

## Temperature Changes in the Troposphere: Beyond the IPCC

### Summary

Discussions of potential climate change have tended to focus on past and possible future changes in surface temperature. These discussions ignore the fact that climate processes occur in the troposphere, and that any assessment of climate variability and change must consider both the surface and the troposphere.

Our current theoretical understanding of greenhouse warming indicates that human emissions of greenhouse gases should warm the troposphere faster than they warm the surface. However, satellite-based measurements of tropospheric temperature indicate that since 1979 the troposphere has warmed at a rate that is significantly slower than the rate of surface warming. Climate models do not simulate this phenomenon, nor can it be explained by natural climate variability, i.e., the effects of volcanic eruptions or El Niño. The disparity between observations and theory-based projections of the rates of tropospheric warming is an indication of our limited understanding of the climate system and raises serious question about our ability to project future climate. However, as is always the case in scientific research, more weight must be given to measured data than to theoretical calculations.

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### Background

Although we live and function on the surface, we misrepresent climate change if we focus only on surface conditions and projections of surface climate. Indeed, it should seem obvious that the atmosphere as a whole, whose mass is about 14.7 pounds above each square inch of the Earth's surface, plays a dominant role in controlling the potential human-induced climate changes that might impact the surface. The processes occurring in the atmosphere produce the weather that affects the surface. Therefore, the processes and variations of the whole atmosphere must be investigated in any assessment of climate variability and change. As a corollary, climate model projections must be validated not only against surface climate conditions, but also against data on upper air temperatures.

Figure 1 shows the zones of the atmosphere. The lowest 9 miles (14 km) are the troposphere, the next 2½ miles (4 km) are the tropopause, and the 20 miles (32 km) above that, the stratosphere. We will be discussing changes in the troposphere, tropopause, and lower stratosphere, which are the zones of the atmosphere in which weather and climate changes occur.

All things being equal, the additional energy trapped in the climate system by human emissions of greenhouse gases should increase the temperature of the

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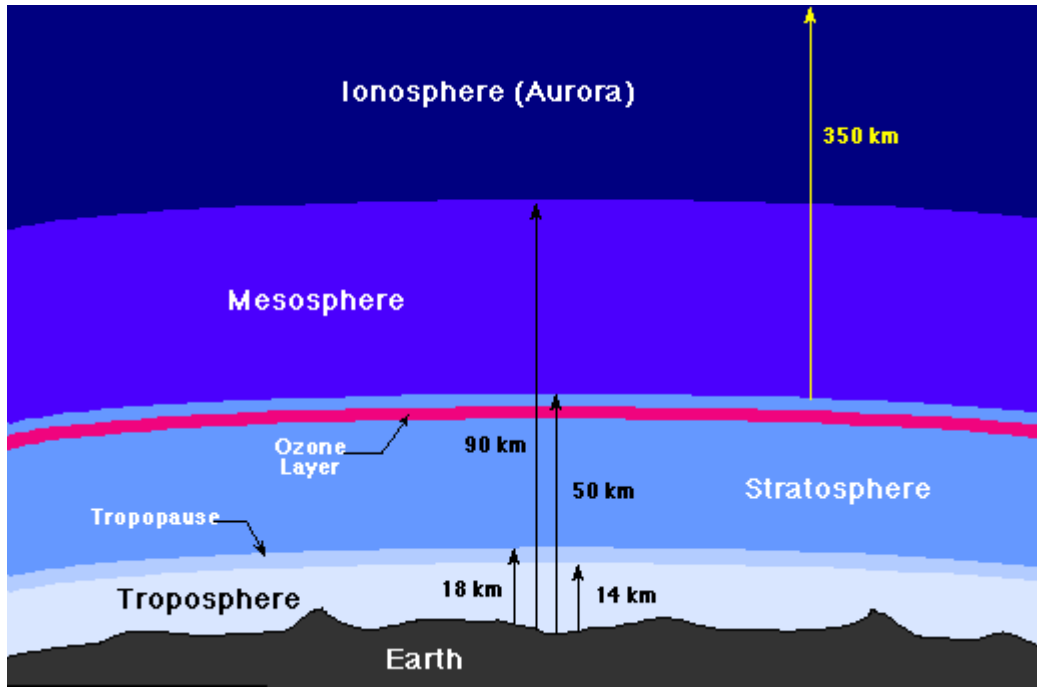


Figure 1 – Zones of the Atmosphere

troposphere. Thus, increasing tropospheric temperature should be one of the earliest and clearest indicators of human-induced climate change. Secondary effects, for example, in changes in storminess, are related to changes in the vertical and horizontal distribution of temperature, and could also be indicators of the influence of greenhouse gas increases. These secondary effects are less certain and more difficult to interpret.

