Greenhouse Effect and Climate Data☆

PD Jones, University of East Anglia, Norfolk, UK

Glossary

Attribution of climate change Relating the climate change to known forcing factors (including the effects of human influences).

Detection of climate change The detection of a change in climate (either in the mean or variability) between one period and another.

Forcing factors Influences that force the climate system, such as natural (solar output changes and volcanic eruptions) and human factors (greenhouse gasses, land-use changes).

Global climate models Computer models (general circulation models) which simulate past, present, and future climates from changes in greenhouse gas concentrations and natural forcing factors.

Greenhouse effect The change in surface temperature caused by the radiative properties of some atmospheric constituents (water vapor and greenhouse gasses). The natural greenhouse effect is being enhanced by increases in the major greenhouse gasses.

Homogeneous Property of a climate series whereby all variations of the series are caused solely by the vagaries of weather and climate.

Major greenhouse gasses Radiatively active gasses in the atmosphere such as carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons. They are increasing as a result of fossil fuel burning, land-use change, and some agricultural activities.

Proxy (paleo) climatic variables Noninstrumental indicators of climate variations (e.g., historical documents, tree growth, ice cores, corals, lake, and marine varves), used as proxy climate evidence for pre-instrumental periods.

Sulfate aerosols Small particles in the atmosphere, due to fossil fuel burning, which reflect incoming radiation and offset the effects of greenhouse gasses.

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Greenhouse Effect and Climate Change

Climate is controlled by the long-term balance between incoming radiation from the sun, which is absorbed by the earth's surface and the atmosphere above, and energy returned to space in the form of infrared radiation. Changes in climate over the last 1000 years that have occurred have been due to modifications of this energy balance caused by natural factors, external to the climate system. More recently, anthropogenic (human) activities (affecting the composition of the atmosphere) have begun to be important. Over the last 10 000 years (the period termed the Holocene), solar output received at the surface has also varied due to the differences in the position of the earth's orbit relative to the sun. This has caused slight variations in summer insolation between different latitudes (the Milankovitch effect).

Natural external influences take two forms: changes in solar output on decade-to-century and longer time scales and reductions in incoming radiation caused by explosive volcanic eruptions. The latter put significant amounts of dust and aerosols into the stratosphere, where it might reside for up to 2–3 years, lowering radiation receipts at the surface. A useful proxy for solar output is the number of sunspots, lower numbers reducing radiation received at the surface by a few tenths of 1%. Impacts on the 11-year time scale are negligible, as the atmosphere/ocean system has little time to respond to the slight changes. Gradual impacts, occurring on near-century time scales, are more likely, but effects are very difficult to detect. Stratospheric dust veils impact radiation balances much more quickly and reduce surface receipts by up to 1%, but only for a year or two, while the dust/aerosols slowly settle back to earth. The effects on surface temperature will tend to be rapid, leading to cooling, particularly over Northern Hemisphere (NH) land areas during the summer season, when there are greater amounts of radiation to perturb. Effects are less noticeable in the Southern Hemisphere (SH) because of the greater area of ocean which moderates influences. Unless explosive eruptions occur closely together in time, the effects of one eruption will have dissipated by the time the next occurs. Volcanic effects therefore occur on high-frequency (interannual) time scales, while solar output changes occur on decade-to-century time scales. Climate is also influenced internally by changes within the ocean (strengths and directions of currents, rates of upwelling, and deepwater formation).

The earth's atmosphere contains relatively small quantities of greenhouse gasses (principally water vapor, carbon dioxide, and methane), which trap some of the infrared radiation, causing average surface temperatures to be much warmer (34 °C) than if the content was just nitrogen and oxygen. CO_2, CH_4, and N_2O levels are, however, increasing as a result of industrial (fossil fuel burning) and agricultural activities, and deforestation, causing the natural greenhouse effect to be enhanced. If current trends in emissions continue, the amount of CO_2 in the atmosphere will double during the twenty-first century. The amounts of several other human-made greenhouse gasses (e.g., halocarbons, Hydrochlorofluorocarbons (HCFCs), the replacements for Chlorofluorocarbons (CFCs)) are also increasing substantially as well.

This enhancement of greenhouse gasses in the atmosphere, due almost entirely to human activities, will change the climate, leading to an increase in the average surface temperature of the earth. In some regions the enhancement is being countered by related air pollution through emissions of sulfate aerosols and soot (also from fossil fuel burning), but cleaner energy systems (principally in North America and Europe) are reducing this influence. Current best estimates from climate models are that, relative to 1990, surface temperatures will rise by 1–3.5 °C by 2100. Because some greenhouse gasses have long lifetimes ($\sim$100 years) in the atmosphere, even if emissions were to cease immediately, the effects of past emissions would continue for centuries. A smaller anthropogenic component from land-use change is beginning to be incorporated into climate model simulations. Recent syntheses of this indicate that it is small and has a slightly negative effect.

This article considers principally the past surface climate record, showing why we are confident that surface temperatures are rising. A shorter section considers precipitation changes, these generally being more important for many facets of human life, particularly in the tropics and sub-tropics. Changes in global climate, though, are nearly always considered in terms of temperature. Relating the observed rises in temperature to the greenhouse gas increases is more than one of simple cause and effect, however, as changes in temperature have occurred in the past. The rise in surface temperature and the increases in greenhouse gas concentrations may be unrelated. Although this is unlikely, given present knowledge and advances in climate modeling, it is vital to relate the two. The linking of cause and effect is the climate change detection issue: is the rise in temperature unequivocally due to the greenhouse gas changes? Related to this, modeling is used to estimate future rates of temperature increase, enabling either adaptation measures to be taken or to determine the levels of mitigation that will be required to minimize rapid rates of change in the near future. After considering the evidence for change over the twentieth century, attempts to explain the changes in temperature are discussed in the detection and attribution context.

Surface Temperature Data

Quality of Temperature Data

Any assessment of trends or changes in temperature requires that all the observations have been taken in a consistent manner. Climatologists refer to this property as homogeneity. Time series of temperature are homogeneous if the variations exhibited are due solely to the vagaries of the weather and climate. Numerous nonclimatic factors influence the basic climate data, causing erroneous conclusions to be drawn regarding the course of temperature change. The factors vary depending on the data source and are briefly considered in the next two subsections for the terrestrial and marine components of the earth's surface.

Land

It is extremely rare for observational protocols and the environment around the observing location to have remained exactly the same during the stations' history. Changes are likely to have occurred with the instruments, their exposure and measurement techniques, in the location of station and the height of the instruments, in the times of observations per day, and the methods used to calculate daily and monthly averages.

The commonly used louvered screen developed by Stevenson in the 1860s/1870s is now the standard around the world, although different countries use variants of a similar design. Prior to this, most thermometers were positioned on poleward-facing walls (i.e., out of direct sunlight), but this poses problems in high-latitude regions in the summer. Methods to take these problems into account have been developed, but it has been necessary to take modern measurements (at the locations of the old sites and using the prescreen exposures) to determine the scale of the problem. Most stations have additionally been moved at least once during their lifetime, sometimes every 10–20 years. Also of importance is the time when observations are made each day. Even today there is no accepted standard, countries being allowed to choose whatever times suit them. English-speaking countries have tended to use the average of the daily maximum and minimum readings taken each day to calculate daily and monthly averages. Some countries have switched to this method, mainly because of its ease, while others retain their national standards (averages of measurements made at fixed hours, between 3 and 24 times per day).

All these problems influence series, often in an abrupt manner (temperatures jumping to a new level by up to 2 °C in extreme cases). Ideally, when new sites or observation protocols are adopted, parallel measurements are recommended, enabling corrections to be calculated. Sadly, although clearly recognized as being necessary, few countries carry out sufficient overlapping measurements. The most common problems relate to location moves, particularly to airports in the 1940s and 1950s. Recently, many countries have switched from mercury-in-glass thermometers to electrical resistance thermisters, to reduce manpower, automating measurements. The sum total of all these problems can be disentangled if adequate station history information is available, but it is generally a tedious process to locate all the necessary information. Much is happening in many National Weather Services but in some, sufficient detail is not available and the longest records are yet to be digitized.

Potentially the most important factor with respect to homogeneity is changes in the environment around the station. The location may have been a small town in the nineteenth century, but now it could be a city of several million. Development around the site (urbanization) leads to relative warming of city sites compared to, still rural, neighbors. On certain days, particularly calm sunny days, cities can be warmer than rural surroundings by up to 10 °C. For monthly averages this reduces up to 1–2 °C, larger for inland continental, compared to coastal, locations. Cities which have grown rapidly over the twentieth century tend to be more affected, compared particularly to European locations where development has taken place over many centuries. Overall, however, the urbanization effect is considered to be relatively small and an order of magnitude smaller than the long-term warming. The warming is confirmed by marine data (next section) and also by satellite estimates of surface temperature which have been made since 1979.

