Chapter 6

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

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Background

There remain differences between independently estimated temperature trends for the surface, troposphere and lower stratosphere, and differences between the observed changes and model simulations, that are, as yet, not fully understood, although recent progress is reported in previous chapters. This Chapter makes recommendations that address these specific problems rather than more general climate research aims, building on the discussions, key findings, and recommendations of the previous chapters. Because the previous chapters fully discuss the many issues, we only provide a summary here. Furthermore, we only list key references to the peer reviewed literature. To ensure traceability and to enable easy cross-referencing we refer to the chapters by e.g., **(C5)** for Chapter 5. We do not specifically refer to sub-sections of chapters.

Much previous work has been done to address, or plan to address, most of the problems discussed in this Report. Rather than invent brand new proposals and recommendations, we have tried to expand and build upon existing ideas emphasizing those we believe to be of highest utility. Key documents in this regard are: the Global Climate Observing System (GCOS) Implementation Plan for the Global Observing System (GCOS, 2004), the wider Global Earth System of Systems (GEOSS) 10 year Implementation Plan Reference Document (GEO, 2005) which explicitly includes the GCOS Implementation Plan as its climate component; and the over-arching Climate Change Science Program plan (CCSP, 2004).

The remainder of this Chapter is split into six sections. Each section discusses requirements under a particular theme, aiming to encapsulate the key findings and recommendations of the earlier chapters and culminating in one main recommendation in each of Sections 1 to 5 and two recommendations in Section 6. Sections 1 to 5 focus on key actions that should be carried out in the near future, making use of existing historical data and current climate models. Section 6 discusses future climate monitoring in relation to the vertical profile of temperature trends in the atmosphere.

1. Constraining observational uncertainty

An important advance since recent in-depth reviews of the subject of this Report (NRC, 2000a, IPCC, 2001) has been a better appreciation of the uncertainties in our estimates of recent temperature changes, particularly above the surface **(C2, C3, C4)**. Many observations that are used in climate studies are taken primarily for the purposes of operational weather forecasting **(C2).** Not surprisingly, there have been numerous changes in instrumentation, observing practices, and the processing of data over time. While these changes have undoubtedly led to improved forecasts of weather, they add significant complexity to attempts to reconstruct past climate trends, **(C2, C4).** The main problem is that such an evolution tends to introduce artificial (non-climatic) changes into the data **(C2)**.

Above the Earth's surface, the spread in independently-derived estimates of climate change, representing what is referred to in this report as "construction" uncertainty **(C2, C4, Appendix)** (Thorne et al., 2005), is of similar magnitude to the expected climate signal itself

(C3, C4, C5). Changes in observing practices have been particularly pervasive aloft, where the technical challenges in maintaining robust, consistent measurements of climate variables are considerably greater than at the surface **(C2, C4, C5)**. This does not imply that there are no problems in estimating temperature trends at the surface. Such problems include remaining uncertainties in corrections that must be made to sea surface temperatures (SSTs) in recent decades **(C2, C4),** and uncertainties in accounting for changes in micro-climate exposure for some individual land stations **(C2, C4)** or simply allowing for genuinely bad stations (Davey and Pielke, 2005). Differences between surface data sets purporting to measure the same variable become larger as the spatial resolution being considered decreases. This implies that many problems tend to have random effects on climate analyses at the large spatial scales, that are the focus of this Report, but can be systematic at much smaller scales **(C2, C3, C4)**.

The climate system has evolved in a unique way, and, by definition the best analysis is that which most closely approaches this actual evolution. However, because we do not know the evolution of the climate system exactly, we have generally had to treat apparently well constructed but divergent data sets, of atmospheric temperature changes in particular, as equally valid **(C3, C4, C5)**. Clearly, this approach is untenable in the longer-term. Thus, it is imperative that we reduce the uncertainty in our knowledge of how the three-dimensional structure of atmospheric temperature has evolved **(C4)**.

To ascertain unambiguously the causes of differences in datasets generally requires extensive metadata[1] for each data set **(C4;** NRC, 2000b**)**. Appropriate metadata, whether obtained from the peer-reviewed literature or from data made available on-line, should include, for data on all relevant spatial and temporal scales:

- Documentation of the raw data and the data sources used in the data set construction to enable quantification of the extent to which the raw data overlap with other similar datasets;
- Details of instrumentation used, the observing practices and environments and their changes over time to help assessments of, or corrections for, the changing accuracy of the data;
- Supporting information such as any adjustments made to the data and the numbers and locations of the data through time;
- An audit trail of decisions about the adjustments made, including supporting evidence that identifies non-climatic influences on the data and justifies any consequent adjustments to the data that have been made; and
- Uncertainty estimates and their derivation.

