Correspondence

SATELLITE AND SURFACE TEMPERATURE DATA AT ODDS?

Reply to John R. Christy and Roy W. Spencer

Based on a series of scientific papers, from Spencer and Christy (1990) to Christy and McNider (1994), a perception has been created in the popular media that satellite measurements of global temperature change are inconsistent with surface measurements and with climate model predictions of global warming rates. Such conclusions, if warranted, would be important. Global temperature change is the most direct anticipated effect of increasing greenhouse gases, as well as an agent contributing to other environmental changes.

We discuss key aspects of the satellite vs. surface and the satellite vs. model issues. The discussion illustrates the potential for increased information from use of multiple data sets, the thesis of our earlier correspondence (Hansen and Wilson, 1993), and it leads to a prediction of changes in satellite measured temperature trends during the remainder of this decade.

We emphasize that Spencer and Christy deserve much credit for combining MSU (Microwave Sounding Unit) data from several satellites and making the data widely available. Although the media communiques have understated the need for complementary temperature measurements, left the impression that surface and tropospheric temperature trends should be the same, and misrepresented model predictions for the rate of climate change, these matters are readily clarified. Extraction of reliable quantitative measures of global change is the more difficult challenge. Our scrutiny of MSU data should be viewed as an indication of the high potential value we see in MSU measurements, especially in combination with radiosonde, surface, and other satellite measurements.

Is there a significant difference between MSU and surface temperature trends? The MSU data span about 15 years, 1979 to the present, over which period the tropospheric temperature retrieval (channel 2R, which is a linear combination of channel 2 readings at different viewing angles) shows a small negative trend. Over the same period measurements of surface air temperature show warming, at least 0.1 °C/decade or 0.15 °C over 15 years, relative to the MSU trends (Table I).

Jones (1994) attempted to explain this difference via transitory effects of volcanos and El Niños, assuming that their impact is twice as large in the troposphere as at the surface. This assumption reduces the satellite trend more than the surface trend, because Pinatubo occurs near the end of the record. The assumption of twice as much volcanic cooling in the troposphere is probably an exaggeration, but even

TABLE I
Measured temperature trends (°C/decade) for 12 and 15 year periods

Measurement	1979–90	1979–93
Surface air, meteorological stations (Wilson and Hansen*)	0.14	0.07
Surface air, ships & meteorological stations (Jones@)	0.17	0.10
Radiosonde (850–300 mb mean, Angell#)	0.12	–0.05
MSU channel 2R (Christy *et al.*, 1995)	0.03	–0.06
MSU channel 2R, W & H spatial coverage	0.02	–0.09
MSU channel 2R, Angell coverage	–0.06	–0.15

* Update of Hansen and Lebedeff (1987).
@ Update of Jones and Wigley (1990).
\# Update of Angell (1986).

this extreme case leaves a surface warming of 0.08 °C/decade, i.e. 0.12 °C in 1979–93, relative to the satellite data.

Is a difference of 0.12 °C–0.15 °C in the measured tropospheric and surface temperature changes significant? It is commonly assumed to be insignificant, because of incomplete spatial coverage in the surface data and the brevity of the satellite record. But restricting the coverage of the satellite to be the same as the surface slightly *increases* the difference (Table I). Therefore the question becomes: can natural variability of temperature within the climate system produce this difference of trends at the two levels?

One tool for investigating natural climate variability is provided by long control runs of global climate models (GCMs). We have examined the difference in the surface and tropospheric temperature trends in a 3000 year run of a GCM (Hansen *et al.*, 1993a; hereafter HLRSW) for 12 and 20 year periods (12 years being the MSU record length up to Pinatubo). The histograms in Figure 1 indicate that a chance difference of 0.1 °C/decade in the surface and troposphere temperature trends over 15 years is barely possible, but, contrary to impressions left by IPCC (1990, 1992) and Jones (1994), it is unlikely.

The natural variability in the climate model which produced Figure 1 appears to be at least as large as in other GCMs and in the real world (HLRSW; Stouffer *et al.*, 1994). Thus we conclude that the observed difference in the surface and satellite temperature trends probably is meaningful and requires a physical explanation.

Is there a significant difference between MSU and radiosonde trends? MSU and radiosondes both sample tropospheric temperature. Because the records are short, especially for MSU, calculated trends can change considerably as each year of data is added, but this does not affect intercomparison if we consider the common period. A more serious problem is the limited spatial coverage of radiosonde locations, which causes a large sampling error in estimating global mean temperature (Hansen and Lebedeff, 1987; Karl *et al.*, 1994). Thus although the radiosonde trend showed

