VERTICAL PROFILES OF TEMPERATURE TRENDS

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This workshop aimed to further our understanding of observed changes in upper-air temperatures and their relationship to observed surface and boundary layer climate evolution by considering where models agree and disagree with the available observations and why, and whether other physical changes accompanying changes in vertical temperature structure can help interpret the evolution of temperature changes. The workshop also served as an important step toward the development of National Oceanic and Atmospheric Administration (NOAA)-led U.S. Climate Change Science Program (CCSP) report (due in the first quarter of 2006) on the same topic and was designed to complement this process.

Technical talks by participants covered a broad range of topics from the latest advances in observational climate records and climate models through

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DOI:10.1175/BAMS-86-10-1471

In final form 17 June 2005

WORKSHOP ON VERTICAL PROFILES OF TEMPERATURE TRENDS

WHAT: Forty-five scientists from four continents discussed changes in vertical temperature structure and what might be causing these changes.
WHEN: 13–17 September 2004
WHERE: Hadley Centre, Met Office, Exeter, United Kingdom

efforts to achieve a process-based understanding of the underlying physical mechanisms driving climate change. It was clear that gaps remain in our understanding of both the changes deduced from upper-air observations and the model responses to our historical estimates as well as measurements of external forcings of the climate system. Encouragingly, we are beginning to quantify and reconcile the reasons behind many of the discrepancies among different observational datasets. The workshop focused on the Tropics and tropical processes, as this is generally recognized to be the region of the greatest observational and model uncertainty. Many speakers pointed out that we have limited our observational analyses to a small subset of the available data sources, especially from satellites, and that even short-lived field campaigns can yield useful information. An invited talk on the Global Energy and Water Experiment (GEWEX) emphasized the importance of considering temperature changes in the context of changes in the energy of the system. This requires a holistic approach encompassing changes in heat and radiative fluxes, water vapor, and clouds. Such an approach is aided by more comprehensive measurements since the beginning of the satellite era.

Four working groups focused on specific problems that make it a challenge to obtain accurate vertical profiles of temperature trends and to understand their physical causes. We summarize below the key points of each discussion.

OBSERVATIONAL TEMPERATURE DATASETS AND CLIMATE MODELS. Dataset comparisons should be undertaken across a range of space and time scales, and these comparisons need to be like for like. Global- or large-scale mean agreement may mask significant regional discrepancies and is insufficient alone to yield unambiguous conclusions. It is important to subsample datasets identically to avoid spatial and temporal sampling issues. For satellites, many biases are quasi global in nature, so global trend differences may hide considerable agreement in the geographical structure of changes. For comparisons between levels (e.g. surface and lower troposphere), there is concern over whether data errors are independent. The paucity and underutilization of available model simulations with a consistent set of the most likely important forcing agents are seen as major impediments to our understanding.

Working Group I concentrated on ways to improve current research efforts. The group also discussed the possible use of different convection schemes in models to try to understand tropical lapse rate behavior. It made the following recommendations and specified reasons where necessary:

1) Researchers should agree and adhere to a set of regions having a physical justification to avoid ambiguity when comparing changes. In particular, there has been uncertainty in the published literature over whether the Tropics should be defined as 20°N–20°S or 30°N–30°S. The former avoids the Ferrel cell descent regions and hence may reasonably be expected to be a better indicator of changes in the Hadley circulation.
2) Dataset producers should use their most recent versions in observational comparisons, and these should be made freely and widely available for bona fide research purposes. The latest version of a group's dataset incorporates the sum total of existing knowledge related to the removal of nonclimatic influences, many of which may not have been identified in earlier versions.
3) While trends can characterize current behavior, they must be used with caution. Despite their common use as a diagnostic of climate change, linear trends may not be the best paradigm given the nature of the time series (Seidel and Lanzante 2004). Analyses such as low-frequency filtering or power spectra should be used to characterize the data. We should consider the climatic homogeneity of the period being analyzed, for example, by taking differences between periods before and after events such as the 1976 regime shift (Trenberth 1990).
4) Similarities in spatial pattern between observed upper-air temperature datasets are often strong, despite quasi-global offsets. Strong pattern congruence would indicate that there are likely to be physical mechanisms driving subglobal-scale temperature evolution. Even if we cannot accurately estimate a global mean response, an understanding of the degree and causes of any congruence would increase our confidence in understanding the underlying processes.
5) An agreed upon set of absolute guidelines or spatially complete weighting fields (or both) urgently needs to be made available to aid in comparing model and radiosonde data to satellite data. The provision of a single vector of weights is insufficient to calculate Microwave Sounding Unit (MSU) radiance-equivalent measures from discrete data on pressure levels. Choices of how to apply these weights can have major effects on the resulting pseudo-MSU series.
6) Evidence of temperature differences within the boundary layer must be considered in addition to those between the surface and the troposphere. There is some evidence of temperature gradient changes within the lowermost portion of the tropical marine boundary layer (between the sea surface and ship decks) since about 1980 (Christy et al. 2001; Folland et al. 2003). This needs further investigation as it may help to explain differences over deeper layers.
7) To help understand the role of climate forcing changes in producing changes in the vertical structure of temperature and water vapor, particularly in the Tropics, a coordinated set of general circulation climate model experiments is required. To this end, Working Groups 1 and 2 made the following recommendation: Experiments should use a variety of models with the same set of climate drivers, such as changes in CO_2 and other well-mixed greenhouse gases, aerosols, including black carbon, and changes in solar irradiance. The same models should run with varying convection schemes, also both in