The sum total of these problems can lead to gradual warming due to environmental changes and abrupt changes (both to warmer or colder absolute temperatures) for all other problems. Several groups in the United Kingdom and the United States have extensively analyzed the basic surface temperature data (between 1 and 7000 stations), adjusting the data for the abrupt changes and removing urban-affected stations, and have reached similar conclusions about the course of temperature change over the instrumental period since 1850 ('**Hemispheric and Global Time Series**' and '**Analyses of the Temperature Record**'). It is highly unlikely that every problem has been corrected for, but the different techniques used give confidence that large-scale changes over the last 160 years are both real and well documented.

Marine

Terrestrial parts of the world constitute only 30% of the earth's surface, so it is vital that we also monitor the oceans if we are to gain more of a global picture. Historical temperature data over marine regions are derived largely from *in situ* measurements of sea surface temperature (SST) and marine air temperature (MAT) taken by ships and buoys. To be of use, each measurement must be associated with a location. Up to 10% of marine data is thought to be mislocated (ships located on the land!), and these values must be discarded. It is obviously harder to reject data still located over the ocean, but all analyses of the raw data also attempt to remove or correct these problems.

Marine data are also beset with homogeneity problems, but they are distinctly different from the terrestrial realm. For MAT data the average height of ship's decks above the ocean has increased during the twentieth century, but more important, daytime measurements are influenced by the solar heating of the ship, rendering only the nighttime MAT (NMAT) data of any value. For SST data, the changes in sampling method from uninsulated canvas buckets (generally prior to the early 1940s) to engine intake measurements (early 1940s onwards) causes an artificial rise in SST values of 0.3–0.7 °C. Since the 1990s, the dominant SST data source is now drifting buoys and these may record slightly lower (0.1–0.2 °C) temperatures than ships. The buoys are most likely to be near the truth, with ships being slightly warm because of the effect of the ship itself.

In combining marine data with land-based surface temperatures, SST data is preferred to NMAT, because they are generally more reliable, principally as there are at least twice as many observations, daytime MAT values having been contaminated by the ships' infrastructure. Absolute values of SST and land air temperatures may differ by up to 10 °C near some coastlines, so we cannot combine the two directly. Instead, we use anomalies (departures or differences from average), assuming that anomalies of SST and MAT agree on climatological (monthly and greater) time scales. Correction of the SST data for the change from canvas buckets is achieved using a physical-empirical model to estimate the degree of sea-water cooling that occurs in buckets of varying design. The cooling depends on the ambient weather conditions, but this can be approximated by climatological averages. Corrections are greatest in regions with the largest air–sea temperature differences (i.e., winters compared to summers), and the technique minimizes residual seasonal cycles in pre-World War II SST values compared to post-1945 values.

Since the marine and land components are independent, the two records can be used to assess each other after they have been separately corrected. The components have been shown to agree by several groups on both hemispheric scales, but also using island and coastal data.

Aggregation of the Basic Data

Both the land and marine data are irregularly located over the earth's surface. To overcome the greater density of data on land, it is necessary to interpolate the data, generally to some form of regular latitude/longitude grid.

Land

Differing station elevations and national practices with regard to the calculation of monthly mean temperatures mean that interpolation to a regular grid is much more easily achieved by converting all the monthly data to anomalies from a common reference period. The period with best available data is 1961–1990. The simplest interpolation scheme is the average of all stations that are located within each 5×5 grid box. More complex interpolation methods yield essentially the same results on all spatial scales. A potential drawback of gridding schemes is that the variance of grid-box time series is affected by changing numbers of stations within each grid box through time, although it is possible to correct for this.

Marine

For SST the aggregation is approached in a somewhat different manner. The random location of each observation means that it is necessary, by interpolation, to derive a climatology for each 1×1 square of the world's oceans for each 5-day period (pentad). SST anomaly values with respect to this climatology are then averaged together for each month for each 5×5 grid box, the same as used for the land component.

Combination into one dataset

Combination of the two components occurs in the simplest manner. Anomaly values are taken from each component. When both are available the two are weighted by the fraction of land/ocean within each grid box. Because island and coastal data in some regions are likely to be considerably more reliable than a few SST observations, no land or marine component can be less than 25%.

Hemispheric and Global Time Series

With the basic data now in 5° latitude/longitude grid boxes, calculation of large-scale averages is relatively simple but must take into account the different size of grid boxes in tropical, compared to polar, latitudes. This is simply achieved by weighting each grid box by the cosine of its central latitude value.

Figure 1 shows annual hemispheric and global time series for the 1850–2012 period. Table 1 gives monthly linear trend values, estimated by least squares, for the three domains calculated over the 152-year period from 1861 to 2012 and for some other subperiods. For the global average, surface temperatures have risen by 0.80 °C, a value that is statistically significant at the 99.9% level. Warming is marginally greater over the NH compared to the SH. Warming is least in magnitude during the NH summer months and may be influenced by the exposure of thermometers ('Quality of Temperature Data' section) during the 1860s and 1870s. Seasonal differences in temperature are much more marked in the NH (with its greater landmass) than over the SH.

While both hemispheres show similar degrees of warming, it is also apparent that many warm and cool years, relative to the underlying trend, are in common. Many anomalous warm years are coincident because they relate to El Niño years in the eastern equatorial Pacific. El Niño events cause somewhat predictable patterns of temperature and precipitation patterns over the world, with more regions experiencing warmer than cooler conditions. Polar regions and much of northern Eurasia are largely unaffected by such an influence. Cooler-than-normal years generally relate to the counterpart of El Niño, La Niña, when anomalous patterns which, to the first order are opposite, occur. A few cool years can be related to the climatic effects of explosive volcanic eruptions which are large enough to put considerable amounts of dust into the stratosphere. Once there, the dust forms a veil over the earth, reducing solar radiation and cooling the surface, particularly land areas. Surface cooling of about 0.2–0.3 °C followed the eruption of Pinatubo in the Philippines in June 1991, mainly in the northern summer months of 1992 and 1993. Volcanic eruptions which affect only the troposphere (e.g., Mt. St. Helens in 1980) have little climatic effect, as their ejecta are quickly dispersed by rain-making processes.

Both hemispheres show long-term warming, but it clearly has occurred in two phases (1920–45 and since about 1975). Spatial patterns of the changes will be considered later. The warmest year of the entire global series was 2010, 0.55 °C above the 1961–90 average, marginally above 2005 (0.54 °C) and 1998 (0.53 °C). For the global average, all the years since 1996 (i.e., 1997–2012) contain the 14 warmest years. 1999 and 2000 are cooler than the 15th warmest year which occurred in 1995.

