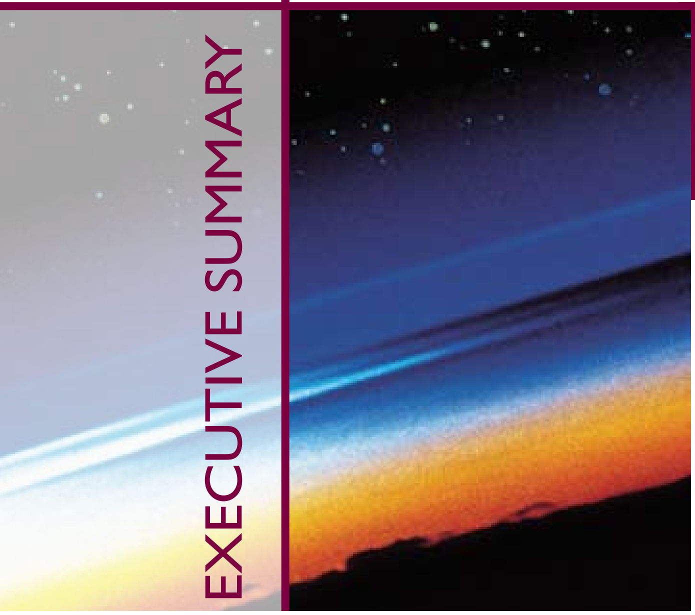

EXECUTIVE SUMMARY

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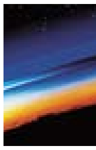
Abstract

Previously reported discrepancies between the amount of warming near the surface and higher in the atmosphere have been used to challenge the reliability of climate models and the reality of human-induced global warming. Specifically, surface data showed substantial global-average warming, while early versions of satellite and radiosonde data showed little or no warming above the surface. This significant discrepancy no longer exists because errors in the satellite and radiosonde data have been identified and corrected. New data sets have also been developed that do not show such discrepancies.

This Synthesis and Assessment Product is an important revision to the conclusions of earlier reports from the U.S. National Research Council and the Intergovernmental Panel on Climate Change. For recent decades, all current atmospheric data sets now show global-average warming that is similar to the surface warming. While these data are consistent with the results from climate models at the global scale, discrepancies in the tropics remain to be resolved. Nevertheless, the most recent observational and model evidence has increased confidence in our understanding of observed climatic changes and their causes.



NEW RESULTS AND FINDINGS

This Report is concerned with temperature changes in the atmosphere, differences in these changes at various levels in the atmosphere, and our understanding of the causes of these changes and differences. Considerable progress has been made since the production of reports by the NRC and the IPCC in 2000 and 2001. Data sets for the surface and from satellites and radiosondes (temperature sensors on weather balloons) have been extended and improved, and new satellite and radiosonde data sets have been developed[1]. Many new model simulations of the climate of the 20th century have been carried out using improved climate models[2] and better estimates of past forcing changes, and numerous new and updated comparisons between model and observed data have been performed. The present Report reviews this progress. A summary and explanation of the main results is presented first. Then, to address the issues in more detail, six questions that provide the basis for the six main chapters in this Synthesis and Assessment Report are posed and answered in Sections 1 through 5 below.

The important new results presented in this Report include:

Global Average Temperature Results

- For observations since the late 1950s, the start of the study period for this Report, the most recent versions of all available data sets show that both the surface and troposphere have warmed, while the stratosphere has cooled[3]. These changes are in accord with our understanding of the effects of radiative forcing agents[4] and with the results from model simulations.

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[1] For details of new observed data see Table 3.1 in Chapter 3.

[2] For details of new models and model simulations see Chapter 5 and http://www-pcmdi.llnl.gov/ipcc/model.documentation.

[3] We use the words "warming" and "cooling" here to refer to temperature increases or decreases, as is common usage. Technically, these words refer to changes in heat content, which may occur through changes in either the moisture content and/or the temperature of the atmosphere. When we say that the atmosphere has warmed (or cooled) over a given period, this means that there has been an overall positive (or negative) temperature change based on a linear trend analysis. For more on the use of linear trends, including a discussion of their strengths and weaknesses, see Appendix A.

[4] The main natural forcing agents are changes in solar output and the effects of explosive volcanic eruptions. The main human-induced ("anthropogenic") factors are: the emissions of greenhouse gases (*e.g.,* carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O]); aerosols (tiny droplets or particles such as smoke) and the gases that lead to aerosol formation (most importantly,

- Since the late 1950s, all radiosonde data sets show that the low and mid troposphere have warmed at a rate slightly faster than the rate of warming at the surface. These changes are in accord with our understanding of the effects of radiative forcing agents on the climate system and with the results from model simulations.

- For observations during the satellite era (1979 onwards), the most recent versions of all available data sets show that both the low and mid troposphere have warmed. The majority of these data sets show warming at the surface that is greater than in the troposphere. Some of these data sets, however, show the opposite - tropospheric warming that is greater than that at the surface. Thus, due to the considerable disagreements between tropospheric data sets, it is not clear whether the troposphere has warmed more than or less than the surface.

- The most recent climate model simulations give a range of results for changes in global-average temperature. Some models show more warming in the troposphere than at the surface, while a slightly smaller number of simulations show the opposite behavior. There is no fundamental inconsistency among these model results and observations at the global scale.

- Studies to detect climate change and attribute its causes using patterns of observed temperature change in space and time show clear evidence of human influences on the climate system (due to changes in greenhouse gases, aerosols, and stratospheric ozone).

- The observed patterns of change over the past 50 years cannot be explained by natural processes alone[5], nor by the effects of short-lived atmospheric constituents (such as aerosols and tropospheric ozone) alone.

Tropical Temperature Results (20°S to 20°N)

- Although the majority of observational data sets show more warming at the surface than in the troposphere, some observational data sets show the opposite behavior. Almost all model simulations show more warming in the troposphere than at the surface. This difference between models and observations may arise from errors that are common to all models, from errors in the observational data sets, or from a combination of these factors. The second explanation is favored, but the issue is still open.

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sulfur dioxide); and changes in land cover and land use (see Chapter 1, Table 1.1). Since these perturbations act to drive or "force" changes in climate, they are referred to as "forcings". Tropospheric ozone [O_3], which is not emitted directly, is also an important greenhouse gas. Tropospheric ozone changes occur through the emissions of gases like carbon monoxide, nitrogen oxides and volatile organic compounds, which, by themselves, are not important directly as greenhouse gases.

