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An alternative explanation for differential temperature trends at the surface and in the lower troposphere

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[1] This paper investigates surface and satellite temperature trends over the period from 1979 to 2008. Surface temperature data sets from the National Climate Data Center and the Hadley Center show larger trends over the 30-year period than the lower-tropospheric data from the University of Alabama in Huntsville and Remote Sensing Systems data sets. The differences between trends observed in the surface and lower-tropospheric satellite data sets are statistically significant in most comparisons, with much greater differences over land areas than over ocean areas. These findings strongly suggest that there remain important inconsistencies between surface and satellite records.

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1. Introduction

[2] Since 1979, when satellite observations of global atmospheric temperature became available, trends in thermometer-estimated surface warming have been larger than trends in the lower troposphere estimated from satellites and radiosondes as discussed in a recent Climate Change Science Program (CCSP) report [*Karl et al.*, 2006]. *Santer et al.* [2005] presented three possible explanations for this divergence: (1) an artifact resulting from the data quality of the surface, satellite and/or radiosonde observations, (2) a real difference because of natural internal variability and/or external forcings, or (3) a portion of the difference is due to the spatial coverage differences between the satellite and surface temperature data. *Santer et al.* [2005] focused on the second and third explanations, finding them insufficient to fully explain the divergence. They suggest in conclusion that, among other possible explanations, "A nonsignificant trend differential would also occur if the surface warming had been overestimated by 0.05°C per decade in the IPCC data."

[3] In the work of *Karl et al.* [2006], attention was given to the first explanation offered by *Santer et al.* [2005], but only with respect to the satellite and radiosonde data. *Karl et al.* [2006, p. 6] conclude that corrections to the satellite data sets have removed any discrepancies: "Independently performed adjustments to the land surface temperature record have been sufficiently successful that trends given by different data sets are reasonably similar on large (e.g., continental) scales, despite the fact that spatial sampling is uneven and some errors undoubtedly remain." *Karl et al.* [2006, p. 7] further state that: "Systematic local biases in surface temperature trends may exist due to changes in station exposure and instrumentation over land, or changes in measurement techniques by ships and buoys in the ocean. It is likely that these biases are largely random and therefore cancel out over large regions such as the globe or tropics, the regions that are of primary interest to this Report."

[4] However, it is unclear whether the assumption of 'randomness' has any scientific ground, as there exists recent research documenting spatially nonrepresentative warming biases in the surface temperature data that were not considered in the CCSP report [see *Hale et al.*, 2006; *Pielke et al.*, 2007a; ~~*Lin et al.*, 2007~~]. Indeed, for the latitudes 20°N to 20°S, the CCSP acknowledges that an unexplained difference between the surface and tropospheric trends still exits (Executive Summary of *Karl et al.* [2006, p.2]):

[5] Although the majority of observational data sets show more warming at the surface than in the troposphere, some observational data sets show the opposite behavior. Almost all model simulations show more warming in the troposphere than at the surface. This difference between models and observations may arise from errors that are common to all models, from errors in the observational data sets, or from a combination of these factors. The second explanation is favored, but the issue is still open.

[6] In our current paper, we consider the possible existence of a warm bias in the surface temperature trend analyses using the following two hypotheses related to the divergence between the surface and lower-tropospheric temperature records since 1979:

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[7] 1. If there is no warm bias in the surface temperature trends, then there should not be an increasing divergence with time between the tropospheric and surface temperature anomalies [*Karl et al.*, 2006]. The difference between lower troposphere and surface anomalies should not be greater over land areas.

[8] 2. If there is no warm bias in the surface temperature trends, then the divergence should not be larger for both maximum and minimum temperatures at high-latitude land locations in the winter.

[9] We conclude that the first explanation offered by *Santer et al.* [2005] provides the most parsimonious explanation for the divergence between surface and lower-troposphere temperature trends, based on recent research suggestive of biases in the surface temperature record. Our findings suggest that the supposed reconciliation of differences between surface and satellite data sets [*Karl et al.*, 2006] has not occurred.

2. Recent Evidence of Biases in the Surface Temperature Record

[10] A growing number of studies have found biases and uncertainties due to nonspatially representative influences in the assessment of multidecadal surface temperature trends [e.g., *Pielke et al.*, 2007a, 2007b; *Christy et al.*, 2006, 2009; *Davey and Pielke*, 2005; *Davey et al.*, 2006; *Hale et al.*, 2006, 2008; *Mahmood et al.*, 2006; *Rogers et al.*, 2007; *Kalnay and Cai*, 2003; *Kalnay et al.*, 2006; *Makowski et al.*, 2008; *Vautard et al.*, 2009]. These biases include poor exposure of observing sites (see also http://www.surfacestations.org/), effects on temperature trends of concurrent multidecadal trends in the local surface air humidity; microclimate, nonspatially representative land use change over time, movement of temperature measurements closer to buildings, changes in the turbulent state of the nocturnal boundary layer by surface development and aerosols, alterations in levels of sulfur dioxide emissions, and the sampling of temperature data at single heights.

