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COMMENTARY ON THE SIGNIFICANCE OF GLOBAL TEMPERATURE RECORDS

Bassett and Lin, in an article in this issue of *Climatic Change*, consider the probability of having a record global temperature during the next few years and how that probability was altered by observed global cooling in 1992. This matter is of interest to mathematicians and climatologists, and it is of special relevance to politicians and the person-in-the-street because the presence or absence of new global temperature records is likely to be considered crucial evidence for or against the reality of anthropogenic greenhouse warming. Thus the analysis and conclusions of Bassett and Lin can be expected to receive increased attention and scrutiny as global temperatures are reported during the remainder of this decade.

The 'bet' which stimulated the Bassett and Lin paper, "a friendly little wager – one which much of the community apparently believes to be very improbable" (Hansen *et al.*, 1990), was that at least one year in the period 1990–1992 would be warmer than any year in the previous century. The bet was devised (Hansen *et al.*, 1990) to illuminate the position and confidence of 'greenhouse skeptics', as well as to draw attention to the issue of whether global temperature change during the next few years has implications for long-term climate change.

Bassett (1992) showed that the significance of the observed record global temperature of 1990 was limited by the fact that the temperature was close to a record level in the immediately preceding years. But the observed cooling of 1992 reduced global temperature to a level well removed from the maxima of the past decade. Thus Bassett and Lin find that the likelihood of a new record temperature in the next three years is small, if the temperature changes are statistical fluctuations. The 'odds' also remain against a new record on the somewhat longer time scale of the remainder of the 1990s.

But if we have 'insider' information about how the climate system works, that knowledge can alter the odds for future global temperature change. Relevant information includes knowledge about climate sensitivity and climate forcings, such as changing greenhouse gas and atmospheric aerosol amounts. For example, some climate model studies suggest that if climate sensitivity is 3 ± 1 °C for doubled CO_2 and increasing greenhouse gases are the dominant climate forcing on decadal time scales, than new records are likely within this decade (Hansen *et al.*, 1993). The drive for warming in the models on this time scale is principally 'unrealized warming' from greenhouse gases added to the atmosphere in the past century. This forcing is sufficient to more than overcome recent global cooling, which was presumably a consequence of the Mt. Pinatubo volcanic eruption (Hansen *et al.*, 1992a).

Thus observed global temperature change in the next several years has the potential to add to our understanding of the climate system. However it is predict-

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able that there will be differences among the several global temperature data sets, that they generally will not all reach global records at the same time, and that there will be disagreements about the data interpretations. These problems can be minimized, and resulting information on the climate system increased, if all of the data sets are examined together, and if the deficiencies which exist in each of the data sets are addressed explicitly.

The most commonly used temperature data sets (Jones *et al.*, 1986a, b; Hansen and Lebedeff, 1987) are based on measurements of surface air (1–2 m height) at meteorological stations. These data refer to the atmospheric level of most practical importance and they have the advantage of reasonably consistent measurements over about a century at many locations. Errors due to problems such as changes of instrumentation, station location, and diurnal sampling require continuing attention (Karl *et al.*, 1989) but are sufficiently small on global average that they do not affect the issue of recent and near future global records. Urban heat island effects are a more serious and systematic source of error, which may have increased the apparent global warming of the past century by about 0.1 °C (Hansen and Lebedeff, 1987; Jones *et al.*, 1990; IPCC, 1990, 1992). But even this error rate, about 0.01 °C per decade, is too small to have much effect on considerations of recent and near future records.

The greatest problem with the meteorological station data for the purpose of determining a global temperature record is the incomplete spatial coverage (Karl *et al.*, 1993). Although a single station provides a measure of the temperature anomaly for a substantial area (Hansen and Lebedeff, 1987), the typical coverage by stations reporting in the past decade results in a two-sigma (95% confidence) error of about 0.07 °C for the global anomaly of annual mean temperature (Hansen and Lebedeff, 1987). This uncertainty places a substantial limitation on the ability to compare different years within the same data set and it causes the ranking of years to be different among data sets with different area samplings. Of course this source of uncertainty can be eliminated in comparing different data sets by restricting consideration to the common area of measurements, but then the net area represented is substantially less than global, even with analysis methods which maximize the effective coverage (Hansen and Lebedeff, 1987; Karl *et al.*, 1993).

Spatial coverage can be improved by combining ship observations with the meteorological station data (IPCC, 1990, 1992; Jones *et al.*, 1991), but the ocean data introduce several additional problems which affect apparent long term temperature change. Ship height and speeds have changed in the past century, as have the methods of measurement. An additional problem is that the sea water temperature, rather than the surface air temperature, often is measured; changes of sea surface temperature in transient climate experiments, at least with the GISS model (Hansen *et al.*, 1988), are considerably muted compared to changes of surface air temperature. Also, 'corrections' for changes in the composition of the buckets used to draw the water (IPCC, 1992) are *ad hoc* and of dubious validity, calling into question the principal impact of that correction, namely relative warmth in the period 1850–1870. The changing locations of the ships within a gridbox cause further error (Trenberth *et al.*, 1992).

