DRAFT WHITE PAPER:

UNDERSTANDING RECENT ATMOSPHERIC TEMPERATURE TRENDS AND REDUCING UNCERTAINTIES

In support of Chapter 3 of the

Strategic Plan for the Climate Change Science Program

Draft dated 26 November 2002

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Preface

On 11 November 2002, the US Climate Change Science Program issued a discussion draft of its *Strategic Plan*. The strategy for each major area of the program is summarized in specific chapters of the draft plan, and for four chapters is described in greater detail in white papers. The white papers, including this one focused on temperature trends, represent the views of the authors and are not statements of policy or findings of the United States Government or its Departments/Agencies. They are intended to support discussion during the US Climate Change Science Program Planning Workshop for Scientists and Stakeholders being held in Washington, DC on December 3 – 5, 2002.

Both the chapters of the plan and the white papers should be considered drafts.

Comments on the chapters of the draft *Strategic Plan* may be provided during the USCCSP Planning Workshop on December 3 – 5, 2002, and during a subsequent public comment period extending to January 13, 2003. The chapters of the *Strategic Plan* will be subject to substantial revision based on these comments and on independent review by the National Academy of Sciences. A final version of the *Strategic Plan*, setting a path for the next few years of research under the CCSP, will be published by April 2003. Information about the Workshop and opportunities for written comment is available on the web site www.climatescience.gov.

Comments that are specific to this white paper – and that are not already conveyed through comments on the related chapter of the plan – should be directed to: Sharon LeDuc [Sharon.leduc@noaa.gov].

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In this paper…

Background

The difference between the rate of warming in the surface temperature and the rate of warming in the mid-tropospheric temperature remains an important, unresolved issue. Climate model simulations forced by anthropogenic changes in atmospheric composition project significant increases in tropospheric temperature, somewhat larger than the temperature increases near the surface. Several analyses of the observational data suggest that since about 1980 the surface has warmed at a rate at least twice that of the troposphere and at about the same rate since about 1960. The failure of the troposphere to warm at the nearly the same rate as the surface during the last few decades raised questions about our understanding of the causes of any change, especially the impacts of enhanced greenhouse gas concentrations, and the data used to calculate temperature trends. For these reasons, the IPCC (2001) devoted considerable discussion to assessing observational data as well as climate model simulations to resolve the apparent differences in the rate of warming projected in climate models compared with those observed in the troposphere and the surface. Climate models were used to help understand how the surface and tropospheric temperatures may have responded differently to a variety of natural and anthropogenic forcings. Prior to the IPCC report, the NRC (2000) attempted to reconcile the differences in the observations from satellites, weather balloons, and the near-surface temperature record derived from surface weather stations and ocean ships and buoys. In the NRC report, differing views were accommodated by recognizing that there were considerable uncertainties in the trends from all sources and a ±0.1°C/decade confidence interval was assigned to the observed tropospheric temperature trends. IPCC (2001) reported the trend of temperature within a confidence interval ranging from 0.0 to 0.2°C for the low-to-mid troposphere since 1979 and 0.2 to 0.4°C since about 1960, similar to the overall increase of near-surface temperatures. Evaluating the difference in the trends since 1979, the IPCC (2001) assessment concluded that it was very likely that there were significantly different trends of temperature between the surface and troposphere, after evaluation of the physical factors and data uncertainties related to substantial differences in temperature trends between the satellite-derived records and radiosondes. The degree of cooling in the stratosphere is stronger in the radiosonde data compared to the satellite estimates, but this is widely thought to be a result of spurious cooling of the radiosonde temperature records (IPCC, 2001). This spurious cooling is attributed to the introduction of the Vaisalla radiosondes, especially in the tropics, during the 1980s and 1990s (Lanzante *et al.*, 2003). Another related issue however, is the degree to which the stratospheric cooling, very likely the result of stratospheric ozone loss and increases in greenhouse gas concentrations, affects upper tropospheric temperature trends. Thus knowledge of changes for all levels of the atmosphere is important to understanding climate variability and change.

Several new analyses of atmospheric temperature change have been completed since the IPCC and NRC reports were published. Uncertainty about the differential rates of temperature change in the atmosphere remains a complex issue from an observational standpoint. Several independent estimates of tropospheric temperature trends based on radiosondes have yielded quite different results ranging from little or no warming to an increase of about 0.2 degrees Celsius per decade since 1958. A new, updated analysis of the satellite record for the 1979 to 2001 period indicates warming in the troposphere of more than 0.1 degrees C per decade. However another updated study shows only a small, statistically insignificant positive trend for the same period. For the global surface temperature there are numerous research groups reporting global surface temperature warming rates of at least 0.15°C/decade since the late 1970s. This increase of temperature is supported by ancillary data such as snow cover and sea ice reduction, permafrost changes, lake and river ice freeze/thaw dates, and other related changes in the environment. Comparable information is not available for the layers above the surface. Although mountain glaciers and high elevation radiosonde sites and surface data might be used (Seidel and Free, 2002), they have not been extensively analyzed in context with mid-tropospheric temperatures.

New climate model simulations have also been analyzed to help interpret the observational data. Coupled climate models with combined anthropogenic and natural forcings have been unable to simulate the largest differences in trends which have been reported by several of the observational analyses. Does this mean that our inability to reliably simulate the observed differential warming is due to a combination of model error and missing or inaccurately-specified external forcings? Or is the difference better explained by observational errors that are not insignificant?

Satellite-based estimates of temperature

The existing dilemma can be traced to the pioneering work of Spencer and Christy (1990). They compiled a record of satellite-derived tropospheric temperatures and noted that the rate of warming from the satellite record was negligible, especially when compared to surface temperature increases. This curious result was most prominent in the tropical and subtropical regions (Fig.1). Spencer and Christy (hereafter referred to as the University of Alabama at Huntsville Team --- UAH) took advantage of the Microwave Sounding Unit (MSU) aboard NOAA polar orbiters. The MSU data provided an all-weather integrated measure of temperature for various atmospheric layers. There were four MSU channels, and their weighting functions are depicted in Fig. 2 for channels 2 and 4, for both the MSU and the Advanced MSU (AMSU) instrument. These two channels have been used to depict both tropospheric and stratospheric temperature trends. UAH derived a synthetic channel called MSU2LT which was formed by differencing view-angles of MSU2 and AMSU5. For the lowest layers, the microwave data are affected by changes in surface emissivity, but above the surface layer this is not a factor. Hence some of the MSU2LT signal comes directly from surface emissions: about 10% over ocean and 20% over land. Over land the radiances are affected by changes in moisture, and over mountains even more signal comes from the surface, so MSU2LT values, although they are weighted for the lower half of the troposphere are subject to increased noise over mountainous terrain, including the Himalayas, Greenland and Antarctica. However, UAH also compute a MSU2 temperature, which reflects the mid and upper troposphere although some stratospheric emissions are included.

Trends in channel 4 have been produced and show the marked cooling in the lower stratosphere that have been linked to ozone depletion and increases in greenhouse gases (IPCC, 2001). Such trends influence MSU2, so examination of these other channels is also needed to provide confidence that the ozone signal is being properly simulated. It would also provide evidence as to whether the volcanic signal (especially the aerosol signal of stratospheric warming) is correctly included in models. These trends are quite large relative to any observational uncertainty, but understanding the causes of these trends is linked to understanding tropospheric and surface trends.