fully coupled mode and with their atmospheric component forced with observed sea surface temperatures and sea ice extents.

CONSTRAINING UNCERTAINTY BY CONSIDERING NONTEMPERATURE VARIABLES. There is increasing recognition that reconciling observed temperature trends requires understanding changes in the global energy and water budget, of which temperature is a single component, and changes in the global general atmospheric circulation. This realization is crucial to the interpretation of observed changes in the atmospheric temperature profile, including surface and near-surface air temperatures, since it is inconceivable that such changes would not be accompanied or caused by changes in the atmospheric circulation and consequent changes in water vapor, clouds, precipitation, radiative fluxes, etc. For instance, we would expect changes in the strength or character of the atmospheric circulation to impact the vertical profile of temperatures, particularly in the Tropics, where the differences between current climate models and available observations are potentially largest. Thus, a more physically coherent picture of the observed temperature changes would be enhanced by observations of the codependent changes in some of these other quantities. Working Group 2 discussed whether the observed evolution in a suite of variables, rather than temperature alone, would provide a more coherent interpretation of climate change and whether such a suite of observations would provide a more stringent test of climate model predictions. The group made the following recommendations to these ends:

1) Because of the tight and complex coupling between energy and water in the climate system, a coordinated and consistent analysis of water vapor and its changes, using both in situ and remotely sensed data, would significantly enhance the analysis of temperature and its variations. Also, reprocessing existing satellite records using current operational systems would substantially contribute to homogeneous records.
2) The analysis of temperature and water vapor records should employ all extensive measurements of these quantities, bringing in many currently underutilized datasets. For instance, many of the systems that provide measurements of temperatures also provide measurements of water vapor. The specific list of datasets that should be used must be wide ranging to exploit the complementary and supplementary characteristics of various measurements. The goal is to provide a detailed and complete determination of the time evolution of the three-dimensional distribution of temperature and water vapor.
3) Special emphasis should be placed on completing, improving, and extending the data products produced from satellite measurements since they offer the most complete (in terms of coverage) and most detailed (in terms of space–time resolution) measurements of temperature and water vapor. In particular, efforts should be made to integrate and exploit the pre-1979 satellite measurements obtained from earlier operational and consistent series of experimental satellites [at least those using the NOAA Vertical Temperature Profile and Scanning radiometers and the National Aeronautics and Space Administration (NASA) Scanning Multichannel Microwave and Electronically Scanning Microwave radiometers]. The data should be made available through a dedicated data center to help determine whether the current products can be usefully extended back to before the apparent 1976–77 climate regime change.
4) Several additional datasets are important for understanding, in general, the observed temperature and water vapor changes and, in particular, for reconciling the tropical temperature profile records. These datasets include the changes of climate forcing induced by changing ozone and aerosol amounts and composition, with an emphasis on their vertical profiles. Also important are datasets on changes of the atmospheric general circulation inferred from meteorological reanalyses, historical surface data, and other circulation model experiments.
5) Understanding fully the causes of observed changes in the basic-state variables of climate—temperature (including surface temperatures) and water vapor—ultimately requires a comprehensive diagnosis of the changes in the complete global energy and water cycle. Combined with estimates of the changed radiative forcings and ocean heat content, such a diagnosis may be able to separate forced from unforced variability, allowing for a more definitive test of climate model sensitivity. To do this, an analysis should be undertaken from 1979 to date using a combination of all in situ and satellite-based data records to tightly constrain our uncertainty. This is the GEWEX goal.

THE STRATOSPHERE'S ROLE IN TROPOSPHERIC TEMPERATURE EVOLUTION. Although upward effects of the troposphere on the stratosphere are well established, downward effects from the stratosphere are only poorly understood. Despite this, possible radiative and dynamical influences of the stratosphere upon the troposphere have been suggested.