[5] "Natural processes" here refers to the effects of natural external forcing agents such as volcanic eruptions and solar variability, and/or internally generated variability.

EXPLANATION OF FINDINGS

These results for the globe and for the tropics characterize important changes in our understanding of the details of temperature changes at the surface and higher in the troposphere. In 2000 and 2001, the NRC and the IPCC both concluded that global-average surface temperature increases were larger and differed significantly from temperature increases in the troposphere. The new and improved observed data sets and new model simulations that have been developed require modifications of these conclusions.

The issue of changes at the surface relative to those in the troposphere is important because larger surface warming (at least in the tropics) would be inconsistent with our physical understanding of the climate system, and with the results from climate models. The concept here is referred to as "vertical amplification" (or, for brevity, simply "amplification"): greater changes in the troposphere would mean that changes there are "amplified" relative to those at the surface.

For global averages, observed changes from 1958 through 2004 exhibit amplification: i.e., they show greater warming trends in the troposphere compared with the surface. Since 1979, however, the situation is different: most data sets show slightly greater warming at the surface.

Whether or not these results are in accord with expectations based on climate models is a complex issue, one that we have been able to address more comprehensively now using new model results. Over the period since 1979, for global-average temperatures, the range of recent model simulations is almost evenly divided among those that show a greater global-average warming trend at the surface and others that show a greater warming trend aloft. The range of model results for global average temperature reflects the influence of the mid- to high-latitudes where amplification results vary considerably between models. Given the range of model results and the overlap between them and the available observations, there is no conflict between observed changes and the results from climate models.

In the tropics, the agreement between models and observations depends on the time scale considered. For month-to-month and year-to-year variations, models and observations both show amplification *(i.e.,* the month-to-month and year-to-year variations are larger aloft than at the surface). This is a consequence of relatively simple physics, the effects of the release of latent heat as air rises and condenses in clouds. The magnitude of this amplification is very similar in models and observations. On decadal and longer time scales, however, while almost all model simulations show greater warming aloft (reflecting the same physical processes that operate on the monthly and annual time scales), most observations show greater warming at the surface.

These results could arise either because "real world" amplification effects on short and long time scales are controlled by different physical mechanisms, and models fail to capture such behavior; or because non-climatic influences remaining in some or all of the observed tropospheric data sets lead to biased long-term trends; or a combination of these factors. The new evidence in this Report favors the second explanation.

I. HOW DO WE EXPECT VERTICAL TEMPERATURE PROFILES TO CHANGE?

Why do temperatures vary vertically (from the surface to the stratosphere) and what do we understand about why they might vary and change over time?

When all forcings are considered, we expect the troposphere to have warmed and the stratosphere to have cooled since the late 1950s.

This question is addressed in both Chapter 1 and Chapter 5 of this Report.

In response to this question, Chapter 1 notes:

(1) Temperatures Vary Vertically

- The global temperature profile of the Earth's atmosphere reflects a balance between radiative, convective and dynamical heating and cooling processes in the surface-atmosphere system. Radiation from the Sun is the source of energy for the Earth's climate. Physical properties of the atmosphere and dynamical processes mix heat vertically and horizontally, yielding the highest temperatures, on average, at the surface, with marked seasonal and spatial variations. In the atmosphere above the surface, the distribution of moisture and the lower air pressure at progressively higher altitudes result in decreasing temperatures with height up to the tropopause (marking the top of the troposphere, *i.e.,* the lower 8 to 16 km of the atmosphere, depending on latitude). Above this, the physical properties of the air produce a warming with height through the stratosphere (extending from the tropopause to ~50 km).

(2) Temperature Trends at the Surface can be Expected to be Different from Temperature Trends Higher in the Atmosphere Because:

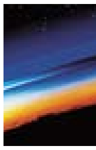
- The physical properties of the surface vary substantially according to location and this produces strong horizontal variations in near-surface temperature. Above the surface, on monthly and longer time scales, these contrasts are quickly smoothed out by atmospheric motions so the patterns of change in the troposphere must differ from those at the surface. Temperature trend variations with height must, therefore, vary according to location.
- Changes in atmospheric circulation or modes of atmospheric variability (*e.g.,* the El Niño-Southern Oscillation [ENSO]) can produce different temperature trends at the surface and aloft.
- Under some circumstances, temperatures may increase with height near the surface or higher in the troposphere, producing a "temperature inversion." Such inversions are more common at night over continents, over sea ice and snow in winter, and in the trade wind regions. Since the air in inversion layers is resistant to vertical mixing, temperature trends can differ between inversion layers and adjacent layers.
- Forcing factors, either natural or human-induced, can result in differing temperature trends at different levels in the atmosphere, and these vertical variations may change over time.

As noted above, temperatures in the atmosphere vary naturally as a result of internal factors and natural and human-induced perturbations ("forcings"). These factors are expected to have different effects on temperatures near the surface, in the troposphere, and in the stratosphere, as summarized in Table 1. When all forcings are considered, we expect the troposphere to have warmed and the stratosphere to have cooled since the late 1950s (and over the whole 20th century). The relative changes in the troposphere and stratosphere provide information about the causes of observed changes.

Within the troposphere, the relative changes in temperature at different levels are controlled by different processes according to latitude. In the tropics, the primary control is the thermodynamics of moist air *(i.e.,* the effects of evaporation at the surface and the release of latent heat through condensation that occurs in clouds as moist air rises due to convection), and the way these effects are distributed and modified by the atmospheric circulation. Thermodynamic principles require that temperature changes in the tropics will be larger in the troposphere than near the surface ("amplification"), largely independent of the type of forcing. In mid to

Table 1: Summary of the most important global-scale climate forcing factors and their likely individual effects on global-, annual-average temperatures; based on Figure 1.3 (which gives temperature information) and Table 1.1 (which gives information on radiative forcing) in Chapter 1, and literature cited in Chapter 1. The stated effects are those that would be expected if the change specified in column 1 were to occur. The top two rows are the primary natural forcing factors, while the other rows summarize the main human-induced forcing factors. The relative importance of these different factors varies spatially and over time. For example, volcanic effects last only a few years in the stratosphere, and slightly longer in the troposphere; while the effects of well-mixed greenhouse gases last for decades to centuries.