[11] These effects can result in positive or negative impacts on temperature trends which are unrepresentative of temperature trends over an area larger than the immediate area of the observation. For example, if vegetation such as trees and shrubs are removed from around the observation site, the maximum temperature can be increased, even without a larger-scale warming, as a result of the loss of cooling by transpiration of water from the plants [*Pielke et al.*, 2004]. The construction of buildings, installation of roadways, removal of vegetation, and other local impacts are examples of changes in the observational environment that have been documented (e.g., see *Jamiyansharav et al.* [2006]; http://www.surfacestations.org/).

[12] While some changes, such as local irrigation, can produce a reduction in daytime temperatures, the extensive alteration of the microclimate in the immediate vicinity of many of the temperature observing sites by other alterations is expected to increase local minimum temperatures (*Kanamaru and Kanamitsu* [2008] also see photographic documentation of temperature observing sites in http://www.surfacestations.org/). Specific changes from irrigation that can increase temperatures at night are larger soil heat capacities that act as a resistance to cooling in the evening [*Shi et al.*, 2005]. Greater conductivity in soils because of water can allow greater flux of heat through the soil to the surface keeping surface temperatures warm. Finally, increased atmospheric humidity can increase downward longwave radiation due to water vapor absorption and reemission (a local greenhouse effect) [*Jacobson*, 2008; U. Nair et al., Radiative impacts of atmospheric aerosols on the nocturnal boundary layer, submitted to *Journal of Geophysical Research*, 2009] The results in the work of *Gallo* [2005] suggest that microclimate influences on temperatures observed at nearby (horizontally and vertically) stations are potentially much greater than influences that might be due to latitude or elevation differences between stations.

[13] *Hale et al.* [2008], for example, found that urbanization resulted in warming of minimum and maximum temperatures. Their conclusion is contrary to the earlier study of the urban effect reported by *Parker* [2004, 2006]. *Hanamean et al.* [2003] found a seasonal dependence in the explained variance of maximum temperatures because of the seasonal cycle of plant growth and senescence while using satellite data to document the detailed landscape in the vicinity of temperature measurement sites in eastern Colorado.

[14] Monitoring temperature at a single height will produce a significant warm bias when the atmosphere has warmed over time [*Pielke and Matsui*, 2005]. This effect will occur even for otherwise ideal locations for making spatially representative temperature measurements. This was documented by *Lin et al.* [2007] who found from observational data that monitoring long-term near-surface daily minimum temperature trends at a single level on light wind nights will not produce the same trends as for long-term temperature trends at other heights near the surface. ~~For instance, were the data from *Lin et al.* [2007] to be representative of biases in other station measurements taken at one height, then about 30% of the tropospheric warming during the 20th century reported by the IPCC would be explained as the result of this factor.~~ A warm bias would occur even for daytime maximum temperatures for land locations at high latitudes during the winter when the surface temperature profile remains stably stratified all day.

[15] The reason for a stable boundary layer warm bias can be summarized as follows. Studies of the lowest tens of meters of the atmosphere [e.g., *Stull*, 1988] show that it cools at night when winds do not advect warm air into the area, and heat is lost to space. As a result, minimum daily temperatures typically occur near sunrise. The nighttime cooling varies with height. With light winds, the cooling is greater near the surface and less aloft, while with stronger winds, which are associated with greater mixing of the air above a particular location, the cooling rate is more uniform with height. The rate of heat loss to space is dependent on several factors, including cloudiness and the local atmospheric concentrations of carbon dioxide and of water vapor [e.g., *Pielke*, 2002]. Under cloudy conditions, cooling is much less. An atmosphere with higher concentrations of the greenhouse gases, CO_2 and H_2O, also reduces the cooling at night. Consequently if, for instance, there is a long-term positive trend in greenhouse gas concentrations or cloudiness over the observing site, it may introduce an upward bias in the observational record of minimum temperatures that necessarily will result in an upward bias in the long-term surface temperature record.