Several other issues emerge, however, when assembling a homogenous record of tropospheric temperatures. Each of the eleven satellites used to measure temperature since 1979, has unique, local sampling times that have changed over its lifetimes. This introduces a diurnal temperature bias, even for temperatures well above the surface layer, and substantial adjustments are required to homogenize the data (Fig. 3). Moreover, each sounding unit on the various satellites has some calibration uncertainties that had to be assessed. The errors in the calibration of MSU have been addressed through numerous analyses (Mo *et al.*, 2001; Christy *et al.*, 2002; Wentz *et al.*, 2001; Mears *et al.*, 2002).

Wentz *et al.* (1998) found that in addition to biases related to calibration and changes in diurnal sampling there were biases introduced into the data due to decays in satellite orbit. Episodic solar wind events reduce orbit altitude, and this significantly affects the tropospheric temperature trends, especially those of the low to mid troposphere. This correction was applied by the Wentz team (hereafter referred to as Remote Sensing Systems --- RSS) in their satellite derived temperature trends and also applied by UAH in the latest versions (D and 5) of their data sets. Since 1995, UAH have at different times calculated the 95% confidence interval of the decadal trend of tropospheric temperature. These estimates range from 0.03°C/decade to 0.06°C/decade, and the UAH temperature trends during 1979-2001 for the two tropospheric layers MSU2LT (surface to about 400hPa) and MSU2 (approximately Sfc to 100hPa) are 0.06 and 0.01°C/decade, respectively. In contrast, MSU2 as processed by RSS finds a warming of approximately 0.10°C/decade.

The difficulty of adequately resolving the temperature trend issue is attested to by the number of revisions to the original data set of UAH and the magnitude of the corrections to the original data that are required (Fig. 4). UAH have just issued version 5 of their MSU temperature record (5 revisions over a 13-year period). RSS, in work submitted for publication, has just released version 1. The rate of warming estimated by from these two science teams is significantly different, despite the dedication of each team to produce the most accurate temperature time series possible. There are at least two differences in the techniques applied to generate the respective time series. First, to correct diurnal drift errors, UAH rely on adjustments derived from satellite measurements themselves made at the appropriate diurnal time slots while RSS employs information from a high-resolution climate model simulation (Fig.3) to apply appropriate corrections. Secondly, the instrument calibration adjustments depend upon temperature differences observed by two satellites simultaneously. RSS use all periods of simultaneous observations while UAH set thresholds to eliminate some overlaps e.g., minimum of one-year overlap and a minimum level of error reduction during the overlap. The resulting calibration adjustments for each instrument are quite similar between the two techniques except for one satellite, NOAA-9 which had short overlaps with other satellites (Fig. 5). The difference in the adjustment for NOAA 9 accounts for about 65% of the total difference of the two MSU2 trends. Currently, RSS and UAH are sharing data and computational algorithms to help explain the difference.

UAH, in searching for independent methods to assess error statistics, compared their satellite record with radiosonde (weather balloon) instrumental data and with radiosonde-guided datasets such as the global analyses produced by the National Centers for Environmental Prediction. UAH contend that the similarity of temperature trends between the radiosonde-based data and the satellite-derived temperatures from UAH is important corroborative evidence to help bolster the confidence in the tropospheric trends produced by their team. In these UAH comparisons, controls were established to eliminate stations with inhomogeneities. However, in large compilations of radiosonde data, complications arise, because the weather balloon data are also subject to time-dependent biases because of numerous changes in instrumentation, site location, proprietary calibrations and adjustments, and ground-station processing methods. These changes are known to have introduced significant time dependent biases in the temperature record, most clearly visible in the stratosphere, and corrections are not free of error. For example, Free *et al.* (2000) reported on the results of several different research teams who attempted to adjust the weather balloon data for time-dependent biases. Inter-comparison of the various adjustments applied by the different teams showed considerable disagreement among the teams related to both the timing and magnitude of adjustments required (Fig.6) during both the satellite and pre-satellite era. [Note: If two teams identify a discontinuity at a station separated by as much as five years within any pentad, this would be considered agreement, at least in terms of calculating multi-decadal trends (Fig. 6)] Despite these problems, the trends from UAH compare favorably with the radiosonde temperature trends. The greatest agreement is for the lowest layer temperatures where radiosonde inhomogeneities are smallest. Other investigators (Wentz *et al.*, 2002; Santer 2002) do not consider the UAH record to be completely independent of the radiosonde record, particularly with regards to decadal trends. Many of the radiosondes used by UAH are in the temperate Northern Hemisphere, where the RSS and UAH results are quite similar, although UAH's comparisons with the trends in the tropics also show exceptional agreement.

Radiosonde-based temperature trends

Several independent estimates of the surface to lower tropospheric trends based on radiosonde temperatures have yielded quite different results. For example, since 1958 Brown *et al.* (2000) found a warming of about 0.20°C/decade and Lazante *et al.* (2003) obtained about 0.15 and 0.00°C/decade for adjusted and unadjusted data (respectively), and Gaffen *et al.* (2000) found a warming of 0.08°C/decade.

Radiosonde data indicate that the rates of surface, tropospheric, and stratospheric temperatures have evolved in a complex way over the past 40 years (Figs. 7 and 8). Gaffen *et al.* (2000) showed that the tropical troposphere warmed relative to the surface over 1960-1978, and thereafter cooled relative to the surface. Others (Lanzante *et al.* ;Brown *et al.* 2000; Hegerl and Wallace*,* 2002) noted similar multi-decadal changes in lapse rate. Over the period 1959-1998, Angell (2000) and Lazante *et al.* (2002) found no discrepancy between the overall warming rates at the surface and in lower troposphere. These results illustrate that lapse-rate changes may not easily be generalized to other periods. The tropospheric/surface temperature trend difference varies from one dataset to another, but most analyses show that there was a step change around the 1976-77 time period, just prior to the start of the satellite record.

Model Simulated Temperature Trends

A number of recent investigations also used climate model simulations to understand whether there could be a physical basis for the differential rates of warming. This work focused on the effects of:

- Differences of spatial coverage between satellite data and surface observations;

- External forcing (primarily explosive volcanic eruptions and stratospheric ozone depletion);
- Modes of natural internal variability.

While the MSU data have near-global coverage, the surface data are spatially incomplete (Karl *et al.*, 1994; Jones *et al.*, 1999) and under-sample some of the muted warming of the southern ocean that occurred during the satellite era. Santer *et al.* (2000) showed that these differences in spatial coverage could explain up to one-third of the difference between surface and lower tropospheric temperature (MSU2LT) trends over 1979-1999. Although the global surface data based on the Reynolds and Smith (1999) analysis included infrared satellite data to provide near-global coverage in the southern oceans, these data have not yet been assessed to determine if this difference disappears with more comprehensive ocean coverage.