	Theoretically expected change in annual-global-average temperature		
Forcing Factor	**Surface**	**Low to Mid Troposphere**	**Stratosphere**
Increased solar output	Warming	Warming	Warming
Volcanic eruptions	Cooling	Cooling	Warming
Increased concentrations of well-mixed greenhouse gases (CO_2, CH_4, N_2O, halocarbons)	Warming	Warming	Cooling
Increased tropospheric ozone (O_3)	Warming	Warming	Slight cooling
Decreased stratospheric ozone	Negligible except at high latitudes	Slight cooling	Cooling
Increased loading of tropospheric sulfate (SO_4) aerosol – sum of direct plus indirect effects	Cooling	Cooling	Negligible
Increased loading of carbonaceous aerosol (black carbon [BC] and organic matter [OM]) in the troposphere – sum of direct plus indirect effects	Regional cooling or warming – possible global-average cooling	Warming	Uncertain
Land use and land cover changes	Regional cooling or warming – probably slight global-average cooling	Uncertain	Negligible



high latitudes, the processes controlling how temperature changes in the vertical are more complex, and it is possible for the surface to warm more than the troposphere. These issues are addressed further in Chapter 1 and Chapter 5.

2. STRENGTHS AND LIMITATIONS OF THE OBSERVATIONAL DATA

What kinds of atmospheric temperature variations can the current observing systems detect and what are their strengths and limitations, both spatially and temporally?

This question is addressed in Chapter 2 of this Report. Chapter 2 draws the following main conclusions:

(1) The observing systems available for this Report are able to detect small surface and upper air temperature variations from year to year as well as trends[6] in climate since the late 1950s (and over the last century for surface observations), once the raw data are successfully adjusted for changes over time in observing systems and practices, and micro-climate exposure. Measurements from all systems require such adjustments. This Report relies solely on adjusted data sets.

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[6] Many of the results in this Report (and here in the Executive Summary) are quantified in terms of linear trends, *i.e.,* by the value of the slope of a straight line that is fitted to the data. A simple straight line is not always the best way to describe temperature data, so a linear trend value may be deceptive if the trend number is given in isolation, removed from the original data. Nevertheless, used appropriately, linear trends provide the simplest and most convenient way to describe the overall change over time in a data set, and are widely used. For a more detailed discussion, see Appendix A.

(2) Independently performed adjustments to the land surface temperature record have been sufficiently successful that trends given by different data sets are reasonably similar on large (*e.g.,* continental) scales, despite the fact that spatial sampling is uneven and some errors undoubtedly remain. This conclusion holds to a lesser extent for the ocean surface record, which suffers from more serious sampling problems and changes in observing practice.

All data sets require careful examination for instrument biases and reliability, and adjustments are made to remove changes that might have arisen for non-climatic reasons.

(3) Adjustments for changing instrumentation are most challenging for upper-air data sets. While these show promise for trend analysis, and it is very likely that current upper-air climate records give reliable indications of directions of change (*e.g.,* warming of the troposphere, cooling of the stratosphere), some questions remain regarding the accuracy of the data after adjustments have been made to produce homogeneous time series from the raw measurements.

- Upper-air data sets have been subjected to less scrutiny than surface data sets.
- Adjustments are complicated, can be large compared to the linear trend signal, involve expert judgments, and cannot be stringently evaluated because of lack of traceable standards.
- Unlike surface trends, reported upper-air trends vary considerably between research teams beginning with the same raw data owing to their different decisions on how to remove non-climatic factors.

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Many different methods are used to measure temperature changes at the Earth's surface and at various levels in the atmosphere. Near-surface temperatures have been measured for the longest period, over a century, and are measured directly by thermometers. Over land, these data come from fixed meteorological stations. Over the ocean, measurements are of both air temperature and sea-surface (top 10 meters) temperature taken by ships or from buoys.

The next-longest records are upper-air data measured by radiosondes (temperature sensors carried aloft by weather balloons). These have been collected routinely since 1958. There are still substantial gaps in radiosonde coverage.

Satellite data have been collected for the upper air since 1979 with almost complete global coverage. The most important satellite records come from Microwave Sounding Units (MSU) on polar orbiting satellites. The microwave data from MSU instruments require calculations and adjustments in order to be interpreted as temperatures. Furthermore, these satellite data do not represent the temperature at a particular level, but, rather, the average temperature over thick atmospheric layers (see Figure 2.2 in Chapter 2). As such, they cannot reveal the detailed vertical structure of temperature changes, nor do they completely isolate the troposphere from the stratosphere. Channel 2 data (mid troposphere to lower stratosphere, T_2) have a latitudinally dependent contribution from the stratosphere, while Channel 4 data (lower stratosphere, T_4) have a latitudinally dependent contribution from the troposphere, factors that complicate their interpretation. However, retrieval techniques can be used both to approximately isolate specific layers and to check for vertical consistency of trend patterns.

All measurement systems have inherent uncertainties associated with: the instruments employed; changes in instrumentation; and the way local measurements are combined to produce area averages. All data sets require careful examination for instrument biases and reliability, and adjustments are made to remove changes that might have arisen for non-climatic reasons. We refer to these as "adjusted" data sets. The term "homogenization" is also used to describe this adjustment procedure.

Reanalyses[7] and other multi-system products that synthesize observational data with model results to ensure spatial and inter-variable consistency have the potential for addressing issues of surface and atmospheric temperature trends by making better use of available information and allowing analysis of a more comprehensive,

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[7] Reanalyses are mathematically blended products based upon as many observing systems as practical. Observations are assimilated into a global weather forecasting model to produce globally comprehensive data sets that are most consistent with both the available data and the assimilation model.

internally consistent, and spatially and temporally complete set of climate variables. At present, however, these products contain biases, especially in the stratosphere, that affect trends and that cannot be readily removed because of the complexity of the data products.

3. WHAT TEMPERATURE CHANGES HAVE BEEN OBSERVED?

What do observations indicate about the changes of temperature in the atmosphere and at the surface since the advent of measuring temperatures vertically?

