Chapter 6
Earth's Surface Temperature

Abstract The Earth is getting warmer and the surface temperature reflects the warming trend. Temperature records are kept and analyzed by several government agencies throughout the world among which are the Goddard Institute of Space Studies in the U. S., the Climate Research Unit in the U. K., the Japan Meteorological Association, and others. Tipping points beyond which nothing can be done to reverse them are discussed. Work by the U.K.'s Met Office and the Climate Research Unit of the University of East Anglia was one of the first to report global warming. James Hansen of GISS reported on their studies and appeared before a committee of the U. S. congress advocating that action be taken to slow or stop warming that was occurring due to greenhouse gases. Scenarios A, B, and C were described by Hansen. Hansen and Lebedeff's paper defining a method of determining a global average temperature is described as is the current method of determination.

Keywords Phil Jones • James Hansen • A1F1 • Temperatures • Land • IPCC • CRU • El Niño-La Niña • NCDC • TAR • GHGs • GISTEMP • CDAT • Public domain • Assurance • Quality • Muller • Anomalies • SSTs • Willett • Anomalies • Köppen • Callendar • Budyko

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know"

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_6,

should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to know	
SSTs	Land temperatures
Richard Muller	IMO
Temperature anomalies	A1F1
El Niño-La Niña Cycle	0.8°C
ICOADS	AOGCMs
ERSST	Global mean surface air temperature
IS92a	NASA/GISS
NOAA/NCDC	1951–1980
IPCC	Urban island effect
BEST study	TAR
Temperature index	Hansen and Lebedeff
Base period	Hadley centre
Quality control	Sea-level rise
1,200 km	0.4°C
SRES	Temperature index
MOHC	Quality assurance
A1T	Tipping point, tipping level, point of no return
GFDL	Buoys
A1 scenario	CRU
A2 scenario	B1 scenario
B2 scenario	

6.1 Introduction

This chapter is concerned with the Earth's surface temperature. The surface temperature was introduced in a previous chapter (Chap. 4) but in this chapter we will consider how temperature records are kept, reduced, analyzed, and how an annual average temperature can be determined.

The initial methodology for obtaining an average global temperature was produced in the 1970s by James Hansen and colleagues at NASA/GISS and formalized in a 1981 paper by Hansen and Lebedeff. This is the same methodology that is used today, with updates, to arrive at a global average temperature.

Determination of the Earth's average surface temperature grew out of work by American, British, Russian, and Japanese scientists working independently. In 1982, Phil Jones and colleagues of the U. K.'s Climate Research Unit (CRU) of the University of East Anglia issued the following statement: "We have produced, using objective techniques, a long-term series of average Northern Hemisphere temperatures." This statement by Jones and his colleagues began what is today CRU's methodology to produce the average annual global temperature of the Earth but it is biased toward the non-Arctic Northern Hemisphere.

The CRU team joined forces with scientists at the U. K. Meteorological Office Hadley Centre (MOHC), who were refining estimates of observed changes in sea-surface temperature (SST). This partnership led to the development of the Hadley Centre/CRU observational record of combined changes in SST and land-surface temperature (HadCRUT) and formed the basis for a global average temperature.

Groups at the NASA/Goddard Institute for Space Studies in New York (GISS) and at the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) in North Carolina independently attempted to reproduce the HadCRUT results. Although all three teams used raw temperature measurements from similar (but non-identical) sets of observing stations, they made different choices in the treatment of these raw measurements and the calculation of area averages. In spite of these differences, the GISS and NCDC analyses confirmed the "warming Earth" findings of the CRU and MOHC scientists; that during the latter half of the twentieth century, Earth's temperature had been rising sharply.

If any single event can be said to have put climate change on the world's policy radar, it was the testimony of NASA scientist James Hansen before Senator Tim Wirth's committee in Congress on June 23, 1988. This event was widely reported by the press and Dr. Hansen became the "face" of global warming and the object of scorn by climate change and global warming skeptics and deniers who were supported mainly by the oil and gas segment of society. Later chapters of this text will introduce the deniers and skeptics and their reasons.

In Hansen's testimony, he used three different scenarios; A, B, and C. They consisted of hypothesized future concentrations of the main greenhouse gases CO_2, CH_4, CFCs, etc., together with a few scattered volcanic eruptions. The details varied for each scenario, but the net effect of all the changes was that Scenario A assumed exponential growth in greenhouse gas forcings, Scenario B was roughly a linear increase in forcings, and Scenario C was similar to B, but had close to constant forcings from 2000 onwards. Scenario B and C had a large volcanic eruption in 1995. Essentially, a high, middle and low estimate were chosen to bracket the set of possibilities. Hansen specifically stated that he thought the middle scenario (B) the "most plausible."

These experiments were started from a control run of the GISS model with 1959 conditions and used observed greenhouse gas forcings up until 1984, and subsequent projections. The results are shown in the illustration below (Fig. 6.1).

The Hansen scenario closest to the observations since 1984 is clearly Scenario B.

Recently (2011) a group of scientists (the Berkeley Earth Surface Temperature or BEST study) led by a well-known climate skeptic and Professor of Physics at the University of California, Berkeley, Dr. Richard Muller, conducted a comprehensive review of methodology used to determine the annual average global temperature of the Earth and found after developing their own methodology, that their results agreed with previous methods used by others and that the annual global land temperature was rising, especially during the latter half of the twentieth century and

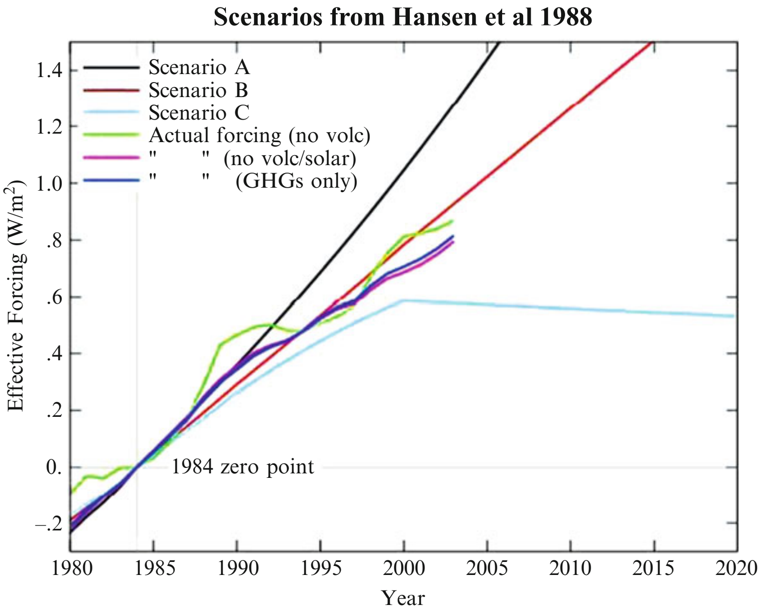

Fig. 6.1 Scenarios presented to the United States Congress in 1998 by James Hansen of NASA/GISS (From RealClimate.com, viewed 1/20/2012. Scenarios from Hansen et al. 1988)

into the twenty-first century. Global warming is real, as climate scientists have been telling the world since at least the 1970s.

