
Observed climate variability and change

Chris K. Folland¹, Thomas R. Karl² and M. Jim Salinger³

¹ Met Office Hadley Centre, Bracknell, UK

² National Climate Data Center, Asheville, USA

³ National Institute for Water and Atmospheric Research, Auckland, New Zealand

An overview is presented of the more prominent conclusions of the “Observed climate variability and change” chapter (Chapter 2) of the Science Report of the *Third Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC) (IPCC 2001). Readers requiring more detail can also access Chapter 2 on the IPCC website at: <http://www.ipcc.ch/pub/tar/wg1/index.htm>.

The scope of the chapter

Observed climate change and variability (definitions in the IPCC Glossary, Appendix I of IPCC 2001) are considered by addressing seven commonly asked questions related to the detection of climate change and sensitivity of the climate to anthropogenic activity. The questions are:

- (i) How much is the world warming?
- (ii) Is the recent warming unusual?

- (iii) How rapidly did climate change in the distant past?
- (iv) Have precipitation and atmospheric moisture changed?
- (v) Are the atmospheric/oceanic circulations changing?
- (vi) Has climate variability, or have climate extremes, changed?
- (vii) Are the observed trends internally consistent?

Chapter 2 emphasises change against a background of variability. The certainty of conclusions that can be drawn about climate from observations depends critically on the availability of accurate, complete and consistent series of observations. For many variables important in documenting, detecting, and attributing climate change, data are still not good enough for really firm conclusions to be reached. This especially applies to global trends in variables that have large regional variations, such as pre-

precipitation, although conclusions about temperature changes are often considerably more firmly based. Nevertheless, new datasets have widened the range of conclusions that can be drawn since the *Second IPCC Assessment Report* (IPCC 1996). A wider range of analytical techniques and tests of the data have also increased our confidence in areas such as surface temperature changes.

How much is the world warming?

Temperature changes at the surface since 1861

Figure 1 shows the extent of the consistency between changes in sea surface temperature (SST), land surface air temperature (LSAT) and air temperature measured over the oceans at night (night marine air temperature (NMAT)) over the period 1861–2000. The greater warming of LSAT in recent decades is clear, but otherwise all three curves have a generally similar shape except that modest cooling of NMAT in the late nineteenth century is not seen in the SST data. The relative coldness of the land

around 1885 to 1895 derives from the Northern Hemisphere continental interiors, particularly in winter, as global coastal land air temperature and adjacent SST anomalies agree well at this time. There are some systematic compensating differences between LSAT and SST in the late nineteenth century in both hemispheres.

Chapter 2 provides a new set of objective estimates of uncertainties in annual and decadal global surface temperature anomalies based on LSAT and SST (the major uncertainties come from uncertainties in systematic measurement biases). Figure 2 shows annual optimally averaged global and hemispheric anomalies and their uncertainties. Annual values based on area weighting are also shown. Noteworthy is the fact that 1998 was the warmest year, and recent data indicate that the eight warmest years have all occurred between 1990 and 2001. Note that 1998 was influenced by the strong 1997/98 El Niño; the warming influence of El Niño on global temperature is empirically well attested. However, 1998 was considerably and highly statistically significantly warmer