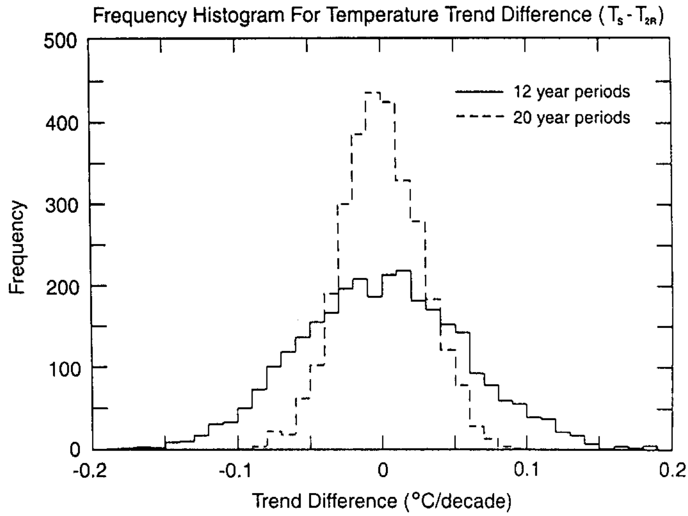

Fig. 1. Frequency histogram for the difference between the temperature trends of surface air and tropospheric temperature in a 3000 year run of a global climate model (Hansen *et al.*, 1993). The vertical weighting function for tropospheric temperature is that for MSU channel 2R with 14% surface weight (Shah and Rind, 1995). Result for 15 year period falls about half way between that shown for 12 and 20 year periods.

warming relative to MSU for several years, the 'global' trends came into near agreement, probably temporarily, when the radiosonde locations experienced a larger cooling in 1993 than the MSU global mean (Table I).

The spatial coverage problem can be avoided by sampling MSU data at the radiosonde locations. When Hansen and Wilson (1993) did this, they found an indication of warming of the radiosonde trend relative to MSU data, by as much as 0.1 °C/decade. This trend difference at the radiosonde sites suggests that the agreement between the global MSU and 63-station radiosonde trends for 1979–93 is accidental, and in time the trends probably will diverge again, unless the reason for the differences at the sites is discovered and corrected.

A priori, the satellite data would not be the prime suspect for explaining the trend difference at the radiosonde locations. There are several known problems with continuity of radiosonde data, especially changes of instrumentation (Gaffen, 1994). Another question is whether there is a sufficient trend in water vapor amount to induce a significant non-temperature trend in Angell's virtual temperature time series (Elliott *et al.*, 1994), a concern emphasized by Christy and Spencer (1995). Here we report a quantitative test of these issues by one of us (HW), which, although very limited, provides valuable insight.

The difference between MSU and radiosonde temperature trends found by Hansen and Wilson (1993) arose mainly from radiosonde locations at latitudes 30° N to 30° S, with the largest differences for stations between 30° N and 10° N. In the latter zone Angell's radiosonde network has 12 stations, among which the data quality and documentation varies substantially (Gaffen, 1994). For example, we believe that at least part of the large temperature trend of the two Indian stations results from identified instrumentation changes (Gaffen, 1994 and pers. comm.). The stations in the 30° N–10° N zone with best instrumental continuity and documentation, thus best suited for a quantitative test, are probably the United States controlled stations (Gaffen, 1994). Will Spangler (pers. comm., 1994) provided us monthly averaged observations of five stations which have nearly complete twice-daily observations from 1979–1993.

Figure 2a shows the MSU channel 2R brightness temperature averaged over these five station locations and compares this with the temperature calculated from the radiosonde profiles multiplied by the vertical weighting function of Spencer and Christy (1992). The absolute difference between the measured MSU temperature and the temperature derived from the radiosonde profile shows the need for a more accurate MSU weighting function, as discussed in the following section. The third curve in Figure 2a is the radiosonde 850–300 mb virtual temperature.

Figure 2b shows the difference of MSU 2R and the radiosonde *temperature* (calculated using the weighting function of Spencer and Christy, 1992) and the difference of MSU 2R and the radiosonde 850–300 mb *virtual temperature*. MSU cools relative to the radiosonde temperature by 0.42 °C/decade and by 0.43 °C/decade relative to the radiosonde virtual temperature.

One conclusion from the similar temperature and virtual temperature trends in Figure 2b is that the cooling we found of MSU relative to radiosondes is not caused by our use of the 850–300 mb virtual temperature. The same conclusion follows from the observation that an implausible specific humidity change of about 90% at 850–300 mb would be needed to cause a 0.6 °C (0.4 °C/decade) virtual temperature change (Elliott *et al.*, 1994) at these stations. Thus, contrary to the implication of Christy and Spencer (1995), virtual temperature effects are not the cause of the difference in satellite and radiosonde temperature trends.

A clue about the cause of the difference between radiosonde and satellite temperature trends at low latitudes is provided by MSU channel 2, at the same five stations, which cools only 0.04 °C/decade relative to the radiosonde temperature profiles multiplied by the channel 2 weighting function. If instrument changes were causing a radiosonde temperature trend, it would be unlikely to disappear at the higher tropospheric level of channel 2. The small trend in channel 2 may be magnified by the MSU 2R procedure of combining different view angles. Perhaps channel 2R is thus more sensitive than channel 2 to hydrometeor effects.