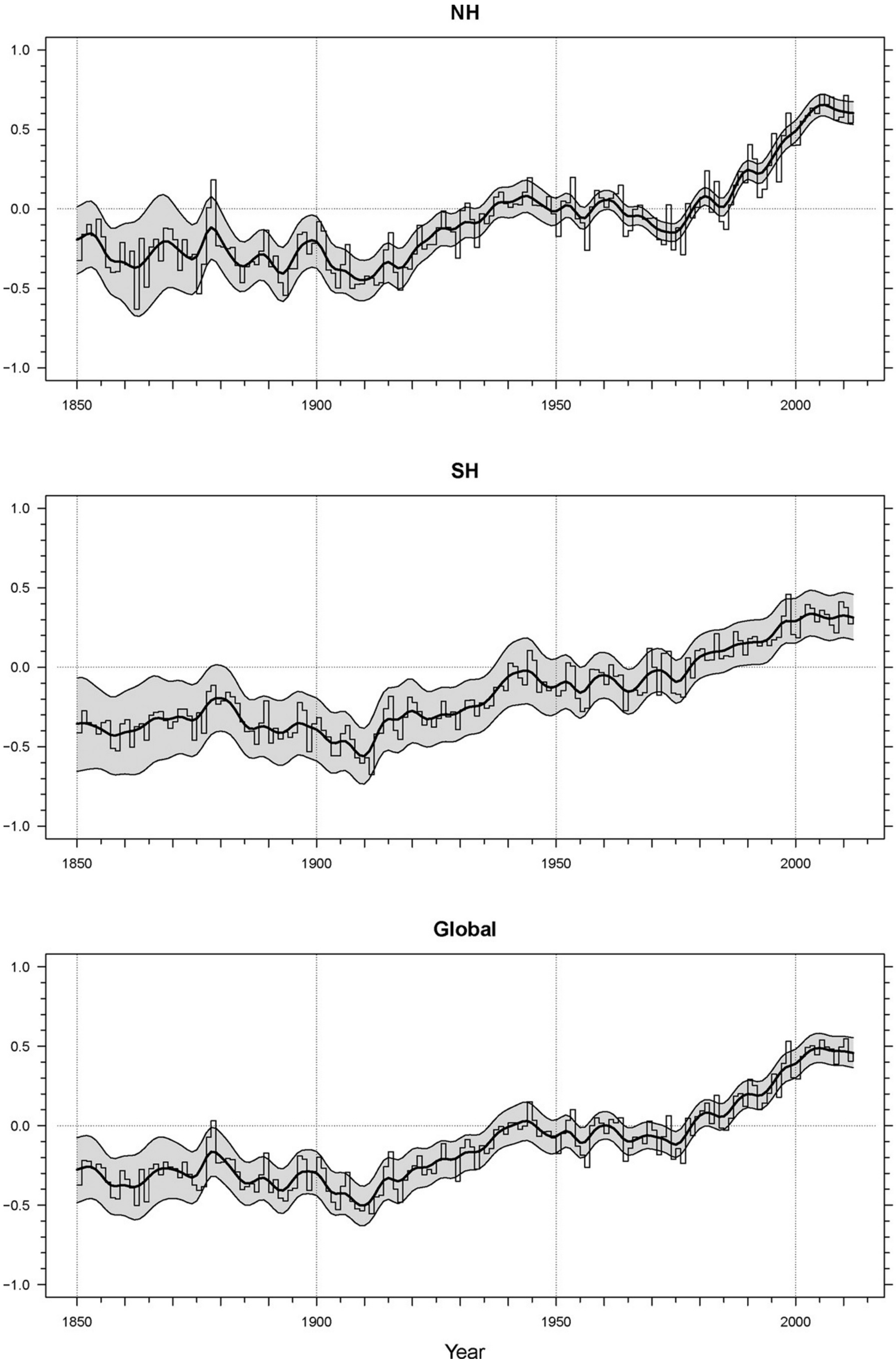

Figure 1 Hemispheric and global temperature averages on the annual time scale (1850–2012 relative to 1961–1990). The smooth curves highlight variations on decade time scales. The gray bands show the 95% uncertainty ranges (2.5–97.5%) on the decadal timescale.

Table 1 Temperature change (°C) explained by the linear trend over three periods (1861–2012, 1951–2012, and 1979–2012). Significant trends at the 95% significance level are emboldened

	1861–2012			*1951–2012*			*1979–2012*		
	NH	*SH*	*Global*	*NH*	*SH*	*Global*	*NH*	*SH*	*Global*
Jan.	0.92	**0.68**	**0.80**	**0.75**	**0.58**	**0.66**	**0.59**	**0.26**	**0.42**
Feb.	**0.97**	**0.64**	**0.80**	**0.85**	**0.56**	**0.71**	**0.64**	**0.30**	**0.47**
Mar.	**1.05**	**0.70**	**0.88**	**1.01**	**0.60**	**0.81**	**0.80**	**0.32**	**0.56**
Apr.	**0.86**	**0.71**	**0.79**	**0.84**	**0.60**	**0.72**	**0.86**	**0.34**	**0.60**
May	**0.77**	**0.78**	**0.78**	**0.73**	**0.55**	**0.64**	**0.73**	**0.28**	**0.51**
Jun.	0.60	**0.86**	**0.73**	**0.74**	**0.52**	**0.63**	**0.77**	**0.37**	**0.57**
Jul.	0.54	**0.78**	**0.66**	**0.74**	**0.57**	**0.66**	**0.83**	**0.37**	**0.60**
Aug.	0.63	**0.78**	**0.71**	**0.71**	**0.56**	**0.63**	**0.84**	**0.32**	**0.58**
Sep.	0.66	**0.76**	**0.71**	**0.69**	**0.54**	**0.61**	**0.80**	**0.30**	**0.55**
Oct.	0.87	**0.75**	**0.81**	**0.76**	**0.55**	**0.65**	**0.88**	**0.34**	**0.61**
Nov.	**1.02**	**0.66**	**0.84**	**0.84**	**0.55**	**0.70**	**0.91**	**0.30**	**0.60**
Dec.	**0.96**	**0.70**	**0.83**	**0.66**	**0.54**	**0.60**	**0.55**	**0.21**	**0.38**
Year	**0.82**	**0.73**	**0.78**	**0.78**	**0.56**	**0.67**	**0.77**	**0.31**	**0.54**

Accuracy of the hemispheric and global series

The series in Figure 1 is subject to three sources of error: bad measurements, residual effects of the homogeneity checks due to urbanization and the bucket corrections over the ocean, and most important, changes in the availability and density of the raw data through time. The latter are referred to in statistical terms as sampling errors. The 95% uncertainty ranges (2.5–97.5%) are shown in Figure 1. Their derivation is described in one of the references in the bibliography (Morice et al., 2012 which is also used for Figures 2 and 3 and Table 1). Errors in the mid-nineteenth century were roughly twice modern values for the NH but are still large even now for the SH, due to sampling effects.

Analyses of the Temperature Record

The surface record has been extensively analyzed, principally over the past 25 years. The series in Figure 1 (or variants of it developed by other groups) has become one of the foremost series in major international reviews of the climate change issue, most recently by the Intergovernmental Panel on Climate Change (IPCC). Here several diverse aspects of the record are analyzed:

Patterns of recent change
Trends in maximum and minimum temperature
Daily extremes of temperature in some long European series
The last 150 years in the context of the last 1000 years

Figure 1 clearly shows recent warming since the late 1970s. This warming is confirmed by satellite estimates of temperature for the lower troposphere since 1979. Both the conventional surface data and the satellite estimates show a warming of about 0.15 °C/decade over this 34-year period. There is also agreement between the marine and terrestrial components and this is confirmed by the widespread retreat of Alpine glaciers around the world and the melting of Arctic sea-ice during the summer season.

Patterns of recent change

Spatial patterns of change are shown in Figures 2 and 3 for the two periods (1951–2012 and the period since we have satellite records, 1979–2012). Patterns are shown seasonally and for the annual average. Even for the most recent period, coverage is not complete, with missing areas over most of the southern mid to high-latitude oceans, parts of the Antarctic and central Arctic, and some continental interiors. Both periods exhibit strong and highly significant warming in the hemispheric averages, but statistical significance is achieved in only relatively few areas on a local basis. A similar number of areas achieve significance in the recent period, but this is no more than would be expected, given the greater areas with data and the stronger warming (see Table 1). Warming is not spread evenly across the seasons, although annually most regions indicate warming. The warming patterns of the two periods show different patterns, particularly between the different seasons.

Trends in maximum and minimum temperatures

Up to now, all the surface temperature analyses have been based on monthly mean temperatures. This situation has arisen due to the widespread availability of this variable. As mentioned earlier, English-speaking countries have tended to measure daily and monthly means using maximum and minimum temperatures. Recently, extensive datasets of monthly mean maximum and minimum temperature have become available for periods since the 1950s. These enable recent warming patterns to be assessed for both day (maximum) and night (minimum) temperature. The difference between day and night (the diurnal temperature range, DTR) should prove a useful variable when considering what the causes of changes might be due to.