6.2 Tipping Points

A tipping point has been taken to mean that a point has been reached beyond which nothing can be done to stop it. Hansen of NASA/GISS talks about tipping levels and points of no return instead of tipping points.

The tipping level is the level of greenhouse gases that will lead to large, undesirable, even disastrous, effects. The Earth has reached the tipping level for several important effects. That is why, according to Hansen, we must go back in CO_2 amounts at least to 350 ppm and possibly lower (in June 2012 the CO_2 level was 396 and 400 ppm in the Arctic).

The point of no return is when the dynamics of the process take over and the process, such as disappearing ice, is out of control and nothing can be done to stop it; an example is an ice sheet or glacier disintegrating because of positive feedback and warming that is already in the pipeline. Unfortunately, Arctic summer sea ice has reached the point where it will disappear within the next few decades. Arctic sea ice has reached its tipping point and it will disappear no matter what humans do to try and save it. Arctic sea ice is at the point of no return and will undoubtedly have severe effects on global weather patterns, especially in the Northern Hemisphere, when all of it disappears.

6.3 Temperature Records

The adequacy and reliability of temperature data and the method of computing the annual average temperature of the Earth have been questioned since the first annual average temperature was calculated. The calculation of an annual average temperature must be done according to very stringent rules agreed upon by international groups of climate scientists and published in the peer-reviewed literature for others to replicate and substantiate. This was done initially by Hansen and his co-workers at NASA/GISS. Their methodology has been vindicated by Professor Muller and his Berkeley team.

There are three well-known reconstructions of monthly global mean surface temperature from instrumental data: NASA's GISTEMP analysis, the CRUTEM analysis (from the University of East Anglia's Climate Research Unit), and an analysis by NOAA's National Climatic Data Center (NCDC). These three analyses of global temperature data are almost identical. The main deficiency is in the CRUTEM's data which does not include sufficient polar data and therefore has a definite warming bias. Now there is a fourth, the BEST team's analysis.

All four analyses use data from the Global Historical Climatology Network (GHCN) and all four give a land-station only reconstruction and, except for the BEST study, a combined land-ocean reconstruction that includes sea surface temperature measurements. The GHCN collects data from more than 40,000 stations that are distributed on all continents and is the largest collection of daily climatological data in the world. The total of 1.4 billion data values includes 250 million values each for maximum and minimum temperatures, 500 million precipitation totals, and 200 million observations each for snowfall and snow depth. Station records, some of which extend back to the nineteenth century, are updated daily where possible and are usually available 1–2 days after the date and time of the observation. All records are subjected to intense quality control and quality assurance checks.

All temperature data are available to the public and analyses have been done independently by many scientists. Their results are identical to those by the entities given above if objective methods of analysis are used with the proper QA/QC for each step.

In addition to the above data collecting and analysis organizations, there is also the European Centre for Medium-Range Weather Forecasts (ECMWF) that collects temperature and other weather-related data and several other European organizations which collect temperature data.

University of Alabama, Huntsville (UAH) and Remote Sensing Systems (RSS) perform analyses from satellite data. The Japan Meteorological Association (JMA) also performs analyses of temperature data as do other agencies around the world. Each agency reports similar trends in temperature that tell us that the global temperature of planet Earth is rising.

6.4 Data Reduction

Because of the massive amounts of temperature and other climate-related data available from around the world, data reduction is necessary. Data reduction cannot be random, however, and must follow guidelines agreed upon by international bodies. Data reduction is defined as the transformation of numerical or alphabetical digital information derived empirically or experimentally into a corrected, ordered, and simplified form. When the information is derived from instrument readings, there may be a conversion from analog to digital form. However, most data today is in digital form; it has been acquired or converted, analyzed and reported digitally.

Data reduction has two meanings: (1) Data reduction by decreasing the dimensionality (exploratory multivariate statistics), and (2) Data reduction by unbiased decreasing of the sample size (exploratory graphics). Sometimes plotting an extremely large data set can obscure an existing pattern. When one has a very large data file, it can be useful to plot only a subset of the data so that the pattern is not hidden by the number of point markers.

These definitions of "data reduction" are both statistical definitions and can be found in many textbooks on basic statistics or at the following website: http://www.statsoft.com/textbook/statistics-glossary/d/?button=0#DataReduction.

6.5 Data Analysis

With massive amounts of data, even with data reduction, there are still massive amounts of temperature data to sort through. Basic statistical techniques are used to analyze these data. Maxima and minima with arithmetic means and standard deviations are used along with tests of significance of the data. Tests of correlation and quality of these data are performed.

The analysis method documented by Hansen and Lebedeff in 1981 showed that the correlation of temperature change was reasonably strong for stations separated by up to 1,200 km, especially at middle and high latitudes. This is the model used by GISS for today's analysis of climate data, with numerous updates as data analysis progresses.

6.6 Climate Data Analysis Tools (CDAT)

Lawrence Livermore National Laboratory has developed a software package which is used specifically for climate data analysis called CDAT (Climate Data Analysis Tools). This software package is:

- Developed at the Program for Climate Model Diagnosis and Intercomparison (PCMDI);
- Designed for climate science data;
- Analysis, conversion, sub-setting and array operations;
- Visualization system (VCS, Xmgrace, VTK);

- Graphical User Interface (VCDAT);
- XML representation (CDML) for datasets;
- Integrated with other packages (like LAS and OPeNDAP);
- Open-source and free.

CDAT is public domain software and is available for download at the following web site: http://www2-pcmdi.llnl.gov/cdat.

Other software packages for data analysis are available online and are in the public domain and can be downloaded.

6.7 Data Reporting

Data reporting is essential for informing the scientific community and the general public about what Earth's climate is doing; whether the Earth is warming or cooling, where the storms are most likely to increase along with their intensity, where will desertification most likely occur, etc. These questions are often answered through the use of climate models (see Chap. 18).

Reports of data analysis results are usually published in major peer-reviewed scientific journals, such as *Nature*, *Science*, *Journal of Climatology*, etc., either online, in hard copy, or both and are stored at major archival sites and available at their individual websites.

6.8 Average Land Temperatures

By the 1970s it became obvious that a method was needed to arrive at an average annual temperature for the Earth in order to compare the yearly average temperature with average temperatures from other years. Only in this way could a trend or trends be calculated to determine whether the Earth was cooling, warming, or staying the same from year to year.

Hansen and colleagues in 1981 showed that, contrary to impressions from northern latitudes which indicated a slight cooling, global cooling after 1940 was small, and there was actually net global warming of about 0.4°C between the 1880s and 1970s. The methods used by the scientists at GISS can be found and downloaded at the following website: http://data.giss.nasa.gov/gistemp/.

6.9 History of the Development of the Global Average Temperature

The analysis method developed by GISS scientists obtained quantitative estimates of the error in annual and 5-year mean temperature change by sampling at station locations that allowed a relatively complete data set which was shown to have realistic space (spatial) and time (temporal) variability.