This information should be made openly available to the research community.

There is evidence, discussed in earlier chapters, for a number of unresolved issues in existing data sets that should be addressed:

- Systematic, historically-varying biases in day-time relative to night-time radiosonde temperature data are important, particularly in the tropics **(C4)**. These are likely to

[1] Metadata are literally "data about data" and are typically records of instrumentation used, observing practices, the environmental context of observations, and data-processing procedures.

have been poorly accounted for by present approaches to quality controlling such data (Sherwood et al., 2005) and may seriously affect trends.

- Radiosonde stratospheric records are strongly suspected of retaining a spurious long-term cooling bias, especially in the tropics **(C4)**.
- Diurnal adjustment techniques for satellite temperature data are uncertain **(C2, C4)**. This effect is particularly important for the 2LT retrieval **(C4)**. Further efforts are required to refine our quantification of the diurnal cycle, perhaps through use of reanalyses, in-situ observations, or measurements from non-sun-synchronous orbiters **(C4)**.
- Different methods of making inter-satellite bias adjustments, particularly for satellites with short periods of overlap, can lead to large discrepancies in trends **(C4)** (see also Section 6).
- Variable biases in modern SST data remain that have not been adequately addressed **(C4)**. Some historical metadata are now available for the first time, but are yet to be fully exploited (Rayner et al., 2005). Better metadata, better use of existing metadata, and use of recently bias-adjusted day-time marine air temperature data are needed to assess remaining artifacts **(C4)**.
- Land stations may have had undocumented changes in the local environment that could lead to their records being unrepresentative of regional- or larger-scale changes **(C2, C4)**.

In addition to making data sets and associated metadata openly available and addressing the issues discussed above, it would be useful to develop a set of guidelines that can be used to help assess the quality of data sets **(C4)**. It is important that numerous tests be applied to reduce ambiguity. There are three types of check that may be used:

1. *Internal consistency checks*

    For example, we expect only relatively small real changes in the diurnal cycle of temperature above the atmospheric boundary layer **(C1)** (Sherwood et al., 2005), so an apparently homogenized data set that shows large changes in the diurnal cycle in these regions should be closely scrutinized.

2. *Inter-dataset comparisons*

    For example, comparisons are needed between radiosonde and MSU temperature measures representing the same regions (Christy and Norris, 2004).

3. *Consistency with changes in other climate variables and parameters*

    This is a potentially powerful but much under-utilized approach and is discussed further in Section 3.

RECOMMENDATION *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. Making better use of existing observational data

There is a considerable body of observational data that have either been under-utilized or not used at all when constructing the data sets of historical temperature changes discussed in this Report **(C2, Table 2.1)**. Estimates of temperature changes can potentially be made from several satellite instruments beside the (Advanced) Microwave Sounding Unit data considered here **(C2, C3).** In particular, largely overlooked satellite datasets should be re-examined to try to extend, fortify or corroborate existing microwave-based temperature records for climate research, e.g., microwave data from other instruments such as the Nimbus 5 (Nimbus E) Microwave Spectrometer (NEMS) (1972) and the Nimbus 6 Scanning Microwave Spectrometer (SCAMS) (1975), infra-red data from the High Resolution Infrared Radiation Sounder (HIRS) suite, and radio occultation data from Global Positioning System (GPS) satellites **(C2)**. Some of these instruments may allow us to extend the records back to the early 1970s. Many unused radiosonde measurements of a relatively short length exist in regions of relatively sparse coverage and, with some effort, could be advantageously used to fill gaps. Many additional surface temperature data exist, mainly over land over the period considered in this Report, but are either not digitized or not openly available. This latter problem is particularly common in many tropical regions where much of the interest in this Report resides. Given the needed level of international cooperation, we could significantly improve our current estimates of tropical temperature changes over land and derive better estimates of the changing temperature structure of the lower atmosphere **(C2)**.