Turning to non-thermometric causes of MSU brightness temperature change (e.g., hydrometeors), note that MSU brightness temperatures averaged over the tropics would need to cool 0.2 °C/decade, relative to the true atmospheric temperature, in order to account for the entire difference between MSU 2R and surface global temperature trends. We do not expect non-thermometric effects to account for the entire difference in view of the evidence that radiosonde inhomogeneities are at least partly responsible. But a non-thermometric contribution at even a frac-

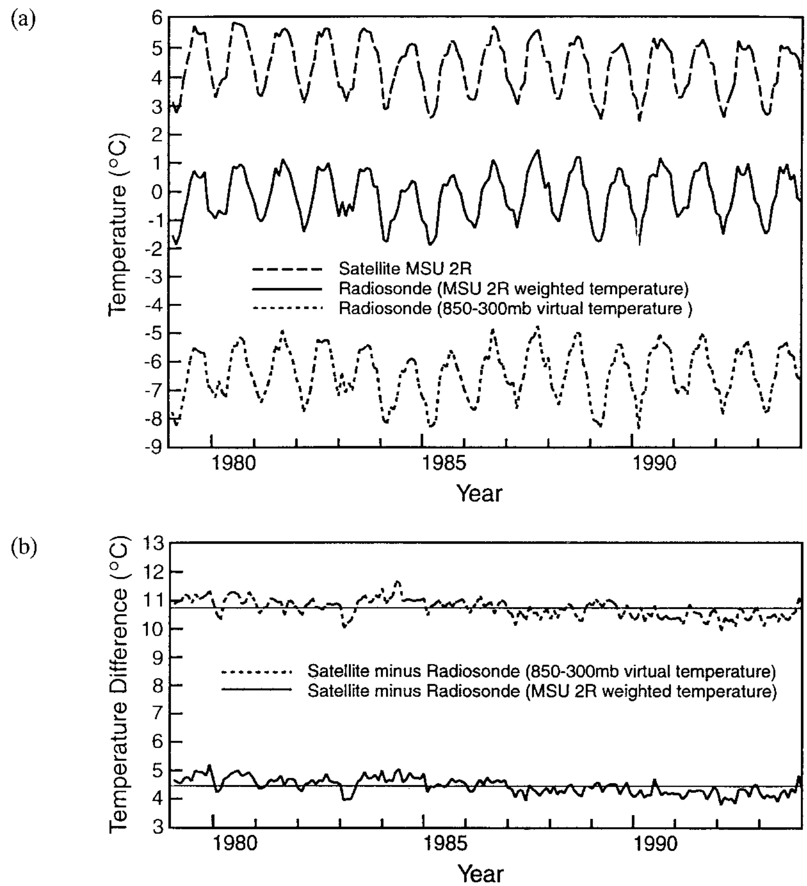

Fig. 2. (a) MSU 2R brightness temperature, radiosonde temperature calculated as the product of the radiosonde temperature profile and the MSU 2R vertical weighting function of Spencer and Christy (1992), and radiosonde 850–300 mb virtual temperature; all three curves are averages for the locations of the five U.S. controlled radiosonde stations between 30° N and 10° N [Wake Island, Guam, Hilo HI, San Juan PR, Brownsville TX]; (b) difference between first and third curves, and the first and second curves, of Figure 2a.

tion of this rate would be important for understanding of global change, which underlies the importance of studies such as that of Prabhakara *et al.* (1995).

We stress again that inaccuracies in the radiosonde record deserve close attention, especially effects of instrument changes. Improvements in the temporal consistency of radiosonde data and documentation of instrumental changes are one of the high priority needs for global change research. As discussed in our previous commentary and below, factors influencing the MSU record such as hydrometeors and changes in the satellite sampling of the diurnal cycle, both of which should have greatest effect at low latitudes, also deserve careful scrutiny.

We conclude that the question of whether there are important differences between radiosonde and MSU global temperature trends cannot be answered definitively at this time. We find evidence of differences at several low latitude radiosonde locations. Some of the difference is due to inhomogeneities in the radiosonde records. Some of the difference may be non-thermometric MSU effects, but more comprehensive studies are needed, including longer, better documented radiosonde measurements. Despite many comparisons already made by Christy and Spencer (1995), additional MSU-radiosonde comparisons and investigations of causes of the differences are warranted, especially at low latitudes.

What level does MSU sample and is it fixed? The MSU weighting functions provided by Spencer and Christy (1992), nominally a function of oxygen opacity at appropriate microwave wavelengths, provide a good rough measure of the atmospheric levels from which the measured microwave radiation emerges. But, as illustrated in Figure 2, the absolute temperature derived by applying these weighting functions for tropospheric temperature retrieval to radiosonde temperature profiles does not agree closely with measured MSU brightness temperatures. An understanding of the causes of this discrepancy is required to assess its possible influence on studies of temperature *change*.

One of us (KS) has carried out microwave radiative transfer calculations, including effects of surface emissivity variations and refraction, as described in a paper available from us (Shah and Rind, 1995). When the radiative transfer calculations are applied to an atmospheric climatology, the simulated brightness temperatures agree well with the measured MSU temperatures, generally within 1–2 °C. However, if instead the channel 2 or 2R weighting functions of Spencer and Christy (1992) are applied to the climatology without the addition of a surface emission term, the simulated brightness temperatures are about 3–8 °C colder than MSU observations. We do not mean to imply that Spencer and Christy are unaware of the surface emission contribution to the MSU signal. Indeed, they include surface emission in their own radiative transfer calculations when comparing results from radiosondes with MSU (Spencer and Christy, 1992). But users of the MSU weighting function need to realize that a surface emission term must be included, with a value mentioned below.