In several studies, external forcing also helped reconcile some of the differential warming. Model results from Bengtsson *et al.* (1999), Hansen *et al.* (1997), and Sante*r et al.* (2000) suggested that both volcanic eruptions and stratospheric ozone depletion may have cooled the troposphere more than the surface over the last several decades. In contrast, Michaels and Knappenberger (2000) found that when the forcings due to volcanoes and ENSO were included in the models there were still large discrepancies between the UAH MSU2LT data and the model simulations. Michaels and Knappenberger (2000) however, assumed that the atmospheric temperature response to the forcings would have the same timescale and shape. Wigley and Santer (2002) and Santer *et al.* (2001) showed that the atmospheric response did not have the same timescale or shape as the forcings. So, a number of observational studies (Christy and McNider (1994), Santer *et al.* (2001), Wigley and Santer (2002), and Free and Angell (2002)) yield conclusions that indicate that some difference in response between the surface and troposphere can be attributed to the timing of volcanic eruptions and ENSO events. There are, however, uncertainties in quantifying the differential cooling caused by these forcings, both in models and observations. These arise from: uncertainties in the volcanic and ozone forcings; from errors in the model responses to these forcings; from the short length of the MSU 2LT record; and from difficulties in deconvolving the temperature effects of volcanoes and ozone depletion from the effects of ENSO variability.

Several recent investigations have explored the differential effects of natural modes of variability on observed surface and tropospheric temperatures. They found that ENSO (Santer *et al.*, 2001; Wigley and Santer, 2002; Hegerl and Wallace, 2002) probably made only minor contributions to overall differences in observed surface and tropospheric warming rates. The same applies to the Arctic Oscillation and to other modes of natural internal variability (Hegerl and Wallace, 2002).

Accounting for coverage differences, volcano and ozone forcing, and natural internal variability helps to explain some, but not all, of the apparent differential warming of the surface and lower troposphere in the observations (Santer *et al.*, 2001; Hegerl and Wallace, 2002).

Interpreting the Results

One can interpret these results in at least two ways. In the first interpretation, the underlying assumption is that uncertainties in existing observational estimates of surface and tropospheric temperature are small enough to demonstrate significant differences in trends that are prominent in the tropical atmosphere and in the southern hemisphere. If this is the case, the recent (since 1979) differential warming of the surface and lower troposphere is real, and we do not fully understand why it exists in the observations, or what factors control its behavior on multi-decadal timescales. Nor can we simulate this differential warming with fidelity in coupled model experiments with combined anthropogenic and natural forcings. For example, the average of six realizations of an atmospheric model (HadAM3, Tett *et al.* 2002) forced with observed volcanic aerosols, SSTs, ozone, sulfates and solar variations produced tropical tropospheric trends significantly warmer than both UAH and RSS mid-tropospheric temperatures since 1979 (Fig. 9). This result is typical of models in general (IPCC 2001). They produce greater tropical tropospheric warming than is observed at the surface.

The second interpretation assumes that observational errors are not trivially small as suggested by the various estimates of global tropospheric temperature increase in both satellite and radiosonde data sets (Fig. 10). The range of the estimates spans 0.1°C/decade. There is also the possibility that the surface-layer warming may have been slightly overestimated in tropical ocean areas where it has been shown that the water temperatures (used in the surface temperature compilations) are warming more rapidly than the air immediately above (Christy *et al.*, 2001).

A substantial underestimate of observed tropospheric temperature changes or an overestimate of surface temperature increases would reduce the apparent differential warming. Coupled with the effects of coverage differences, external forcing, and internal variability of the atmospheric vertical profile, residual errors in the observations could fully resolve the apparent discrepancy between surface and tropospheric warming rates. Under this second interpretation, there is no serious inconsistency between modeled and observed tropospheric temperature trends (Sante*r et al.*, 2002; Figure 11).

The truth may lie somewhere between these two interpretations. Observational errors (in both the surface and MSU2 data) may be responsible for some of the current difference between estimated surface and tropospheric warming rates, and model errors (in both the forcing and response) may help to explain why current coupled climate models cannot reliably simulate the “observed” differential warming.

Summary

Three primary issues have arisen related to the temperature trends of the troposphere and the surface. First, there was criticism of studies that claim to have identified human effects on global climate because the models used in such studies could not simulate the temperature records during the satellite era (Singer, 1999, 2001). This criticism relies on observational records of tropospheric temperature change derived from radiosondes and the UAH satellite-based Microwave Sounding Unit (MSU). Both records show little warming of the troposphere since operational MSU temperature measurements began in 1979 (Parker *et al.*, 1997; Christy *et al.*, 1998; Folland *et al.*, 2001). In contrast, model simulations of the response to anthropogenic forcing often show pronounced tropospheric warming over this period (*e.g.,* Santer *et al.*, 2001; Tett *et al.*, 2002). Second, concern regarding the accuracy of the temperature trends was raised because of the apparent failure of the troposphere to warm over the past 24 years as anticipated from climate model simulations. For example, Singer (1999) questioned the recent warming of the Earth's surface, which is estimated to range from 0.15 to 0.20°C/decade. The reality of recent surface warming has been confirmed by numerous investigations (*see*, *e.g.*, Jones *et al.*, 1999; *National Research Council*, 2000; IPCC 2001, NRC, 2001)), although it was noted that in some areas, like the tropical Pacific, ocean temperatures may have warmed more than near-surface boundary layer temperatures (Christy *et al.*, 2001). Third, RSS (Wentz et al. 2002, and Mears et al. 2002) provided an independent re-evaluation of the tropospheric satellite record and found substantial warming, raising a question as to whether the troposphere really had little warming over the past 24 years. However, the substantial agreement between various radiosonde-based datasets and the UAH results continue to lend credibility to the minimal warming they observed in the global troposphere. Some researchers argue that the UAH adjustments were guided by comparisons with radiosondes thereby affecting the independence of the radiosonde and satellite data. UAH denies these claims noting that all MSU2LT processing was established prior to the radiosonde comparisons and although processed in the same way, the MSU2 and MSU4 show noticeable disparities when compared to radiosondes. Despite the high correlations, when compared observation-by-observation Hurrell *et al.* (2000) showed that there were substantial differences between the MSU2LT and individual radiosonde station data. It is unclear exactly how much of his difference is due to inaccuracies of the radiosonde or the satellite data. It is interesting that the two groups get nearly the same trends at many northern hemisphere mid-latitude radiosonde sites, while globally the trends found by the two groups are quite different (0.1°C/decade), as shown in the following table:

Latitude	UAH 1979-2001 trend	RSS 1979-2001 trend
85°N-20°N	+0.12 °C/decade	+0.17 °C/decade
20°N-20°S	+0.01 °C/decade	+0.09 °C/decade
20°S-85°S	-0.10 °C/decade	+0.03 °C/decade

A Way Forward

What can be done to improve our understanding of how temperatures have changes and why?