### Measuring Upper-Air Temperatures

Two systems have been used over the last seventy years to provide weather information from the atmosphere above the surface: weather balloons and satellites.

#### Weather Balloons

The first data sets to provide long-term upper air weather information came from instrument packages carried aloft by balloons. Early packages were crude, mainly providing information on the speed and direction of winds by visual or radar tracking as the balloon

ascended. Later packages also monitored temperature, pressure, and humidity. Data from these instruments was converted into radio signals and transmitted to nearby ground stations. The whole package, weather monitors and radio transmitter, is known as a radiosonde. Temperature, pressure, and humidity were more difficult to measure accurately, as numerous factors influenced the readings. For example, thermistors (electronic thermometers) always experience a time lag in their response to the temperature of the air through which they ascend, making it difficult to assign a precise vertical level to the reported temperature. Also the sun heats the package housing or sensor itself, which tends to produce temperature readings warmer than that of the ambient air.

The magnitude of these time-lag and solar-heating problems are unique for each type of instrument employed at the weather balloon stations. As a result, merging data from different stations is a difficult task. To multiply uncertainties further, many countries build their own versions of radiosondes, and new versions have been continually developed and

used through the years. The lack of systematic instrumentation for weather balloons through time, combined with virtually no on-site inter-comparison between old and new devices, created discontinuities in the historical data record that in many cases were found to be significant. For example, a change from one instrument to another of a different manufacturer could produce a discontinuity of 3°C at the lower stratospheric levels (Parker et al., 1997), which makes it impossible to detect trends on the order of 0.05°C per decade.

Despite these difficulties, there have been several attempts to construct global data sets of upper-air temperatures. In one of the first, Angell (2000) assembled data from 63 weather balloon stations with mostly complete records and with few instrument changes. Due to the rapid horizontal mixing of the upper atmosphere, fewer data points are required to construct a global average than for the surface, whose temperature is far more variable. This dataset provided evidence of large year-to-year variations in upper-air temperatures, sudden stratospheric warming during winter near the poles, and the combination of induced tropospheric cooling and stratospheric warming as a result of volcanic eruptions.

However, questions raised about the accuracy of the long-term trends in Angell's data led to further studies by NOAA, the UK Meteorological Office, and the Russian Research Institute for HydroMeteorological Information. All have produced weather balloon-based global average temperature histories for the troposphere using a combination of statistical techniques and expert judgment. The different approaches used by these groups have led to significant differences in their estimates of the trends in tropospheric temperatures.

### *Satellite-Based Temperature Measurements*

Since late 1978, NOAA polar orbiting satellites have carried instruments that measure microwave emissions that can be correlated with the temperature of the lower troposphere (surface to about 5 miles), mid-troposphere (surface to about 11 miles), and lower stratosphere (10 to 15 miles). With the launch and commissioning of the NOAA-15 spacecraft in August 1998, the original microwave unit (MSU) was replaced by an advanced unit (AMSU), providing more measurement capability.

Microwave emission measurements produce signals that are largely dependent on atmospheric temperature alone. The impacts of clouds, dust, water vapor (heavy rain is screened out), and variations in microwave emissions from the surface (surface emissivity) are small, and thus have virtually no impact on the long-term temperature histories (Spencer et al., 1990). But other factors, which create spurious trends in the data that are of the same magnitude as the change in temperature being sought, must be dealt with. For example, the time at which a polar orbiting spacecraft crosses a fixed point tends to drift to earlier or later in the day over a period of years. A 2 p.m. crossing time may drift to 5 p.m., which introduces a spurious cooling trend because the atmosphere naturally cools between 2 and 5 p.m. Instrument calibration issues also have been discovered, as well as satellite biases and orbital decay effects.