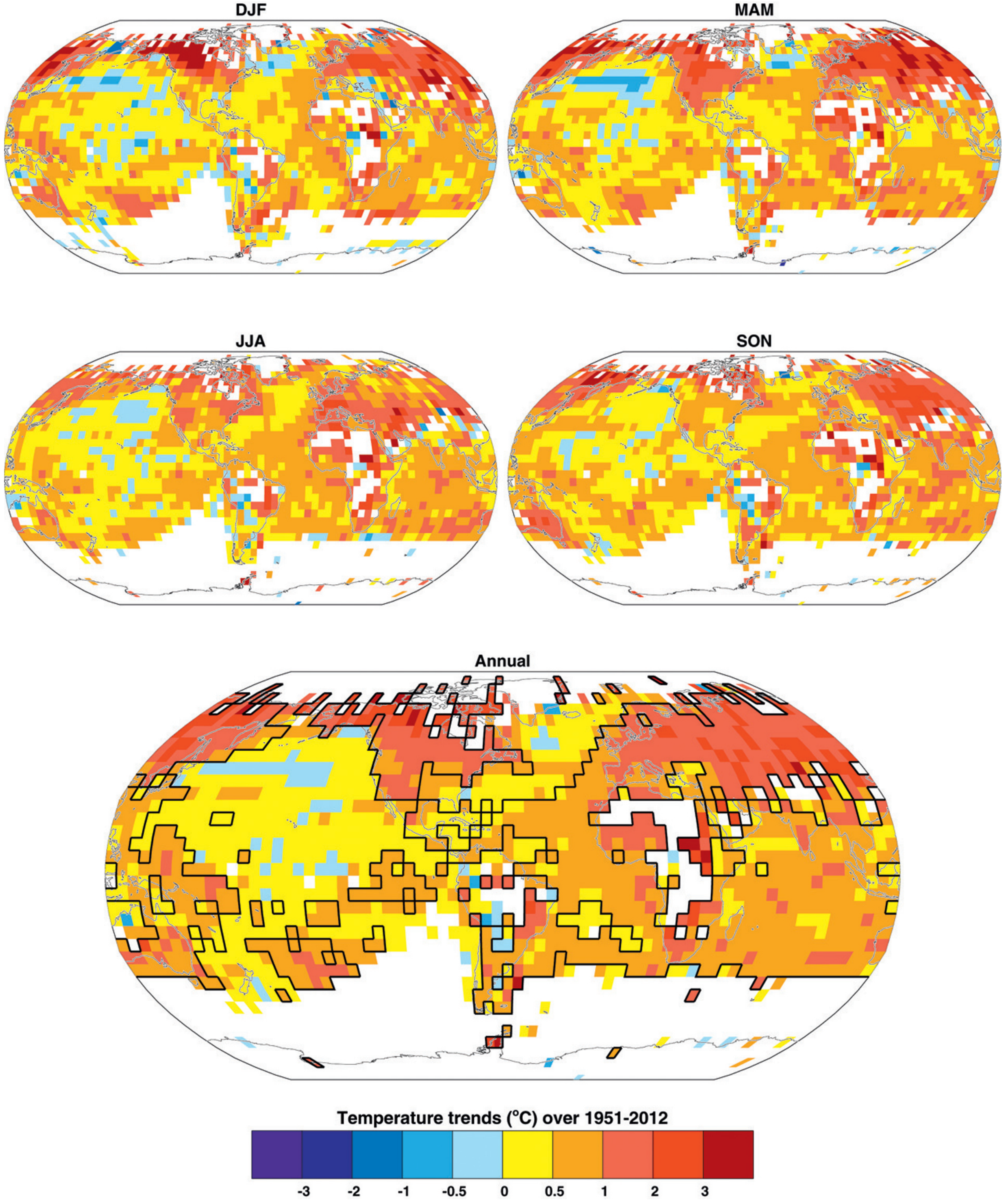

Figure 2 Trend of temperature on a seasonal and annual basis for the 62-year period 1951–2012. Boxes with significant linear trends at the 95% level (allowing for autocorrelation) are outlined by heavy black lines. At least 2 (8) months' data were required to define a season (year), and at least 75% seasons or years were required to calculate a trend.

Homogeneity of the series poses more severe problems than for mean temperatures, as the various factors discussed earlier generally cause differential effects in the maximum and minimum series, and station history information is even more important to decide upon adjustments. Analyses are restricted to the period 1951–2012 because of data availability issues in many regions of the world. Figure 4 shows trends over these 62 years for maximum and minimum temperatures and the DTR. Minimum temperatures

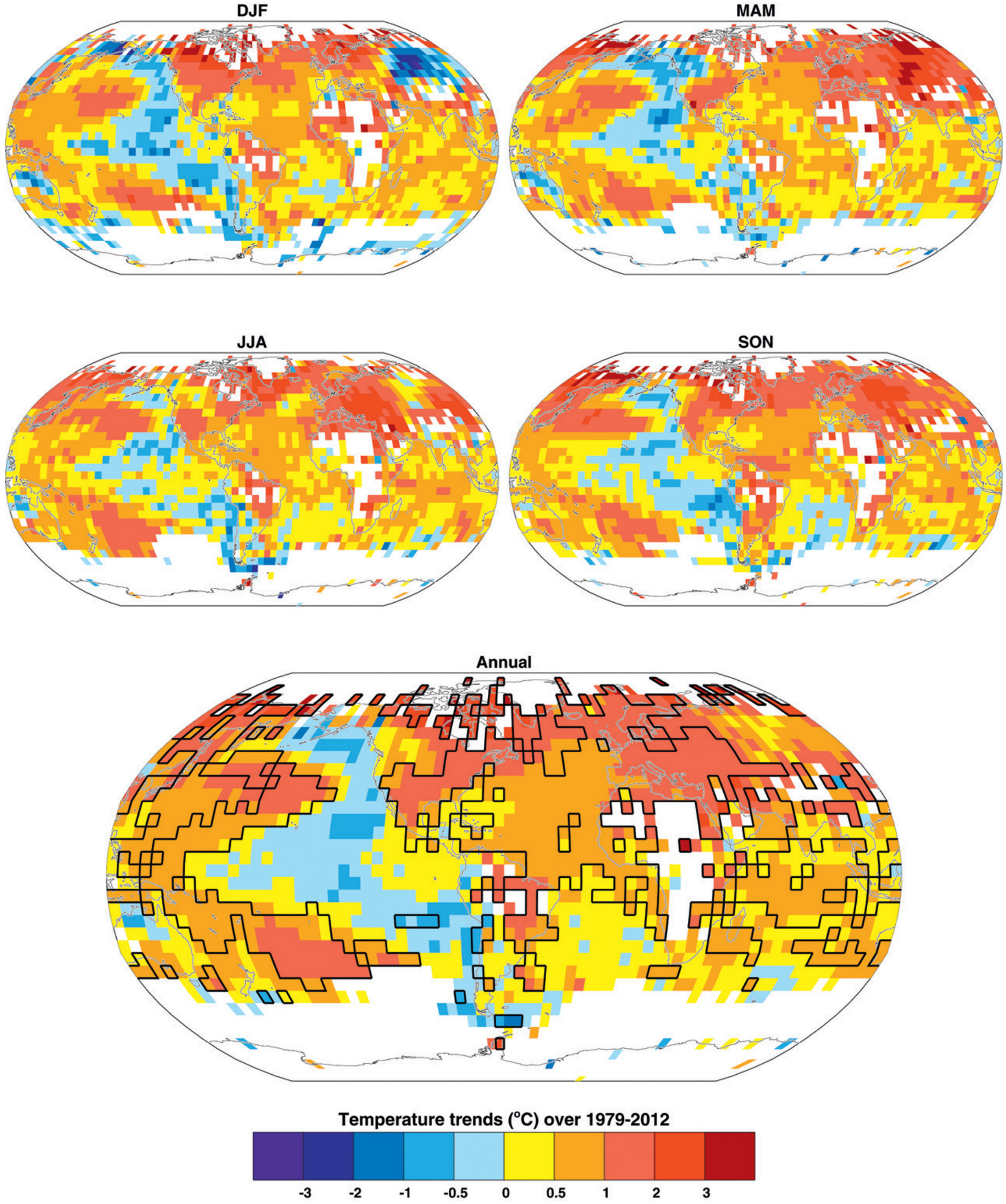

Figure 3 Trend of temperature on a seasonal and annual basis for the 1979–2012 period. Boxes with significant linear trends at the 95% level (allowing for autocorrelation) are outlined by heavy black lines. At least 2 (8) months' data were required to define a season (year), and at least 75% the seasons or years were required to calculate a trend.

decrease in only a few areas, while maximums show decreases over slightly larger areas, notably the extreme east of Canada, parts of northwestern and southern South America and parts of northern Australia. The DTR shows decreases in many regions.

Combining all regions, 'global' minimum averages warmed more than maximum temperatures and so DTR deceased. This DTR decrease was more marked up to about 1980, after which globally averaged DTR trends show little change. In most regions, these differential trends can be clearly related to increases in cloudiness, which will raise nighttime, compared to daytime, temperatures.