In addition to the recovery and use of such existing data, we need to improve the access to metadata for existing raw observations **(C2)**. Additional information on when and how changes occurred in observing practices, the local environment, etc., is potentially available in national meteorological and hydrometeorological services. Such metadata would help reduce current uncertainties in estimates of observed climate change. In the absence of comprehensive metadata, investigators have to make decisions regarding the presence of heterogeneities (non-climatic jumps or trends) using statistical methods alone. Statistical methods of adjusting data for inhomogeneities have a very useful role, but are much more valuable in the presence of good and frequent metadata that can be used to confirm the presence, type, and timing of non-climatic influences. Metadata requirements will vary according to observing system, but, if in doubt, all potentially important information should be included. For example, surface temperature metadata may include:

- Current and historical photographs and site sketches to ascertain changes in micro-climate exposure and their timing, collected during the routine site inspections made by most meteorological services;
- The history of instrumentation changes;
- Changes in the way stations are maintained and in their immediate environment;
- Changes in observers; and
- Changes in observing and reporting practices.

For other instrument types, e.g., for humidity measurements, the detailed metadata requirements will vary. A further discussion on the challenges of collecting climate data can be found in Folland et al. (2000).

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

3. **Multivariate analyses**

Temperature changes alone are a necessary, but insufficient, constraint on understanding the evolution of the climate system. Even with a perfect knowledge of temperature changes, knowledge about changes in the climate system would be incomplete. Consequently, understanding temperature trends also requires knowledge about changes in other measures of the climate system. For example, changes in atmospheric circulation and accompanying dynamical effects, and also in latent heat transport, have significant implications for vertical profiles of temperature trends **(C1)**.

Changes in variables other than temperature may be used to confirm the attribution of climate change to given causes **(C5)** and to test the physical plausibility of reported temperature changes **(C3, C4)**. It is likely that to fully understand changes in atmospheric temperature, it will be necessary to consider changes in at least some of the following physical parameters and properties of the climate system beside its temperature:

- Water vapor content **(C1, C5)**
- Ocean heat content **(C5)**
- The height of the tropopause **(C5)**
- Wind fields
- Cloud cover and the characteristics of clouds
- Radiative fluxes
- Aerosols and trace gases

- Changes in glacial mass, sea ice volume, permafrost and snow cover **(C5)**

Our current ability to undertake such multivariate analyses of climate changes is constrained by the relative paucity of accurate climate datasets for variables other than temperature. Furthermore, since our analysis of temperature datasets has highlighted the importance of construction uncertainty in determining trends **(C2, C4, Appendix),** it is very likely that similar considerations will pertain to these other data types. It is therefore necessary to construct further independent estimates of the changes in these variables even where datasets already exist. Similar considerations to those discussed in Section 1 are also important for these additional data.

RECOMMENDATION *Efforts should be made to create climate quality[2] data sets for a range of variables other than temperature. These 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 parameter in order to assess the magnitude of construction uncertainties.*

4. **Climate quality reanalyses**

Reanalyses are derived from Numerical Weather Prediction (NWP) (forecast) models run retrospectively with historical observations to produce physically consistent, fully global fields with high temporal and spatial resolution. As in NWP, reanalyses employ all available observations to produce their analysis and minimize the instantaneous differences between

[2] "Climate quality" refers to a record for which the best possible efforts have been made to identify and remove non-climatic effects that produce spurious changes over time.

the available observations and a background forecast field initiated a number of hours earlier. Reanalyses also use the same NWP model throughout the reanalysis period. However, as for observed climate datasets, pervasive changes in the raw observations lead to discontinuities and spurious drifts **(C2)**. Because such discontinuities and drifts have been identified in the temperature fields of the current generation of reanalyses, these have been deemed inappropriate for the purpose of long-term temperature trend characterisation by this Report's authors **(C2, C3). However,** it is recognised that some progress has been made (e.g., Simmons et al., 2004, **C2**). This does not preclude the usefulness of reanalyses for characterizing seasonal to interannual timescale variability and processes, or trends in other, related, variables such as tropopause height **(C5)**. Indeed, they have proven to be a very important tool for the climate research community.