There are two inferences from the radiative calculations relevant to understanding of the differences between MSU and surface air temperature trends. First, surface emission should be included in studies of how physical processes may affect surface and tropospheric temperature trends by different amounts. Below we illustrate this quantitatively for the case of ozone depletion. Second, the close absolute agreement of the simulated and measured brightness temperatures, when surface emission *is* included, places an upper limit on unscreened hydrometeor effects in the MSU data, as discussed presently.

Rain and ice crystals, as well as oxygen, can affect the atmospheric level from which the MSU signal arises, and, as the altitude distribution of these hydrometeors may change when climate changes, the level sampled by MSU may also change (Hansen and Wilson, 1993). Although areas of most extreme hydrometeor opacity are screened from the MSU record, Prabhakara *et al.* (1995) demonstrate that the

MSU record retains substantial hydrometeor contamination. Because the radiative transfer calculations of Shah and Rind (1995) exclude hydrometeor effects, the difference between their calculations and the MSU observations can be examined for evidence of hydrometeor effects.

The results of Shah and Rind (1995), specifically their Figure 8a, contain a suggestion of a moderate hydrometeor effect. Over land areas, where surface emissivity is near unity, the brightness temperature calculated for a purely gaseous atmosphere on average is warmer than observed (hydrometeors would be colder than a surface with emissivity near unity), while over water, snow, and ice, which have emissivities substantially less than unity, calculations and observations tend to differ in the opposite sense. But the differences are small, typically 1–2 °C. Therefore, because of factors such as possible errors in the modeled climatology and uncertainties in surface emissivities, we take this only as an approximate *upper limit* to hydrometeor effects.

If hydrometeors affect MSU temperatures by 1 °C it is conceivable that hydrometeor *changes* affect MSU trends by a few hundredths of a degree per decade, i.e., hydrometeors might account for a portion of the 0.1 °C/decade difference between surface and tropospheric trends. But, unfortunately, at present we have no good way to convert an estimate of unscreened hydrometeor impact on brightness temperature to an estimate of the possible impact on temporal changes of brightness temperature. If the cloud and precipitation physics in climate models are developed to sufficient realism, they could provide the input for radiative calculations of hydrometeor effects. Of course, ideally we would like global measurements of hydrometeor properties simultaneous with temperature measurements. This would be possible with appropriate multifrequency microwave observations.

We conclude that the level sampled by MSU is specified reasonably well by the weighting functions of Spencer and Christy (1992), provided that a surface emission term is added. The surface contribution varies with location, but averages about 14% for channel 2R and 6% for channel 2, as specified in more detail by Shah and Rind (1995). We also conclude, mainly from the study of Prabhakara *et al.*, that there is evidence for an unscreened hydrometeor influence on MSU temperatures. Additional information is needed to determine whether hydrometeor *changes* significantly influence MSU temperature *trends*.

Is there significant MSU sampling bias or instrument sensitivity change? MSU does not make an accurate absolute temperature measurement, but rather looks for relative change and is thus dependent on instrument stability and transfer of calibration from one satellite to another. We noted (Hansen and Wilson, 1993) that changes of temporal sampling, e.g., of the diurnal cycle, could give a false trend to the MSU data. Similarly, subtraction of the seasonal cycle from the individual satellite records may be imperfect due to differences among the instrument sensitivities, their temporal samplings, or incompleteness of the cycles.

As one verification of the effect of sampling changes, we note the recent correction of the MSU data for a three hour diurnal drift of the NOAA-11 satellite

(Christy *et al.*, 1995), which altered the channel 2R trend by about −0.045 °C over 15 years. This change is included in Table I trends.

A second example of uncertainties introduced by sampling imperfections is provided by comparison of channel 2R trends derived from the MSU zonal mean data and the MSU globally gridded data. The two data sets, derived from the same measurements with different procedures for averaging over space and time, have a relative trend of 0.03 °C over 15 years. The difference of these two global temperature time series suggests, small discontinuities at times of satellite handoffs, but the discontinuities at most offer a hint, not an explanation, for the trend difference.

Another uncertainty for long term trends is the possibility of a small change in instrument sensitivity. Although MSU is calibrated by viewing the cosmic background and a warm target, the absolute accuracy does not approach 0.01 °C. Thus all or part of instrumental change can escape detection, even with overlapping measurements from different satellites, if the change has the same sense on the two satellites.

We conclude that there are uncertainties in the MSU temperature trends of at least several hundredths of a degree Celsius per decade. MSU errors will vary with latitude, as the effect of hydrometeors, the diurnal cycle, and the seasonal cycle all vary with latitude, and the MSU data normalizations are done separately for each latitude zone (Christy, pers. comm.). Our limited comparison with radiosondes (Hansen and Wilson, 1993) found largest differences at low latitudes. It is important to have better-documented absolutely calibrated radiosonde stations in all latitude zones, as there is no other known way to tie down absolutely the long-term temperature trends.