They derived an error estimate that only addressed error due to incomplete spatial coverage of measurements. As there are other potential sources of error, such as urban warming near meteorological stations, etc., many other methods have been used to verify the approximate magnitude of inferred global warming, the latest of which is the very comprehensive methodology developed by the Berkeley Earth Surface Temperature study (BEST) that was discussed in Chap. 4. These methods include inference of surface temperature change from vertical temperature profiles in the ground (boreholes) at many sites around the world, rate of glacier retreat at many locations, and studies by several groups of the effect of urban and other local human influences on the global temperature record. All of these yield consistent estimates of the approximate magnitude of global warming, which now stands at about twice the magnitude that GISS reported in 1981, or about 0.8°C. The BEST study concluded that the warming has been on the order of 0.91°C since the 1950s.

Further affirmation of the reality of the warming is its spatial distribution, which has the largest values at locations remote from any local human influence, with a global pattern consistent with that expected for response to global climate forcings; larger in the Northern Hemisphere than the Southern Hemisphere, larger at high latitudes than low latitudes, and larger over land than over ocean.

Some improvements in the original analysis were made including use of satellite-observed night lights to determine which stations are located in urban and near-urban areas, the long-term trends of those stations being adjusted to agree with long-term trends of nearby rural stations.

6.10 Current Analysis Method

The temperature analysis used today uses satellite observed nightlights to identify measurement stations located in extreme darkness and adjusts temperature trends of urban and near-urban stations for non-climatic factors, verifying that urban effects on analyzed global change are small. Alternative choices for the ocean data are tested.

The GISS scientists showed that global temperature is sensitive to estimated temperature change in Polar Regions, where observations are limited. They suggested use of 12-month (n×12) running mean temperature to fully remove the annual cycle and improve information content in temperature graphs. They concluded that global temperature continued to rise rapidly in the past decade, despite large year-to-year fluctuations associated with the El Niño-La Niña cycle of tropical ocean temperature, discussed later in Chap. 13. Record high global temperature during the period with instrumental data was reached in 2010. The current analysis is now based on the adjusted GHCN v3 data for the data over land and on NOAA/NCDC's ERSST for data over the oceans.

The temperature analysis is limited to the period since 1880 because of poor spatial coverage of stations and decreasing data quality prior to that time. Meteorological station data provide a useful indication of temperature change in the Northern Hemisphere extra-tropics for a few decades prior to 1880, and there are a small number of station records that extend back to previous centuries. However, GISS scientists think that analyses for these earlier years need to be carried out on a station by station basis with an attempt to discern the method and reliability of measurements at each station. Global studies of still earlier times depend upon incorporation of proxy (substitute) measures of temperature change.

The Intergovernmental Panel on Climate Change (IPCC AR4 2007) issued the following statement:

"*The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.*" The report goes on to note that these findings come with a *"very high confidence rate that the globally averaged net effect of human activities since 1750 has been one of warming. Warming of the climate system is unequivocal as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.*"

The IPCC's conclusion that "global warming is unequivocal" and there is a very high rate of confidence that it is the result of human activities since 1750 (or the start of the Industrial Revolution) is hardly in doubt.

All temperature analyses indicate that during the last two decades (1990–1999 and 2000–2009, as of June 2012), globally averaged land temperatures have been higher than in any two decades in the past 150 years. Over the past 100 years (since 1912), a global temperature increase of 0.45°C per 100 years has been observed. Since the interpretation of the rise in temperature is a key issue for global warming, the accuracy of the data needs to be carefully considered. A number of potential problems may have affected the land temperature record, as follows:

- Spatial coverage of the data is incomplete (as it always will be; it is impossible to ever have complete coverage unless it is by more than one satellite) and varies considerably;
- Satellite instruments decay; as one satellite instrument decays, another is sent up to replace it and there is always a question if the new data is the same as the old data; there are statistical methods which are used to test the two data sets;
- Changes have occurred in the observing schedules and practices;
- Changes have occurred in the exposure of thermometers;
- Recording stations have changed their locations;
- Changes in the environment, especially urbanization, have taken place around many recording stations (this is the "heat island effect").

The potential problems with temperature data given above have been largely accounted for in the data sets used for annual, decadal, and monthly figures as the BEST results substantiated.

The oceans comprise about 71% of the Earth's surface. Obviously, a compilation of global temperature variations must include ocean surface temperatures as well as readings from land stations. Scientists have created historical analyses of global sea surface temperatures (SSTs) which are derived mostly from observations taken by commercial ships and the latest information from Argo floats.

6.11 Temperature Anomalies

Temperature data are reported as anomalies compared to a zero degree (0°) standard that is the average temperature for a range of years (as stated in Fig. 2.1 as 1951–1980). Temperatures are given as annual arithmetic means either above or below the standard for that graph. In Fig. 2.1, annual means (averages) are along the solid black line with a 5-year running mean indicated by the black line.

Temperature anomaly refers to the deviation from the average of global temperature. The term "temperature anomaly" means a departure from a reference value or long-term average temperature; the departure from a norm. A positive anomaly indicates that the observed temperature was warmer than the reference value, while a negative anomaly indicates that the observed temperature was cooler than the reference value. The reference value is the average or value of the arithmetic mean from a given period of time such as the mean temperature from 1991 to 2000.

The global temperature is calculated using anomalies because they give a more accurate picture of temperature change than actual raw temperature readings. When calculating an average temperature for a region, factors like station location or elevation affect the data, but when looking at the difference from the average for that same location, those factors are less critical. For example, while the actual temperature on a hilltop will be different than in a nearby valley on a given day or month, stations in both places will show a similar trend in temperature when you calculate the change in temperature compared to the average for that station. The change is what is important, not the raw temperatures.

Using anomalies also helps minimize problems when stations are added to or removed from the monitoring network.

In mountainous areas, most observations come from the inhabited valleys, so the effect of elevation on a region's average temperature must be considered as well. For example, a summer month over an area may be cooler than average, both at a mountain top and in a nearby valley, but the absolute temperatures will be quite different at the two locations. The use of anomalies in this case will show that temperatures for both locations were below average.

Using reference values computed on smaller, more local, scales over the same time period establishes a baseline from which anomalies are calculated. This effectively normalizes the data so they can be compared and combined to more accurately represent temperature patterns with respect to what is normal for different places within a region.

For these reasons, large-area summaries incorporate anomalies, not the temperature itself. Anomalies more accurately describe climate variability over larger areas than absolute temperatures do, and they give a frame of reference that allows more meaningful comparisons between locations and more accurate calculations of temperature trends. The Fig. 2.1 shows temperatures as anomalies. The temperature index is simply the method of stating the temperatures as temperature anomalies instead of actual raw temperatures.

Combined land and ocean temperatures have increased rather differently in the two hemispheres. A rapid increase in the Northern Hemisphere temperature during the 1920s and 1930s contrasts with a more gradual increase in the Southern Hemisphere. Both hemispheres had relatively stable temperatures from the 1940s to the 1970s, although there is some evidence of cooling in the Northern Hemisphere during the 1960s and 1970s. Since the 1960s in the Southern Hemisphere but after 1975 in the Northern Hemisphere, temperatures have risen sharply.

While globally-averaged records offer a means of assessing climate change, it is important to recognize that they represent an over-simplification. Significant latitudinal and regional differences in the extent and timing of warming exist. In addition, winter temperatures and night-time minimums may have risen more than summer temperatures and day-time maximums.