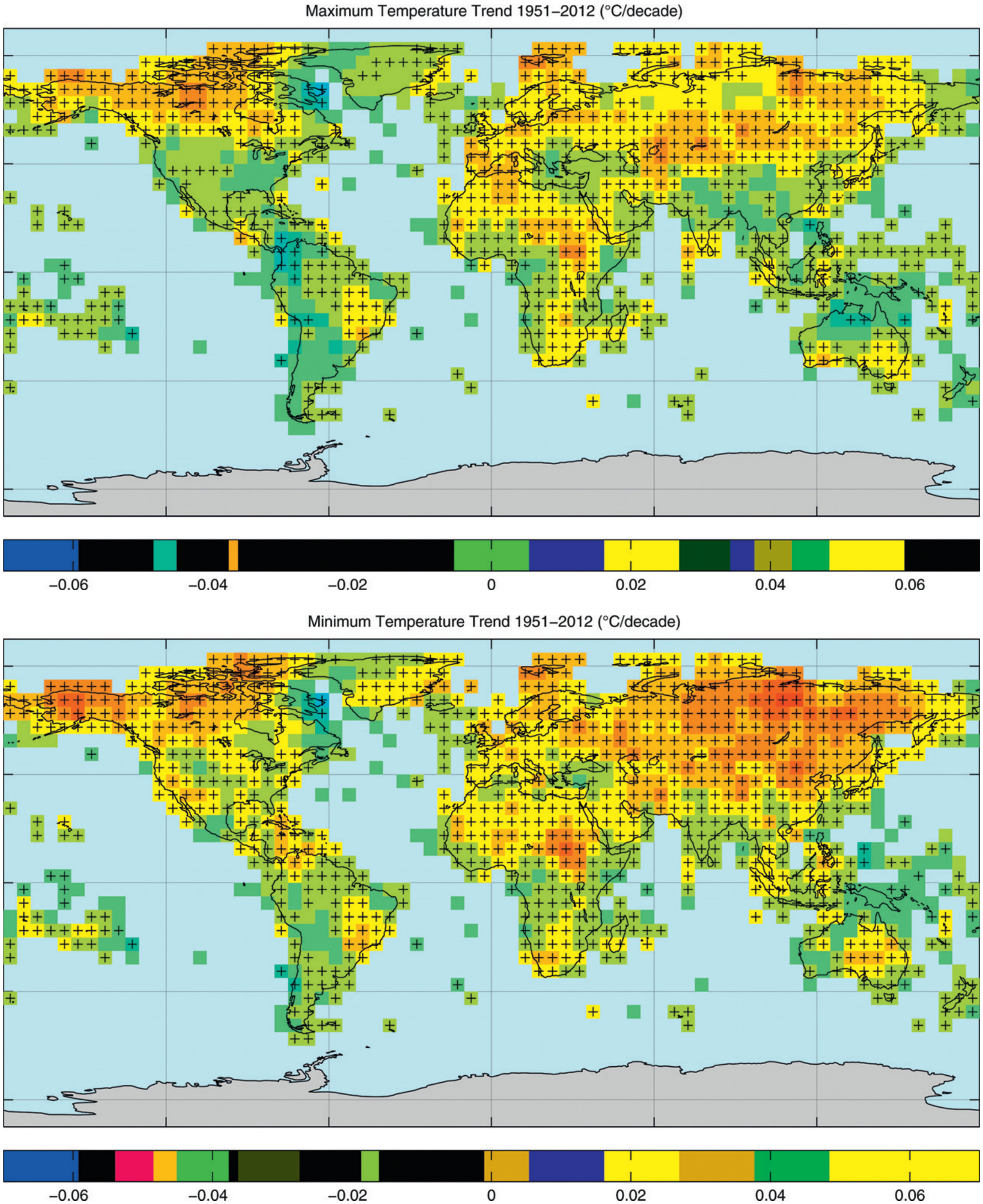

Figure 4 Trends of temperature (°C/decade) on an annual basis for the 1951–2012 for maximum temperatures, minimum temperatures, and the diurnal temperature range (DTR). Where the trends are statistically significant, they are shown with a black plus sign. This figure and Figure 8 come from Harris et al. (2013) reference in the bibliography.

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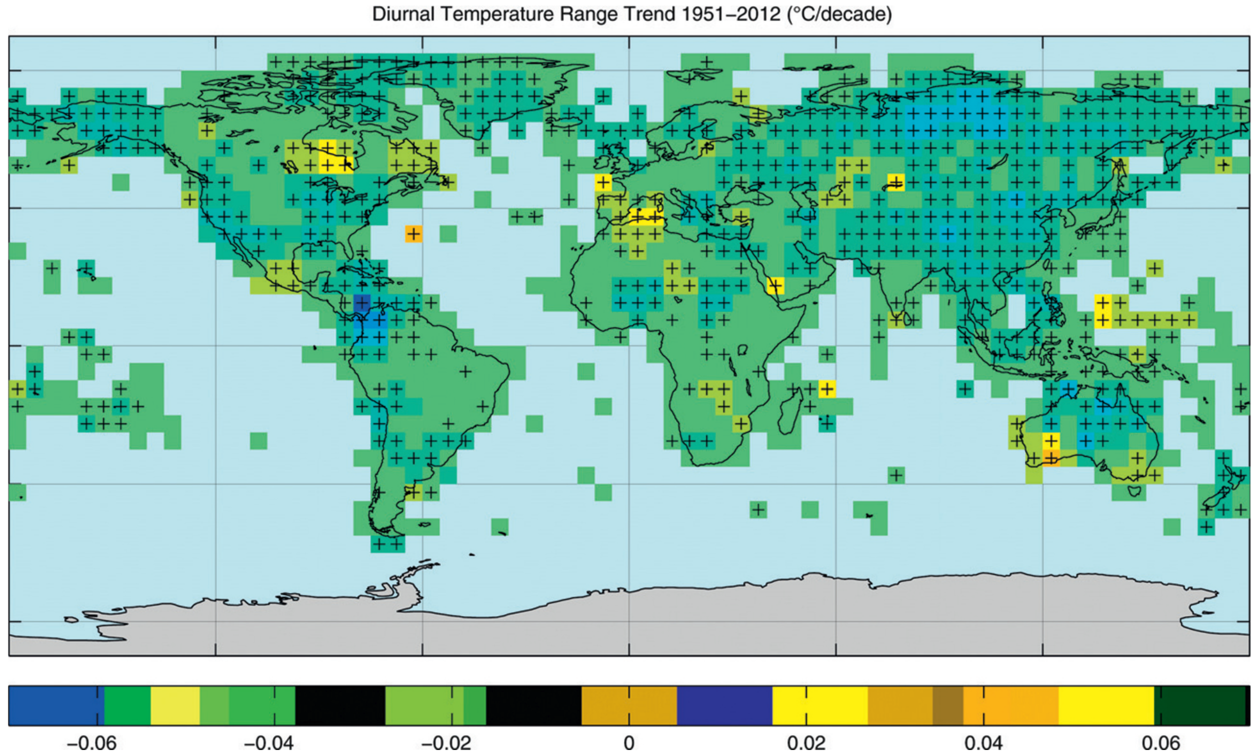

Figure 4 (Continued)

Longer records, back to the turn of the twentieth century, are available in a few limited regions. Analyses over the United States and southern Canada, for example, show little change over the first half of the twentieth century.

Daily temperature extremes in long European series

The last two sections have considered extremes on a monthly basis, but public perception of climate change is often considered by daily extremes or runs of warm/cold days. In the context of the global warming issue, daily data are relatively unimportant, as detection and attribution of human influences is concerned primarily with underlying trends on decadal time scales. In the public and political worlds, though, changing frequencies of daily extremes are how much of the global warming debate is perceived.

Daily temperature series present even greater problems to climatologists with respect to homogeneity than monthly data. Site and observation time changes are particularly important, and in some cases it may not be possible to fully correct for all the problems. Few long daily temperature series, therefore, are totally homogeneous. Furthermore, the availability of long series is often restricted in many areas (particularly the tropics) to the last 60 years. Changes in the frequency of extremes may be occurring, but without long series it is difficult to judge whether recent changes are really unprecedented. Here, we look at the long daily record, referred to as the Central England Temperature series. This extends back to 1772 on a daily basis and to 1659 as monthly averages.

The public perception of extremes is clearly cold winter and hot summer days, but in different regions it is necessary to define somewhat arbitrarily what is meant by cold and hot. A cold-day threshold of 0 °C clearly has important consequences, but what is hot in northern Europe clearly differs from what would be regarded as hot in southern Europe. Also, considering only absolute extremes ignores changes that might be taking place in the transition seasons. A better and universally applicable means of defining extremes is to let the data define the thresholds and to allow these to change during the year.

The first step is an analysis to define the annual cycle of temperature on a daily basis, based on a common period such as 1961–90. Some smoothing of this cycle is necessary, as 30 years is a relatively short period for definition. The 1961–90 period is chosen for compatibility with the other analyses in this section. Variability of a single day's temperatures from the annual cycle shows greater variability in Britain during winter compared to summer. Also, as most station data series (not just in the United Kingdom) throughout the year, but particularly in winter, tend to be negatively skewed, so a normal distribution would be inappropriate as this would give a bias to the cold-day count. Instead, it is necessary to fit a gamma distribution to the daily anomalies for each day of the year, again using the thirty 1961–90 days for each day. Now it is a simple matter to count the number of days above the 90/95th (warm/very warm) and below the 10th/5th (cold/very cold) percentiles in a calendar year or in a season.

Figure 5 shows counts of warm/cold days for some of the Central England Temperature series. Recent increases in warm days clearly, despite a few cooler recent years, exceed similar counts in all decades back to the eighteenth century. Cold-day counts, in contrast, are clearly lower than at any period in the long records. Even the higher counts in 2010 and 2012 are only comparable

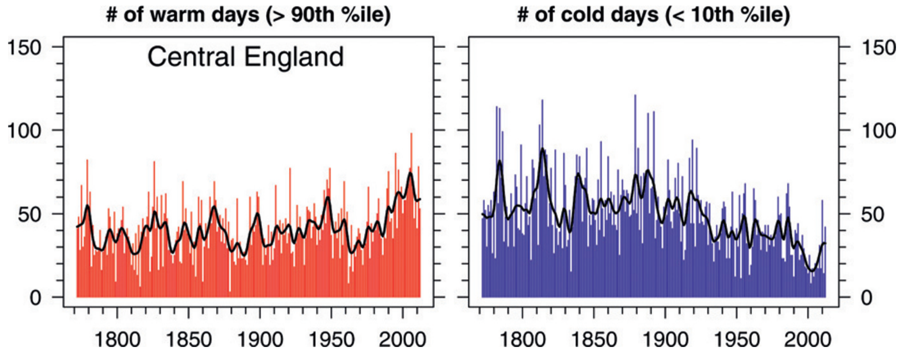

Figure 5 Annual counts of cold days (<10th percentile) and warm days (>90th percentile) for the Central England temperature series for 1772–2012. The smooth curves highlight variations on decade time scales.

with counts during the 1950–80s. The analysis method is insensitive to the choice of base period, another choice producing similar trends but centered about a different base. For comparison, Figure 6 shows the seasonal and annual average temperatures for the Central England Temperature series back to 1659. Warm/cold-day counts clearly covary with the annual average temperatures.