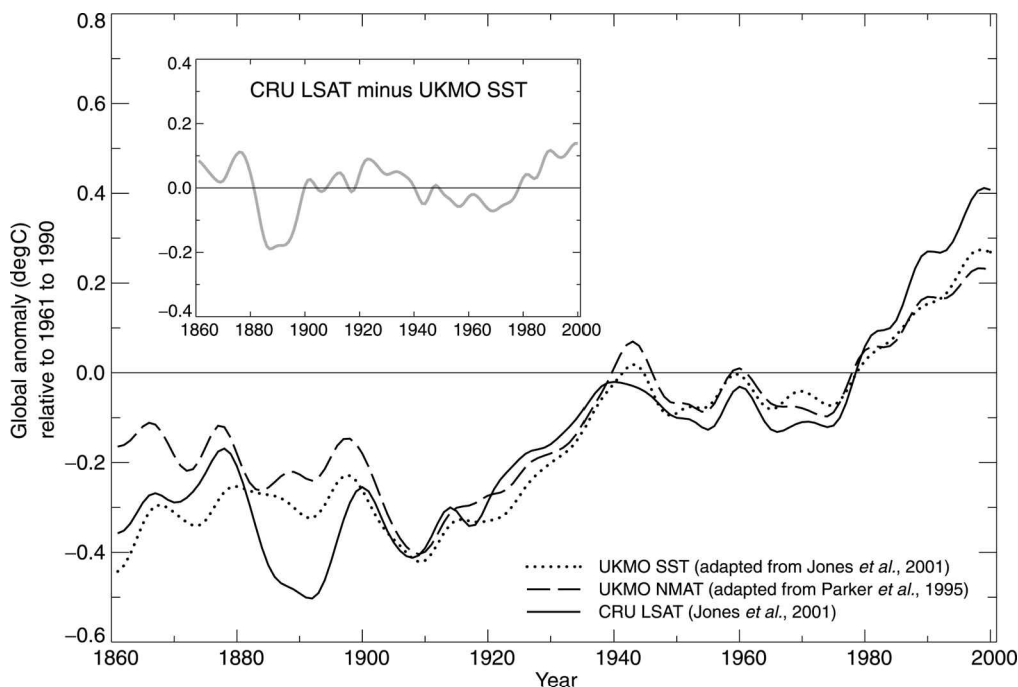


Fig. 1 Smoothed annual anomalies of global average sea surface temperature (SST) (degC), 1861–2000 relative to 1961–90 (dotted), night marine air temperature (NMAT) (dashed), and land-surface air temperature (LSAT) (solid). The smoothed curves were created by using a 21-point binomial filter giving near-decadal averages. Also shown (inset) are smoothed differences between LSAT and SST anomalies.