One of the most important factors in climate change science, of course, is global temperature. Temperature is recorded in most parts of the world by weather stations, buoys, satellites, ships, balloons, and rockets. Global temperature records go back to the written record of mankind, before the invention of the thermometer, but these earlier records are, of course, anecdotal.

The U.S. National Aeronautics and Space Administration (NASA) and the U.S. National Oceanic and Atmospheric Administration (NOAA) both released their final evaluations of global temperatures in 2011 on January 20th, 2012. They provide two of the longest-standing and most reliable annual evaluations of the climate, using data from the Goddard Institute for Space Studies (GISS) and National Climatic Data Center (NCDC).

While there are always going to be slight differences (because they use slightly different methodologies and instruments for collecting the data), their trends, as well as those from other notable temperature databases, line up closely. The graph below (Fig. 6.2) is a graph constructed in 2010 of global temperature anomalies from these databases (as well as a few others) since 1890, to give a graphic example of their correlation.

Instrumental observations over the past 160 years or so show that temperatures at the Earth's surface have risen globally, with important regional variations. For the global average, warming in the last Century has occurred in two phases, from the 1910s to the 1940s (0.35°C), and more strongly from the 1970s to the present (0.55°C), a total of 0.90°C. An increasing rate of warming has taken place over the last 25 years, and 12 of the 13 warmest years on record have occurred in the past 13 years (including 2010, which is tied with 2005 as the warmest year on record). Above the surface, global observations since the late 1950s show that the troposphere (from the Earth's surface up to an altitude of about 10 km) has warmed at a slightly greater rate than the surface, while the stratosphere (from an altitude of about 10–30 km) has cooled markedly since 1979. This is in accord with physical expectations and most model results if the warming is caused by the greenhouse effect. The stratosphere cools due to heat being trapped nearer the surface.

Confirmation of global warming comes from warming of the land and oceans, destruction of coral reefs (often referred to as bleaching), rising sea levels, glaciers melting, sea ice retreating and disappearing in the Arctic, diminished snow cover in the Northern Hemisphere, the increasing extinction of species, the melting of permafrost, and the migration of flora and fauna to areas that are warming; that is, to

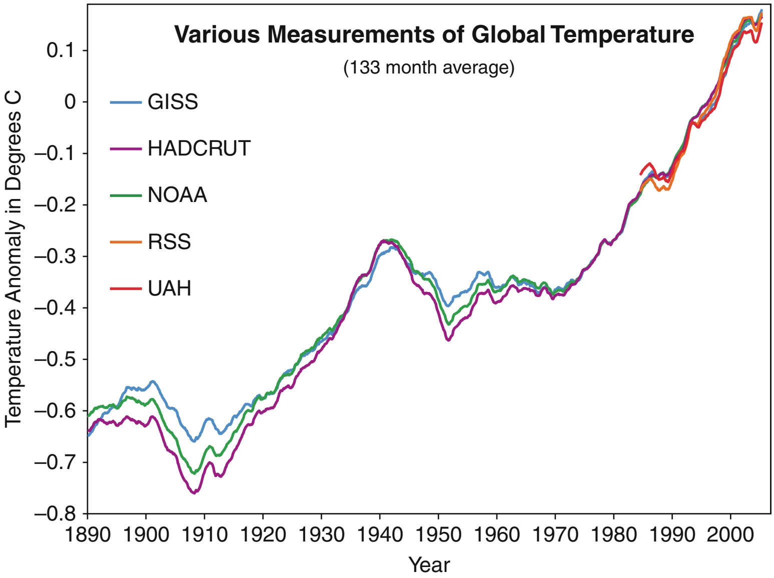

Fig. 6.2 Temperature anomalies in degrees Celsius from 1890 to 2010. *GISS* Goddard Institute of Space Studies, *HADCRUT* Hadley Centre Climate Research Unit Temperature, *NOAA* National Oceanographic and Atmospheric Administration, *RSS* Remote Sensing Systems, *UAH* University of Alabama at Huntsville (From SkepticalScience.com, viewed 1/21/2012)

higher altitudes and higher latitudes. Global warming is causing an increase in species extinction in those organisms that cannot migrate, migrate fast enough, or adapt. There is some concern that the Earth may be experiencing the start of the sixth great mass extinction that the planet has undergone since life began.

There is no single thermometer for measuring the global temperature. Instead, individual measurements are taken multiple times every day at several thousand stations over the land areas of the world and are combined with thousands more measurements of sea surface temperature taken from buoys and ships moving over the oceans to produce an estimate of global average temperature every month.

Scientists have to work with data they acquire, observe, or have collected from the past and analyze those data for accuracy with the best tools available to them; then make decisions as to whether to use those data or not depending on their accuracy. This is why levels of uncertainty are given in the majority of figures representing past temperature data.

Prior to the development of instruments to record temperatures, the written word was used to reveal the weather and temperature. It was "unusually cold in London this winter" or "unusually warm." Shortly after the invention of the thermometer in the early 1600s, efforts to quantify and record the temperature began. The first meteorological network was formed in northern Italy in 1653 and reports of temperature observations were published in the earliest scientific journals. By the latter part of the nineteenth century, systematic observations of the temperature and weather were being made in almost all inhabited areas of the world. International coordination of meteorological observations from ships began in 1853.

The International Meteorological Organization (IMO) was formed in 1873. Its successor, the World Meteorological Organization (WMO), works to promote, maintain, and distribute standardized meteorological observations. Even today, with uniform observations, there are still four major obstacles to turning instrumental observations into accurate global time series for temperature:

1. Access to the data in usable format. Much of the earlier data were not in a standard format and they had to be standardized;
2. Quality control to remove or edit erroneous data points. This is done to ensure and increase accuracy;
3. Quality assurance. Homogeneity assessments and adjustments where necessary to ensure the fidelity of the data; and
4. Area-averaging in the presence of substantial gaps.

Much has been made recently of the effect of El Niño and La Niña on climate models and global temperature calculations. The illustration below (Fig. 6.3) correlates global temperature and the El Niño – La Niña index. It also shows the three major volcanic eruptions of the later twentieth century (since 1960) and their effect on the global temperature. Large volcanic eruptions that cause volcanic particles to stay in the atmosphere have a cooling effect which may last about 2 years.

As the majority of land on Earth is located in the Northern Hemisphere, earlier temperature records are more abundant and complete from this part of the globe than from the Southern Hemisphere. More recent temperature data show more global coverage. The illustration below (Fig. 6.4) shows the change in climate forcing from 1978 to 2008 in the Northern Hemisphere.

One consequence of working only with temperature change is that analysis does not produce estimates of absolute temperature. For those who require an absolute global mean temperature, NASA/GISS scientists have estimated the 1951–1980 global mean surface air temperature as 14°C with uncertainty several tenths of a degree Celsius. That value was obtained by using a global climate model to fill in temperatures at grid points without observations, but it is consistent with results based on observational data. Different kinds of climate models are discussed in Chap. 18.