[16] Because of changes to the atmosphere over the past century, there are several reasons why we should expect the nighttime cooling in the lower atmosphere to have been reduced. One reason for this is that carbon dioxide concentrations have increased, such that the effect of well-mixed greenhouse gas concentrations on near-surface temperature measurements has also increased. This increase is also expected to be higher for growing urban and industrial locations where carbon dioxide can locally accumulate when the large-scale wind flow is weak. An increase of water vapor over time would have the same effect. Also, an increase of cloudiness has been reported which has the effect of reducing nighttime cooling [*Karl et al.*, 1997].

[17] From 1950 to at least the mid-1990s, minimum temperatures on land have increased about twice as fast as maximum temperatures [*Easterling et al.*, 1997]. This may be attributable in part to increasing cloudiness, which reduces daytime warming by reflection of sunlight while retarding the nighttime loss of heat [*Karl et al.*, 1997].

[18] As noted, the minimum temperature occurs in the shallow, cool nocturnal boundary layer (NBL). The NBL is a delicate, nonlinear dynamical system that may be disrupted by increases in surface roughness, surface heat fluxes or radiative forcing. Under strong cooling and light winds, the surface becomes decoupled from the warm air above. A small change in any of these may then trigger coupling, or the downward mixing of warmer air which significantly raises minimum temperature readings. This disruption need occur only a few extra times per year to generate a warmer minimum temperature trend over time. In fact nighttime temperatures are more about the state of turbulence in the atmosphere than the temperature in the deep atmosphere. As an example, the minimum temperature will be quite different based on factors that influence turbulence, such as roughness or wind speed even if the temperature of the deep atmosphere aloft is the same [*McNider et al.*, 1995; *Shi et al.*, 2005]. Candidates for increasing these decoupling events are buildings (roughness), surface heat capacity changes such as irrigated deserts or pavement (heat flux), increased water vapor and increased aerosols (radiative forcing). All of these decoupling events have been observed [*Pielke et al.*, 2007a, 2007b; *Christy et al.*, 2009]. Increases in greenhouse gases can also cause a disruption of the nocturnal boundary layer as enhanced downward radiation destabilizes the NBL allowing more warm air from aloft to be mixed to the surface [*Walters et al.*, 2007]. However, any upward trends in nighttime temperatures are due to this redistribution of heat and should not be interpreted as an increased accumulation of heat [*Walters et al.*, 2007].

[19] In circumstances where nighttime cooling is reduced systematically over time, (i.e., under trends of greater atmospheric greenhouse gases, an increase in cloudiness or NBL decoupling), the resulting effect will be to increase minimum temperatures. Relatively speaking, this increase in minimum temperatures is greater on nights with light winds than on nights with strong winds. Minimum daily temperatures are, of course, important to the calculation of long-term global temperature trends because they are used as input to calculate the daily mean temperatures.

[20] When there is a long-term trend of a reduction in nighttime cooling due to the disruption of the nocturnal boundary layer whether from land use change or greenhouse gases, then when temperature data are collected, the combination of all of the minimum temperatures on light and strong wind nights will result in an overstatement of heat accumulation trends by tenths of a degree.

[21] Because the land surface temperature record does in fact combine temperature minimum and maximum temperature measurements, where there has been a reduction in nighttime cooling due to this disruption, the long-term temperature record will have a warm bias. The warm bias will represent an increase in measured temperature because of a local redistribution of heat, however it will not represent an increase in the accumulation of heat in the deep atmosphere. The reduction in nighttime cooling that leads to this bias may indeed be the result of human interference in the climate system (i.e., local effects of increasing greenhouse gases, surface conditions, aerosols or human effects on cloud cover), but through a causal mechanism distinct from the large-scale radiative effects of greenhouse gases. Local land use surface changes in which the local surface roughness and local heat release are altered [see also *de Laat*, 2008] will also result in a warming bias at night if the local vertical temperature lapse rate is made less stable over time.

[22] The effects of these warm biases in the surface temperature record have not been adequately considered in seeking to explain the divergence between surface air and tropospheric temperature trends. Our analysis explores whether the characteristics of the divergence are consistent with the evidence for bias in the land surface record. Specifically, we test two hypotheses:

[23] 1. If there is no warm bias in the surface temperature trends, then there should not be an increasing divergence with time between the lower troposphere and surface temperature anomalies. The difference between lower-troposphere and surface temperature anomalies should not be greater over land areas.

[24] 2. If there is no warm bias in the surface temperature trends then the divergence should not be larger for both maximum and minimum temperatures at high-latitude land locations in the winter.