As implied by the discussion above this will require reducing the uncertainty related to documenting the rate and magnitude of temperature change and new model simulations to test our understanding of the observed changes and variations. These are enumerated below:

IMPROVING OBSERVING SYSTEMS AND THE DATA RECORD

To help resolve this issue and ensure that future monitoring systems deliver data free of time-dependent biases a focused effort is required to improve retrospective and prospective atmospheric measurements of temperature. This includes:

- Transforming the GCOS upper air network (GUAN) into an Upper Air Climate Reference Network (UACRN):
    - An improved international radiosonde network adhering the GCOS monitoring principles with special emphasis on radiosondes in the tropics and subtropics where data are most difficult to harmonize with the surface. Threatened GUAN sites should be maintained, and support and training should be provided to operators where required. Operators should be informed of the purposes and value of their data. They should receive statistics on the performance of the GUAN stations, and have Internet access to products created with the aid of GUAN. All GUAN sites should adhere to the GCOS Climate Monitoring Principle such that the GUAN can be transformed to an UACRN.
    - Original daily and monthly data, quality-controlled data and bias-adjusted data and metadata should continue to be stored and accessible in the GUAN Archive at NOAA/NCDC. All GUAN data are deemed “essential” in accordance with WMO Resolution 40, and are to be exchanged free of charge.
    - More comprehensive information regarding the type of radiosondes used by various countries and how they have changed over the decades. This also includes manufacturer hardware adjustments applied to the pre-processing of the data. Rectifying obstacles that have limited past work in this area will be a priority.
    - Development of a remote, unmanned system to monitor upper air properties should be investigated.
- Adhering to the GCOS satellite monitoring principles
    - Of particular concern related to the microwave satellite record are the adjustments required for the NOAA-9 satellite. Increased attention on calibration issues during this period is warranted.
    - Although the MSU record is currently adjusted for calibration errors, it is apparent that there is a need to better understand the source of these errors, so that the calibration algorithms can be improved. Many of the errors in the calibration of MSU have been reduced by RSS and UAH as well as Mo *et al.* (2001), but more work is needed to physically account for these errors.
    - MSU channel 1 has not previously been used for lower tropospheric trend studies because accurate corrections for the surface emissivity are required to properly extract the lower tropospheric temperature. Similarly, infrared

sounding channels on the High Resolution Infrared Sounder (HIRS) instrument are also more sensitive to lower tropospheric temperature than MSU channel 2. Valuable ancillary data to help resolve temperature changes could result from surface emissivity corrections for MSU channel 1 and for HIRS highly accurate cloud detection and improvements in spectroscopic radiative transfer.

- More effort to obtain observations and data from overlapping measurements when instruments change, or there are changes in spatial and temporal sampling, for the various observing systems, e.g., radiosondes, surface observations, and satellites.
- Consideration for a new network of high-altitude GCOS global surface network stations (GSN) that would be located in the middle troposphere and be in pristine conditions, e.g., North and South America mountains from northwestern North America to the Antarctic Peninsula, in Eurasian mountains from western Europe to the Himalayas.
- An effort should be made to provide limited on-going support for established producers of global temperature datasets so as to allow near-real time analysis and monitoring by decadal changes and variations by NOAA, e.g., (National Climatic Data Center's Climate Monitoring Program)

NEW MODELING SIMULATIONS

- Simulation in the historical record of the spatial and temporal sampling of the actual record of the NOAA polar orbiting satellites used to calculate tropospheric and stratospheric temperatures.
- Additional ensemble simulations of the climate of the last 40 to 50 years from several of the key climate models with the inclusion of both natural and anthropogenic forcings is crucial to trying to explain the observed changes.
- Analysis of data from new model re-analysis projects will aid in understanding any significant time-dependent biases that may have affected the observing systems.

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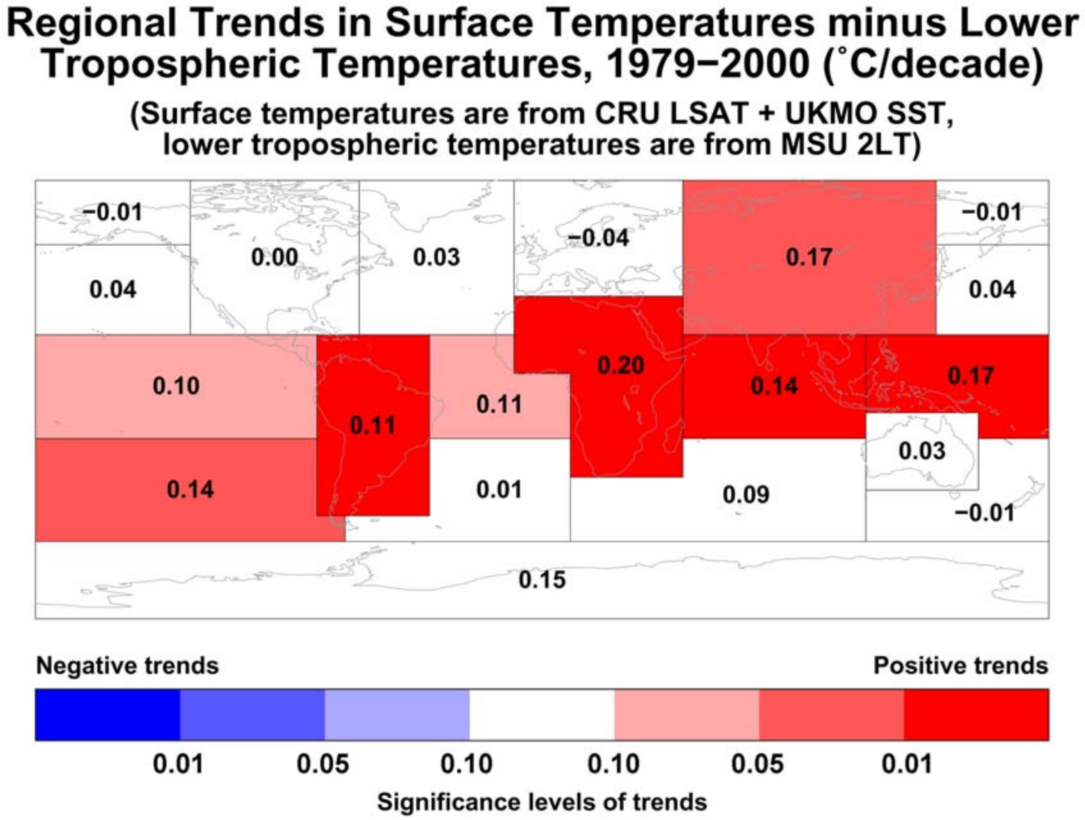
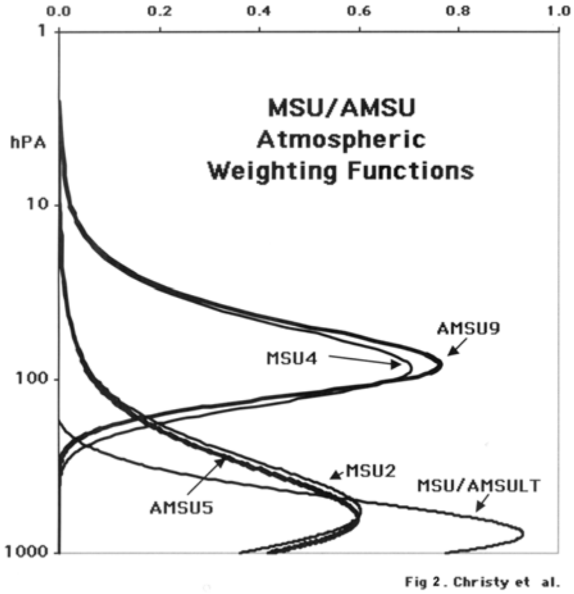
Illustrations