What is our understanding of the contribution made by observational or methodological uncertainties to the previously reported vertical differences in temperature trends?

These questions are addressed in Chapters 3 and 4 of this Report. The following conclusions are drawn in these chapters. Supporting information is given in Figure 1 and Figure 2.

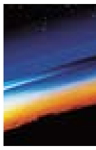
(1) Surface temperatures: For global-average changes, as well as in the tropics (20°S to 20°N), all data sets show warming at the surface since 1958, with a greater rate of increase since 1979. Differences between the data sets are small.

- Global-average temperature increased at a rate of about 0.12°C per decade since 1958, and about 0.16°C per decade since 1979. In the tropics, temperature increased at about 0.11°C per decade since 1958, and about 0.13°C per decade since 1979.

- Systematic local biases in surface temperature trends may exist due to changes in station exposure and instrumentation over land[8], or changes in measurement techniques by ships and buoys in the ocean. It is likely that these biases are largely random and therefore cancel out over large regions such as the globe or tropics, the regions that are of primary interest to this Report.

(2) Tropospheric temperatures: All data sets show that the global- and tropical-average troposphere has warmed from 1958 to the present, with the warming in the troposphere being slightly more than at the surface. For changes from 1979, due to the considerable disagreements between tropospheric data sets, it is not clear whether the troposphere has warmed more than or less than the surface.

Errors in observed temperature trend differences between the surface and the troposphere are more likely to come from errors in tropospheric data than from errors in surface data.



- Global-average tropospheric temperature increased at a rate of about 0.14°C per decade since 1958 according to the two radiosonde data sets. For the period from 1979, temperature increased by 0.10°C to 0.20°C per decade according to the two radiosonde and three satellite data sets. In the tropics, temperature increased at about 0.13°C per decade since 1958, and between 0.02°C and 0.19°C per decade since 1979.

- Errors in observed temperature trend differences between the surface and the troposphere are more likely to come from errors in tropospheric data than from errors in surface data.

- It is very likely that estimates of trends in tropospheric temperatures are affected by errors that remain in the adjusted radiosonde data sets. Such errors arise because the methods used to produce these data sets are only able to detect and remove the more obvious causes, and involve many subjective decisions. The full consequences of these errors for large-area averages, however, have not yet been fully resolved. Nevertheless, it is likely that a net spurious cooling corrupts the area-averaged adjusted radiosonde data in the tropical troposphere, causing these data to indicate less warming than has actually occurred there.

- For tropospheric satellite data, a primary cause of trend differences between different versions is differences in how the data from different satellites are merged together. Corrections required to account for drifting measurement times are also important.

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[8] Some have expressed concern that land temperature data might be biased due to urbanization effects. Recent studies specifically designed to identify systematic problems using a range of approaches have found no detectable urban influence in large-area averages in the data sets that have been adjusted to remove non-climatic influences (*i.e.,* "homogenized").

- Comparisons between satellite and radiosonde temperatures for the mid troposphere to lower stratosphere layer (MSU channel 2; T_2) are very likely to be corrupted by excessive stratospheric cooling in the radiosonde data.

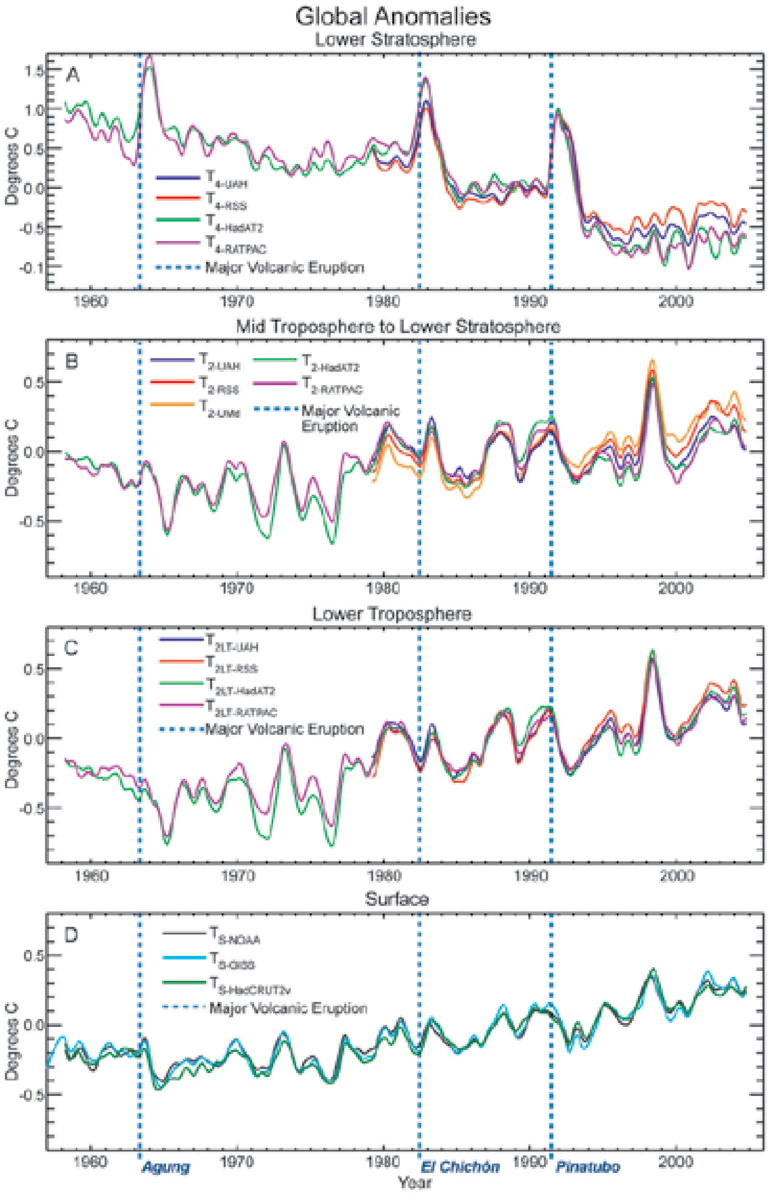


Figure 1: Observed surface and upper air global-average temperature records. From top to bottom: A, lower stratosphere (denoted T_4) records from two satellite analyses (UAH and RSS) together with equivalently weighted radiosonde records based on HadAT2 and RATPAC data; B, mid-troposphere to lower stratosphere (T_2) records from three satellite analyses (UAH, RSS and UMd) together with equivalently weighted radiosonde records based on HadAT2 and RATPAC; C, lower troposphere (T_{2LT}) records from UAH and RSS (satellite), and from HadAT2 and RATPAC (equivalently weighted radiosonde); D, surface (T_S). All time series are based on monthly-average data smoothed with a 7-month running average, expressed as departures from the Jan. 1979 to Dec. 1997 average. Note that the T_2 data (panel B) contain a small contribution (about 10%) from the lower stratosphere. Information here is from Figures 3.1, 3.2 and 3.3 in Chapter 3.