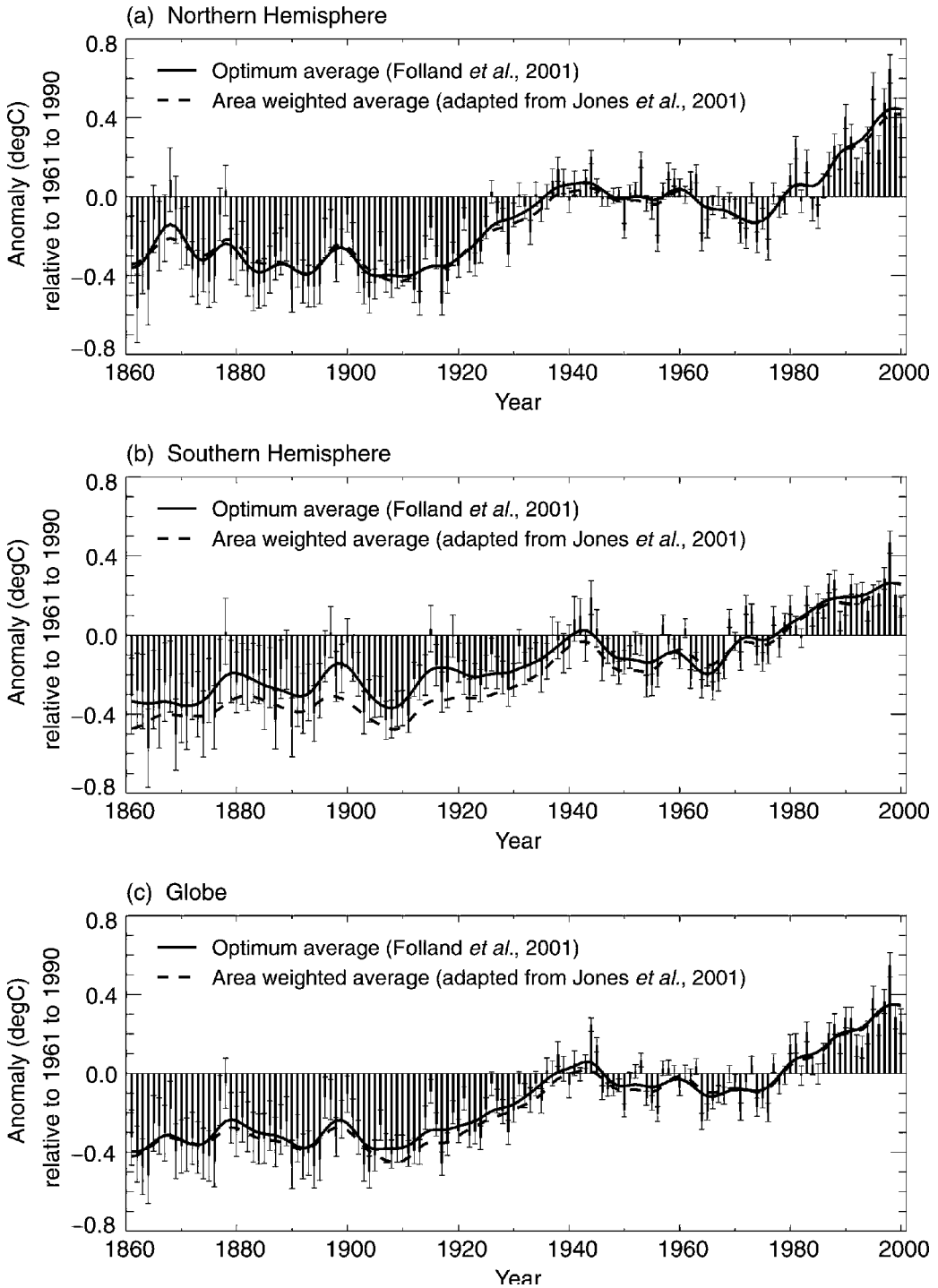


Fig. 2 Unsmoothed and smoothed combined annual land surface air and sea surface temperature anomalies (degC), 1861–2000 relative to 1961–90, calculated using optimum averages (bars and solid smoothed curves) for (a) Northern Hemisphere, (b) Southern Hemisphere, and (c) globe. The dashed smoothed curves are corresponding area-weighted averages.

than 1983, a year warmed by the comparable 1982/83 El Niño. Recent data indicate that 2001 was the second warmest year in the record, with no warming influences from El Niño.

The global trend from 1861 to 2000 can be cautiously interpreted as an equivalent linear warming of 0.61 degC over the 140-year period with a 95% confidence level uncertainty of ± 0.16 degC. From 1901 an equivalent warming of 0.57 degC has occurred with an uncertainty of ± 0.17 degC. These results led to the key conclusion that the best estimate of global surface temperature change is a 0.6 degC increase since the late nineteenth century with a 95% confidence interval of 0.4 to 0.8 degC. This represents an overall increase in temperature change of 0.15 degC compared to that assessed in IPCC (1996). The increase is partly due to the additional data for 1995–2000, improved methods of analysis, and because IPCC (1996) decided not to change the value in the *First IPCC Assessment Report* published in 1990, despite slight additional warming.

Twentieth-century temperature trends show a broad pattern of tropical warming, while extratropical trends have been more variable. Warming from 1910 to 1945 was initially concentrated in the North Atlantic and nearby regions. The Northern Hemisphere shows cooling during the period 1946 to 1975, while the Southern Hemisphere shows some warming. The recent 1976 to 2000 warming was largely globally synchronous, but emphasised in the Northern Hemisphere continents during winter and spring, with slight year-round cooling in parts of the Southern Hemisphere oceans and Antarctica. North Atlantic cooling between about 1960 and 1985 has recently reversed. Overall, warming over the Southern Hemisphere has been more uniform during the instrumental record than that over the Northern Hemisphere.

There is also evidence for a faster rise in night-time than daytime temperatures over many continental areas over the period 1950–93 for which sufficient data exist, though some, mainly coastal, regions do not show this behaviour. The rate of temperature increase during this period (for land areas sampled, considerably less than global in extent) was near

0.1 degC/decade and 0.2 degC/decade for maxima and minima, respectively. A partial cause is the likely increase in cloudiness over the same period, which would suppress daytime maxima and increase minima.