NASA/GISS scientists found that the correlation of neighboring station temperature records had no significant dependence on direction between the stations. They also examined the sensitivity of analysed global temperature to the chosen limit for station radius of influence (1,200 km). The global mean temperature anomaly was insensitive to this choice for the range from 250 to 2,000 km. The main effect is to make the global temperature anomaly map smoother as the radius of influence increases. However, global maps of temperature anomalies using a small radius of influence are useful for detecting stations with a temperature record that is inconsistent with stations in neighbouring regions.

The standard GISS analysis interpolates among station measurements and extrapolates anomalies as far as 1,200 km into regions without measurement stations as described by Hansen and Lebedeff. Resulting regions with defined temperature

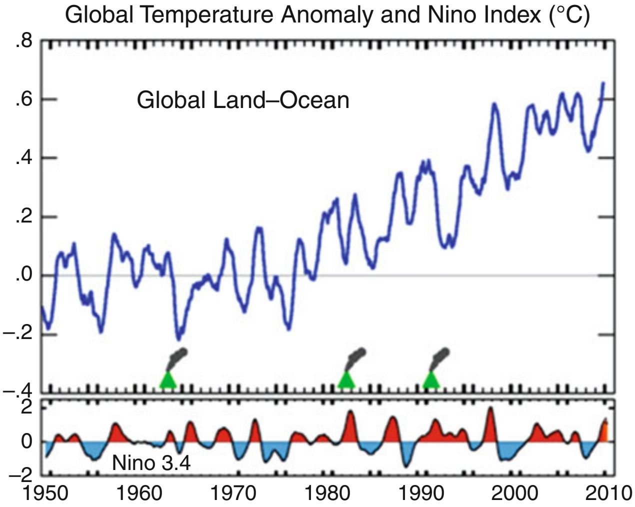

Fig. 6.3 *Blue curve*: 12-month running-mean global temperature. Note correlation with Niño index (*red*=El Niño, *blue*=La Niña). Large volcanoes (*green*) have a cooling effect for ~2 years (NASA/GISS, Public Domain)

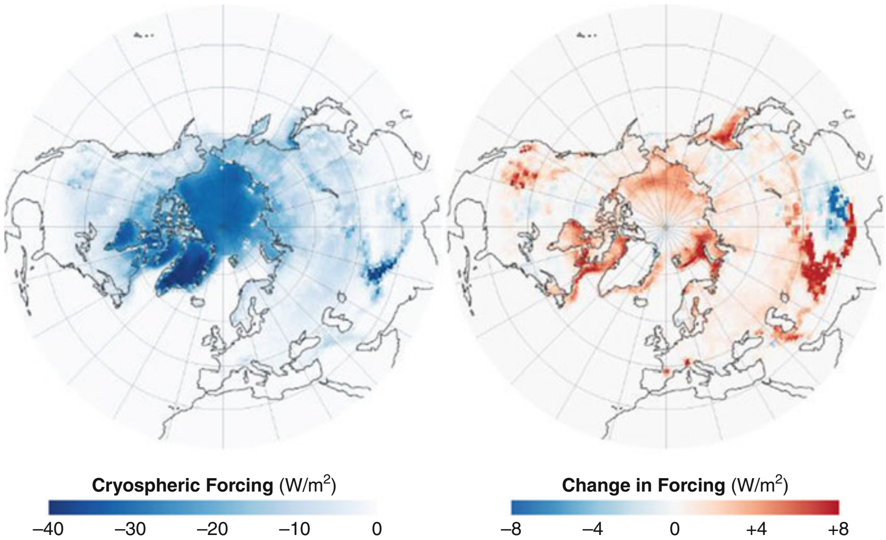

Fig. 6.4 The change in climate forcing in the Northern Hemisphere. The *left image* shows how much energy the Northern Hemisphere's snow and ice reflected on average between 1979 and 2008. *Dark blue* indicates more reflected energy, in Watts per square meter (W m^{-2}), and thus more cooling. The Greenland ice sheet reflects more energy than any other single location in the Northern Hemisphere. The second-largest contributor to cooling is the cap of sea ice over the Arctic Ocean. The *right image* shows how the energy being reflected from the cryosphere has changed between 1979 and 2008. When snow and ice disappear, they are replaced by dark land or ocean, both of which absorb more energy than ice. The image shows that the Northern Hemisphere is absorbing more energy, particularly along the outer edges of the Arctic Ocean, where sea ice has disappeared, and in the mountains of Central Asia (NASA, Public Domain)

anomalies are used to calculate a temperature anomaly history for large latitude zones. Early versions of the GISS analysis method calculated the global temperature anomaly time series as the average for these several latitude zones, with each zone weighted by the area with defined temperature anomaly. That definition can result in the global temperature anomaly differing from the average anomaly for the two hemispheres by as much as several hundredths of a degree during the early decades (1880–1920) when spatial coverage was especially poor.

6.12 History of Temperature Recordings

Temperature records taken at the Earth's surface are critical to the interpretation of climate change. Do these records indicate the Earth is cooling, getting hotter, or staying steady? Do more recordings of temperature allow more accurate calculations of an annual global temperature?

A brief history of temperature recordings that are used for temperature trends is discussed below.

Wladimir Köppen, a German climatologist**,** was the first scientist (in 1881) to overcome many of the obstacles in gathering temperature data in an effort to study the effect of changes in Sunspots. Köppen considered examination of the annual mean temperature to be an adequate technique for quality control of far distant stations. Using data from more than 100 stations, Köppen averaged annual observations into several major latitude belts and then area-averaged these into a near-global temperature time series.

Guy Stewart Callendar (1938), an English engineer and inventor, produced the next global temperature time series expressly to investigate the influence of CO_2 on temperature. Callendar examined about 200 station records. Only a small portion of them were deemed defective. After removing two Arctic stations because he had no compensating stations from the Antarctic region, he created a global average using data from 147 stations.

Most of Callendar's data came from World Weather Records (WWR). Initiated by a resolution at the 1923 IMO Conference, WWR was a monumental international undertaking producing a 1,196-page volume of monthly temperature, precipitation, and pressure data from hundreds of stations around the world, some with data starting in the early 1800s. In the early 1960s, scientists had these data digitized at the U. S.'s National Climatic Data Center (NCDC). The WWR project continues today under the auspices of the WMO with the digital publication of decadal updates to the climate records for thousands of stations worldwide.

H.C. Willett (1950) also used WWR as the main source of data for 129 stations that were used to create a global temperature time series going back to 1845. While the resolution that initiated WWR called for the publication of long and homogeneous records, Willett took this one step further by carefully selecting a subset of stations with as continuous and homogeneous a record as possible from the most recent update of WWR, which included data through 1940. To avoid over-weighting certain areas such as Europe, only one record, the "best" available, was included from each 10° latitude and longitude square. Station monthly data were averaged into 5-year periods and then converted to anomalies with respect to the 5-year period 1935–1939. Each station's anomaly was given equal weight to create the global time series.

Callendar created a new near-global temperature time series in 1961 and cited Willett as a guide for some of his improvements. Callendar evaluated 600 stations with about three-quarters of them passing his quality checks. At the time unknown to Callendar, a former student of Willett, Mitchell in 1963 had created his own updated global temperature time series using slightly fewer than 200 stations and averaging the data into latitude bands.

