both land and ocean domains, and in both sea surface temperature (SST) and nighttime marine air temperature over the oceans. However, for the globe as a whole, surface air temperatures over land have risen at about double the ocean rate after 1979 (more than 0.27°C per decade vs. 0.13°C per decade), with the greatest warming during winter (December to February) and spring (March to May) in the Northern Hemisphere.

Changes in extremes of temperature are also consistent with warming of the climate. A widespread reduction in the number of frost days in mid-latitude regions, an increase in the number of warm extremes and a reduction in the number of daily cold extremes are observed in 70 to 75% of the land regions where data are available. The most marked changes are for cold (lowest 10%, based on 1961–1990) nights, which have become rarer over the 1951 to 2003 period. Warm (highest 10%) nights have become more frequent. Diurnal temperature range (DTR) decreased by 0.07°C per decade averaged over 1950 to 2004, but had little change from 1979 to 2004, as both maximum and minimum temperatures rose at similar rates. The record-breaking heat wave over western and central Europe in the summer of 2003 is an example of an exceptional recent extreme. That summer (June to August) was the hottest since comparable instrumental records began around 1780 (1.4°C above the previous warmest in 1807) and is very likely to have been the hottest since at least 1500.

Recent warming is strongly evident at all latitudes in SSTs over each of the oceans. There are inter-hemispheric differences in warming in the Atlantic, the Pacific is punctuated by El Niño events and Pacific decadal variability that is more symmetric about the equator, while the Indian Ocean exhibits steadier warming. These characteristics lead to important differences in regional rates of surface ocean warming that affect the atmospheric circulation.

Urban heat island effects are real but local, and have not biased the large-scale trends. A number of recent studies indicate that effects of urbanisation and land use change on the land-based temperature record are negligible (0.006°C per decade) as far as hemispheric- and continental-scale averages are concerned because the very real but local effects are avoided or accounted for in the data sets used. In any case, they are not present in the SST component of the record. Increasing evidence suggests that urban heat island effects extend to changes in precipitation, clouds and DTR, with these detectable as a 'weekend effect' owing to lower pollution and other effects during weekends.

Average arctic temperatures increased at almost twice the global average rate in the past 100 years. Arctic temperatures have high decadal variability. A slightly longer warm period, almost as warm as the present, was also observed from the late 1920s to the early 1950s, but appears to have had a different spatial distribution than the recent warming.

Lower-tropospheric temperatures have slightly greater warming rates than those at the surface over the period 1958 to 2005. The radiosonde record is markedly less spatially complete than the surface record and increasing evidence suggests that it is very likely that a number of records have a cooling bias, especially in the tropics. While there remain disparities among different tropospheric temperature trends estimated from satellite Microwave Sounding Unit (MSU and advanced MSU) measurements since 1979, and all likely still contain residual errors, estimates have been substantially improved (and data set differences reduced) through adjustments for issues of changing satellites, orbit decay and drift in local crossing time (i.e., diurnal cycle effects). It appears that the satellite tropospheric temperature record is broadly consistent with surface temperature trends provided that the stratospheric influence on MSU channel 2 is accounted for. The range (due to different data sets) of global surface warming since 1979 is 0.16°C to 0.18°C per decade compared to 0.12°C to 0.19°C per decade for MSU estimates of tropospheric temperatures. It is likely, however, that there is slightly greater warming in the troposphere than at the surface, and a higher tropopause, with the latter due also to pronounced cooling in the stratosphere.

Lower stratospheric temperatures feature cooling since 1979. Estimates from adjusted radiosondes, satellites (MSU channel 4) and reanalyses are in qualitative agreement, suggesting a lower-stratospheric cooling of between 0.3°C and 0.6°C per decade since 1979. Longer radiosonde records (back

to 1958) also indicate cooling but the rate of cooling has been significantly greater since 1979 than between 1958 and 1978. It is likely that radiosonde records overestimate stratospheric cooling, owing to changes in sondes not yet accounted for. Because of the stratospheric warming episodes following major volcanic eruptions, the trends are far from being linear.

Precipitation has generally increased over land north of 30°N over the period 1900 to 2005 but downward trends dominate the tropics since the 1970s. From 10°N to 30°N, precipitation increased markedly from 1900 to the 1950s, but declined after about 1970. Downward trends are present in the deep tropics from 10°N to 10°S, especially after 1976/1977. Tropical values dominate the global mean. It has become significantly wetter in eastern parts of North and South America, northern Europe, and northern and central Asia, but drier in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Patterns of precipitation change are more spatially and seasonally variable than temperature change, but where significant precipitation changes do occur they are consistent with measured changes in streamflow.

Substantial increases are found in heavy precipitation events. It is likely that there have been increases in the number of heavy precipitation events (e.g., 95th percentile) within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate and observed significant increasing amounts of water vapour in the atmosphere. Increases have also been reported for rarer precipitation events (1 in 50 year return period), but only a few regions have sufficient data to assess such trends reliably.

Droughts have become more common, especially in the tropics and subtropics, since the 1970s. Observed marked increases in drought in the past three decades arise from more intense and longer droughts over wider areas, as a critical threshold for delineating drought is exceeded over increasingly widespread areas. Decreased land precipitation and increased temperatures that enhance evapotranspiration and drying are important factors that have contributed to more regions experiencing droughts, as measured by the Palmer Drought Severity Index. The regions where droughts have occurred seem to be determined largely by changes in SSTs, especially in the tropics, through associated changes in the atmospheric circulation and precipitation. In the western USA, diminishing snow pack and subsequent reductions in soil moisture also appear to be factors. In Australia and Europe, direct links to global warming have been inferred through the extreme nature of high temperatures and heat waves accompanying recent droughts.