A more homogeneous reanalysis that minimized time-dependent biases arising from changes in the observational network would be of enormous benefit for multivariate analyses of climate change **(C2, C3)**. Advances in NWP systems, which will continue to happen regardless of climate requirements, will inevitably lead to better future reanalyses of interannual climate variability. Some advances, such as so-called 'feedback files'[3] from the data assimilation of reanalyses, could be uniquely helpful for climate reanalysis and should be encouraged for this reason if no other. However, to determine trends accurately from reanalyses will also require intensive efforts by the reanalysis community to understand which observations are critical for trend characterization and to homogenize these data insofar as possible to eliminate non-climatic changes before input to the reanalysis system. This in turn requires observing system experiments (OSEs) where the impact on trends of

[3] "Feedback files" are diagnostic summaries of adjustments applied to data during assimilation.

different observation types from land, radiosonde, and space-based observations are assessed. A few examples (far from an exhaustive list) are:

- Run a short period (e.g., a year) of reanalysis with and without radiosonde temperatures.
- Carry out experiments incorporating long radiosonde data records only, then repeat with additional less certain but spatially more complete short radiosonde records.
- Successively include or remove specific satellite retrievals (e.g., MSU Channel 2).
- Carry out test reanalyses for one or more decades with different corrections to the observed data for inhomogeneities within their construction uncertainty estimates.

Progress would depend on reanalyses and data construction experts from all the key groups working closely together.

RECOMMENDATION *Consistent with Key Action 24 of GCOS (2004)*[4] *and a 10 Year Climate Target of GEOSS (2005), efforts should be made to create several homogeneous atmospheric reanalyses. Particular care needs to be taken to identify and homogenize critical input climate data, and to more effectively manage large-scale changes in the global observing system to avoid non-climatic influences.*[5]

5. **Better understanding of uncertainties in model estimates**

[4] Parties are urged to give high priority to establishing a sustained capacity for global climate reanalysis, to develop improved methods for such reanalysis, and to ensure coordination and collaboration among Centers conducting reanalyses.

[5] A focal point for planning of future U.S. reanalysis efforts is the CCSP Synthesis and Assessment Product 1.3: "Re-analyses of historical climate data for key atmospheric features. Implications for attribution of causes of observed change". Ongoing progress in the planning of future U. S. reanalysis efforts can be found at: http://www.joss.ucar.edu/joss_psg/meetings/climatesystem/

New state-of-the-art global climate models have simulated the influences of natural and anthropogenic climate forcings on tropospheric and surface temperature. The simulations generally cover the period since the late nineteenth century, but results are only reported over the period of primary interest to this Report, 1979-1999 (the satellite era), in Chapter 5. Taken together, these models, for the first time, consider most of the recognized first-order climate forcings and feedbacks as identified in IPCC (2001), NRC (2003), and NRC (2005). This is an important step forward **(C5)**.

However, most individual models considered in this Report still do not make use of all likely important climatic forcings **(C5, Table 5.2)**. In addition, many of the forcings are not yet well quantified. 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. This makes it difficult to separate intrinsic differences between models from the effects of different forcings on predicted temperature trends. Thus, within the “ensemble of opportunity” considered in this Report **(C5),** it is difficult to separate differences in:

- Model physics and resolution;
- The details of the way the forcings are applied in the experiments;
- The chosen history of the changes in the forcing.

To better quantify the impacts of the various forcings on vertical temperature trends, a further suite of experiments is needed along the following lines:

- Runs with one forcing applied in a single experiment with a given model; these are already required in some detection and attribution studies **(C5)**. They have been performed for a small number of models already. This approach is particularly important for the recently developed and spatially heterogeneous land use / land cover change and black carbon aerosol forcings **(C5)**.

- Apply the same forcing in exactly the same manner to a suite of models so that the differences that result are due unambiguously to model differences **(C5)**.
- Apply the full range of important forcings, with their uncertainties explicitly sampled to a small subset of the most advanced models to gain an overall estimate of the effects on temperature trends of the uncertainties in these forcings.

It is recognized that there are many problems in achieving this, so a considerable effort will be needed over a number of years. In addition, these model runs should be compared to the full range of observational estimates to avoid ambiguity **(C5)**. Finally, detection and attribution studies should be undertaken using this new range of observations and model-based estimates to reassess previous results; which have consistently identified a human-induced influence **(C5).**

RECOMMENDATION *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 more formally separate 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. **Future monitoring of climate**