What are model-predicted global warming rates? Christy and McNider (1994) state that climate models predict a global warming rate of 0.3 to 0.4 °C/decade. This is a factor of four larger than the underlying observed warming rate of 0.09 °C/decade which they infer from MSU channel 2R for 1979–93 after attempting to remove empirically El Niño and volcanic effects.

Where did the 0.3–0.4 °C/decade come from? Christy and McNider cite Boer *et al.* (1992) and Manabe *et al.* (1991). Boer *et al.* (1992) performed only an equilibrium doubled CO_2 experiment, from which no rate of warming can be deduced. Manabe *et al.* (1991) did a transient simulation with CO_2 increasing at 1%/year, i.e., 3.5 ppm/year. Actual CO_2 increase in 1979–93 was 1.4 ppm/year (P. Tans, private communication), i.e., only 40% of the rate in the GCM simulation.

Transient simulations should account for other known climate forcings, which both enhance and diminish the CO_2 forcing, as well as their uncertainties. Transient simulations for the period 1979–93 have been published by Hansen *et al.* (1981, 1988, HLRSW), the 1981 simulations being made with a 1-D climate model and the others with GCMs. The simulations used broad ranges of climate sensitivities (up to 5.6 °C for doubled CO_2) and climate forcing scenarios, including in some cases measured or estimated changes of several trace gases and aerosols. Calculated surface air temperature warming rates for 1979–93 were ≤ 0.2 °C/decade, with values 0.1–0.15 °C/decade for the most plausible forcing scenarios and climate sensitivities (say 3 °C for doubled CO_2).

We conclude that the 0.3–0.4 °C/decade global warming rate cited by Christy and McNider (1994) is a strawman, representative of computer model results for the middle of the next century under 'business-as-usual' scenarios, i.e., continued exponential growth of emissions. That rate is not relevant to the period 1979–1993. A model-based prediction for near-term changes of the tropospheric temperature trend is given below.

Are tropospheric and surface temperature trends expected to be the same? Most mechanisms for global climate change are expected to alter surface and tropospheric temperature by similar amounts, because of the convective coupling of these levels. But some climate forcings can alter the surface and tropospheric temperature trends by significantly different amounts. We illustrate this with a specific quantitative example.

Ozone depletion was included in the transient GCM simulations of HLRSW, with the trend of column ozone from TOMS (Stolarski *et al.*, 1991) and the vertical profile of stratospheric ozone change from SAGE (McCormick *et al.*, 1992). The observed ozone trend data was from 1978–90, with depletion at half this rate assumed for 1970–78 and 1990–2000. HLRSW reran one simulation excluding the ozone change, illustrating (their Figure 21) that the ozone depletion cooled the tropopause region and that observed temperatures contained a 'fingerprint' of the ozone depletion.

Here we examine further the HLRSW simulations, which were carried out for the 1850–2000 time scale without regard to satellite vs surface issues, to illustrate expected tropospheric and surface temperature response to plausible global climate forcings. In addition we rerun all 18 GCM simulations of HLRSW for 1970–2000 with ozone fixed at the profile used for 1850–1970, thus isolating the impact of ozone change on the temperature profile. The 18 runs consist of six climate forcing scenarios and three climate sensitivities (0.5, 1.5 and 3.6 °C for doubled CO_2). We average results over the six forcing scenarios, which are comparable in magnitude, to allow the impact of the small ozone climate forcing to be examined.

Figure 3a compares the radiosonde temperature data of Oort and Liu (1993) for 1970–89 with the GCM temperature trends of HLRSW, which included the ozone depletion. The case of high climate sensitivity is in rather good agreement with the observations, with warming in the troposphere but cooling above 12 km altitude. Figure 3b shows that the good agreement is a consequence of the ozone depletion. This is a different illustration of the 'fingerprint' of ozone depletion already shown by HLRSW.

Figure 3c shows that the impact of ozone change varies strongly with altitude. Ozone cooling of the surface is less than the average effect in the troposphere. The contrast between surface and tropospheric impacts may actually be greater or less than shown, because of uncertainties in the profile of ozone change.