Radiative effects are

- stratospheric ozone depletion and changes in tropospheric forcing: due to UV or longwave (LW) radiation (multidecadal);
- tropospheric LW forcing: from increases in stratospheric well-mixed greenhouse gases (WMGG) (multidecadal);
- tropospheric LW forcing: from changes in stratospheric water vapor (multidecadal);
- tropospheric forcing via stratosphere: from solar irradiance changes due to UV and ozone changes (periodic and decadal);
- influence of volcanic gases and water vapor in the lower stratosphere: through radiative effects and the influence on cirrus clouds (interannual to decadal).

Dynamical effects are

- modulation of the annular modes in the troposphere via stratospheric circulation changes;
- changes in stratospheric upwelling in the Tropics and downwelling in the extratropics (Brewer–Dobson circulation), which would affect the chemical lifetimes;
- stratospheric cooling effects on the depth of the tropical tropopause layer, the stratospheric static stability, and tropospheric convection;
- stratospheric effects on tropopause height;
- quasi-biennial oscillation (QBO)-induced variations in stratospheric temperature and winds on interannual time scales, which might impact tropospheric processes;
- stratospheric influence on the Hadley circulation and subtropical jets, perhaps through changes in refractive index to planetary waves and hence eddy driving of the mean flow.

While there are several plausible mechanisms, Working Group 3 made a number of specific recommendations to try to further elucidate the importance of these factors to tropospheric temperature changes.

1) Addressing tropospheric temperature effects caused by changes in stratospheric trace gases and stratospheric temperature requires modeling studies. A first step is to consider the instantaneous radiative heating rate and radiative–convective model temperature response. Investigating radiative heating effects requires two runs of a single-column model and a) change in the lower stratospheric temperature (10–100 hPa) by 1 K (perturbation fixed in the integration and b) change, as in a), but including ozone and WMGG change (1979–2000). Considering radiative–convective responses requires GCM experiments with trace gas perturbations in the stratosphere only. Three experiments, run in a number of models, are envisaged to assess the likely range of uncertainty: WMGG plus minimum ozone depletion, WMGG plus maximum ozone depletion, and WMGG plus water vapor changes.
2) We should explicitly resolve the impact of stratospheric temperature variations on analyses of tropospheric temperature variations. Particular to the Tropics is the potential for aliasing the QBO cycle onto stratospheric temperature trends leading to an overall trend in the satellite era dependent upon the QBO phase at the beginning and the end of the observing period. This could affect the longwave heating of the troposphere and thus the temperature trend in the troposphere, especially in the deep Tropics.
3) Efforts should be made to reevaluate the forcing due to stratospheric aerosols from Mount Pinatubo and its evolution. This period was relatively well observed and might provide useful checks on model realism. Uncertainties originate in the aerosol microphysics and optics as well as the forcing. There is subsequent uncertainty in the stratospheric temperature and circulation response and the resulting final tropospheric response.
4) It is important that efforts are made to continue the time series of the stratospheric temperature record provided by the Stratospheric Sounding Units (SSUs), using the Advanced Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) satellites. It will be necessary to provide documented analyses of the SSU radiances-to-temperatures inversion. SSUs overlap with MSU4 but also provide information in the higher parts of the stratosphere, which will prove useful in discriminating between competing hypotheses of the causes of stratospheric changes that might impact the tropospheric response.

IMPROVING BOTH HISTORICAL AND FUTURE CLIMATE RECORDS. Historically, the observing system has been geared toward real-time numerical weather prediction requirements. This has compromised the long-term climate records, particularly away from the surface. Although numerous investigators have tried to correct for nonclimatic effects in the historical records, there are still many opportunities for improvement, and for making more quantifiable error estimates. For example, reanalysis products are an underutilized resource with potential advantages in producing physically consistent realizations of the climate system. However, changes in instrumentation, particularly the introduction of satellite data, and large data gaps cause time-varying biases in reanalyses (Bengtsson et al. 2004). Furthermore, using reanalyses to correct data might make observations artificially similar to models. Therefore, Working Group 4 suggested strategies to create suitable reanalyses of "climate change" quality, particularly for atmospheric temperature. Comparisons between datasets created by independent investigators are also needed to try to understand the systematic effects of methodological choices (Thorne et al. 2005) and to try to extract a more accurate realization of historical climate changes. Key to the future is the development of global Reference Climate Networks offering multi-instrument redundancy to fully characterize changes and provide strong constraints on more complete networks, such as the Global Climate Observing System (GCOS) Upper-Air Network (GUAN).