Meanwhile, research in Russia was proceeding with a very different method to produce large-scale time series. Mikhail Budyko used smoothed, hand-drawn maps of monthly temperature anomalies as a starting point. While restricted to analysis of the Northern Hemisphere, this map-based approach not only allowed the inclusion of an increasing number of stations over time (e.g., 246 in 1881, 753 in 1913, 976 in 1940 and about 2,000 in 1960) but also the utilization of data over the oceans.

A great deal of effort has been spent increasing the number of stations and digitizing historical station data as well as addressing the continuing problem of acquiring up-to-date data; there can be a long lag-time between making an observation and the data getting into global data sets. During the 1970s and 1980s, several teams produced global temperature time series. Advances especially worth noting during this period include the extended spatial interpolation and station averaging technique of GISS scientists and the Hadley Centre's CRU's painstaking assessment of homogeneity and adjustments to account for discontinuities in the record of each of the thousands of stations in a global data set. Since then, global and national data sets have been rigorously adjusted for homogeneity using a variety of statistical approaches.

6.13 Sea Surface Temperatures (SSTs)

As the importance of ocean data became increasingly recognized, a major effort was initiated to seek out, digitize, and initiate quality control of historical archives of ocean data. This work has since grown into the International Comprehensive Ocean–atmosphere Data Set (ICOADS), which has coordinated the acquisition, digitization and synthesis of data ranging from transmissions by Japanese merchant ships to the logbooks of South African whaling boats. The amount of sea surface temperature (SST) and related data acquired continue to grow as more data points are added throughout the World Ocean.

The U.S. National Oceanic and Atmospheric Administration maintains a National Data Buoy Center (NDBC) web page (http://www.ndbc.noaa.gov/). Part of NDBC is the Argo global float array coupled with the Jason satellite altimeter system. Together the Argo and Jason data sets will be assimilated into computer models developed by the Global Ocean Data Assimilation Experiment (GODAE) that will allow a test of scientists' ability to forecast ocean climate.

ICOADS offers surface marine data spanning the past three centuries, and simple gridded monthly summary products for 2° latitude by 2° longitude boxes back to 1,800 (and 1° by 1° boxes since 1960); these data and products are distributed worldwide. As it contains observations from many different observing systems encompassing the evolution of measurement technology over hundreds of years, ICOADS is probably the most complete and heterogeneous collection of surface marine data in existence.

As fundamental as the basic data work of ICOADS is, there have been two other major advances in SST data. The first was adjusting the early observations to make them comparable to current observations. Prior to 1940, the majority of SST observations were made from ships by hauling a bucket on deck filled with surface water and placing a thermometer in it. This is no longer done, but the older data had to be revised.

Most of the ship observations are taken in narrow shipping lanes, so the second advance has been increasing global coverage in a variety of ways. Direct improvement of coverage has been achieved by the internationally coordinated placement of drifting and moored buoys. The buoys began to be numerous enough to make significant contributions to SST analyses in the mid-1980s and have subsequently increased to more than 1,000 buoys transmitting data at any one time. Since 1982, satellite data, anchored to *in situ* observations, have contributed to near-global coverage on land and sea. In addition, several different approaches have been used to interpolate and combine land and ocean observations into the current global temperature time series. To place the current instrumental observations into a longer historical context requires the use of proxy data (proxy data in this case is data that are derived from methods other than direct recordings or observations of temperature such as annual tree-rings, ice cores, radiometrics, and isotope ratios). The U.S. NOAA maintains the SST records; and these may be found at the NOAA web site: http://www.noaa.gov.

Despite the fact that many recent observations are digitized and automatic, the vast majority of data that go into global surface temperature calculations (over 400 million individual readings of thermometers at land stations and over 140 million individual *in situ* SST observations) have depended on the dedication of tens of thousands of individuals for well over a century. Climate science owes a great debt to the work of these individual weather station observers who record temperatures, as well as to international organizations such as the IMO, WMO, and the Global Climate Observing System (GCOS), which encourage the taking and sharing of high-quality meteorological observations. They are too often ignored and not given the credit they so richly deserve.

The illustration below (Fig. 6.5) shows estimated mean temperatures from 1850 to 2005 in the top graph and the bottom maps show the temperature distribution on the Earth's surface (left) and in the troposphere (right). The troposphere temperatures are measured by satellite and range from the surface to an altitude of an average of 10 km.