(3) Lower stratospheric temperatures: All data sets show that the stratosphere has cooled considerably from 1958 and from 1979 to the present, although there are differences in the linear trend values from different data sets.

- The largest differences between data sets are in the stratosphere, particularly between the radiosonde and satellite-based data sets. It is very likely that the discrepancy between satellite and radiosonde trends arises primarily from uncorrected errors in the radiosonde data.

Figure 1 shows the various temperature time series examined in this Report.

For the lower stratosphere, the cooling trend since the late 1950s (which is as expected due to the effects of greenhouse-gas concentration increases and stratospheric ozone depletion) is punctuated by short-term warming events associated with the explosive volcanic eruptions of Mt. Agung (1963), El Chichón (1982) and Mt. Pinatubo (1991).

Both the troposphere and the surface show warming since the late 1950s. For the surface, most of the temperature increase since 1958 occurs starting around 1976, a time coincident with a previously identified climate shift. For the balloon-based tropospheric data, a major part of the temperature increase since 1958 also occurs around 1976, in the form of a relatively rapid rise in temperature. The shift in 1976 is important because it occurs just before the start of the satellite era.

The dominant shorter time scale fluctuations are those associated with the El Niño-Southern Oscillation phenomenon (ENSO). The major ENSO warming event in 1998 is obvious in all records. Cooling following the eruptions of Mt. Agung and Mt. Pinatubo is also evident, but the cooling effect of El Chichón is masked by an ENSO warming that occurred at the same time. The changes following volcanic eruptions *(i.e.,* surface and tropospheric cooling and stratospheric warming) are consistent with our physical understanding and with model simulations.

Global-average temperature changes over the periods 1958 through 2004 and 1979 through 2004 are shown in Figure 2 in degrees Celsius and degrees Fahrenheit.

4. ARE MODEL SIMULATIONS CONSISTENT WITH THE OBSERVED TEMPERATURE CHANGES?

Computer-based climate models encapsulate our understanding of the climate system and the driving forces that lead to changes in climate. Such models are the only tools we have for simulating the likely patterns of response of the climate system to different forcing mechanisms. The crucial test of our understanding is to compare model simulations with observed changes to address the question:

How well can the observed vertical temperature changes be reconciled with our understanding of the causes of these changes?

In addressing this question, Chapter 5 draws the following conclusions ...

FINGERPRINT PATTERN STUDIES

(1) Results from many different pattern-based "fingerprint"[9] studies (see Box 5.5 in Chapter 5) provide consistent evidence for human influences on the three-dimensional structure of atmospheric temperature changes over the second half of the 20th century.

- Fingerprint studies have identified greenhouse gas and sulfate aerosol signals in observed surface temperature records, a stratospheric ozone depletion signal in stratospheric temperatures, and the combined effects of these forcing agents in the vertical structure of atmospheric temperature changes.

(2) Natural factors (external forcing agents like volcanic eruptions and solar variability and/or internally generated variability) have influenced surface and atmospheric temperatures, but cannot fully explain their changes over the past 50 years.

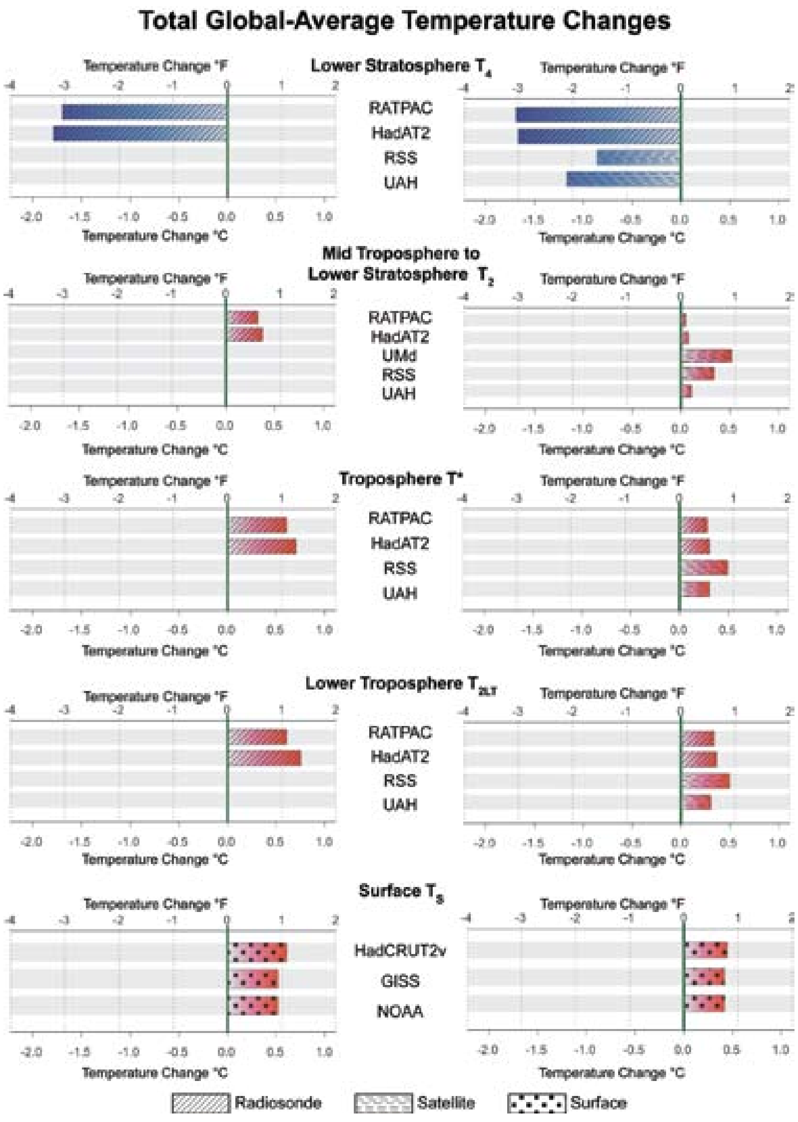
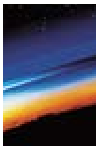