The last 150 years in the context of the last 1000 years

Global average surface temperature has clearly risen over the last 160 years (Figure 1), but what significance does this have when compared to changes over longer periods of time? The last millennium is the period for which we know most about the pre-instrumental past, particularly spatially, but it must be remembered that such knowledge is considerably poorer than since 1850. The millennium, particularly the last 500 years, is also the most important when considering attribution of recent changes to human influences. Earlier millennia are also important, but they are known to have experienced longer-time-scale changes in solar irradiance caused by orbital changes (the Milankovitch effect), bringing, for example, higher irradiance in summer to northern high latitudes around 9000 years ago.

Information about the past millennium comes from a variety of high-frequency and low-frequency proxy sources. High-frequency sources, giving information on the annual time scale, include early instrumental records (back to the late seventeenth century in Europe), written historical documents (mainly Europe and the Far East), tree-ring densities and widths (mid to high latitudes of both hemispheres), ice cores (both polar ice caps and also high-elevation tropical and smaller polar-latitude ice caps), corals (tropical), some highly resolved lake and marine sediments and temperature estimates from cave deposits (stalagmites and stalactites). Low-frequency (decade-to-century time scale change) evidence comes from boreholes, glacial advances/retreats, and peat, lake, and marine cores. Uncertainties in all proxy information are considerable, both because evidence is restricted to where these written and natural archives survive, and more important, all proxy records are only imperfect records of past temperature change.

The last two decades have seen a dramatic improvement in both availability of past evidence and also in information from diverse regions and sources. Figure 7 compares several different reconstructions of NH temperature change for the last millennium. The reconstructions are of different parts of the year (sometimes just for summer, sometimes for the whole year) so, based on the instrumental record, would be expected to differ somewhat. For those purporting to represent annual timescale variations, it must be remembered that few proxy reconstructions represent winters in the past, yet study of the instrumental record tells us that winter season variability dominates annual timescale variability in the NH. None of the series is strictly independent of the others, as they contain some common component sources, but each has made different assumptions in averaging.

All the series do not extend to the most recently complete year (2012) as work on a number of the proxies was undertaken some years ago. In addition, ice-core proxies cannot be used for the last 30 years or so in Greenland as the snow and firn have not completely formed solid ice. Similarly, highly resolved lake and marine cores rarely extend to the year of coring due to the sediments not being fully compacted. Documentary sources rarely extend to the instrumental period, so are generally updated to the present using degraded instrumental temperatures.

The most striking feature of the multiproxy averages is the warming during the twentieth century, both for its magnitude and duration. Agreement with the instrumental record should be taken as read, as all the components of the series have, to some extent, been calibrated against instrumental data, either locally or at the hemispheric scale. The twentieth century was the warmest of the millennium, and the warming during it was unprecedented. The warmest years are clearly recent ones, but all earlier centuries have important error ranges to consider in this respect.

Earlier studies, using considerably fewer proxy datasets, have considered the past millennium and two periods, the Little Ice Age (variously defined as 1450–1850) and the Medieval Warm period (less well defined in the literature, but 900–1200 encompasses most earlier work) are often discussed. To some extent, these two periods have become accepted wisdom, but the various curves in Figure 7 indicate only partial support for the two periods. Spatial analysis of the proxy data shows that no periods in the millennium were universally colder or warmer everywhere, considerable variability being present. The latter is to be expected even by studying the instrumental period since 1850. Just as the early 1940s were warm in many parts of the world but Europe was

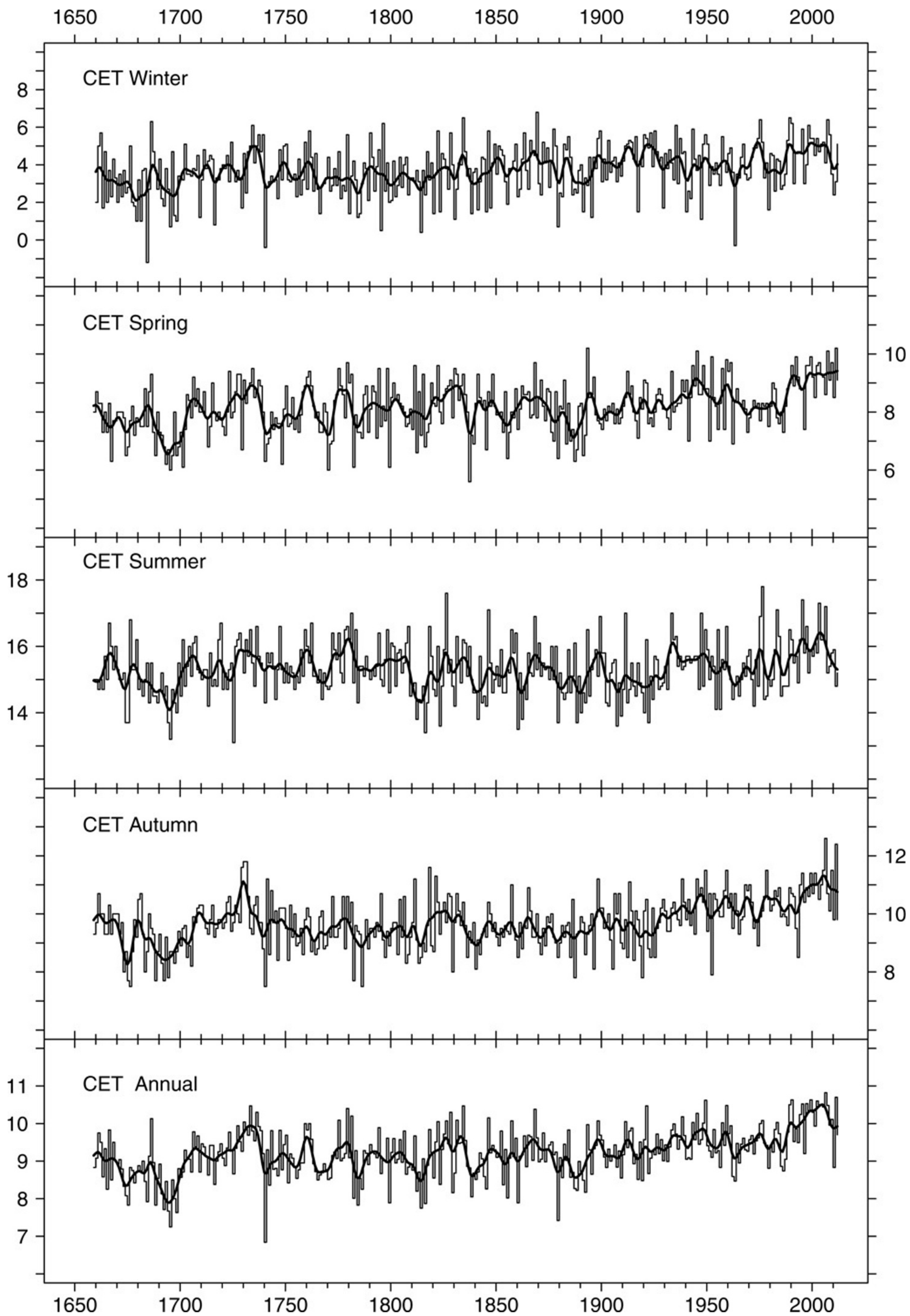

Figure 6 Seasonal and annual temperature averages for the Central England temperature series for 1659–2012. The smooth curves highlight variations on decade time scales.

cold, the early seventeenth century was cool in many regions but was relatively mild in Iceland. In many respects, therefore, paleoclimatology is in the process of reassessing the evidence for these past periods, and further changes are in prospect as more evidence becomes available.