3. Data

[25] Surface temperature anomalies were calculated from the HadCRUT3v data set [*Brohan et al.*, 2006] and the National Climatic Data Center (NCDC) data set [*Smith and Reynolds*, 2005]. The HadCRUT3v is a variance-adjusted data set and is a combination of the CRUTEM3v land surface temperature analysis and the HadSST2 analysis over oceans [*Rayner et al.*, 2006]. The NCDC data set is a combination of in situ SST anomalies as calculated by *Smith and Reynolds* [2004] and a land surface temperature analysis based on the Global Historical Climatology Network (GHCN) [*Peterson and Vose*, 1997].

[26] Satellite temperature anomalies were calculated based on data from the Microwave Sounding Unit (MSU) and Advanced MSU (AMSU) and interpreted by algorithms provided by the University of Alabama in Huntsville (UAH) [*Christy et al.*, 2007] and Remote Sensing Systems (RSS) [*Mears and Wentz*, 2005]. Both satellite temperature records are based on calibrations of radiances detected from MSU channel 2 and AMSU channel 5 from nine different MSUs

Table 1. Global, Land, and Ocean Per Decade Temperature Trends and Ratios Over the Period From 1979 to 2008[a]

Data Set	Global Trend	Land Trend	Ocean Trend
Temperature (°C)			
NCDC Surface	0.16 [0.12–0.20]	0.31 [0.23–0.39]	0.11 [0.07–0.15]
Hadley Centre Surface	0.16 [0.12–0.21]	0.22 [0.17–0.28]	0.14 [0.08–0.19]
UAH Lower Troposphere	0.13 [0.06–0.19]	0.16 [0.08–0.25]	0.11 [0.04–0.17]
RSS Lower Troposphere	0.17 [0.10–0.23]	0.20 [0.12–0.29]	0.13 [0.08–0.19]
Ratio			
UAH Lower Troposphere/NCDC	0.8	0.5	1.0
RSS Lower Troposphere/NCDC	1.1	0.6	1.2
UAH Lower Troposphere/Hadley	0.8	0.7	0.8
RSS Lower Troposphere/Hadley	1.1	0.9	0.9

[a] All linear trends are statistically significant at the 95% level; 95% confidence intervals are given in brackets. NCDC, National Climatic Data Center; RSS, Remote Sensing Systems; UAH, University of Alabama in Huntsville.

and 3 different AMSU instruments on satellites that have been launched at various times since 1978. In this analysis, lower-tropospheric temperatures from UAH and RSS are investigated. The time period from 1979 to 2008 is examined in this analysis, based on the availability of satellite temperature records.

[27] We generally have more confidence in the UAH satellite data set compared with the RSS data set, because of its closer agreement with adjusted radiosonde data [*Christy and Norris*, 2006; *Christy et al.*, 2007; *Randall and Herman*, 2008; *Christy and Norris*, 2009] and other consistency metrics [*Christy and Norris*, 2006]. In particular, when comparing the difference in tropical temperature between the 3 years before and after 1 January 1992, RSS exhibits a warming of +0.09°C while many other data sets indicate differences of −0.06°C to +0.03°C. This has a noticeable impact on the metric of linear trend since it occurs near the center of the time series [*Christy et al.*, 2007]. Nonetheless, our analysis uses both the UAH and RSS data sets.

4. Results

[28] We first calculate global linear temperature trends over the 1979–2008 time period for the NCDC, HadCRUT3v, UAH, and RSS data sets. We examine global trends and then subdivide trends into land and ocean, respectively.

[29] Table 1 displays per decade trends over the 30-year period for all time series. All time series show an increasing trend over the 30-year time period. All of these trends are statistically significant at the 95% level based on a p-test. Ninety-five percent confidence intervals are also provided taking into account the autocorrelation of the residuals based upon the methodology outlined by *Santer et al.* [2008]. Confidence intervals for all remaining tables are calculated in the same way.

[30] Table 1 also clearly shows that there has been enhanced warming over land areas when compared with ocean areas, especially in the surface temperature data sets. For example, the NCDC data set indicates nearly three times as much warming over land areas as over ocean areas during the past 30 years. Over this same time period, the UAH lower-troposphere temperature estimate indicates about half as much warming over land areas, which is contradictory to the expected global surface/lower-troposphere amplification that is calculated from the lapse rate enhancement in the global models [*Santer et al.*, 2005; *Karl et al.*, 2006; *Douglass et al.*, 2007]. The global amplification ratio of 19 climate models listed in CCSP SAP 1.1 indicates a ratio of 1.25 for the models' composite mean trends and 1.19 in their composite median values over a 21-year period that is completely contained within the 30-year record used here. Thus, in 19 realizations this consistent ratio was calculated. This was also demonstrated for land-only model output (R. McKitrick, personal communication, 2009) in which a 24-year record (1979–2002) of GISS-E results indicated an amplification factor of 1.25 averaged over the five runs. Thus, we choose a value of 1.2 as the amplification factor based on these model results. All ratios are lower than the 1.2 factor amplification expected from the models except for the ratio between the NCDC surface data set and the RSS lower-troposphere data over oceans.