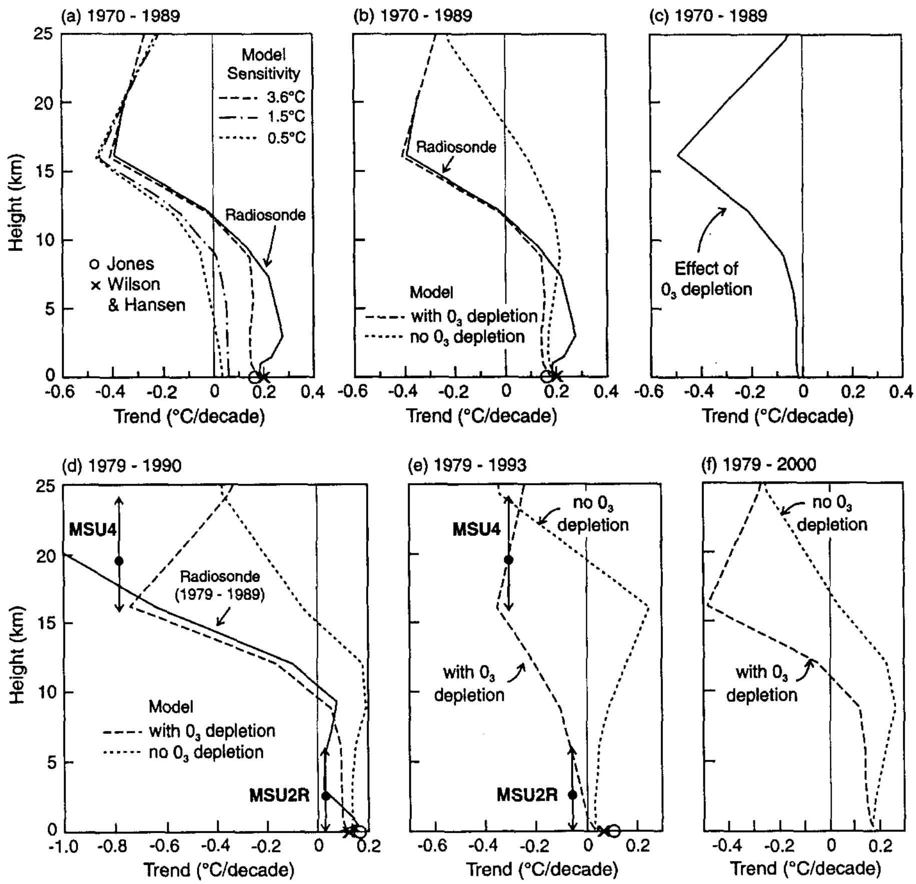

Fig. 3. Global temperature trend for 1970–89 (a, b, c); 1979–90 (d); 1979–93 (e); and 1979–2000 (f). The radiosonde data of Oort extends only through 1989. The model results in (a) illustrate the effect of different climate sensitivities; the highest sensitivity, 3.6 °C for doubled CO_2, is the most realistic and is used for (b)–(f); (b) and (c) illustrate explicitly the impact of ozone changes on the temperature profile; (d) and (e) begin in 1979 to allow comparison with MSU; arrows marking MSU observed values contain 70% of the signal for MSU channel 4 and 85% of the signal for channel 2R; (f) shows model projected temperature trends for 1979–2000.

Figures 3d and 3e show temperature trends beginning in 1979, so that comparison with MSU can be included. The periods covered, 1979–90 and 1979–93, allow the impact of Pinatubo (stratospheric warming and tropospheric cooling) to be identified. Results are shown without ozone change to further clarify ozone's impact on the vertical temperature profile. We emphasize that the ozone change

TABLE II
Climate model temperature trends (°C/decade)

Level/model	1970–89	1970–2000	1979–90	1979–93	1979–98
Surface air					
Sensitivity = 3.6 °C	0.18	0.19	0.12	0.04	0.16
w/o O_3 change	0.20	0.19	0.17	0.05	0.15
Sensitivity = 1.5 °C	0.06	0.10	0.14	0.04	0.11
w/o O_3 change	0.09	0.11	0.16	0.05	0.13
12-run mean	0.12	0.14	0.13	0.04	0.14
w/o O_3 change	0.14	0.15	0.16	0.05	0.14
MSU channel 2R					
Sensitivity = 3.6 °C	0.16	0.16	0.11	–0.02	0.11
w/o O_3 change	0.19	0.20	0.16	0.05	0.16
Sensitivity = 1.5 °C	0.05	0.09	0.11	0.01	0.11
w/o O_3 change	0.09	0.11	0.18	0.05	0.13
12-run mean	0.11	0.12	0.11	0.00	0.11
w/o O_3 change	0.14	0.15	0.17	0.05	0.15
MSU channel 4					
Sensitivity = 3.6 °C	–0.32	–0.31	–0.48	–0.28	–0.36
w/o O_3 change	–0.09	–0.09	–0.23	–0.10	–0.14
Sensitivity = 1.5 °C	–0.31	–0.29	–0.46	–0.29	–0.33
w/o O_3 change	–0.08	–0.09	–0.19	–0.04	–0.13
12-run mean	–0.31	–0.30	–0.47	–0.29	–0.35
w/o O_3 change	–0.09	–0.09	–0.21	–0.07	–0.13

was included already in all of the scenarios of HLRSW, because it is a known climate forcing and reasonably well characterized.

We conclude that the assumed ozone change cools the troposphere more than it cools the surface. This result is clearest if we average over the 12 runs with plausible climate sensitivities (Table II), which shows that for the period 1979–93 the ozone change cools the MSU 2R level by 0.06 °C/decade but cools the surface by only 0.03 °C/decade. The gap between tropospheric and surface cooling by ozone would have been slightly (0.01 °C/decade) larger if we had used the MSU 2R weighting function of Spencer and Christy (1992) rather than that of Shah and Rind (1995).

These quantitative results depend on the accuracy of the assumed profile of ozone change. SAGE observations extend down only to 17 km and are uncertain at the lower levels. We assumed constant tropospheric ozone in the Southern Hemisphere and about 20% increase in the Northern Hemisphere over 1970–2000. Also our GCM had only two layers in the stratosphere; more precise analysis requires a stratosphere-troposphere model.