These problems place limits on the accuracy with which the ocean data can determine temperature change, just as other problems limit the accuracy of conclusions from the meteorological station data. Nevertheless, both data sets have substantial capability for determining near term temperature records, with the limitation that the relative ranking of global temperature for different years is uncertain for pairs of years with temperature difference less than about 0.1 °C. Because of the differing characteristics, strengths and weaknesses of the ocean and meteorological station data sets, it is informative to examine both data sets separately, as well as combined.

Nearly optimum spatial coverage can be otained from polar orbiting satellites, although existing satellite instrumentation is not capable of measuring surface air temperature. The most developed satellite data for thermal monitoring is that of the Microwave Sounding Unit (MSU) on operational weather satellites (Spencer and Christy, 1992). MSU channel 2 measures thermal emission at 53.74 GHz, which arises mainly from an O_2 absorption band. When analyzed as a function of emission angle ('channel 2R') the measured radiation comes principally from the 400–1000 mb pressure level in the Earth's atmosphere (Spencer and Christy, 1992). A long term precise record of the temperature for this level will be extremely valuable, but it must be recognized that the temperature change of that region can be considerably different than that of the surface air. For example, the large global warm anomaly of March 1990 (the most extreme monthly anomaly in both the East Anglia and GISS surface air analyses) was muted in the MSU measurements (Spencer and Christy, 1992) compared to surface air measurements. That temperature anomaly was caused mainly by unusual warmth over northern Asia, where a stable temperature profile may confine the most extreme temperature anomalies to low layers. Thus the MSU and the meteorological stations measure different, complementary quantities. Although the GCMs indicate that long term greenhouse warming trends should be comparable at the surface and in the troposphere, the ranking of individual years may differ between these two atmospheric levels.

An additional issue with the MSU data is its uncertain capability for measuring global temperature trends on decadal time scales. This uncertainty arises for several reasons. The first problem is that the atmospheric level sampled by MSU changes with time, unlike the meteorological station measurements, which are taken at a fixed height. The level sampled by MSU changes because atmospheric opacity at 53.74 GHz is caused not only by O_2, but also by water substance, especially ice crystals and raindrops, which can change in amount and altitude. In particular, GCMs suggest that, on global average, these water substances extend to higher levels in the atmosphere as the climate warms (Hansen *et al.*, 1991). Because temperature decreases with altitude in the troposphere, this would cause the MSU to measure a smaller temperature trend than that occurring at a fixed level.

Although regions of heaviest precipitation are screened out during MSU data reduction (Spencer *et al.*, 1990), this screening is imperfect, and thus it is important to determine whether changes in the non-oxygen sources of opacity are sufficient to alter measured temperature change.

A second problem with the MSU data is the possibility of a change of instrument sensitivity with time. MSU does not make an accurate absolute temperature measurement, but rather looks for relative change and is thus dependent upon stability of the instrument and upon simultaneous measurements by successive satellites to allow transfer of calibration from one instrument to another. Comparisons of MSU measurements with radiosonde station data (Spencer *et al.*, 1991) suggest that instrument drift is small for some of the instruments contributing to the MSU time series, but even a small calibration drift could be important in searches for global decadal change. Moreover, the 'tag team' approach, as opposed to an absolute temperature measurement, requires that *every* satellite-to-satellite 'hand off' be flawless; otherwise both the long term temperature trend and the relative ranking of different years can be altered. Finally, we note that changes of the temporal sampling of the satellite data, for example of the diurnal cycle, can introduce biases which have not been adequately analyzed.

Radiosondes (weather balloons) provide an alternative measurement of tropospheric temperature, with advantages and disadvantages relative to the satellite data. Because the radiosonde data are obtained *in situ*, the problem of the uncertain and possibly changing altitudes of remotely sensed temperature is largely avoided. Changes of radiosonde instrumentation with time are much less of an issue for temperature than for water vapor in the troposphere (Elliott and Gaffen, 1991), and the effect of instrument changes on temperature is less in the troposphere than in the stratosphere (Gaffen, private communication). However, tropospheric temperature trends are affected by instrumental system changes (Nash and Schmidlin, 1987; Ivanov *et al.*, 1991), and by calibration and procedural changes, as documented to a substantial degree by Gaffen (1993). The most serious problem with radiosondes for detecting record annual temperature is probably their poor spatial coverage. For example, Hansen and Lebedeff (1987) show that the uncertainty in the global annual temperature with the 63 station radiosonde network used by Angell and Korshover (1983) is about twice that for the surface air meteorological station network.