[31] Table 2 displays the difference in trends between the NCDC and the HadCRUTv3, and the UAH and RSS lower-troposphere data sets, respectively, for the globe, over land areas only and over ocean areas only. Statistically significant (at the 95% level) trend differences are evident between the NCDC and both lower-tropospheric data sets over land areas as well as the HadCRUTv3 surface data sets with the UAH lower-tropospheric data over land areas as well as for the entire globe. The HadCRUTv3 and RSS lower-tropospheric data set does not show a statistically significant trend difference over the past 30 years. However, as summarized in *Christy and Norris* [2009] and in several other recent papers, [e.g., *Christy and Norris*, 2006; *Christy et al.*, 2007; *Randall and Herman*, 2008] there is a documented spurious warm shift in RSS data around 1992 that is the source of virtually all of the difference between the two satellite data sets. Thus, the closer agreement of RSS with the surface temperature data sets is likely largely due to this spurious jump.

[32] On the basis of the large majority of the findings in Table 2, hypothesis one can be rejected. Specifically, we find that the divergence between surface and lower-tropospheric temperatures documented by *Santer et al.* [2005] has likely continued. This divergence is consistent with evidence of a warm bias in the surface temperature record.

[33] Over ocean areas, trend differences are not statistically significant, while over land areas, differences are significant between the NCDC and UAH and RSS lower-troposphere data sets as well as the Hadley Centre and UAH lower-troposphere data set. ~~These differences are consistent with a warm bias associated with minimum temperatures in the construction of the NCDC and HadCRUTv3~~

Table 2. Global, Land, and Ocean Per Decade Temperature Trends Over the Period From 1979 to 2008 for the NCDC Surface Analysis Minus UAH Lower Troposphere Analysis and the Hadley Centre Surface Analysis Minus RSS Lower Troposphere Analysis[a]

Data Set	Global Trend (°C)	Land Trend (°C)	Ocean Trend (°C)
NCDC minus UAH	**0.04** [0.00–0.08]	**0.15** [0.08–0.21]	0.00 [−0.04–0.05]
NCDC minus RSS	0.00 [−0.04–0.04]	**0.11** [0.07–0.15]	−0.02 [−0.07–0.02]
Hadley Center minus UAH	**0.03** [0.00–0.07]	**0.06** [0.02–0.10]	0.03 [−0.01–0.07]
Hadley Center minus RSS	−0.01 [−0.04–0.03]	0.02 [−0.02–0.06]	0.00 [−0.04–0.04]

[a]Trends that are statistically significant at the 95% level are bold; 95% confidence intervals are given in brackets.

~~analyses from surface stations over land areas as discussed by *Lin et al.* [2007].~~

[34] We next examine the difference between lower-tropospheric data from UAH and RSS and the expected lower-tropospheric temperatures given surface measurements from NCDC and HadCRUTv3 and the assumed 1.2 factor in the global models [*Santer et al.*, 2005]. Table 3 displays the linear trends of these differences. All land surface/lower-troposphere trends become statistically significant when including the amplification factor. All global trends also become statistically significant except for the difference between the Hadley Centre and the RSS lower-troposphere data set. Over ocean areas, only the differences between the Hadley Centre and RSS lower-troposphere data set are statistically significant. Figures 1 and 2 display the differences between the NCDC surface analyses and lower-troposphere data sets and the Hadley Centre surface analyses and lower-troposphere data sets, respectively. Also plotted is the trend difference that would be expected given the 1.2 amplification factor expected from the models.

[35] The warm bias in the temperature data would most likely be in evidence over land areas where larger vertical temperature stratification occurs near the ground along with a reduction of the atmospheric cooling rate. This effect will be largest in the higher latitudes, especially in minimum temperatures during the winter months, since any reduction in the cooling rate of the ~~of the~~ atmosphere will result in a particularly large temperature increase near the ground surface in this strongly stably stratified boundary layer.