Recent temperature changes above the surface

There has been much controversy about apparent differences in the rate of warming of the surface and the atmosphere in the low to mid-troposphere. Analysis of global temperature trends since 1958 in the low to mid-troposphere from balloons shows a warming of about +0.1 degC/decade, which is similar to the average rate of warming at the surface. Since the early 1960s no significant trends have been detected for the global mean temperature in the uppermost troposphere. Satellites have been available only since 1979. Between 1979 and 2000, based on satellites and balloons, the lower-tropospheric trend has been small. By contrast, surface temperature trends for 1979 to 2000 were significantly positive, at 0.16 ± 0.06 degC/decade. The trend in the difference of the surface and lower-tropospheric series of 0.13 ± 0.06 degC/decade is statistically significant. This is in contrast to near-zero surface temperature trends over 1958–78 when the global lower-tropospheric temperature rose by 0.03 degC/decade relative to the surface. It is very likely that these significant differences in trends between the surface and lower troposphere are real. The differences are particularly apparent in many parts of the tropics and subtropics where the surface has warmed faster than the lower troposphere since 1979. In some other regions, *e.g.* North America, Europe and Australia, lower-tropospheric and surface trends are very similar over this period. These multidecadal differences in trend between the surface and the lower troposphere have caused much controversy and research but a full explanation is still not available.

Temperature changes within the ocean

The rate at which the ocean is warming is potentially very important for quantifying the global net radiation imbalance at the surface.

New analyses, particularly by Levitus *et al.* (2000b), of the increasing number of accessible sub-surface ocean temperature data show that the global ocean heat content has increased since the late 1950s. This increase is superimposed on substantial global decadal variability. More than half the heating is contained in the uppermost 300 m where it is equivalent to an average temperature increase of 0.037 degC/decade. Extension of the analysis to the upper 3000 m shows that similar changes in heat content have occurred over intermediate and deep waters in all the basins, especially in the North and South Atlantic and the south Indian Oceans. The change in global ocean heat content from the 1950s to the 1990s is equivalent to a net downward surface heat flux of 0.3 W m^{-2} over the whole period.

Is the recent warming unusual?

A major development has been quantitative

estimates of large-scale temperature changes over the past millennium using mostly non-instrumental or 'proxy' data such as tree rings, corals, borehole temperatures, etc. Figure 3 shows several recent analyses. The main conclusion is that the magnitude of Northern Hemisphere warming over the twentieth century is likely to have been the largest of any century in the last 1000 years. The 1990s are also likely to have been the warmest decade of the millennium in the Northern Hemisphere and 1998 is likely to have been the warmest year. Because fewer data are available, less is known about annual averages prior to 1000 years before the present and for conditions prevailing in most of the Southern Hemisphere prior to 1861. Importantly, the evidence does not support the existence of globally synchronous periods of cooling or warming associated with the 'Little Ice Age' and 'Medieval Warm Period'. However, reconstructed Northern Hemisphere temperatures in Fig. 3 do show a