Nevertheless, the radiosonde data can provide a test relevant to these issues by comparison of temperatures measured by the Angell and Korshover network with MSU data for the same lcoations. This comparison eliminates differences due to incomplete spatial coverage, although not the generally smaller differences which may arise from different temporal sampling. Figure 1 shows the temperature change derived from the 63 station radiosonde network used by Angell and Korshover (1983) and that based on MSU data for the same 63 locations. There is a hint that short term climate fluctuations, such as the 1983 and 1991–2 El Niño warmings and the 1992 Pinatubo cooling may be more muted in the MSU data

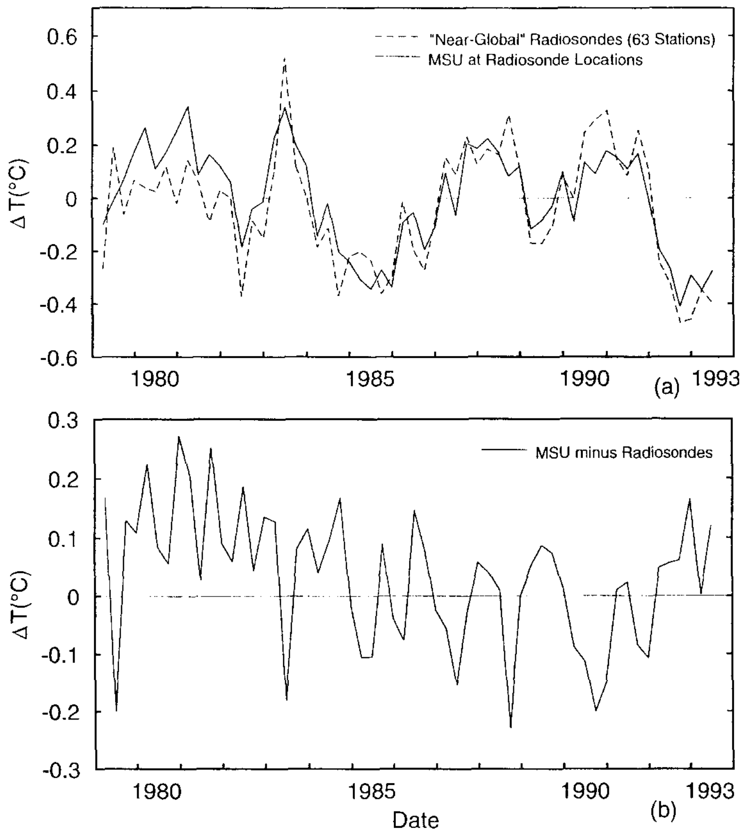

Fig. 1. Comparison of seasonal temperature change for the 63 station near-global radiosonde network for Angell and the satellite MSU channel 2R data for the same 63 locations. The temperature change is relative to the mean for the base period 1982–1991. The radiosonde data is the mean for levels from 850 to 300 mb, while the nominal vertical weighting function for MSU measurements is given by the 'tropospheric retrieval' curve in Figure 1 of Spencer *et al.* (1991). The trend of the MSU-radiosonde difference (b) is –0.10 °C/decade, or about –0.15 °C for the 14+ year period of record.

than in the radiosonde data. The more important result is that there is a substantial difference in the MSU and radiosonde temperature trends for the same locations over the 14 year period. This difference is large enough to affect determination of annual record temperatures as well as measurement of any global warming trend.

The fact that MSU and radiosondes measure different temperature changes is consistent with the possibility that the atmospheric level sensed by the microwave measurements changes in altitude as the climate changes. Unexplained seasonal modulation of MSU/radiosonde temperature differences (Spencer *et al.*, 1990) might also be a result of seasonal changes in non-oxygen sources of microwave opacity. The relationship between the remotely measured temperature change and the temperature change at a fixed level in the atmosphere can be investigated via microwave radiative transfer studies, however satisfactory analysis will also require precise measurements of changes in the atmospheric sources of microwave opacity. It is equally important to examine the radiosonde records for effects of instrumental changes mentioned above, and to improve the continuity of radiosonde operational procedures.

Several conclusions follow from the above considerations. First, we must anticipate substantial differences among the several measures of global temperature, and in particular the different temperature histories cannot be expected to always yield congruent occurrences of global records. This is a result of the fact that different quantities are being measured, as well as uncertainties and errors that occur in every measurement method.

Second, detailed comparisons of the several different temperature data sets have the potential to yield additional information not attainable from any one of the data sets alone, as well as a better understanding of the merits and constraints of each data set. Thus it would be a mistake to try to choose one data set as the basis to search for global temperature change. Also it is important to maintain and improve existing surface air and radiosonde networks including better documentation and calibration of instrumentation changes, in addition to satellite monitoring.

Third, interpretation of temperature changes that are observed in the future depends upon precise simultaneous measurements of the changes of other quantities such as water vapor, clouds, and precipitation. These data are needed not only to define climate forcings and feedbacks (Hansen *et al.*, 1992b), and thus to analyze cause and effect of observed climate change, but also to evaluate the possible influence of these changing atmospheric quantities on remote sensing measurements of temperature.

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