[36] This difference is found to be the case when examining the CRUTEM3v maximum and minimum temper-

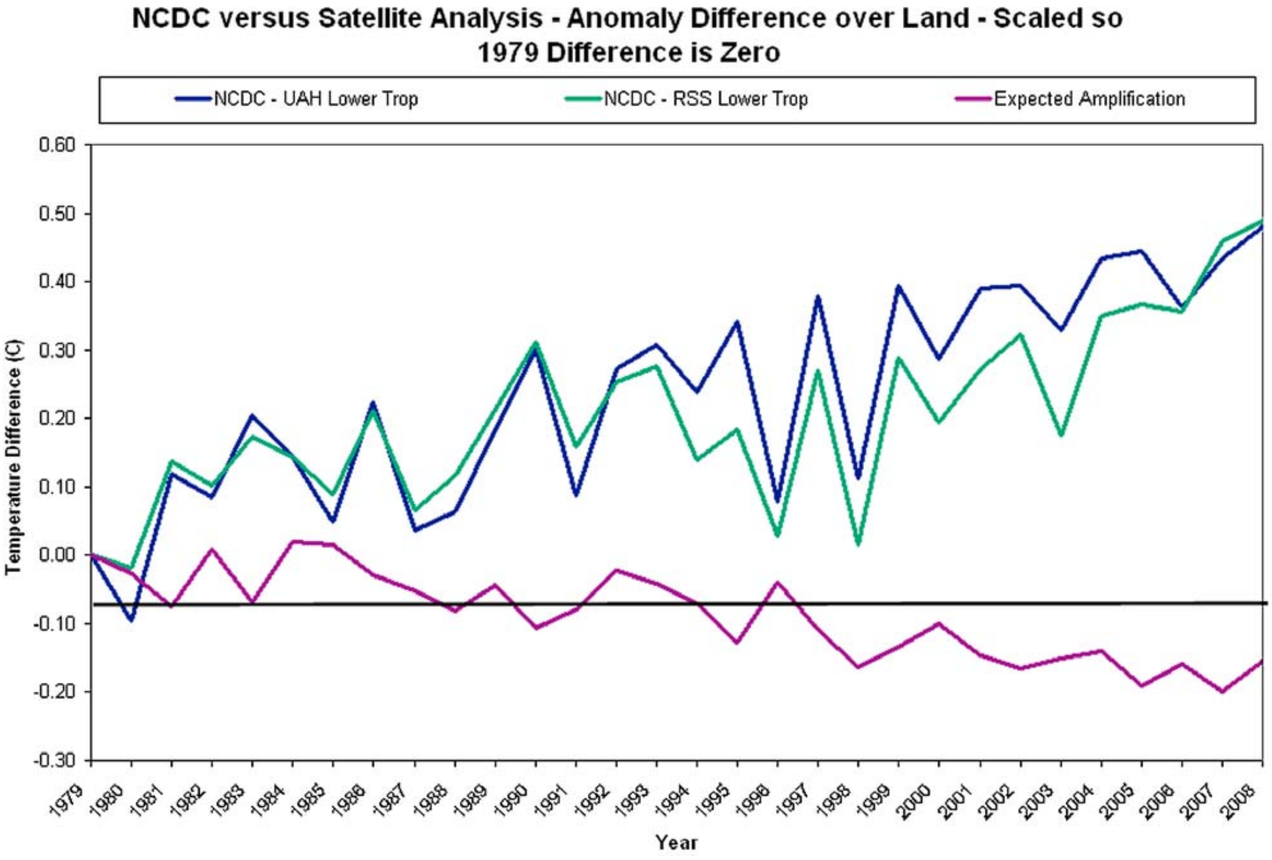

Figure 1. NCDC minus UAH lower troposphere (blue line) and NCDC minus RSS lower troposphere (green line) annual land temperature differences over the period from 1979 to 2008. The expected anomaly difference given the model amplification lapse rate factor of 1.2 is also provided. All differences are normalized so that the difference in 1979 is zero.