Figure 2: Total global-average temperature changes for the surface and different atmospheric layers, from different data sets and over two periods, 1958 to 2004 and 1979 to 2004. The values shown are the total change over the stated period in both degrees Celsius (°C; lower scales) and degrees Fahrenheit (°F; upper scales). All changes are statistically significant at the 5% level except RSS T_4 and RATPAC, HadAT2 and UAH T_2. Total change in °C is the linear trend in °C per decade (see Tables 3.2 and 3.3 in Chapter 3) times the number of decades in the time period considered. Total change in °F is this number times 1.8 to convert to °F. For example, the Table 3.2 trend for NOAA surface temperatures over January 1958 through December 2004 is 0.11°C/decade. The total change is therefore 0.11 times 4.7 decades to give a total change of 0.53°C, Multiplying this by 1.8 gives a total change in degrees Fahrenheit of 0.93°F. Warming is shown in red, and cooling in blue.



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[9] Fingerprint studies use rigorous statistical methods to compare the patterns of observed temperature changes with model expectations and determine whether or not similarities could have occurred by chance. Linear trend comparisons are less powerful than fingerprint analyses for studying cause-effect relationships, but can highlight important differences and similarities between models and observations.

When models are run with natural and human-induced forcings, simulated global-average temperature trends for individual atmospheric layers are consistent with observations.

Linear Trend Comparisons

(3) When models are run with natural and human-induced forcings, simulated global-average temperature trends for individual atmospheric layers are consistent with observations.

(4) Comparing trend differences between the surface and the troposphere exposes potentially important discrepancies between model results and observations in the tropics.

- In the tropics, most observational data sets show more warming at the surface than in the troposphere, while almost all model simulations have larger warming aloft than at the surface.

Amplification of Surface Warming in the Tropical Troposphere

(5) Amplification means that temperatures show larger changes aloft than at the surface. In the tropics, on monthly and inter-annual time scales, both models and observations show amplification of temperature variability in the troposphere relative to the surface. This amplification is of similar magnitude in models and observations. For multi-decadal trends, models show the same amplification that is seen on shorter time scales. The majority of the most recent observed data sets, however, do not show this amplification.

- This inconsistency between model results and observations could arise either because "real world" amplification effects on short and long time scales are controlled by different physical mechanisms, and models fail to capture such behavior; or because non-climatic influences remaining in some or all of the observed tropospheric datasets lead to biased long-term trends; or a combination of these factors. The new evidence in this Report - model-to-model consistency of amplification results, the large uncertainties in observed tropospheric temperature trends, and independent physical evidence supporting substantial tropospheric warming (such as the increasing height of the tropopause) - favors the second explanation. However, the large observational uncertainties that currently exist make it difficult to determine whether or not models still have significant errors. Resolution of this issue requires reducing these uncertainties.

Other Findings

(6) Because of differences between different observed data sets and differences between models, it is important to account for both model and observational uncertainty in comparisons between modeled and observed temperature changes.

- Large "construction" uncertainties in observed estimates of global-scale atmospheric temperature change can critically influence the outcome of consistency tests between models and observations.

(7) Inclusion of previously ignored, spatially variable forcings in the most recent climate models does not fundamentally alter conclusions about the amplification of warming in the troposphere relative to the surface.

- Changes in sulfate aerosols and tropospheric ozone, which have spatially variable forcings, have been incorporated routinely in climate model experiments for a number of years. It has been suggested that the spatially heterogeneous forcing effects of black carbon aerosols and land use/land cover changes may have had significant effects on regional temperatures that might modify previous conclusions regarding vertical temperature changes. These forcings have been included for the first time in about half of the global model simulations considered here. Within statistical uncertainties, model simulations that include these forcings show the same amplification of warming in the troposphere relative to the surface at very large spatial scales (global and tropical averages) as simulations in which these forcings are neglected.

Chapter 5 analyzes state-of-the-art model simulations from 19 institutions from around the world, run using combinations of the most important natural and human-induced forcings. The Chapter compares the results of these simulations with a number of different observational data sets for the surface and different atmospheric layers, resulting in a large number of possible model/observed data comparisons.

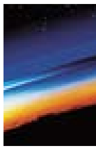
Figures 3 and 4 summarize the new model results used in this Report, together with the corresponding observations. Figure 3 gives results for global-average temperature, while Figure 4 gives results for the tropics (20°S to 20°N). Model and observed results are compared in these Figures using linear trends over the period January 1979 through December 1999[10] for the surface, for individual layers, and (right-hand panels) for surface changes relative to the troposphere. Rectangles are used to illustrate the ranges of both model trends (red rectangles) and observed trends (blue rectangles). Individual observed-data trends are also shown.

Since statistical uncertainties (see Appendix A) are not shown in these Figures, the rectangles do not represent the full ranges of uncertainty. However, they allow a useful first-order assessment of similarities and differences between observations and model results. Overlapping rectangles in the Figures indicate consistency, while rectangles that either do not overlap or show minimal overlap point to potential inconsistencies between observations and model results.

For global averages (Fig. 3), models and observations generally show overlapping rectangles. A potentially serious inconsistency, however, has been identified in the tropics. Figure 4G shows that the lower troposphere warms more rapidly than the surface in almost all model simulations, while, in the majority of observed data sets, the surface has warmed more rapidly than the lower troposphere. In fact, the nature of this discrepancy is not fully captured in Fig. 4G as the models that show best agreement with the observations are those that have the lowest (and probably unrealistic) amounts of warming (see Chapter 5, Fig. 5.6C). On the other hand, as noted above, the rectangles do not express the full range of uncertainty, as they do not account for the large statistical uncertainties in the individual model trends or the large constructional and statistical uncertainties in the observed data trends.