The University of Alabama in Huntsville (UAH) produces temperature histories of lower and mid-troposphere and the lower stratosphere that merge data from the nine MSUs and two AMSUs. Generally only two spacecraft are

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operational at any given time, each lasting about four to six years, and each is launched to replace an older one that has failed or is nearing retirement. Remote Sensing Systems (RSS) of San Rafael, California, has recently begun producing mid-troposphere and lower stratosphere temperature histories from raw MSU/AMSU data using methodologies for making the required adjustments that differ from those of UAH (Mears et al., 2003). The different methodologies lead to different estimates of tropospheric temperature trends. However, in general, independent weather balloon-based trend calculations show greater consistency with UAH than with RSS.

Recently Vinnikov and Grody (2003) published an analysis of satellite temperature data which they claimed corrected for daily and seasonal cyclic effects. Their analysis showed the temperature of the troposphere rising faster than the temperature of the surface. However, their analysis also showed a daily cycle in which temperature peaked at about 11:00 a.m., declined until about 3:30 p.m., and then peaked again at about 9:00 p.m. This pattern is contrary to everything we know about daily temperature patterns. Temperature in the atmosphere rises in the morning, peaks in the early afternoon, and then declines. The UAH analysis shows a peak temperature at about 1:30 p.m.; the RSS analysis shows the peak at about 2:00 p.m.; both reasonable findings.

## Results and Error Estimates

For the 1979 – 2002 period, UAH's analysis of mid-troposphere temperatures shows a warming trend of  $0.032^{\circ}\text{C}$  per decade with a 95 percent confidence interval of  $\pm 0.05^{\circ}\text{C}$  per decade (Christy et al., 2003). RSS' analysis shows a warming trend of  $0.115^{\circ}\text{C}$  per decade 95 percent confidence interval of  $\pm 0.02^{\circ}\text{C}$  per decade (Mears et al., 2003). With a given that the two error ranges do not overlap, it is likely that one or both of the error ranges is underestimated.