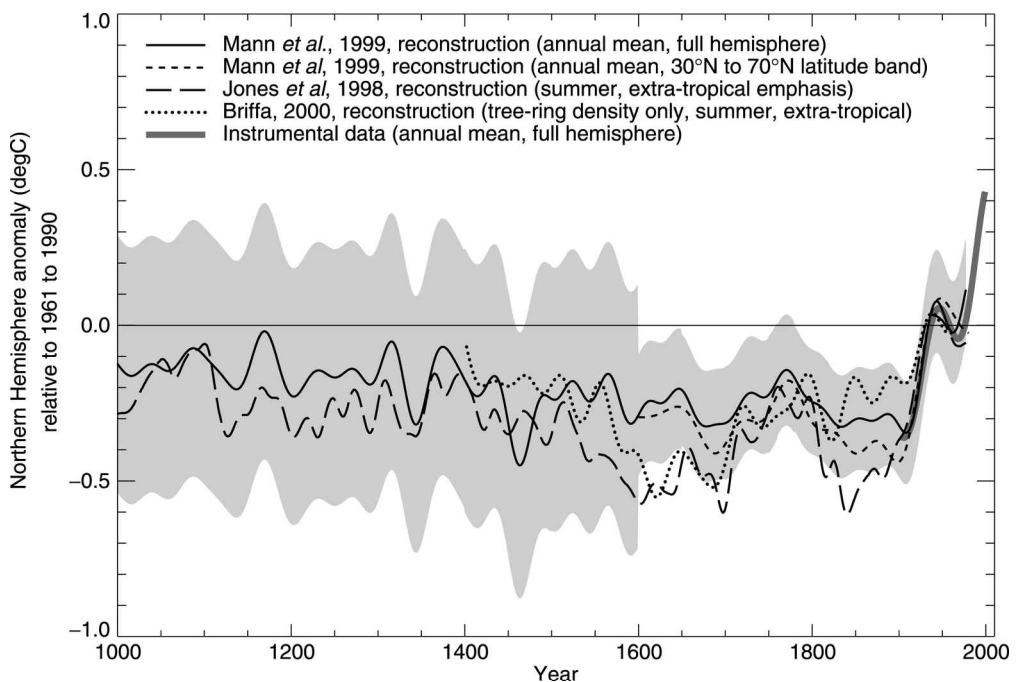


Fig. 3 Comparison of warm season (Jones *et al.* 1998) and annual mean (Mann *et al.* 1999) multiproxy-based and warm season tree-ring-based (Briffa 2000) millennial Northern Hemisphere temperature reconstructions. The recent instrumental annual mean Northern Hemisphere temperature record to 1999 is shown for comparison. Also shown is an extratropical sampling of the Mann *et al.* (1999) temperature pattern reconstructions more directly comparable in its latitudinal sampling emphasis to the Jones *et al.* series. The self-consistently estimated 2 standard error limits (shaded region) for the smoothed Mann *et al.* (1999) series are shown. The horizontal zero line denotes the 1961–90 reference period mean temperature. All the series were smoothed with a 40-year Hanning-weights low-pass filter, with boundary constraints imposed by padding the series with its mean values during the first and last 25 years.

cooling during the fifteenth to nineteenth centuries and a relatively warm period during the eleventh to fourteenth centuries, though the latter period is still cooler than the late twentieth century.

How rapidly did climate change in the distant past?

It is very likely that large and rapid decadal temperature changes occurred during the last glacial and its deglaciation (between about 100 000 and 10 000 years ago), particularly in higher latitudes of the Northern Hemisphere. During the last deglaciation, local increases in temperature are likely to have been as large as 5 to 10 degC over several decades. For the same period there is evidence of less pronounced but nearly synchronous changes worldwide, except in high southern latitudes. Over the past 420 000 years, Antarctic ice cores have provided new evidence of striking almost in-phase changes of temperature, carbon dioxide and methane through the ice age cycles (Fig. 2.22 of Chapter 2). This suggests a close link between surface temperature and greenhouse gases over a long period before the influence of human activities. Finally, there is emerging evidence for significant, rapid (time-scales of several decades or more), regional temperature changes during the last 10 000 years, well before the period for which anthropogenic influences could have been important (Fig. 2.24 of Chapter 2). However, the evidence does not indicate that any such events were global in scale.

Have precipitation and atmospheric moisture changed?

Instrumental records of land surface precipitation show an increase of 0.5 to 1%/decade in much of the Northern Hemisphere midlatitudes and high latitudes. In contrast, over much of the subtropical land areas rainfall has decreased during the twentieth century (by 0.3%/decade), but this trend has weakened in recent decades. Other precipitation indicators suggest that some large parts of the tropical oceans have had more precipitation in recent decades, and that precipitation has significantly

increased over tropical land areas during the twentieth century as a whole (2.4%/century). The increase in precipitation over the tropics is not evident during the past few decades. In the Southern Hemisphere, the pattern of island rainfall in parts of the South Pacific has changed since the mid-1970s, associated with the more frequent occurrence of the warm phase of the El Niño Southern Oscillation (ENSO).

Changes in water vapour mixing ratio have been analysed for selected regions using *in situ* surface observations as well as lower-tropospheric measurements based on satellites and weather balloons. A pattern of overall surface and lower-tropospheric water vapour mixing ratio increases over the past few decades is emerging, although there are likely to be some time-dependent biases in these data and regional variations in trends. The more reliable datasets indicate that it is likely that total atmospheric water vapour has increased by several per cent per decade over many regions of the Northern Hemisphere since the early 1970s. Changes over the Southern Hemisphere cannot yet be assessed.

Balloon observations of stratospheric water vapour above 18 km show an increase of about 1%/year for the period from 1981 to 2000. Shorter satellite records show a similar positive trend, suggesting that the change is global in character, but they also indicate a slowing of the positive trend after 1996.