The potential discrepancy identified here is a different way of expressing the amplification discrepancy described in Section 4, item (5) above. It may arise from errors that are common to all models, from errors in the observational data sets, or from a combination of these factors. The second explanation is favored, but the issue is still open.

A potentially serious inconsistency has been identified in the tropics. The favored explanation for this is residual error in the observations, but the issue is still open.



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[10] This is the longest period common to all model simulations.

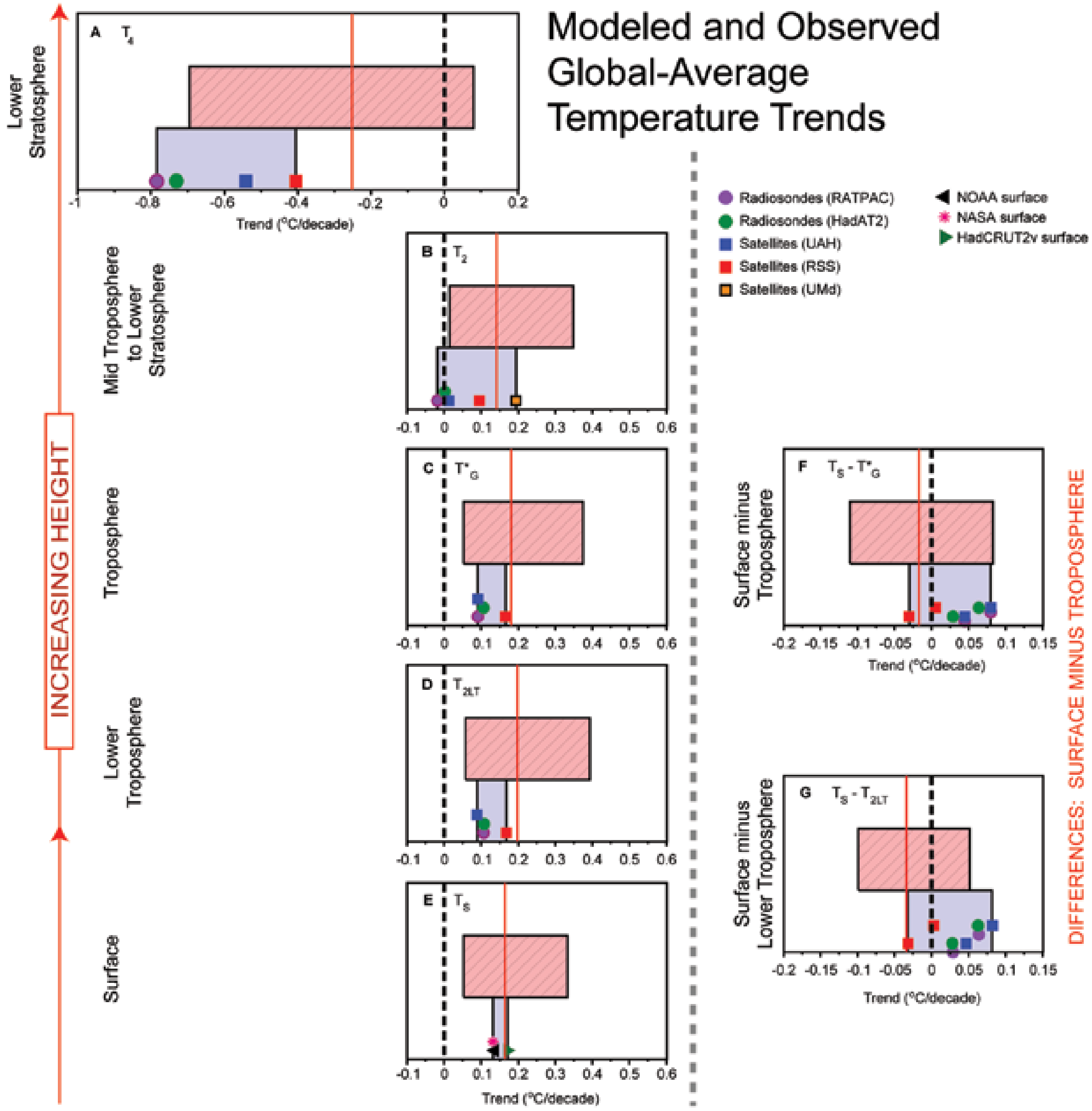


Figure 3: Comparison of observed and model-simulated global-average temperature trends (left-hand panels) and trend differences (right-hand panels) over January 1979 through December 1999, based on Table 5.4A and Figure 5.3 in Chapter 5. The upper red rectangles in each box show the range of model trends from 49 model simulations. The lower blue rectangles show the range of observed trends, with the individual trends from different data sets indicated by the symbols. From bottom to top, the left-hand panels show trends for the surface (T_S), the lower troposphere (T_{2LT}), the troposphere (T^*), the mid troposphere to lower stratosphere (T_2), and the lower stratosphere (T_4). The right-hand panels show differences in trends between the surface and either the troposphere or the lower troposphere, with a positive value indicating a stronger warming at the surface. The red vertical lines show the average of all model results. The vertical black dashed lines show the zero value. For the observed trend differences, there are eight values corresponding to combinations of the four upper-air data sets (as indicated by the symbols) and either the HadCRUT2v surface data or the NASA/NOAA surface data (which have almost identical trends).