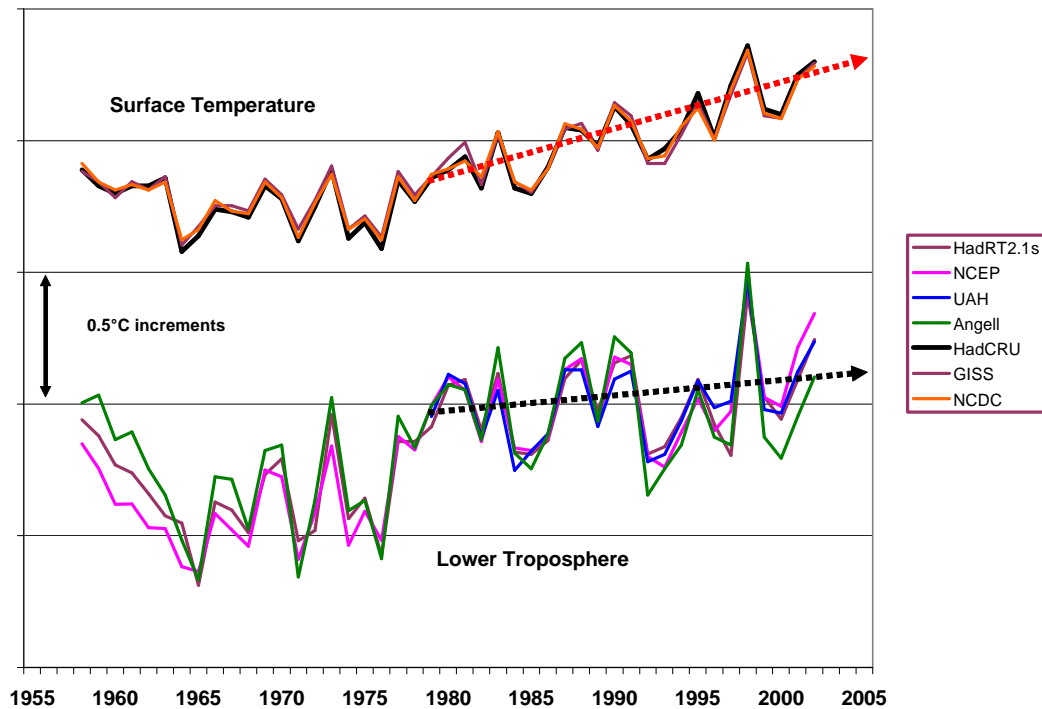
## Comparison of Available Datasets

As indicated earlier, the trend in upper air temperatures is one of the key metrics in understanding climate change. This metric is very sensitive to errors in the temperature history. Thus, assessing decadal trends is a demanding test for these histories, especially when the differences between the datasets are generally less than  $0.10^{\circ}\text{C}$  per decade. Indeed the year-to-year variability is generally well captured by all of the datasets presented here so that inter-correlations are high (Seidel et al., 2004).

Evidence of increased temperatures over decadal time scales, which would indicate global warming, must be extracted from temperature histories characterized by some level of error, as well as significant year-to-year variability related to events such as El Niño-Southern Oscillation (ENSO) and volcanoes. Below the stratosphere the anticipated rate of human-induced warming is about  $0.1$  to  $0.3^{\circ}\text{C}$  per decade, so errors or year-to-year impacts of  $0.1^{\circ}\text{C}$  per decade approach the magnitude of the temperature trend being sought. As a result, much attention is given to assessing trends and their errors by both observationalists and modelers.

In comparing the data sets with each other and with climate model projections, we shall focus on global and tropical temperature variations and trends in the troposphere. The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) (Folland, et al., 2001) concluded that surface and tropospheric temperature trends were virtually identical over high latitude continents such as North America and Europe. The observational data are displayed in Figure 2. Significant year-to-year variability in temperatures is evident as shown by warm-phase ENSO events (e.g., the 1998 El Niño), cool phase events (e.g., the 1989 La Niña), and cooling following large volcanic eruptions that inject sunlight-reflecting aerosols in the stratosphere (e.g., Mt. Pinatubo,

## Lower Tropospheric and Surface Temperature variations 1958-2002



**Figure 2.** History of global annual temperatures measured at the surface (upper curves) and measured in the lower atmosphere (lower curves) from 1958 to 2002 from a variety of datasets (HadCRU=Hadley Center Climate Research Unit surface measurements; NCDC=National Climatic Data Center surface measurements; GISS=Goddard Institute for Space Sciences surface measurements; HadRT2.1=version 2.1 of the Hadley Center Radiosonde Temperatures; UAH=University of Alabama-Huntsville Satellite-derived measurements; Angell=Angell's radiosonde measurements; NCEP=National Center for Environmental Prediction radiosonde data set).

1991–1992). Volcanic and ENSO events account for about 60 percent of the monthly to seasonal variability in tropospheric temperatures (Santer et al., 2001).

The data sets in Figure 2 have been compared in numerous studies including IPCC (Intergovernmental Panel on Climate Change) and NRC (National Research Council) reports. They fall into two main groupings: weather balloon based and satellite-based. However, the methods used to construct these data sets are so different that the differences within each grouping are larger than the differences between groupings.

The data reveals that satellite-based temperature trends are generally more positive (i.e., they show more increase in temperature) than weather balloon-based trends. Differences increase with altitude, indicating that spurious stratospheric cooling related to instrument changes in the weather balloons is the likely cause. Thus, reliability of trends based on weather balloon data decreases as altitude increases. On the other hand, adjustments to the satellite-based data sets become more straightforward (e.g., fewer surface emissivity issues) as the altitude increases.

In all cases, global and tropical temperature

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trends for the lower troposphere since 1979 are more negative (i.e., they show less increase in temperature) than those for the surface. Looking at a longer period, since 1958, surface and tropospheric temperature trends are not significantly different. As Figure 2 demonstrates, the temperature shift in 1976–1977, also seen in the North Pacific atmospheric circulation, is the source of the difference between the tropospheric trend from 1958–2002 and from 1979–2002 (Folland et al., 2001).

