New observational evidence for global warming from satellite

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[1] Accurate measurements of surface radiative temperature, i.e. skin temperature, would be more directly interpretable in terms of the surface response to increase of greenhouse gases than the more conventional screen temperatures. Such measurements have not previously been attempted because of the difficulties of converting existing observations into a meaningful measurement. We have developed procedures for removing the effects of changing satellite orbits and cloud contamination from skin temperatures estimated from AVHRR channels 4 and 5, and so provide a first estimate of the trends of land surface skin temperature over the last two decades. The estimated land temperature increase is not only much greater than that for the atmosphere but also apparently somewhat larger than the estimates of surface air temperature increase from in situ measurement. *INDEX TERMS:* 1640 Global Change: Remote sensing; 1620 Global Change: Climate dynamics (3309); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions

1. Introduction

[2] Analyses of surface air temperature (SAT) over the globe have shown over the past century a global increase of about 0.4 to 0.8°C, and in the past two decades of about 0.2°C over the oceans and about 0.3 °C over land [*National Research Council* (*NRC*), 2000]. The increase over land has been larger than that over the oceans consistent with the smaller heat capacity of land and the observed warming of the surface ocean [*Levitus et al.*, 2000]. If convection rapidly mixes the troposphere in a vertical column, the surface and tropospheric temperatures should change together [*Schneider and Dickinson*, 1974; *Ramanathan*, 1981; *Manabe and Stouffer*, 1980]. However, a smaller increase of temperature of the lower to mid-troposphere of about 0.0–0.2°C over the past two decades is reported from recent analyses of satellite and radiosonde data [*NRC*, 2000]. This relatively small increase of tropospheric temperature, if real, suggests a need to obtain more observational information related to the variation of temperature change with altitude to be able to better interpret and model the observed change.

[3] This paper analyzes satellite surface skin temperature (T_s) and compares it with "Stephenson screen" surface air temperatures (SAT) [*Jin and Goetz*, 2001; *Jones et al.*, 1999]. This thermodynamic temperature, measured by thermometers sheltered by a wooden box, located 1.5–2 m above short grass and water-permeable, has provided the conventional observations used to assess the occurrence of global climate change. The radiometric "skin" temperature, is derived from the thermal emission of the Earth's surface. A brightness temperature is calculated from spectral radiances observed by satellite thermal infrared sensors and after removing surface emissivity and atmospheric effects, used to infer skin temperature [*Jin and Goetz*, 2001 and reference therein]. Such data can provide more uniform and denser coverage than that from traditional SAT measurements, which are not designed, sited, or maintained to provide reliable climatic records [*Karl et al.*, 1994].

[4] The spectral radiances from channels 4 and 5 of the NOAA Advanced Very High Resolution Radiometer (AVHRR) estimate skin temperature [*Agbu and James*, 1994; *Wan and Dozier*, 1996] at a spatial resolution of 1 Km at nadir, sampled twice daily, for two decades. However, various problems such as orbit drift, cloud contamination, inadequate sampling of the diurnal variation, may degrade the usefulness of the skin temperature measurements for study of climate change. Corrections for these problems have been developed to reduce such errors [*Jin and Dickinson*, 1999, 2000; *Jin*, 2000; *Jin and Treadon*, 2001] and to produce a diurnal cycle of land surface skin temperature. The resulting data set, referred to as "LSTD", is inferred from the thermal emission of terrestrial surfaces that have a line of sight to the overlying atmosphere, i.e. some combination of vegetation canopies and soils. The data include the 24-hour average, maximum and minimum values of diurnal cycle, and are tabulated at monthly intervals and 8 km resolution. The individual monthly average values are estimated to be uncertain by about 2°C and may include spatially varying biases because of variations in surface emissivity and other such factors. However, such biases are expected to largely cancel in considering only anomalies from the time averaged values.