The various series in Figure 7 differ in some respects with regard to the coldest and warmest periods of the millennium, but they have all analyzed orders of magnitude more data than was available in the early 1960s when the Little Ice Age and Medieval Warm period were first introduced. The cooler centuries of the millennium were the sixteenth to the nineteenth, the seventeenth being the coldest in Europe and the nineteenth the coldest in North America. These regions are still the best studied, and it will be vital in the future to extend our knowledge to other areas, particularly in the SH. At present, for every one long SH record, there are probably 20 in the NH. Just as with the instrumental record, it is important to gain as much evidence from as many regions as possible, if we are

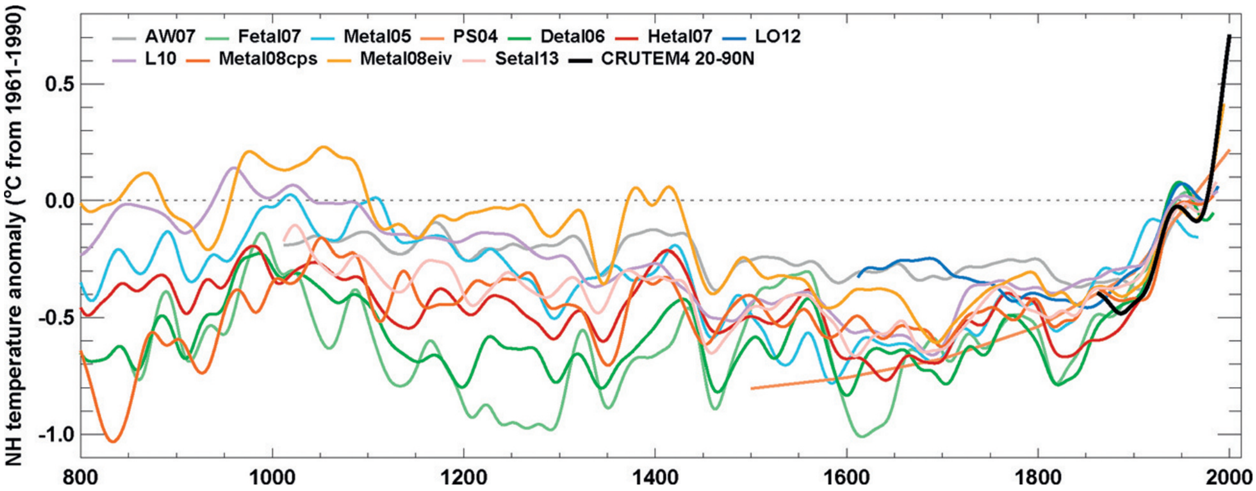

Figure 7 Reconstructions of Northern Hemisphere temperatures from CE 800–2000 based on several different combinations of proxy data (multiproxy averages). All the series have been smoothed with a 50-year Gaussian filter and all are plotted as departures from the 1961 to 1990 average. The different reconstructions are shown by the colored lines, the black being the instrumental record for calendar year average for land areas N of 20°N. The colors correspond to the key at the top of the graph, with the abbreviations related to scientific references given at the end of this article ([AW07] – Ammann and Wahl, 2007; [Detal06] – D'Arrigo et al., 2006; [Fetal07] – Frank et al., 2007; [Hetal07] – Hegerl et al., 2007; [LO12] – Leclercq and Oerlemans, 2012; [L10] – Ljungqvist, 2010; [Metal08cps and Metal08eiv] – Mann et al., 2008; [Metal05] – Moberg et al., 2005; [PS04] – Pollack and Smerdon, 2004; [Setal13] – Shi et al., 2013). The two smoother lines (PS04 and LO12) do not use any high-frequency proxy information, but are instead based on lower-frequency responding proxies (boreholes and glacier advances/retreats). All the series have been assembled within the last decade and represent cutting-edge research in paleoclimatology.

to understand fully how global and hemispheric temperatures have varied over this long time. No single region or location is more representative of the NH average than anywhere else, and doubt should not be cast on this large-scale average just because it might differ in its course of change compared to an individual site reconstruction. For example, if we were able to develop long winter reconstructions for Scandinavia and Greenland, we would expect their variations to be out of phase. Contrasts in the timing of changes between regions and particularly between the hemispheres must be recognized if we are to fully understand the causes of the changes. A more complete understanding of the causes of the changes will allow us to determine how much climate can change naturally, enabling us to better distinguish the degree of human influence on surface temperature during the twentieth century.

Precipitation Records

Homogeneity and Aggregation

As with temperature data, precipitation measurements are subject to problems with homogeneity. The greater spatial variability of monthly precipitation totals means that slight changes in location, rain gage design, and elevation can seriously impair the reliability of long-term records. Furthermore, although the network of available data is slightly better (in terms of gages per area) than temperature, grid-box or regional averages are less reliable because of the higher levels of spatial variability. Time series of neighboring (<100 km) temperature sites are likely to be highly correlated with one another ($r > 0.95$), but for precipitation the correlation is likely to be only 0.6–0.8, lower if the precipitation is mainly convective, higher if it is principally of frontal origin.

Despite the issues of accuracy, several groups have produced grid-box datasets at various resolutions from $1° \times 1°$ to $5° \times 5°$. Unlike their temperature counterparts, datasets are confined to land areas. Assessments over marine regions are beginning to be made using various satellite sensors, but they are confounded by the inevitable changes in sensors and records only extend back to the mid-1970s. Attempts to improve the records are important, though, as it is necessary to provide global-scale observational databases with which to test simulations of general circulation models.

Analyses of Grid-Box Datasets

Figure 8 shows trends in precipitation on an annual basis for the period 1951–2012. The pattern of change is considerably more spatially variable than for temperature with markedly fewer areas showing statistically significant trends. Also, because of different rainy seasons in many tropical and subtropical regions, annual trends are not that meaningful, but they give insights into the available data and the sorts of analyses that can be achieved. Analysis of precipitation trends and understanding the reasons for the changes is important to many facets of society, such as agriculture, water resources, and forestry. Changes are generally more important than for temperature, but it is much harder to document and diagnose the trends and relate them to human influences.

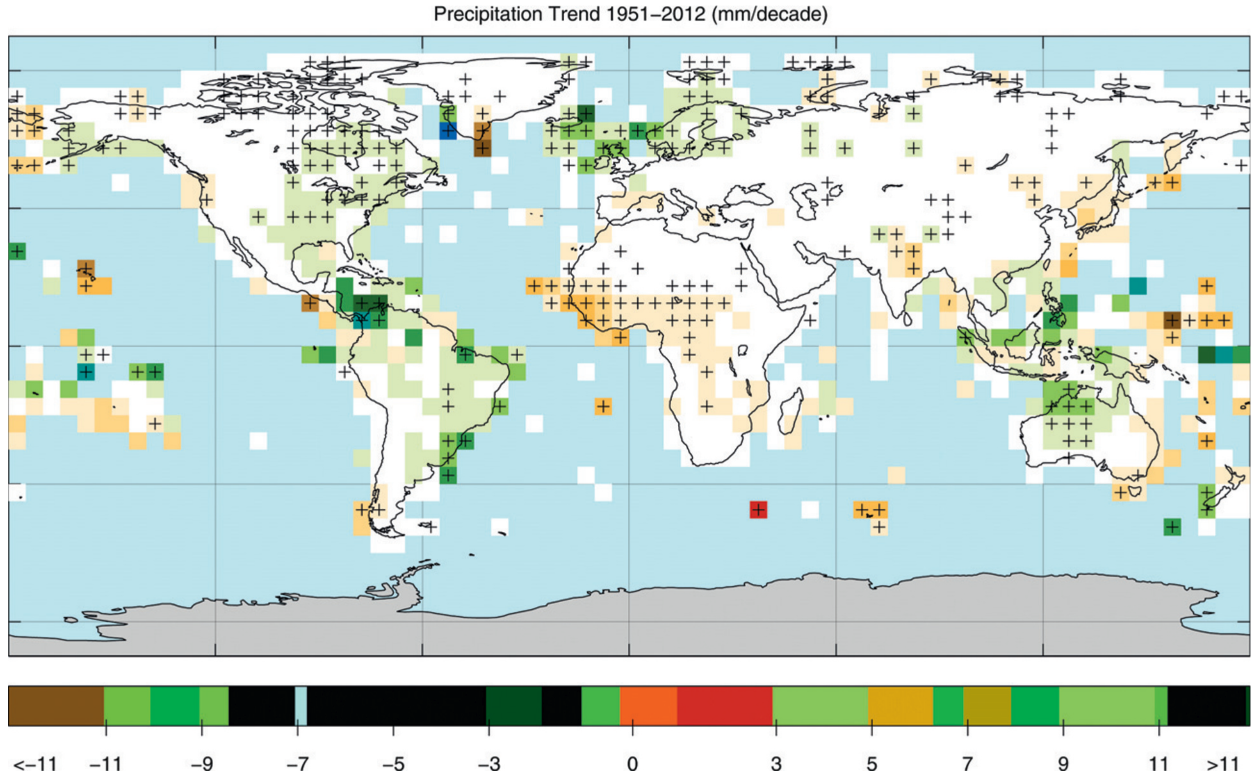

Figure 8 Trend in annual precipitation totals (mm/decade) for the period 1951–2012. Statistically significant trends are marked with a plus sign.

Longer-Term Series

As with temperature, there are precipitation records extending back to the eighteenth century in Europe. Proxy reconstructions are possible in some regions, as tree growth is crucially dependent on precipitation amounts in some regions. Also, documentary records from Europe and the far East contain more references to precipitation than temperature, generally in the form of diary information allowing monthly rain-day counts to be made. This is particularly evident in China and Japan. In Japan, official records enable wet and dry days to be mapped each day for the whole of the Edo period from 1600 to 1850.