Figure 1



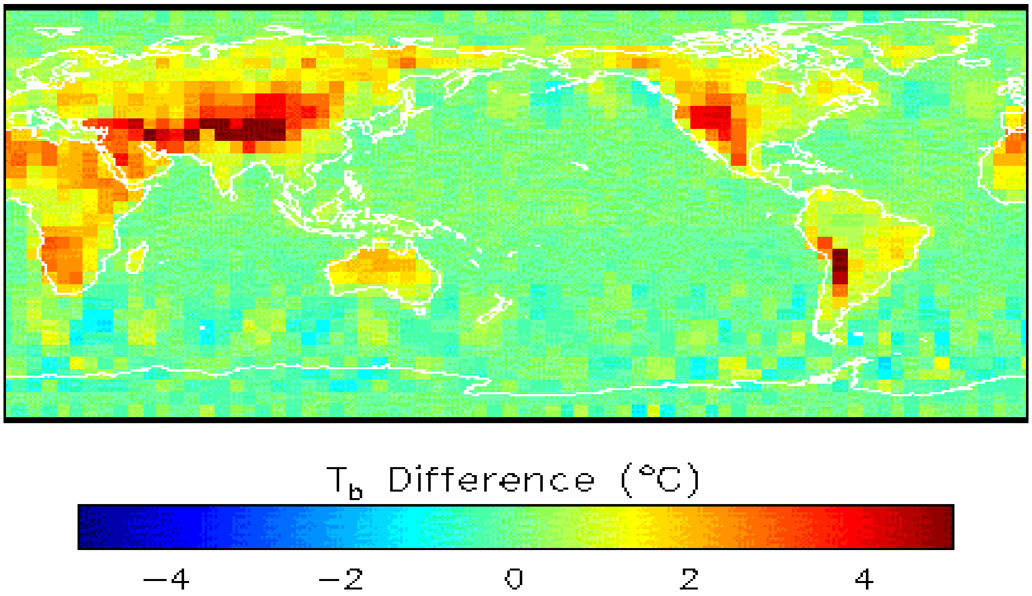
Regional trends of surface temperature minus lower tropospheric temperatures (°C/decade). Surface temperatures are from IPCC (2001) and lower tropospheric temperatures from Christy *et al.* (2000).

Figure 2



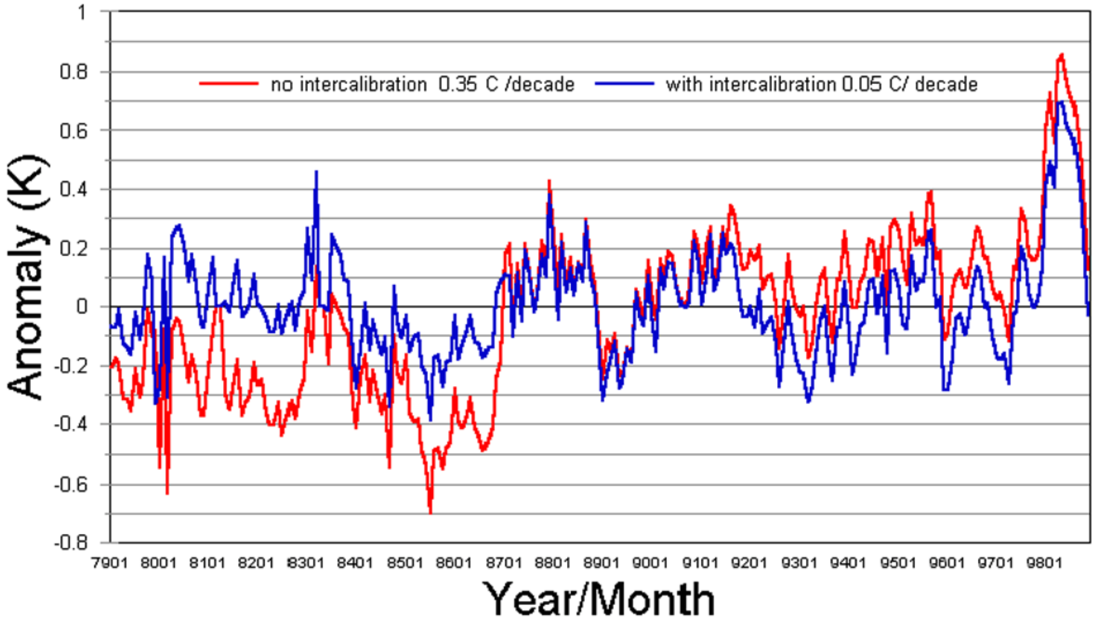
MSU channels and their atmospheric weighting functions used on NOAA operational satellites since 1979 (from Christy, 2002).

Figure 3



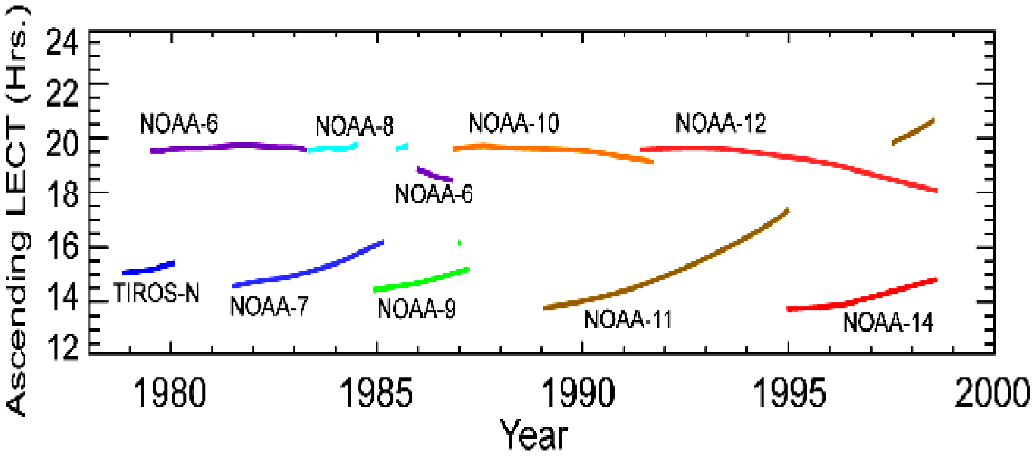
Simulated MSU2 mean diurnal amplitude for the June, nadir view (from Wentz, 2002).