2. Results

[5] This paper examines the trend implied by this land skin temperature for the period 1982–1998 using July and January data. The SAT observations are sited irregularly and have been remapped into 5 by 5 degrees. We likewise scale up skin temperature data from 8 km resolution into 5 by 5 degree using quality control filters in which obviously biased 8 km pixel values are removed. Figure 1a shows the anomalies of the global mean for this data from 1982 to 1998. The trend obtained by linear regression is about 0.43°C/decade. This value varies between 0.4–0.5°C per decade depending on how global average and annual mean are calculated. A Monte Carlo error analysis [*Wilks*, 1995] indicates that the probability of the measured trend differing from the actual one by more than 0.2°C/decade due to sampling is less than 10% (Figure 1b). Departures from the trend result from climate variability, e.g., El Niño, La Niña, and volcanic cooling, that are also seen in the SAT [*NRC*, 2000]. For example, the eruption of Mt. Pinatubo reduce global land temperatures over the period 1992–1995 [*NRC*, 2000], and the 97–98 El Niño elevated land temperatures in 1998. Some uncorrected artifacts in the skin temperature record of the effects of volcanic aerosols and of the piecing together of the different AVHRR instruments and records undoubtedly remain.

[6] Figure 2a shows that the annual averaged diurnal range, i.e., maximum temperature (T_{max}) minus the minimum temperature (T_{min}), decreases by about 0.16°C/decade. Figure 2b is the time series of annual global T_{max} and T_{min}. This decrease of diurnal range is consistent with estimates that the diurnal range of SAT decreased by about 0.1°C over the period but the latter estimate is

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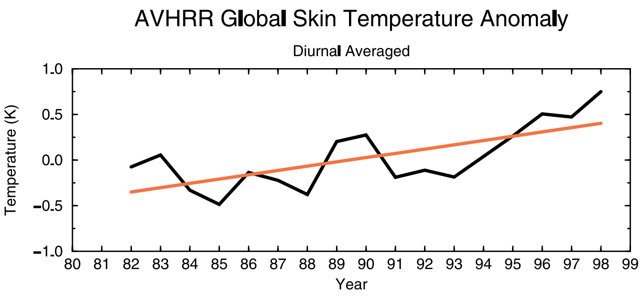

Figure 1a. Time series of global-mean surface skin temperature anomalies from 1982 to 1998. The straight line shows the trend fitted by linear regression based on the method of least squares. The anomalies are from the mean of 1982–1998.

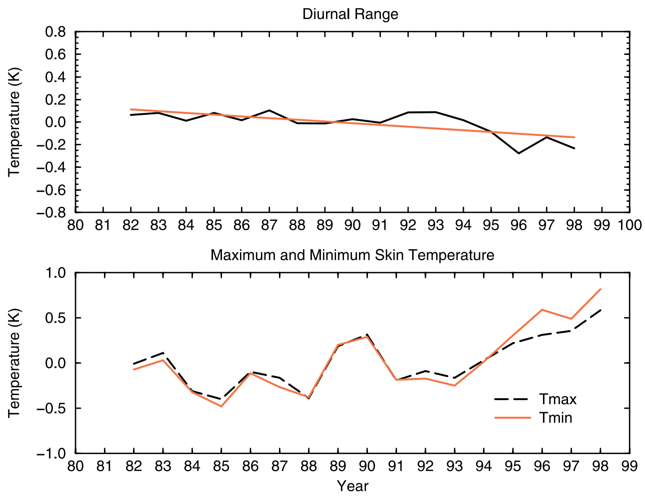

Figure 2. Same as Figure 1a, (a) for skin temperature diurnal range ($T_{max}-T_{min}$). (b) for maximum skin temperature (T_{max}) and minimum skin temperature (T_{min}), respectively.

rather uncertain because of inadequate spatial coverage [*NRC*, 2000; *Jones et al.*, 1999].

[7] Figure 3 compares the anomalies of global land skin temperature from this study and SAT from Jones [*Jones et al.*, 1999] over 1982 to 1998, for January and July respectively. The slope of the SAT data used here is 0.28°C/decade for both months whereas the January and July skin temperature slopes are larger by 0.25°C and 0.06°C, respectively. A trend of skin temperature much larger than that of SAT is seen primarily in January. Because of the large variability of the January time series this difference is not statistically significant. However, winter and nighttime temperatures are less constrained by surface energy fluxes to follow air temperatures than are daytime and summer values so such excess warming may be real. The geographical distribution of the slope of multi-year skin temperature (not shown) suggests that the skin temperature of some land areas, for example central North America and northern Eurasia decreases from 1982–1998.