1) Efforts should be made to create one or more climate change–quality reanalyses. This might proceed in two stages. First, a combination of groups would create an optimized radiosonde temperature and perhaps a humidity dataset combining as much data as possible to be used in a reanalysis model. This requires the input data to be carefully screened for homogeneity in advance and for any biases to be as time invariant as possible to minimize systematic errors in trends. A second phase would include satellite temperature data similarly treated and preferably extended back a few years before the tropical climate jump around 1977. Carrying out reanalyses at separate centers utilizing the same input data would provide valuable measures of the impacts of model choice and where the remaining uncertainties lie.
2) All major climate datasets should include quantitative error estimates on all resolved space and time scales, and a comprehensive suite of intragridbox data statistics where data are presented in gridded form. Their derivations should be well documented. Since different methodological choices for homogenization can be the largest cause of uncertainty in climate change estimates (Thorne et al. 2005), efforts should be made to encourage at least three independent groups to construct such datasets for any given data type. Doing this will yield better understanding of the true uncertainties in datasets.
3) Efforts to rescue radiosonde data and metadata should be targeted in the Tropics and the Southern Hemisphere where dataset uncertainties are largest and spatial coverage is poorest. Novel approaches to the inclusion of shorter-term data in these regions might yield extra coverage and greater understanding. It is important to retrieve both data and metadata records, as the metadata add significant value in helping us decide upon the veracity of the data.
4) We require a comprehensive observing network design for upper-air observations incorporating ground-based, radiosonde, and satellite-based observations in an end-to-end process. The GUAN and GCOS Surface Networks (GSN) should be fully implemented as the baseline networks (Mason et al. 2003). A smaller reference network of globally distributed "super" sites should be developed utilizing higher-quality radiosondes and upward-looking instruments (radar, lidar, GPS, microwave sensors, etc.) and providing a number of collocated comparisons with satellite measurements. Key to this is having multi-instrument redundancy whereby the same variable (e.g. temperature) is measured by more than one instrument to allow for the explicit calculation of time-varying instrumental biases. This will reduce ambiguity in climate records.
5) To date, there has been one multidecadal analysis of the heat content of the ocean, and our understanding of its errors is poor. Since ocean heat content is the major component of the total stored atmosphere–ocean energy, high priority should be given to further research, including the construction of additional versions of such datasets and a better understanding of the error characteristics.
6) Modeling of climate change requires better "observations" of a number of the forcing agents, including atmospheric aerosols (anthropogenic and natural), black carbon, land use and land cover, land surface dynamics, and the biological effects of increased CO_2.
7) There is published evidence that changes in cloud characteristics may have impacted the tropical atmospheric circulation and thus its tropospheric lapse rate (Wielicki et al. 2002). Cloud datasets are difficult to homogenize and are intrinsically complicated because high, medium, and

low clouds are all individually important. We recommend that a major effort be made to better homogenize existing cloud data, which includes providing error characteristics. This effort should be extended into the future in ways that will allow quick calculations of cloud effects on the tropospheric lapse rate, especially in the Tropics.

ACKNOWLEDGMENTS. Met Office authors were funded by the Department for the Environment, Food and Rural Affairs, and the Government Meteorological Research program. Through their contributions, this paper is held under British Crown Copyright. Funding for many participants was provided through NOAA's Climate Services Program. U.S. government manuscripts have no copyright restrictions.

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CROSS-CUTTING RECOMMENDATIONS

There were a few overarching topics that came up repeatedly within the technical talks, the CCSP discussions, and the working groups at the workshop on vertical profiles of temperature trends. These topics form our core recommendations.

1) In trying to resolve any differences between surface and tropospheric temperature trends, we should consider full spatial fields and a range of indicators. Such efforts should be concentrated in the Tropics, where our uncertainty in both the observations and the models is greatest.
2) In constructing a range of observed datasets, we have made significant progress in understanding the observational uncertainty in temperature trends aloft. The lack of a sufficient range of climate models run with a consistent set of external forcings, however, limits our ability to similarly assess model uncertainty. There should be a concerted effort to run such a suite of models to permit a more thorough intercomparison.
3) To date, we have used only a small subset of available in situ, and particularly satellite, data in climate research. There are numerous alternative data sources for temperature and other variables, which have been either underutilized or, due to data restrictions, not used at all. There are satellite data prior to the December 1978 NOAA polar orbiter TOVS series that might enable us to extend satellite records back to about 1973. Efforts should be made to better utilize currently available data and to rescue historical data before they are permanently lost.
4) Reanalyses have been run with heterogeneous input data, which compromises long-term homogeneity. There is a need for a climate quality reanalysis where the input data are tightly constrained to avoid any aliasing in of sampling and other biases. The same constrained input data should be assimilated by more than one center to estimate sensitivity to the reanalysis system. Further advances in the assimilation and model numerical schemes are also desirable to make optimal use of more input data.
5) For future monitoring to be effective, it is imperative that we set up a well-distributed and maintained climate reference network of observing stations consisting of high-quality instruments and multi-instrument redundancy (more than one instrument measuring each variable of interest, e.g., temperature). This is necessary to provide transfer standards for the more globally complete monitoring provided by radiosondes, satellites and reanalyses used primarily for real-time weather prediction.