Are the atmospheric/oceanic circulations changing?

ENSO and related variations

The frequency and intensity of ENSO has been unusual since the mid-1970s compared with the previous 100 years. Warm-phase ENSO episodes have been relatively more frequent, persistent, or intense than the opposite cold phase during this period but it is not known whether this behaviour is linked to global warming. This late twentieth-century behaviour of ENSO is related to variations in precipitation and temperature over much of the global tropics and subtropics and some midlatitude areas. The overall effect is likely to have made a small contribution to the increase in global surface temperature during the last few decades. On

decadal time-scales, the Interdecadal Pacific Oscillation (IPO) in SST and sea-level pressure (SLP) anomalies is related to ENSO but with somewhat different SST and SLP patterns; it is likely to be a Pacific-wide manifestation of the Pacific Decadal Oscillation (PDO) defined for the Northern Hemisphere. It is likely that the IPO and PDO modulate ENSO-related climate variability in many regions on decadal time-scales. These phenomena have been in a positive, warm tropical Pacific and cold extratropical north-west and south-west extratropical Pacific phase since about 1976, at least up to 1998.

Midlatitude to high-latitude variations

In the Northern Hemisphere, the winter North Atlantic Oscillation and the associated Arctic Oscillation (which appears to be largely the same phenomenon) show decadal to multi-decadal variability. Since the 1970s these oscillations have been in a phase that gives stronger westerly winds over much of extratropical Eurasia in the winter half-year. They have been associated with strong cold-season warming over extratropical Eurasia since the 1970s, but cooling in some regions further south. In the Southern Hemisphere, the not dissimilar High Latitude Mode or Antarctic Oscillation has been in an enhanced positive phase in the last 15 years with stronger westerly winds over the Southern Ocean.

Has climate variability, or have climate extremes, changed?

New analyses show that in regions where total precipitation has increased it is very likely that there have been even more pronounced increases in heavy and extreme daily to multi-daily precipitation events. The converse is also true. In some regions, heavy and extreme precipitation events have increased, despite the fact that total precipitation has decreased or remained constant. This is attributed to a decrease in the frequency of precipitation events. Changes in the frequency of heavy precipitation events can arise from several causes, *e.g.* changes in atmospheric moisture or circulation. Over the latter half of the twentieth century it is likely that there has been a 2 to 4%

increase in the frequency of heavy precipitation events reported by the available observing stations in the midlatitudes and high latitudes of the Northern Hemisphere.

In many regions inter-daily temperature variability has decreased. Increases in daily minimum temperatures are lengthening the freeze-free season in most midlatitude and high-latitude regions. A significant reduction in the frequency of extreme low monthly mean and seasonal average temperatures across much of the globe has occurred since the late nineteenth century. However, a relatively smaller increase in the frequency of extreme high monthly and seasonal average temperatures has been observed.