3. Discussion

[8] The greenhouse gases added in the last two decades globally have reduced outgoing thermal radiation by about 1 W/m^2 [*IPCC*, 1995]. This reduction must be balanced by energy flux into the oceans, enhanced albedo from cloud and aerosol changes, and increased thermal emission out of the troposphere. Models and observations indicate a flux of about 0.4 W/m^2 into the oceans [*Levitus et al.*, 2000] so that the other factors must account for about 0.6 W/m^2, contributed by the troposphere above the boundary layer and by the surface and strongly coupled near surface air. If a standard climate sensitivity factor of 0.5°C/W/m^2 is assumed, then the effective radiating temperature should increase by 0.3°C. An increase of tropospheric temperature of only 0.1°C implies some combination of smaller sensitivity, more energy flux into the ocean than stated above, and a surface that warms more than the overlying atmosphere. Skin temperature changes in excess of that of the air by as much as 0.1 to 0.2°C would increase outgoing fluxes substantially and also contribute to the required balance over land.

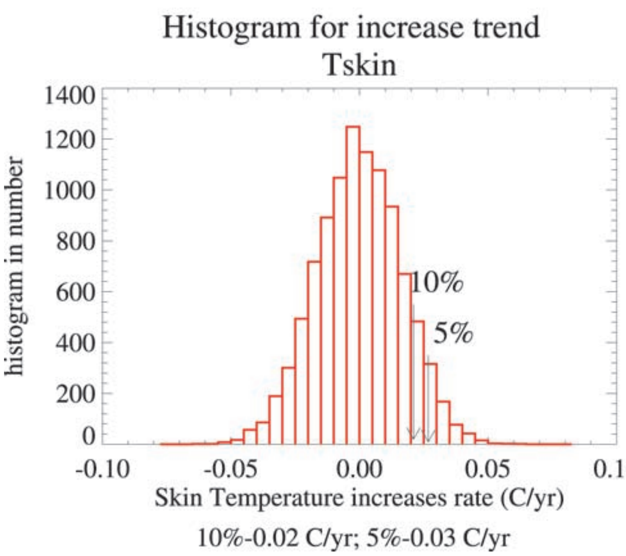

Figure 1b. Histogram for the increase trend of skin temperature. Following a Monte Carlo method, the annual anomalies of skin temperature shown in Figure 1a are re sampled 10,000 times using a random generator. Then slopes of the trend of the resamples are calculated and are shown in this histogram. 10% (or 5%) means only 10% (or 5%) slopes falls above this value.

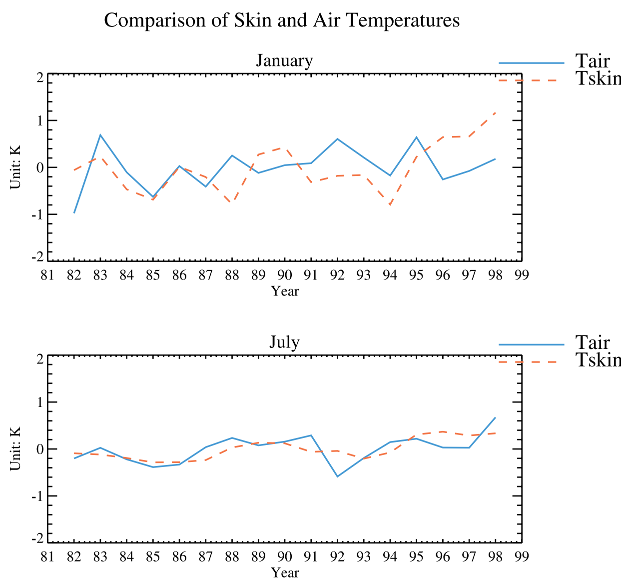

Figure 3. Seasonality of skin and air temperature anomalies, (a) for January and (b) for July.

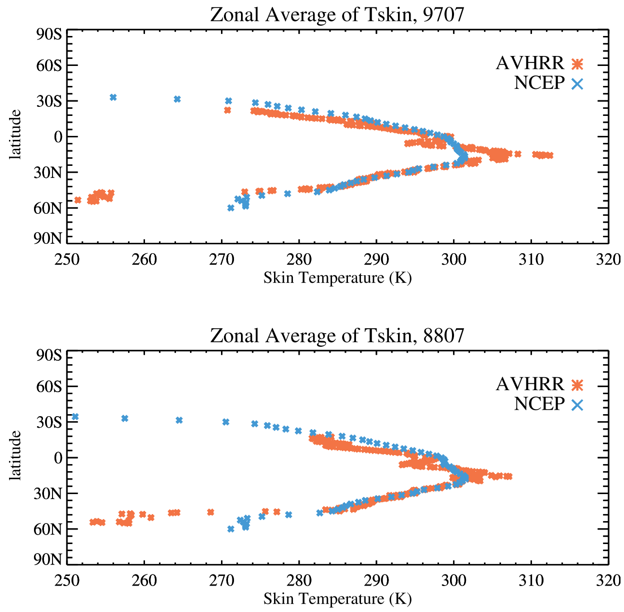

Figure 4. Zonal mean of AVHRR diurnal averaged skin temperature and NCEP reanalysis. (a) for July 1997; and (b) for July 1988.