Thus we do not claim to have adequately analyzed the impact of ozone depletion on the vertical temperature profile. However, the calculations are sufficient to provide an example of a factor which affects tropospheric temperature differently than surface temperature. Indeed, given the clear 'fingerprint' of ozone depletion (Figure 3 here and Figure 21 of HLRSW), it is much more than a hypothetical example.

We conclude that there are mechanisms which affect surface and tropospheric temperature by different amounts. Indeed, we have shown that a realistic ozone change cools the troposphere about 0.03 °C/decade more than it cools the surface. There still remains a difference of 0.05–0.10 °C/decade in the surface and MSU temperature trends which must be accounted for by other deterministic mechanisms, unforced internal climate variability or observational error.

What tropospheric temperature trends are expected the remainder of this decade? An indication of expected near-term changes in global temperature is provided by the same model simulations of HLRSW which we have found to be in reasonable agreement with past temperatures. As shown by HLRSW and Figure 3f, this model predicts a strong shift to warming in the remainder of this decade. In the model the 1979-to-date tropospheric temperature trend becomes positive by 1995–96, as the effect of Pinatubo aerosols fades, ozone depletion slows, and other greenhouse gases continue to increase. The 1979–2000 tropospheric temperature trend reaches 0.10–0.15 °C/decade, while the surface trend reaches 0.15–0.20 °C/decade.

Caveats and explanations concerning these predictions must include considerations of uncertainties in the climate forcings, model deficiencies, and temperature measurements. We assume there will be no large volcanic eruption in the remainder of this decade. Tropospheric aerosols are assumed to change little in this period. Growth rates in the 1990s of the well-mixed trace gases, especially CH_4 and CFCs, have fallen below the rate assumed by HLRSW, but the effect of this overestimate should be small, as much of the predicted warming is realization of greenhouse gas forcing added in previous decades. Assumed ozone changes, especially in the troposphere, are perhaps most uncertain; our calculations (HLRSW) assumed a slowing of ozone depletion rates in the 1990s.

The greatest model uncertainty is probably the prescribed ocean heat transport, which ignores the possibility of a sudden switch in the mode of ocean circulation. Climate modelers assign large uncertainties to parameters affecting model sensitivity, but we have argued that empirical evidence ties down climate sensitivity rather tightly (HLRSW).

The predicted lower tropospheric warming refers to the level sampled by MSU 2R. If differences persist between radiosonde temperatures and co-located MSU soundings, the best absolute comparison with the model may be provided by radiosondes with instrumentation continuity.

Discussion. The difference between surface and satellite temperature trends, at least 0.12–0.15 °C over 15 years, is almost certainly significant. We do not have the data needed for conclusive interpretation of its causes, but is seems likely to involve a combination of factors. Ozone change, reasonably well observed, may account for about 0.05 °C over 15 years. Urban warming of surface air, if of the order of 0.1 °C/century (IPCC, 1990; Hansen and Lebedeff, 1987), could account for 0.01–0.02 °C. Principal candidates for nonthermal causes of MSU temperature trends are difficult to quantify with available information, but appear to be several hundredths of a degree Celsius per decade. These mechanisms, plus the noise level of about 0.05 °C/decade (Figure 1), mean that presently there is not a significant discrepancy between surface and satellite temperature trends.

We have shown that GCM simulations, based on several known climate forcings including ozone depletion and carried out independently of MSU considerations, are in rather good agreement with overall observations. The same climate model predicts significant near-term temperature changes, with the 1979-to-date tropospheric temperature trend becoming positive by 1995–96 and reaching a value 0.10–0.15 °C/decade by 2000. These changes are measurable and will provide a valuable test of our understanding of global climate change.

We conclude that surface and satellite temperature change data are really not at odds. Rather they have the potential to provide, in combination, a powerful tool for analyzing global change. Temperature change need not be the same at all altitudes, and deviations from uniformity contain invaluable information on the mechanisms of change. Exploitation of this potential requires good data for the profile of temperature change, as can be provided by radiosondes, as well as the global coverage attainable from satellites, and absolutely calibrated surface measurements. Interpretation of measured temperature changes will require monitoring of global climate forcings and feedbacks (Hansen *et al.*, 1993b).

Although we have pointed out uncertainties regarding MSU data at the level of several hundredths of a degree Celsius per decade, this is not meant as a negative comment regarding the value of the MSU data. On the contrary, our interest is sparked by the great potential of these data, and it is hoped that highlighting these matters will only make the data all the more valuable. Spencer and Christy are to be commended for their hard work in preparing the MSU data set and for the care and completeness with which they have assessed and presented statistics for several possible sources of error. Undoubtedly the MSU data will be an important component of future global change studies.

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References

Angell, J. K.: 1986, 'Annual and Seasonal Global Temperature Changes in the Troposphere and Low Stratosphere, 1960–1985', *Mon. Wea. Rev.* **114**, 1922–1930.

Boer, G. J., McFarlane, N., and Lazare, M.: 1992, 'Greenhouse Gas-Induced Climate Change Simulated with the CCC Second-Generation General Circulation Model', *J. Clim.* **5**, 1045–1077.