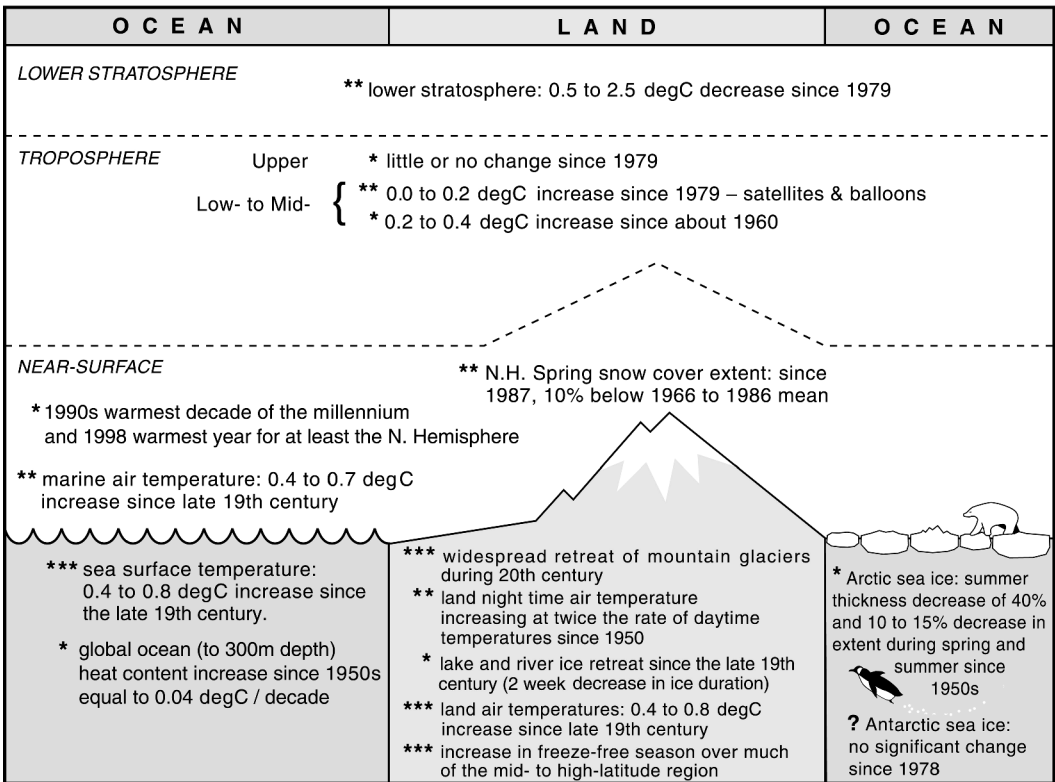
Changes in tropical and extratropical storm intensity and frequency are dominated by inter-decadal to multi-decadal variations, with no significant trends evident over the twentieth century. Different methods of analyses make it difficult to draw definitive conclusions about changes in storm activity, especially in the extratropics.

Are the observed trends internally consistent?

It is very important to compare trends in the various indicators to see if a physically consistent picture emerges, as this will critically affect the final assessment of our confidence in any such changes. A number of qualitative consistencies among the various indicators of climate change have increased our confidence in our analyses of the historical climate record. Figures 4(a) and 4(b) summarise changes in various temperature and hydrological indicators, respectively, and provide a measure of confidence about each change. Of prime relevance are the changes identified below:

- (i) Temperature over the global land and oceans, with two estimates for the latter, are measured and adjusted independently (since 1893), yet all three show quite consistent increasing trends over the twentieth century (Fig. 1). The nearly worldwide decrease in mountain glacier extent and mass is consistent with twentieth-century global temperature increases.

Temperature Indicators



Likelihood: {
 *** Virtually certain (probability > 99%)
 ** Very likely (probability ≥ 90% but ≤ 99%)
 * Likely (probability > 66% but < 90%)
 ? Medium likelihood (probability > 33% but ≤ 66%)

Fig. 4(a) Schematic of observed variations of various temperature indicators. In the bottom left-hand corner '1950s' is corrected from '1940s' in Chapter 2. In the bottom three-starred statement of the central area 'increase' is corrected from 'reduction' in Chapter 2. The main text of Chapter 2 is consistent with these changes.

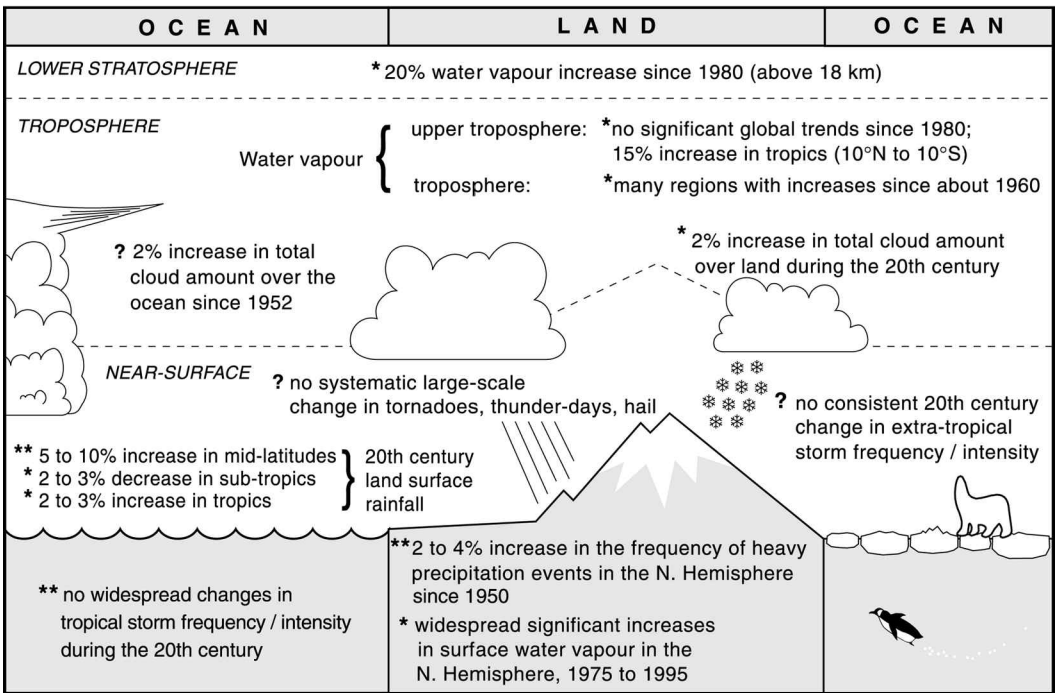
A few recent exceptions in maritime coastal areas have been affected by atmospheric circulation changes and related precipitation increases.