Much of this Report hitherto has concerned historical climate measurements. However, over the coming decades new, mainly space-based, observations will yield very large increases in the volume and types of data available. These will come from many different instruments making measurements with greater accuracy and detail, especially in the vertical direction, and with greater precision **(C2, C3)**. In fact, new types of more accurate data such as temperature and moisture profiles from GPS radio-occultation measurements are already available, although, as yet, few efforts have been made to analyse them **(C2, C3)**. Current and planned multi-spectral infra-red satellite sounders such as the Atmospheric InfraRed Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI) have much finer vertical resolution than earlier satellite sounders used in the Report. They have the potential to resolve quite fine vertical and horizontal details of temperature and humidity through the depth of much of the atmosphere. These higher spectral resolution data should also permit a continuation of records equivalent to earlier coarser infrared satellite data (e.g., from the HIRS satellite instruments). The new suite of satellite data will not only prove useful for sensing changes aloft. For example, satellite data to remotely sense sea-surface temperatures now include microwave products that can sense surface temperatures even in cloudy conditions (C4). The Global Ocean Data Assimilation Experiment (GODAE) High-resolution Sea Surface Temperature (SST) Pilot Project (GHRSST- PP) has been established to give international focus and coordination to the development of a new generation of global, multi-sensor, high-resolution SST products (Donlon et al., 2005).

Many other agencies and bodies (e.g., NRC, 2000b; GCOS, 2004; GEOSS, 2005; CCSP, 2004) have already made recommendations for managing such new data developments. These include such subjects as:

- Adherence to the GCOS Climate Monitoring Principles, needed to create and maintain homogenous data sets of climate quality and for which there is a special set for satellites (GCOS, 2004, Appendix 3)
- Continuation of records equivalent to current monitoring abilities: e.g., use new and more detailed satellite data to create equivalent MSU measures of temperature to allow the indefinite extension of the historical records used in this Report.
- Full implementation of national and international climate monitoring networks such as the GCOS Upper-Air Network and the GCOS Surface Network.
- Overlap of measurement systems as they evolve in time.

This last point is of primary importance. It was given prominence by NRC (2000b) and is emphasized in the GCOS Climate Monitoring Principles and leads to the following recommendation. If this recommendation had been followed in the past, one of the major problems in producing a homogeneous record of MSU temperatures would have been largely removed **(C4)**:

RECOMMENDATION: *The GCOS Climate Monitoring principles should be fully adopted. In particular when any type of instrument for measuring climate is changed or re-sited, the period of overlap between the old and new instruments or configurations should be 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 satellite.*

Finally, we expand on a recommendation made in GCOS (2004) that is imperative for successful future monitoring of temperatures at and above the Earth's surface. The main lesson learned from this Report is that great difficulties in identifying and removing non-climatic influences from upper-air observations have led to a very large spread in trend estimates **(C2, C3, C4)**. These differences can lead to fundamentally different interpretations both of the extent of any discrepancies in trends between the surface and the troposphere **(C3,C4)**; and of the skill of climate models **(C5)**. The problem has arisen because there has been no high quality reference or "ground truth" data, however restricted in scope, against which routine observations can be compared to facilitate rigorous removal of non-climatic influences.

Our key recommendation in this regard is a set of widely distributed (perhaps about 5% of the operational radiosonde network) reference sites that will provide high quality data for anchoring more globally-extensive monitoring efforts (satellites, reanalyses, etc.). At such reference sites (which could coincide with selected GCOS Upper Air Network (GUAN), GCOS Surface Network (GSN) or Global Atmospheric Watch (GAW) sites) there would be full, high-quality measurements of atmospheric column properties, both physical and chemical. This requires a large suite of instrumentation and redundancy in measurements[6]. These globally distributed reference sites should incorporate upward looking instruments

[6] Measurement of the same parameter by two or more independent instruments

(radar, lidar, GPS-related data, microwave sensors, wind profilers, etc.) along with high-quality temperature, relative humidity and wind measurements on balloons regularly penetrating well into the stratosphere[7] A key requirement is an end-to-end management system including archiving of coincident observations made from over-flying satellites. The data would be made openly available. The development of such a reference network is recommended in outline by GCOS (2004). The ideas are currently being discussed in more detail as part of an on-going process led by NOAA and WMO. Further details can be found at http://www.oco.noaa.gov/workshop/.

RECOMMENDATION *Following Key Action 12[8] of the GCOS Implementation Plan (GCOS, 2004), develop and implement a subset of about 5% of the operational radiosonde network as reference network sites for all kinds of climate data from the surface to the stratosphere.*

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[7] Recent inter-comparisons under the auspices of WMO suggest that new operational sondes are as accurate as proposed reference sondes (C4; Pathack et al., 2005), which may reduce costs.
[8] Parties need to: … establish a high-quality reference network of about 30 precision radiosonde stations and other collocated observations. …

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