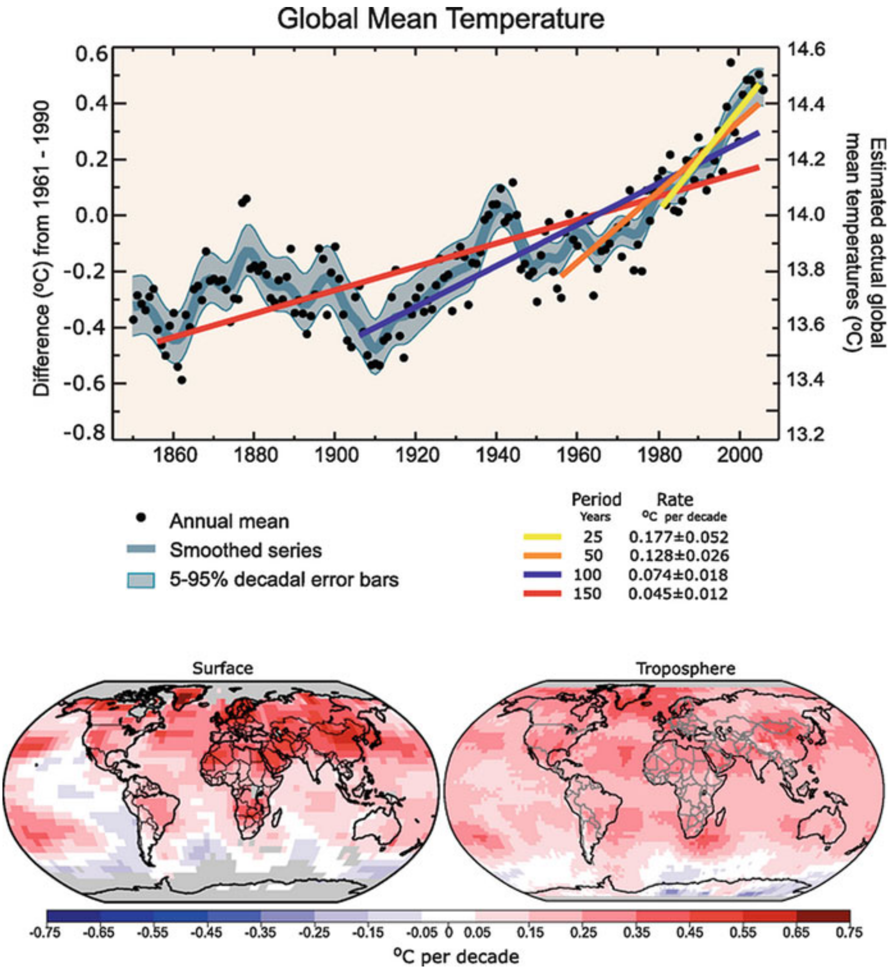

Fig. 6.5 (*Top*) Annual global mean observed temperatures (*black dots*) along with simple fits to the data. The *left hand axis* shows anomalies relative to the 1961–1990 average and the *right hand axis* shows the estimated actual temperature (°C). Linear trend fits to the last 25 (*yellow*), 50 (*orange*), 100 (*purple*) and 150 years (*red*) are shown, and correspond to 1981–2005, 1956–2005, 1906–2005, and 1856–2005, respectively. Note that for shorter recent periods, the slope is greater, indicating accelerated warming. The *blue curve* is a smoothed depiction to capture the decadal variations. To give an idea of whether the fluctuations are meaningful, decadal 5–95% (*light grey*) error ranges about that line are given (accordingly, annual values do exceed those limits). Results from climate models driven by estimated radiative forcings for the twentieth century suggest that there was little change prior to about 1915, and that a substantial fraction of the early twentieth-century change was contributed by naturally occurring influences including solar radiation changes, volcanism and natural variability. From about 1940 to 1970 the increasing industrialization following World War II increased pollution in the Northern Hemisphere, contributing to cooling, and increases in carbon dioxide and other greenhouse gases dominate the observed warming after the mid-1970s. (*Bottom*) Patterns of linear global temperature trends from 1979 to 2005 estimated at the surface (*left*), and for the troposphere (*right*) from the surface to about 10 km altitude, from satellite records. *Grey areas* indicate incomplete data. Note the more spatially uniform warming in the satellite tropospheric record while the surface temperature changes more clearly relate to land and ocean (IPCC AR4, 2007)

6.14 Projections of Future Temperatures

Climate change scientists use climate models with different scenarios to try and project future climates. Scientists do not predict future climates but use historical data and models to project climate scenarios into the future. Historical data are used in history matching (or hindcasting) because if a model can be used to match the climate events of the past it may be used to project events into the future, such as temperature increases.

The two illustrations below show results of models from the IPCC Third Assessment Report (IPCC AR3 or TAR, 2001) (Fig. 6.6), and those from the IPCC Fourth Assessment Report (IPCC AR4, 2007) (Fig. 6.7). The IPCC provides temperature "projections" as part of their assessment reports. These projections are based on scenarios using various amounts of CO_2 to drive global circulation models (GCMs). These projections are not predictions. The IPCC does not make predictions. Scientists may try and predict the weather but not the climate.

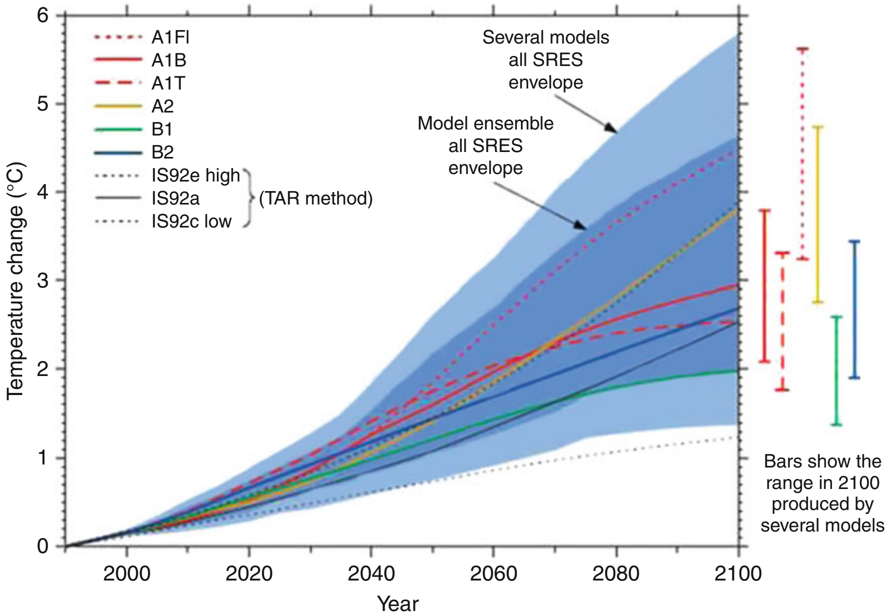

Fig. 6.6 This figure shows Figure 9.14 from the IPCC Third Assessment Report (TAR). It shows temperature projections to 2100: "results are relative to 1990 and shown for 1990–2100. Future changes for the six illustrative Special Report on Emission Scenarios (SRES) using a simple climate model tuned to seven Atmospheric-Ocean General Circulation Models (AOGCMs). Also for comparison, following the same method, results are shown for IS92a (from the TAR). The *dark blue* shading represents the envelope of the full set of 35 SRES scenarios using the simple model ensemble mean results. The *light blue* envelope is based on the Geophysical Fluid Dynamics Laboratory (USA) (GFDL_R15_a) and DOE PCM parameter settings. The *bars* show the range of simple model results in 2100 for the AOGCM model tunings" (From IPCC AR3, 2001)

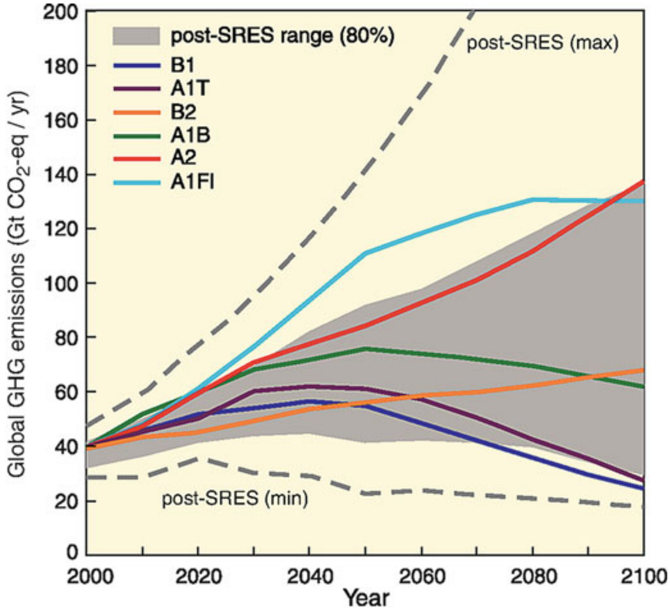

Fig. 6.7 Global GHG emissions (in $GtCO_2$-eq per year) in the absence of additional climate policies: six illustrative SRES marker scenarios (*coloured lines*) and 80th percentile range of recent scenarios published since SRES (post-SRES) (*gray shaded area*). *Dashed lines* show the full range of post-SRES scenarios. The emissions include CO_2, CH_4, N_2O and F-gases {WGIII 1.3, 3.2, Figure SPM.4}

6.15 The IPCC Special Report on Emission Scenarios (SRES), 2007

Descriptions of the IPCC Emission Scenarios as stated in their Emissions Report (SRES, 2007) A1, A2, B1 and B2 are given below.