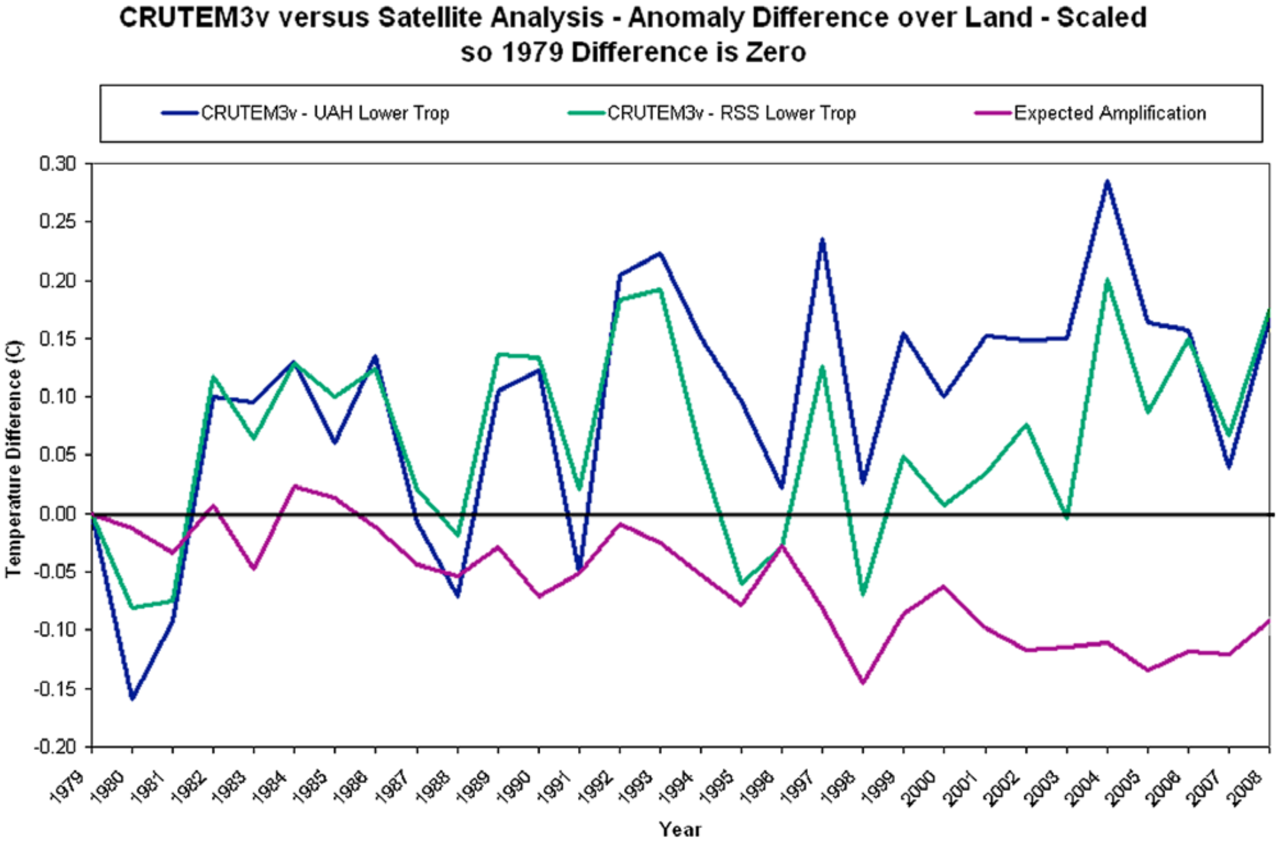

Figure 2. CRUTEM3v minus UAH lower troposphere (blue line) and CRUTEM3v minus RSS lower troposphere (green line) annual land temperature differences over the period from 1979 to 2008. The expected anomaly difference given the model amplification lapse rate factor of 1.2 is also provided. All differences are normalized so that the difference in 1979 is zero.

atures over the 1979–2005 period, using data available on the Website of the Royal Netherlands Meteorological Institute (KNMI) climate explorer: http://climexp.knmi.nl/. CRUTEM3v did not have data available south of 60°S, so we investigate the maximum and minimum temperature trends averaged over all land areas from 60 to 90°N. This data is only available through 2005, which is why the time period examined is different than the 1979–2008 period examined for the remainder of the paper.

[37] Table 4 displays the trends in maximum and minimum temperature for the globe for the entire year, as well as December–February and June–August along with the trends in maximum and minimum temperature for the area from 60 to 90°N for the same months. Note that the northern polar areas have received considerably more warming in the boreal winter with regards to minimum temperatures than with regards to maximum temperatures. The reader should be careful in interpreting these results, however, since the 95% confidence intervals for maximum and minimum temperatures in the polar areas during the winter months is quite large. The trend in minimum temperatures in northern polar areas is statistically significantly greater than the trend in maximum temperature at the 95% level during the winter months. This is consistent with the findings reported by *Pielke and Matsui* [2005] and *Pielke et al.* [2007a] of a warm bias in the global analysis of surface temperature trends. This is also consistent with the view that column climate sensitivity is dependent on the depth of the boundary layer [*Esau*, 2008]. At higher latitudes, boundary layer depths are in general lower and more stable and thus heat is distributed

Table 3. Global, Land, and Ocean Per Decade Temperature Trends Over the Period From 1979 to 2008[a]