Christy et al. (2001) demonstrated that since 1979, sea-surface temperature, measured anywhere from 1 meter to 20 meters depth and used in all “surface temperature” data sets, shows greater warming than the air immediately above the ocean surface, measured on ship decks and buoys. Therefore, the rate of warming in the tropics is apparently greatest in the water, and decreases within the atmosphere.

### **Comparing Climate Model Projections with the Data**

The issue of different trends at the surface and in the tropical troposphere has attracted significant attention in the scientific community due to the inability of climate model simulations to reproduce this result (NRC 2000a; NAS, 2001). In virtually all climate model simulations, increased greenhouse gas concentration results in the troposphere warming at a faster rate than the surface. With several observational estimates of the tropospheric and surface warming rates we are in a position to test this model result.

### **Climate Model Considerations**

One of the main conclusions from the IPCC TAR was that the surface warming of the second half of the last century (i.e., since 1950) was mostly due to human-induced changes in the atmospheric concentrations of greenhouse gases. This conclusion was based on climate model simulations of surface temperature trends for the last 140 years. But the surface temperature trend was zero from 1950 to 1979, indicating that all of the net global surface temperature increase from 1950 to 2000 occurred after 1979. That is precisely the period for which tropospheric temperature measurements from satellites are available. We can directly compare surface and tropospheric temperatures for the period in which IPCC claimed that human-induced temperature increase was most evident.

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Chase et al. (2003) examined the probability of finding a significant difference in trends between the surface and troposphere over multiple 22-year periods. They used

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four long-term climate model simulations, incorporating both unforced (no increase in greenhouse gas concentrations) and forced (increased greenhouse gas concentration) cases. *They concluded that none of the model projections, forced or unforced, simulated the currently observed situation of a large and highly significant surface warming accompanied by little or no warming aloft.* It appears that the models incorrectly simulate heat transfer in the atmosphere, an important factor in projecting future temperature, and that they are currently incapable of producing reliable estimates of atmospheric temperature trends.

A 2001 National Academy of Sciences report (NAS 2001) promoted evidence for human induced climate change, but its conclusion about the surface/troposphere disparity was less firm:

The finding that the surface and troposphere temperature trends have been as different as observed over intervals as long as a decade or two is difficult to reconcile with our current understanding of the processes that control the vertical distribution of temperature in the atmosphere.

“Our current understanding” is a phrase that means the “results of climate model simulations.” What the NAS statement implies, then, is that the inability of climate models to reproduce the behavior of important quantities like tropospheric temperature and energy content represents an inconsistency that should not be discounted in assessing predictions of future climate.

### *Explanations Based on Natural Fluctuations*

One possible explanation for the disparity between surface and tropospheric temperature trends relates to the representativeness of the past twenty-four years against the background of natural climate variability. Perhaps natural climate variations could account for this disparity. (By implication then, it would follow

that climate models in general do not contain proper natural variations.) The especially strong volcanic eruptions of 1982 and 1991, coupled with significant warm ENSO events of 1982–1983 and 1997–1998, could have had differing impacts on surface and troposphere temperatures because these temperatures respond differently to changes in energy input. In general the troposphere responds with greater amplitude, while the surface, constrained by the large thermal inertia of the oceans, displays a more muted impact. Christy and McNider (1994) determined that Mt. Pinatubo’s eruption in 1991 caused the troposphere to cool by at least 0.7°C, while surface temperatures fell by less than 0.4°C.

However, the effects of volcanoes and El Niños do not explain the disparity between surface and tropospheric temperature trends. Recent studies (Michaels and Knappenberger, 2000; Santer, et al., 2001) show that when the influences of volcanoes and ENSOs are statistically removed from surface and tropospheric temperature histories, the rate of surface warming still exceeds the rate of tropospheric warming.

### **Conclusion**

In conclusion, observations indicate that since 1979 the troposphere has warmed at a rate that is significantly slower than the rate of surface warming. The climate science incorporated into climate models indicates that if anthropogenic emissions of greenhouse gases are the cause of the warming observed during the second half of the 20th century, the troposphere should have warmed at a faster rate than the surface. This disparity between observations and climate model simulations calls into question the validity of both the models and their projections of future climate.

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