Figure4



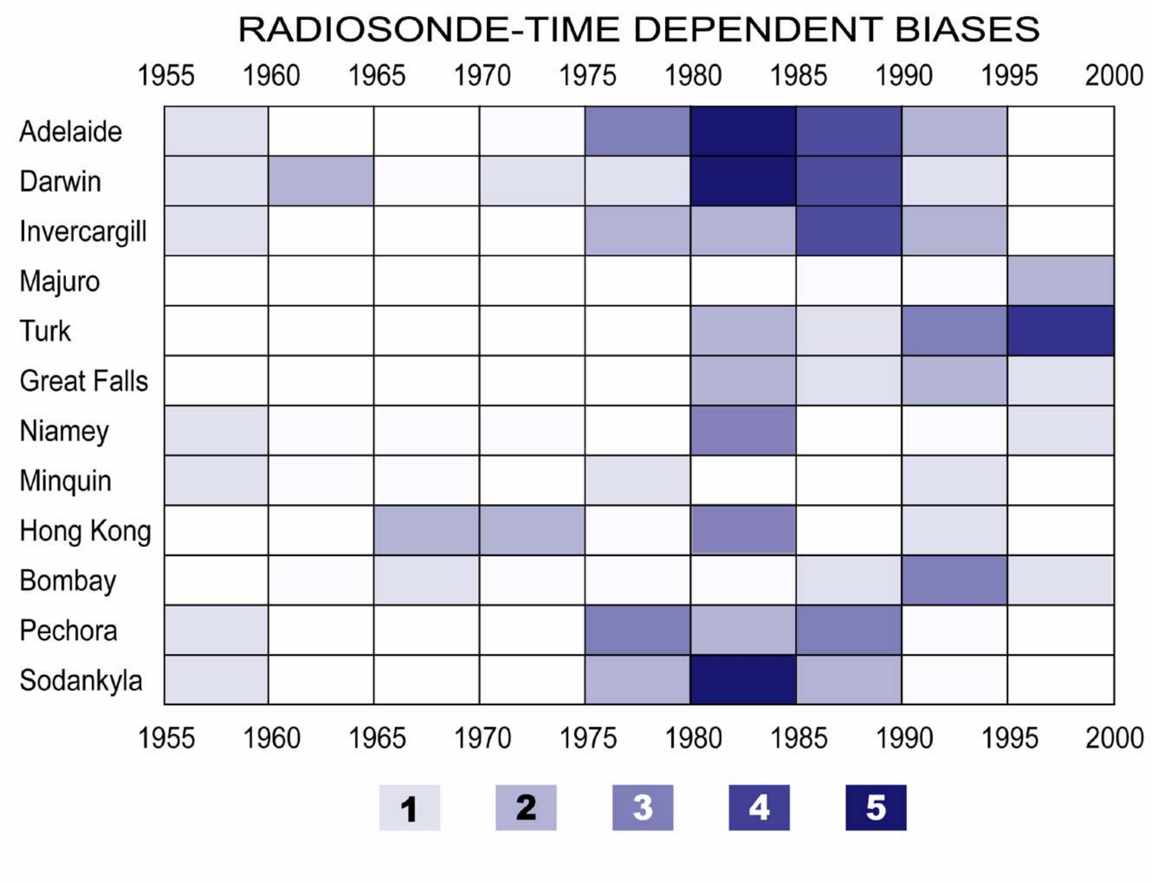
Typical MSU channel 2 anomalies with and without satellite intercalibration (provided by Goldberg 2002).

Figure 5



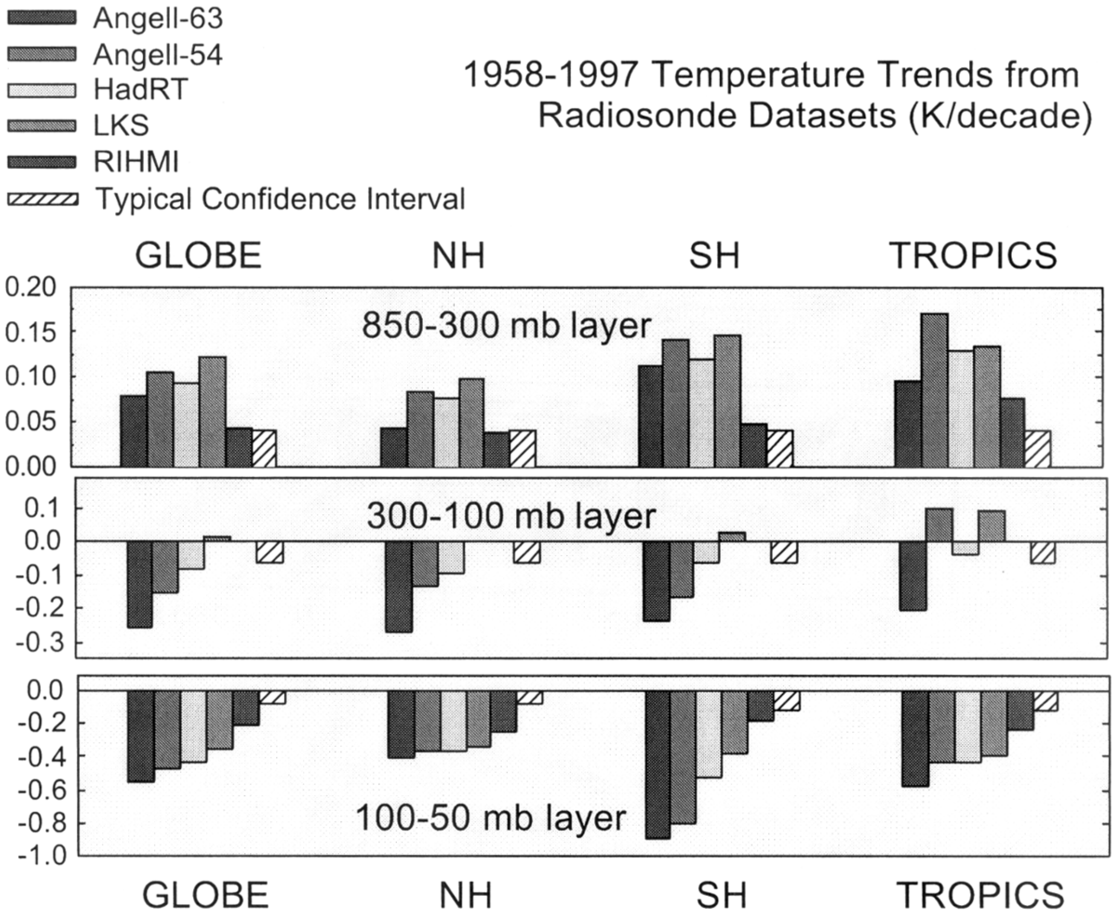
Local equatorial crossing time for NOAA satellites show the long-term drift (from Wentz, 2002).