Tropospheric water vapour is increasing. Surface specific humidity has generally increased after 1976 in close association with higher temperatures over both land and ocean. Total column water vapour has increased over the global oceans by $1.2 \pm 0.3\%$ per decade from 1988 to 2004, consistent in pattern

and amount with changes in SST and a fairly constant relative humidity. Strong correlations with SST suggest that total column water vapour has increased by 4% since 1970. Similar upward trends in upper-tropospheric specific humidity, which considerably enhance the greenhouse effect, have also been detected from 1982 to 2004.

'Global dimming' is neither global in extent nor has it continued after 1990. Reported decreases in solar radiation at the Earth's surface from 1970 to 1990 have an urban bias and have reversed in sign. Although records are sparse, pan evaporation is estimated to have decreased in many places due to decreases in surface radiation associated with increases in clouds, changes in cloud properties and/or increases in air pollution (aerosols), especially from 1970 to 1990. However, in many of the same places, actual evapotranspiration inferred from surface water balance exhibits an increase in association with enhanced soil wetness from increased precipitation, as the actual evapotranspiration becomes closer to the potential evaporation measured by the pans. Hence, in determining evapotranspiration there is a trade-off between less solar radiation and increased surface wetness, with the latter generally dominant.

Cloud changes are dominated by the El Niño-Southern Oscillation and appear to be opposite over land and ocean. Widespread (but not ubiquitous) decreases in continental DTR since the 1950s coincide with increases in cloud amounts. Surface and satellite observations disagree about total and low-level cloud changes over the ocean. However, radiation changes at the top of the atmosphere from the 1980s to 1990s, possibly related in part to the El Niño-Southern Oscillation (ENSO) phenomenon, appear to be associated with reductions in tropical upper-level cloud cover, and are linked to changes in the energy budget at the surface and changes in observed ocean heat content.

Changes in the large-scale atmospheric circulation are apparent. Atmospheric circulation variability and change is largely described by relatively few major patterns. The dominant mode of global-scale variability on interannual time scales is ENSO, although there have been times when it is less apparent. The 1976–1977 climate shift, related to the phase change in the Pacific Decadal Oscillation and more frequent El Niños, has affected many areas and most tropical monsoons. For instance, over North America, ENSO and Pacific-North American teleconnection-related changes appear to have led to contrasting changes across the continent, as the west has warmed more than the east, while the latter has become cloudier and wetter. There are substantial multi-decadal variations in the Pacific sector over the 20th century with extended periods of weakened (1900–1924; 1947–1976) as well as strengthened circulation (1925–1946; 1976–2005). Multi-decadal variability is also evident in the Atlantic as the Atlantic Multi-decadal Oscillation in both the atmosphere and the ocean.

Mid-latitude westerly winds have generally increased in both hemispheres. These changes in atmospheric circulation are predominantly observed as ‘annular modes’, related to the zonally averaged mid-latitude westerlies, which strengthened in most seasons from the 1960s to at least the mid-1990s, with poleward displacements of corresponding Atlantic and southern polar front jet streams and enhanced storm tracks. These were accompanied by a tendency towards stronger winter polar vortices throughout the troposphere and lower stratosphere. On monthly time scales, the southern and northern annular modes (SAM and NAM, respectively) and the North Atlantic Oscillation (NAO) are the dominant patterns of variability in the extratropics and the NAM and NAO are closely related. The westerlies in the Northern Hemisphere, which increased from the 1960s to the 1990s but which have since returned to about normal as part of NAO and NAM changes, alter the flow from oceans to continents and are a major cause of the observed changes in winter storm tracks and related patterns of precipitation and temperature anomalies, especially over Europe. In the Southern Hemisphere, SAM increases from the 1960s to the present are associated with strong warming over the Antarctic Peninsula and, to a lesser extent, cooling over parts of continental Antarctica. Analyses of wind and significant wave height support reanalysis-based evidence for an increase in extratropical storm activity in the Northern Hemisphere in recent decades until the late 1990s.

Intense tropical cyclone activity has increased since about 1970. Variations in tropical cyclones, hurricanes and typhoons are dominated by ENSO and decadal variability, which result in a redistribution of tropical storm numbers and their tracks, so that increases in one basin are often compensated by decreases over other oceans. Trends are apparent in SSTs and other critical variables that influence tropical thunderstorm and tropical storm development. Globally, estimates of the potential destructiveness of hurricanes show a significant upward trend since the mid-1970s, with a trend towards longer lifetimes and greater storm intensity, and such trends are strongly correlated with tropical SST. These relationships have been reinforced by findings of a large increase in numbers and proportion of hurricanes reaching categories 4 and 5 globally since 1970 even as total number of cyclones and cyclone days decreased slightly in most basins. The largest increase was in the North Pacific, Indian and southwest Pacific Oceans. However, numbers of hurricanes in the North Atlantic have also been above normal (based on 1981–2000 averages) in 9 of the last 11 years, culminating in the record-breaking 2005 season. Moreover, the first recorded tropical cyclone in the South Atlantic occurred in March 2004 off the coast of Brazil.

The temperature increases are consistent with observed changes in the cryosphere and oceans. Consistent with observed changes in surface temperature, there has been an almost worldwide reduction in glacier and small ice cap (not including Antarctica and Greenland) mass and extent in the

20th century; snow cover has decreased in many regions of the Northern Hemisphere; sea ice extents have decreased in the Arctic, particularly in spring and summer (Chapter 4); the oceans are warming; and sea level is rising (Chapter 5).