A1. The A1 scenario describes a future world of very rapid economic growth, global population that peaks in mid-Century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions

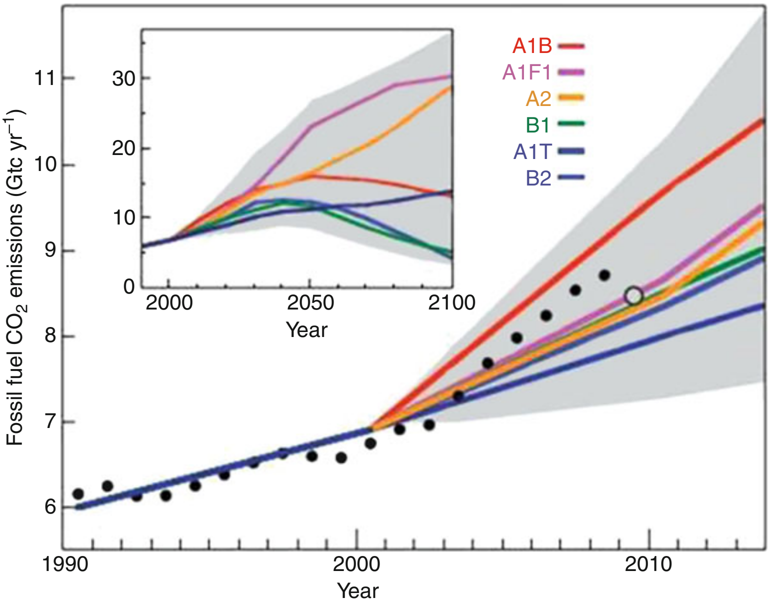

Fig. 6.8 Fossil Fuel CO_2 emissions. The graph shows that estimates of annual industrial CO_2 emissions in gigatonnes of carbon per year (Gt year^{-1}) for 1990–2008 (*black circles*) and for 2009 (*open circle*) fall within the range of IPCC scenarios (*grey shaded area*) and of the six IPCC illustrative marker scenarios (*colored lines*). The *inset* shows these scenarios to the year 2100. At the *top* is a fossil fuel intensive scenario (Manning et al., Nature Geoscience 3, 376–377 (2010) doi: 10.1038/ngeo880)

converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other scenarios.

B1. The B1 scenario describes a convergent world with the same global population that peaks in mid-Century and declines thereafter, as in the A1 scenario, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 scenarios. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The illustration above (Fig. 6.6) shows temperature projections to 2100 with the scenarios from the IPCC Third Assessment Report.

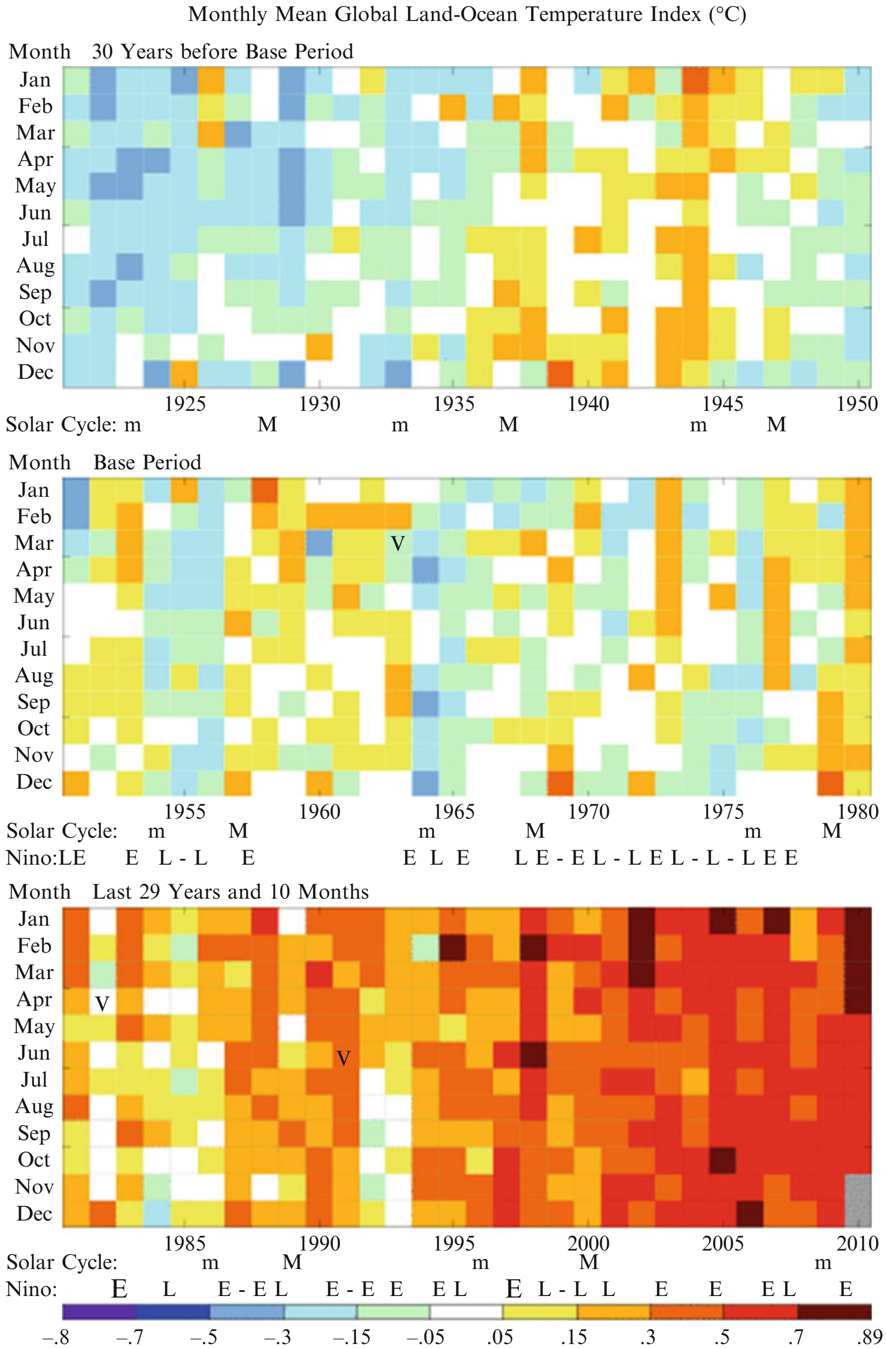

Fig. 6.9 Monthly mean global land-ocean temperature index (°C); (*Top Panel*) 30 years prior to the Base Period. (*Middle Panel*) The Base Period. (*Bottom Panel*) Past 30 years (1980–2010) (NASA/GISS, Public Domain)

The illustration above (Fig. 6.7) shows global greenhouse gas emissions according to the IPCC AR4 scenarios in gigatonnes of carbon dioxide equivalent per year (Gt $CO_{2\text{-eq}}$ year^{-1}).

The illustration above (Fig. 6.8) shows fossil fuel CO_2 emissions. The graph shows that estimates of annual industrial CO_2 emissions in gigatonnes of carbon per year (Gt year^{-1}) for 1990–2008 (black circles) and for 2009 (open circle) fall within the range of IPCC scenarios (grey shaded area) and of the six IPCC illustrative marker scenarios (colored lines).

The illustration above (Fig. 6.9) shows temperature changes plotted monthly starting in 1920 through October 2010 and color-coded according to the temperature scale along the base of the figure. The temperature increases over this time period are striking.

Additional Readings

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