Data Set	Global Trend (°C)	Land Trend (°C)	Ocean Trend (°C)
NCDC amplified minus UAH	**0.07** [0.02–0.11]	**0.21** [0.13–0.29]	0.03 [−0.02–0.07]
NCDC amplified minus RSS	**0.03** [−0.01–0.07]	**0.17** [0.12–0.22]	0.00 [−0.04–0.04]
Hadley amplified minus UAH	**0.07** [0.03–0.10]	**0.11** [0.07–0.14]	**0.06** [0.02–0.09]
Hadley amplified minus RSS	0.03 [−0.01–0.06]	**0.07** [0.04–0.09]	**0.03** [−0.01–0.06]

[a] For an assumed 1.2 amplification factor for the NCDC surface analysis minus UAH lower troposphere analysis, an assumed 1.2 amplification factor for the NCDC surface analysis minus RSS lower troposphere analysis, an assumed 1.2 amplification factor for the Hadley Centre surface analysis minus UAH lower troposphere analysis, and an assumed 1.2 amplification factor for the Hadley Centre surface analysis minus RSS lower troposphere analysis. Trends that are statistically significant at the 95% level are bold; 95% confidence intervals are given in brackets.

Table 4. Linear Trends for Maximum and Minimum Temperature for CRUTEMv3 for the Entire Globe and for 60–90°N Over the Period From 1979 to 2005[a]

Data Set	Globe	60–90°N
Annual CRUTEM3v Maximum Temperature	0.31 [0.21–0.41]	0.47 [0.11–0.83]
Annual CRUTEM3v Minimum Temperature	0.31 [0.21–0.41]	0.52 [0.16–0.87]
Dec–Feb CRUTEM3v Maximum Temperature	0.29 [0.13–0.45]	0.28 [−0.36–0.92]
Dec–Feb CRUTEM3v Minimum Temperature	0.32 [0.12–0.52]	0.41 [−0.23–1.05]
Jun–Aug CRUTEM3v Maximum Temperature	0.29 [0.19–0.39]	0.40 [0.20–0.61]
Jun–Aug CRUTEM3v Minimum Temperature	0.30 [0.18–0.41]	0.40 [0.19–0.60]

[a]Confidence intervals of 95% are given in brackets.

over a shallower layer making the proportional response greater. This leads to more warming at the surface than aloft and thus is not indicative of heat accumulation in the deep atmosphere.

[38] Physically, the nighttime boundary layer is not a good place to detect the accumulation of heat. While its temperature response to forcing is greater because of the inverse depth dependence mentioned above, the stable boundary layer is so shallow in most cases that it represents an insignificant mass of the atmosphere. Additionally, as shown by *Walters et al.* [2007], any positive forcing such as additional greenhouse gases destabilizes the boundary layer, increases its depth, and mixes warm air aloft to the surface. Thus, the warming is amplified at the surface but represents a redistribution of heat rather than accumulated heat from the additional forcing. Use of surface data in which minimum temperatures are included in the data set then leads to a direct warm bias if interpreted as a heat accumulation from both the column depth dependency and the destabilization. This finding (difference in land trends) and its likely physical explanation allows us to reject hypothesis two. The divergence is larger for minimum temperatures over land locations and for both maximum and minimum temperatures at high-latitude land locations in the winter.

5. Conclusions

[39] We find that there have, in general, been larger linear trends in surface temperature data sets such as the NCDC and HadCRUTv3 surface data sets when compared with the UAH and RSS lower-tropospheric data sets, especially over land areas. This variation in trends is also confirmed by the larger temperature anomalies that have been reported for near surface air temperatures [e.g., *Zorita et al.*, 2008; *Chase et al.*, 2006, 2008; *Connolley*, 2008]. The differences between surface and satellite data sets tend to be largest over land areas, indicating that there may still be some contamination because of various aspects of land surface change, atmospheric aerosols and the tendency of shallow boundary layers to warm at a greater rate [~~*Lin et al.*, 2007;~~ *Esau*, 2008; *Christy et al.*, 2009]. Trends in minimum temperatures in northern polar areas are statistically significantly greater than the trends in maximum temperatures over northern polar areas during the boreal winter months.

[40] We conclude that the fact that trends in thermometer-estimated surface warming over land areas have been larger than trends in the lower troposphere estimated from satellites and radiosondes is most parsimoniously explained by the first possible explanation offered by *Santer et al.* [2005]. Specifically, the characteristics of the divergence across the data sets are strongly suggestive that it is an artifact resulting from the data quality of the surface, satellite and/or radiosonde observations. These findings indicate that the reconciliation of differences between surface and satellite data sets [*Karl et al.*, 2006] has not yet occurred, and we have offered a suggested reason for the continuing lack of reconciliation.

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