Figure 6



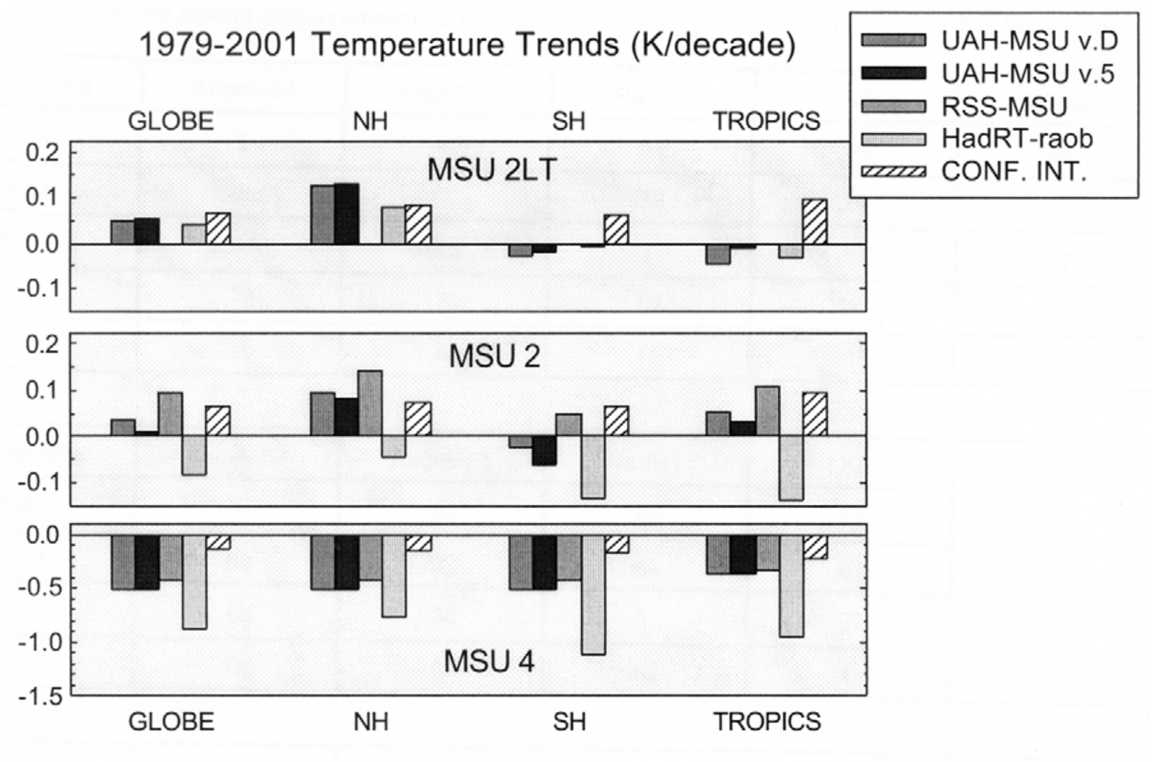
The degree of agreement between various research teams evaluation the radiosonde record at a selected set of stations as described in Free *et al.*, (2000). This depiction is adapted from Free et. al (2000). For each pentad the percent of teams that identified a potential discontinuity is shaded in increments of 20% (each team identifying a discontinuity represents 20% of the group)

Figure 7



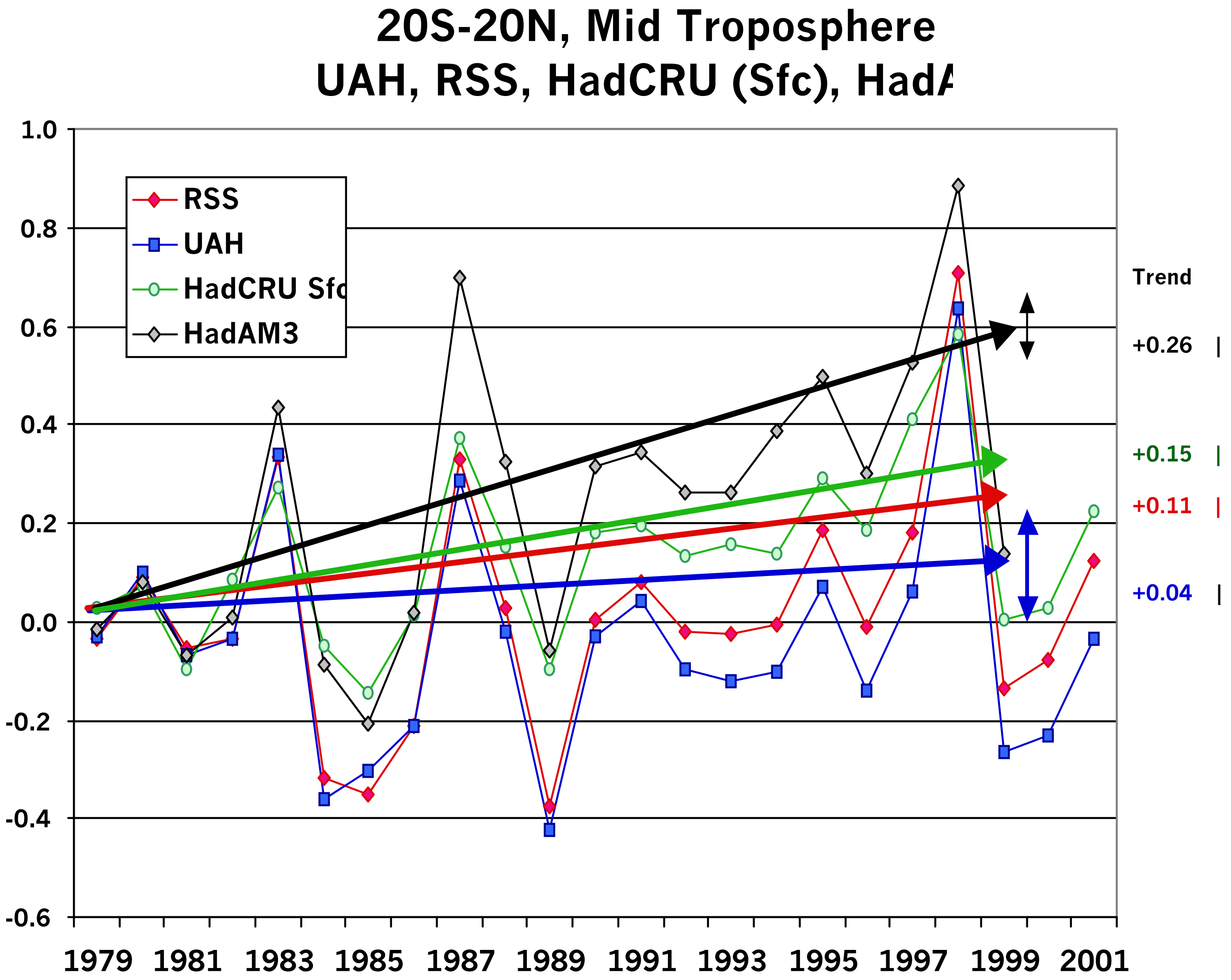
Trends in global temperature for 1958-97 for three vertical layers, in four regions, from radiosonde datasets. The confidence intervals shown are typical values of the two standard deviation uncertainty estimates. The midpoint of the confidence intervals can be placed at the value of each trend (based on preliminary results from Seidel *et al.*, 2003 without peer review). (Angell-63; Angell-54; HadRT; LKS; RIHMI are all analyses produced by different research teams using different methods)