[9] Although hypothetical increases of land skin temperature much in excess of the observed increases of the troposphere may help satisfy system requirements for enhanced radiative fluxes to balance the increases in greenhouse gases, they may be problematical in their implications for changes in turbulent exchange of energy between the surface and atmosphere. This coupling is much stronger during the day and summer than at night and winter. During the latter times, the overall stable stratification of the overlying atmosphere may allow substantial changes in the difference between surface and atmospheric temperatures, as has been commonly described as positive lapse-rate feedback in climate model simulations [*Schneider and Dickinson*, 1974]. The skin temperature data indicate that much of the excess over air temperature change has occurred under these conditions. During daytime and summer conditions, it is difficult to account for changes between surface and air temperatures as large as 0.1 °C unless there is a substantial reduction in land evapotranspiration, such as from the stomatal closure from increasing concentrations of CO_2.

4. Evaluation and Error Analysis

[10] Uncertainties in the satellite observations, e.g., the spectral emissivity for channels 4 and 5, introduce errors into the LSTD. Values used for emissivity are estimated to be in error by 0.5% for vegetation and for 1% for bare soil. Consequently, temperatures are uncertain by −0.7 °C to 0.4 °C for a inaccuracy of 1% in emissivity ([*Prata et al.*, 1995], also his Figure 14). Effects of aerosols and atmospheric composition also contribute to the uncertainty of estimated skin temperatures. Remote sensing researchers [*Prata et al.*, 1995; *Becker and Li*, 1995] state that the (AVHRR) LST data can achieve an accuracy of 1–2 K. Tests of several sets of emissivity combinations, from 0.93 to 0.98 for bare soil and vegetated areas in wet and dry conditions (as suggested by [*Prata et al.*, 1995]) indicate that errors in emissivity can alter an individual pixel's skin temperature by up to to 1–2 K, but that global averaged effects are much lower and the trend of global averaged T_s is changed very little. The orbits of NOAA-series satellites drift toward orbits farther from noon, and as corrected for here by modeling of the climatological diurnal cycle of skin temperature (see referenced papers for details). Skin temperatures under clouds have been estimated by modeling and extrapolation from adjacent surfaces under clear sky. Corrections have also been estimated for effects of volcanic eruptions and precipitation.

[11] Validation of the accuracy of the LSTD is problematical. There are no other reliable in situ or remote sensing observations-for such. However, the LSTD can be compared with data obtained by modeling the land surface processes as constrained by observed overlying atmospheric variables, i.e., near surface winds, temperatures, humidity, surface radiation, and precipitation. Although perhaps questionable in some of these aspects, it is useful to compare with the data from the NCEP/NCAR reanalysis [*Kistler et al.*, 2001]. Figure 4 compares zonal mean AVHRR-based T_s with NCEP reanalysis for July 1997 (Figure 4a) and July 1988 (Figure 4b), for land areas only. Evidently, the two agree with each other very well except the tropical areas. The assimilation has known problems in the tropics [*Trenberth et al.*, 2001], and the AVHRR skin temperature retrieval may have biases from low emissivities in arid regions. The cold areas southward of 60S are snow-covered and their temperatures are not retrieved in AVHRR data.

5. Conclusions

[12] Data from the AVHRR satellite indicate that the temperature of land surface has warmed substantially in most regions over the last two decades and globally at a rate of about 0.43 ± 0.2°C per decade, consistent with the increase of global land air temperature but apparently somewhat larger. The data set providing the diurnal cycle of land temperature also gives a decrease in the diurnal range of 0.16 ± 0.05°C per decade. The skin temperature climatology estimated from the data show considerable spatial and temporal structures. Some of these structures are known to be real as established by correlation with the SAT change [*Jin et al.*, 1997], and some either result from changes in the land temperature difference or artifacts in the temperature estimates caused by volcanic aerosol, unknown physics, or retrieval uncertainties.

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