Christy, J. R. and McNider, R. T.: 1994, 'Satellite Greenhouse Signal', *Nature* **367**, 325.

Christy, J. R. and Spencer, R. W.: 1995, 'Assessment of Precision in Temperatures from the Microwave Sounding Units', *Clim. Change* **30**, 97–102 (this issue).

Christy, J. R., Spencer, R. W., and McNider, R. T.: 1995, 'Reducing Noise in the MSU Daily Lower Tropospheric Global Temperature Data Set', *J. Clim.* (in press).

Elliott, W. P., Gaffen, D. J., Kahl, J. D. W., and Angell, J. K.: 1994, 'The Effect of Moisture on Layer Thickness Used to Monitor Global Temperatures', *J. Clim.* **7**, 304–308.

Gaffen, D. J.: 1994, 'Temporal Inhomogeneities in Radiosonde Temperature Records', *J. Geophys. Res.* **99**, 3667–3676.

Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., and Russell, G.: 1988, 'Global Climate Changes as Forecast by the Goddard Institute for Space Studies Three-Dimensional Model', *J. Geophys. Res.* **93**, 9341–9364.

Hansen, J., Johnson, D., Lacis, A., Lebedeff, S., Lee, P., Rind, D., and Russell, G.: 1981, 'Climate Impact of Increasing Atmospheric Carbon Dioxide', *Science* **213**, 957–966.

Hansen, J., Lacis, A., Ruedy, R., Sato, M., and Wilson, H.: 1993a, 'How Sensitive is the World's Climate?', *Nat. Geogr. Res. Explor.* **9**, 143–158.

Hansen, J. and Lebedeff, S.: 1987, 'Global Trends of Measured Surface Air Temperature', *J. Geophys. Res.* **92**, 13345–13372.

Hansen, J., Rind, D., DelGenio, A., Lacis, A., Lebedeff, S., Prather, M., Ruedy, R., and Karl, T.: 1991, 'Regional Greenhouse Climate Effects', in Schlesinger, M. E. (ed), *Greenhouse-Gas-Induced Climatic Change*, Elsevier, Amsterdam, pp. 211–229.

Hansen, J. and Wilson, H.: 1993, 'Commentary on the Significance of Global Temperature Records', *Clim. Change* **25**, 185–191.

Hansen, J., Rossow, W., and Fung, I.: 1993b, 'Long-Term Monitoring of Global Climate Forcings and Feedbacks', NASA CP 3234, 91 pp.

Intergovernmental Panel on Climate Change: 1990, in Houghton, J. T., Jenkins, C. J., Ephraums, J. J. (eds.), *Climate Change, The IPCC Scientific Assessment*, Cambridge Univ. Press, 365 pp.

Intergovernmental Panel on Climate Change: 1992, in Houghton, J. T., Callander, B. A., and Varney, S. K. (eds.), *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, Cambridge Univ. Press, 200 pp.

Jones, P. D.: 1994, 'Recent Warming in Global Temperature Series', *Geophys. Res. Lett.* **21**, 1149–1152.

Jones, P. D. and Wigley, T. M. L.: 1990, 'Global Warming Trends', *Sci. Amer.* **263**, 84–91.

Karl, T. R., Knight, R. W., and Christy, J. R.: 1994, 'Global and Hemispheric Temperature Trends: Uncertainties Related to Inadequate Spatial Sampling', *J. Clim.* **7**, 1144–1163.

Manabe, S., Stouffer, R., Spelman, R., and Bryan, K.: 1991, 'Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2', *J. Clim.* **4**, 785–818.

McCormick, M. P., Veiga, R. E., and Chu, W. P.: 1992, 'Stratospheric Ozone Profile and Total Ozone Trends Derived from the SAGE I and SAGE II Data', *Geophys. Res. Lett.* **19**, 269–272.

Oort, A. H. and Liu, H.: 1993, 'Upper-Air Temperature Trends over the Globe', 1958–89', *J. Clim.* **6**, 292–307.

Prabhakara, C., Nucciarone, J. J., and Yoo, J. M.: 1995, 'Examination of Global Mean Temperature Sensing from Microwave Sounding Unit (MSU): 1) Radiative Transfer Considerations', *Clim. Change* (in press).

Shah, K. P. and Rind, D.: 1995, 'Use of Microwave Brightness Temperatures with a General Circulation Model', submitted to *J. Geophys. Res.*

Spencer, R. W. and Christy, J. R.: 1990, 'Precise Monitoring of Global Temperature Trends from Satellites', *Science* **247**, 1558–1562.

Spencer, R. W. and Christy, J. R.: 1992, 'Precision and Radiosonde Validation of Satellite Gridpoint Temperature Anomalies', *J. Clim.* **5**, 858–866.

Stolarski, R. S., Bloomfield, P., and McPeters, R. D.: 1991, 'Total Ozone Trends Deduced from Nimbus 7 TOMS Data', *Geophys. Res. Lett.* **18**, 1015–1018.

Stouffer, R. J., Manabe, S., and Vinnikov, K. Ya.: 'Model Assessment of the Role of Natural Variability in Recent Global Warming', *Nature* **367**, 634–636.

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