Figure 8



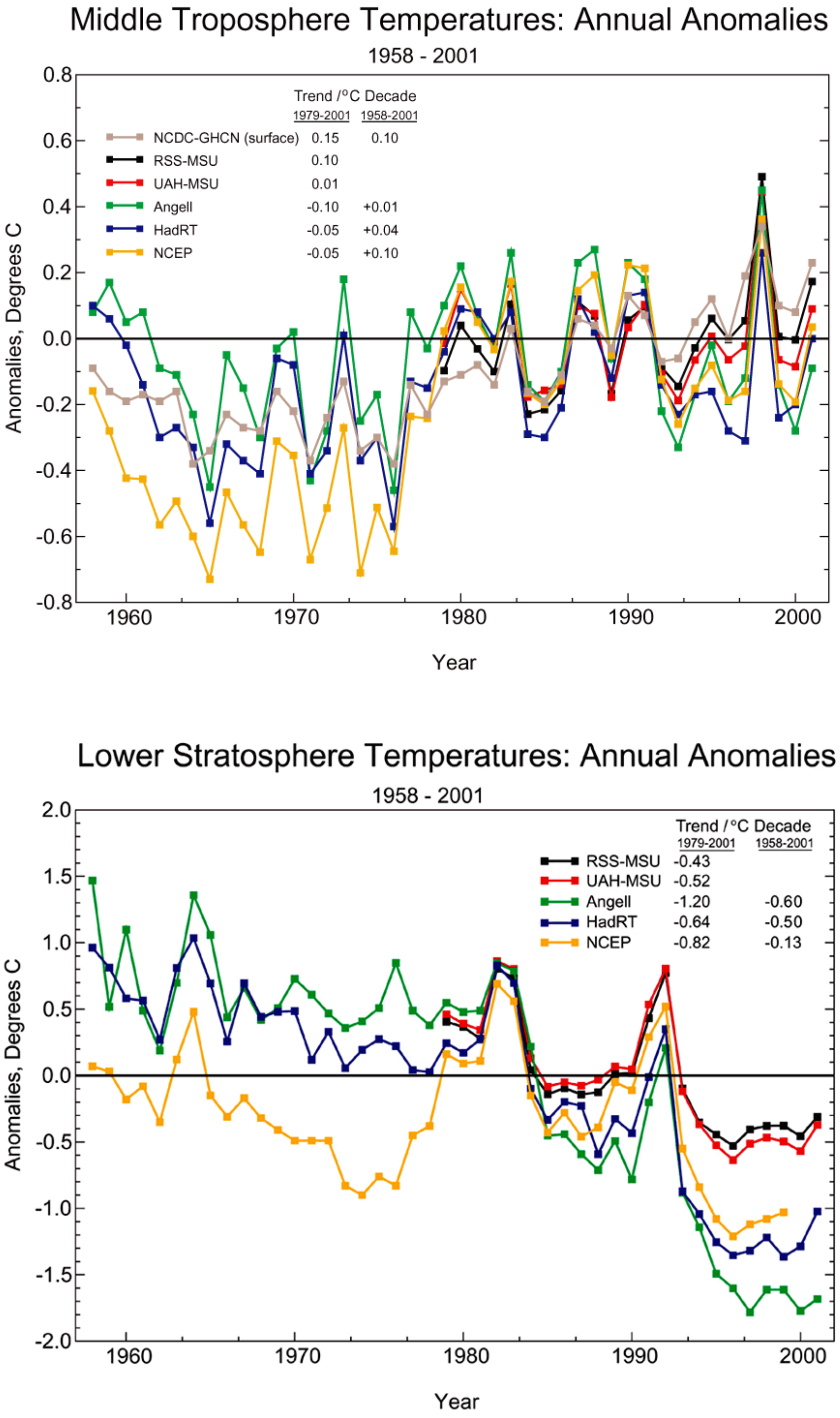
Same as Figure 6 except for 1979-2001 and for both satellite and radiosonde data sets.

FIGURE 9



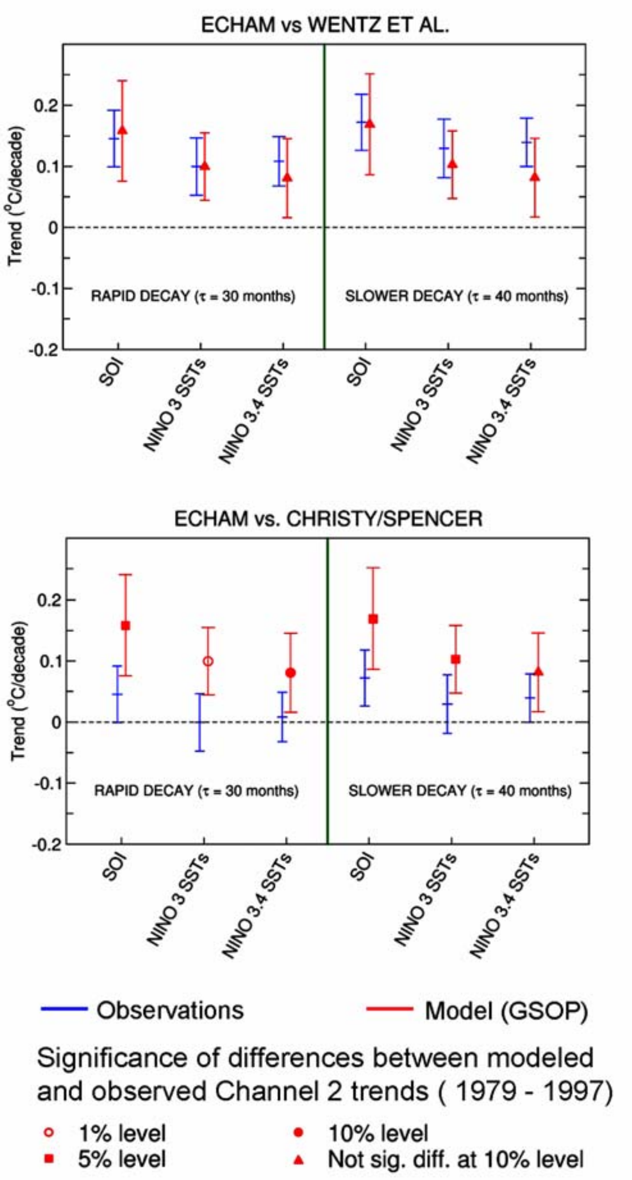
Tropical temperature variations for 1979-1999 for: (Black) Average of six realizations of mid-tropospheric temperatures of Hadley Atmospheric Model Version 3 (Tett *et al.* 2002) forced with observed volcanic aeorsols, SSTs, ozone, sulfates and solar variations, (Green) observed surface temperature (HadCRU), (Red) RSS mid troposphere and (Blue) UAH mid troposphere. Vertical arrows represent the 95% confidence interval in the trend line (from Tett *et al.*, 2002).

Figure 10



Globally averaged time series of tropospheric and stratospheric temperatures from various research teams using radiosondes, satellites or model reanalysis data, as compiled by Christy and Easterling (2002).

Figure 11



Statistical significance of differences between simulated and observed channel 2 temperature trends. Observed trends are from two different sources (*Christy et al.*, 2000, and *Wentz et al.*, 2002). Model equivalent channel 2 trends are from a greenhouse gas-sulfate-ozone ("GSOP")experiment performed by *Bengtsson et al.* (1999) with the ECHAM4/OPYC coupled model. The comparison involves "residual" trends after removal of estimated ENSO and volcano effects from model and observed data (*Santer et al.*, 2001). The range of residual trends arises from uncertainties in the assumed decay time for a volcanic signal and from the choice of index used for removal of ENSO influences. All trends were computed with global-mean monthly-mean data spanning the 228-month period January 1979 through December 1997, the period of the GSOP integration.