- (ii) Though less certain, substantial proxy evidence points to the exceptional warmth of the late twentieth century relative to the last 1000 years. The 1990s are likely to have been the warmest decade of the past 1000 years over the Northern Hemisphere as a whole.
- (iii) Since 1979, trends in worldwide LSAT derived from high-quality records at weather stations in the Northern Hemisphere, in regions where urbanisation is likely to have been strong, agree closely with satellite-derived

temperature trends in the lower troposphere above the same regions. This suggests that urban heat-island biases have not significantly affected assessed surface temperature over the period.

- (iv) Decreases in spring snow-cover extent since the 1960s in the duration of lake and river ice over at least the last century, and emerging evidence for decreases in permafrost, relate well to increases in Northern Hemispheric surface air temperatures. The systematic decrease in spring and summer Arctic sea-ice extent in recent decades is broadly consistent with increases of temperature over most of the adjacent land and ocean. A large reduction in the thickness of summer

Hydrological and Storm-Related Indicators



Likelihood: {
 *** Virtually certain (probability > 99%)
 ** Very likely (probability ≥ 90% but ≤ 99%)
 * Likely (probability > 66% but < 90%)
 ? Medium likelihood (probability > 33% but ≤ 66%)

Fig. 4(b) Schematic of observed variations of various hydrological and storm-related indicators

and early autumn Arctic sea-ice over the last 30 to 40 years is consistent with this decrease in spatial extent, but we are unsure to what extent poor temporal sampling and multi-decadal variability are affecting the conclusions. However, Antarctic sea-ice extent shows no reductions in the last 25 years.

- (v) The increases in lower-tropospheric water vapour and temperature since the mid-1970s are qualitatively consistent with an enhanced hydrological cycle. This is, in turn, consistent with a greater fraction of precipitation being delivered from extreme and heavy precipitation events, primarily in areas with increasing precipitation, e.g. midlatitudes and high latitudes of the Northern Hemisphere.

In conclusion, the variations and trends of the examined indicators consistently and very

strongly support an increasing global surface temperature over at least the last century, although substantial shorter-term global and regional deviations from this warming trend are very likely to have occurred.

References

The reader should refer to the printed chapter or the website version for details and references. Where used, references are quoted in a form appropriate to the complete list of Chapter 2 references.

Acknowledgements

We wish to gratefully acknowledge the many contributions of the other lead authors of the “Observed climate variability and change” chapter: J. R. Christy (USA), R. A. Clarke (Canada), G. V. Gruza (Russia), J. Jouzel

(France), M. E. Mann (USA), J. Oerlemans (The Netherlands) and S.-W. Wang (China), as well as about 140 other contributing authors. The first author wishes to acknowledge support from Department of the Environment, Food and Rural Affairs contract

PECD/7/12/37 and from the Government Research Program.

Correspondence to: Mr C. K. Folland, Met Office Hadley Centre, London Road, Bracknell, Berkshire RG12 2SY. e-mail: chris.folland@metoffice.com

© Crown copyright, 2002.