Figure 9 shows seasonal and annual precipitation series for England and Wales (EWP) back to 1766. This region always had a high density of gages, official records run by the Meteorological Office since about 1860, but always many amateur meteorologists recording amounts, sometimes through many generations of the same family. EWP is comprised of seven records in each of five regions covering the area. All the seasons show considerable variability from year to year, with little evidence of longer-time-scale changes. Winters have, however, become wetter in the second half of the record since about 1860 and summers recently have become slightly drier. This region is generally in the path of the main westerly wind belts of the NH. Averages for more tropical regions will exhibit even greater year-to-year variability, particularly in regions that are strongly influenced by the El Niño/Southern Oscillation phenomenon. Despite this, the slight variations on the 5- to 10-year time scale often severely impact water resources and agriculture over EWP, leading to regular droughts and floods.

Changes in Daily Extremes

The database of precipitation data analyzed in Figure 8 is only available monthly. Although the measurements have been taken daily, long and dense networks of data are not always readily available at the daily time scale. Data have recently been analyzed for a few regions (United States, southern Canada, Russia, China, Australia, and parts of Europe). In some of these regions, increases in heavy rainfall have been noted, but the signal is far from uniform. The result is not unexpected, as a warmer atmosphere can hold more moisture and potentially release more in each event. The result is therefore consistent with modeling scenarios, but attributing it to human influences requires a stronger response or considerably more comprehensive and longer datasets so that greater understanding of the natural variability of daily rainfall amounts can be produced.

Precipitation is vital to measure, and to attempt to predict, as it has a strong influence on a number of sectors, but its strongly variable nature both in space and time, and the fact that it is much more poorly modeled than temperature means that it is a poor choice with regard to climate change detection.

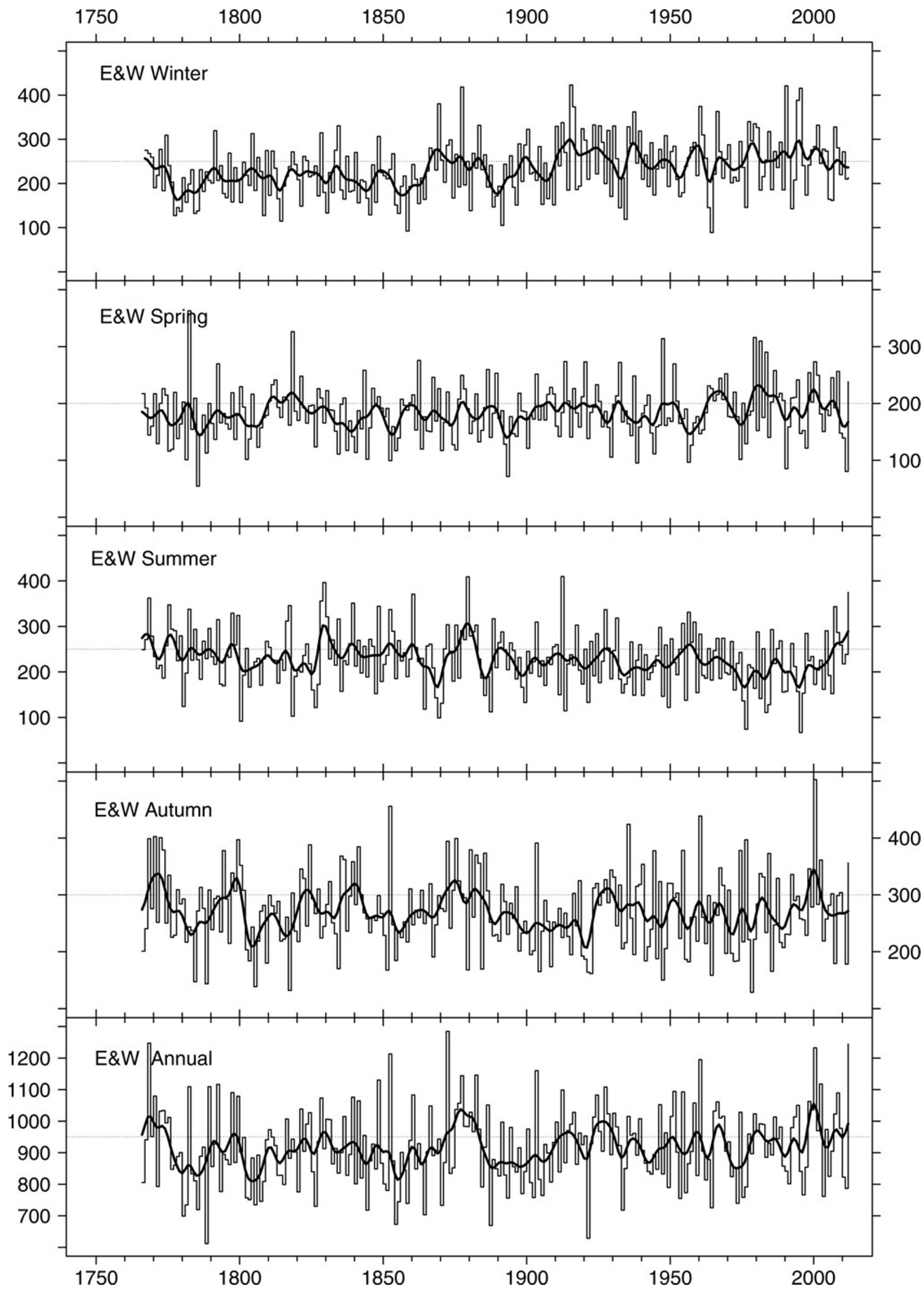

Figure 9 Seasonal and annual precipitation totals for the England and Wales precipitation average, 1766–2012. The smooth curves highlight variations on decade time scales.

Climate Change Detection and Attribution

Climate modeling work indicates that increases in greenhouse gasses as a result of anthropogenic activities will lead to warming. The previous section has clearly shown that the world has warmed, the increase in global average surface temperatures being highly significant both compared to year-to-year variability over the instrumental period and to longer-time-scale changes over the last millennium. Although we have detected the change, temperatures have varied in the distant and recent past, so how can we attribute the changes to human activities? The increase might have occurred without any human interference.

The second step in detection studies, attributing the changes to human causes, makes use of climate models, which allow us to estimate the climatic effects of a range of human-induced and natural factors. Attribution requires that the changes agree, with statistical confidence, with those modeled. The human factors considered by models include both the increasing atmospheric concentrations of greenhouse gasses, the direct and indirect effects of sulfate aerosols, and the effects of land-use changes. Natural factors included are solar output changes, the effects of volcanic eruptions, internal variability of the climate system (mainly with respect to the oceans), and interactions among all the external and internal forcing factors.

The 0.8 °C rise in globally averaged temperatures is compatible with, in terms of both magnitude and timing, that predicted by models which take the combined influences of human factors and solar variability into account. More recent studies of attribution have considered the patterns of temperature change, both spatially and in the vertical column of the atmosphere, and also been extended to daily variability in both temperature and precipitation data. Climate models indicate that the warming will not take place evenly, with cooling possible in a few regions. Warming will occur throughout most of the troposphere, but with cooling evident in the stratosphere. Looking at these detailed changes in patterns, therefore, provides more powerful techniques than dealing with large-scale averages only. It is likely that different forcing factors have different signatures in their temperature response, so with adequate data and a large enough response we should be able to distinguish the different influences. There is the tacit assumption in such studies that our modeling is a sufficiently good simulation of reality, that is, we have considered everything. While this assumption is unlikely to be strictly true, we should be confident that we have considered and correctly parameterized all important factors.

Comparisons between observed and modeled patterns at the surface and in the vertical column of the atmosphere have now been made. Model predictions show increasing agreement with the changes in temperature that have occurred over the last 50 years. Agreement is not perfect, but we would not expect it to be, as there are known inadequacies in both the models and our past history of known forcing factors. The best agreements come from the models which account for both greenhouse gasses and the effects of sulfate aerosols. In statistical terms, the correspondence between the two is unlikely to have occurred by chance. Studies of this kind are at the forefront of climate change science and are likely to be revised after each new generation of climate models becomes available. Improvements in data are also a factor, but of less importance compared to computer developments enabling us to improve the realism of the models by going to finer and finer resolution.

The agreements between observations and models are seen through similarities at the largest of spatial scales, contrasts between the hemispheres, between the land and ocean parts of the world, and at different levels in the vertical. It is not possible, nor will it be for several decades to come, to say that particular changes locally can be attributed to human influences. Although attribution studies are heavily dependent on statistics, the modeling results accord with our basic physical understanding of the climate system.

Despite the climate community concluding in the last four IPCC reports that the warming of the climate cannot be explained without the influence of human modifications to the composition of the atmosphere, we need to continue efforts to improve both our modeling and our data collection and analysis, particularly for the recent pre-instrumental past. Our knowledge at this time, while being highly suggestive, is still incomplete in some aspects. For example, although the majority of climate scientists are confident in detection and attribution claims, we cannot quantify exactly how much of the warming is human induced. Ideally, if our models were totally adequate and our knowledge of the changes in forcing over the last millennium much better than it is, we would expect to be able to retrodict the course of regional and global temperature change over this time. The fact that we are quite close shows the advances that have been made over the last 20–30 years. There should, however, be neither room for complacency by the scientists, nor reluctance to continue funding by agencies, as there is still much work to be done and much more to understand.

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