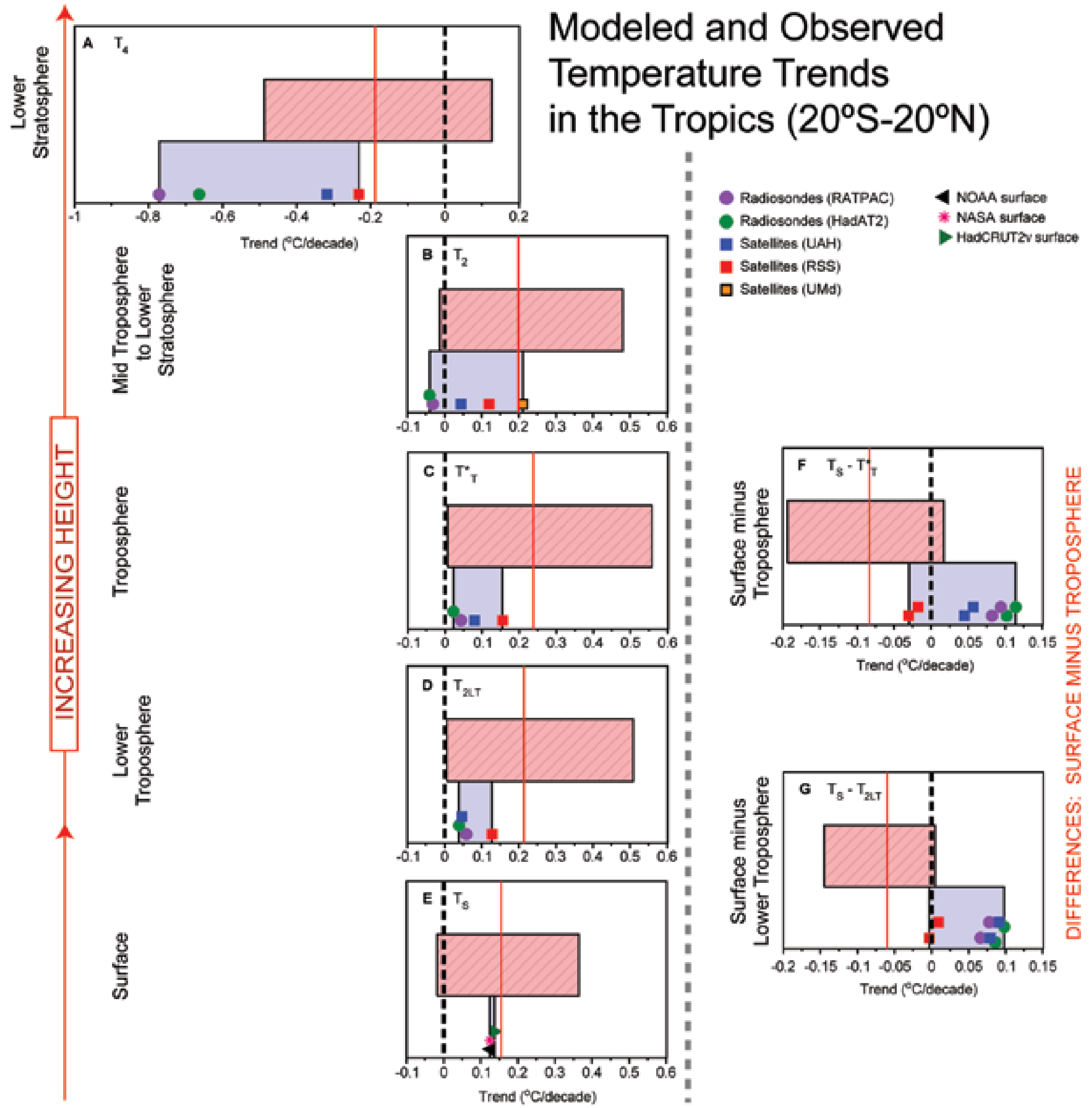
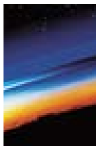


Figure 4: As Figure 3, but for the tropics (20°S to 20°N), based on Table 5.4B and Figure 5.4 in Chapter 5. Note that, in the tropics, the tropospheric radiosonde data (green and purple filled circles in panels C and D) may have a cooling bias and that it is unlikely that this bias has been completely removed from the adjusted data used here. Note also that the (small) overlap in panel G is deceptive because the models in this overlap area have unrealistically small amounts of warming. On the other hand, the rectangles do not express the full range of uncertainty, as they do not account for uncertainties in the individual model or observed data trends.



5. RECOMMENDATIONS

What measures can be taken to improve the understanding of observed changes?

In answer to this question, drawing on the material presented in the first five chapters of this Report, a set of primary recommendations has been developed and is described in detail in Chapter 6. The items described in Chapter 6 expand and build upon existing ideas, emphasizing those that are considered to be of highest utility. The seven inter-related recommendations are:

(1) The independent development of data sets and analyses by several scientists or teams will help to quantify structural uncertainty. In order to encourage further independent scrutiny, data sets and their full metadata *(i.e.,* information about instrumentation used, observing practices, the environmental context of observations, and data-processing procedures) should be made openly available. Comprehensive analyses should be carried out to ascertain the causes of remaining differences between data sets and to refine uncertainty estimates.

(2) Efforts should be made to archive and make openly available for independent analysis surface, balloon-based, and satellite data and metadata that have not previously been exploited. Emphasis should be placed on the tropics and on the recovery of satellite data before 1979 (which may allow better characterization of the climate shift in the mid-1970s).

(3) Efforts should be made to develop new or reprocess existing data to create climate quality data sets[11] for a range of variables other than temperature *(e.g.* atmospheric water vapor content, ocean heat content, the height of the tropopause, winds and clouds, radiative fluxes, and cryospheric changes). These data sets should subsequently be compared with each other and with temperature data to determine whether they are consistent with our physical understanding. It is important to create several independent estimates for each variable in order to assess the magnitude of construction uncertainties.

(4) Efforts should be made to create several homogeneous atmospheric reanalyses. Particular care needs to be taken to identify and homogenize critical input climate data. Identification of critical data requires, in turn, observing system experiments where the impacts and relative importance of different observation types from land, radiosonde, and space-based observations are assessed.

(5) Models that appear to include the same forcings often differ in both the way the forcings are quantified and how these forcings are applied to the model. Hence, efforts are required to separate more formally uncertainties arising from model structure from the effects of forcing uncertainties. This requires running multiple models with standardized forcings, and running the same models individually under a range of plausible scenarios for each forcing.

(6) The GCOS (Global Climate Observing System) climate monitoring principles should be fully adopted. In particular, when any type of instrument for measuring climate is changed or re-sited, there should be a period of overlap between old and new instruments or configurations that is sufficient to allow analysts to adjust for the change with small uncertainties that do not prejudice the analysis of climate trends. The minimum period is a full annual cycle of the climate. Thus, replacement satellite launches should be planned to take place at least a year prior to the expected time of failure of a key instrument.

(7) A small subset (about 5%) of the operational radiosonde network should be developed and implemented as reference sites for all kinds of climate data from the surface to the stratosphere.

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[11] Climate quality data sets are those where the best possible efforts have been made to identify and remove non-climatic effects that might produce spurious changes over time.