Industrial CO_2 emissions as a proxy for anthropogenic influence on lower tropospheric temperature trends

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[1] Surface temperature trends during the last two decades show a significant increase which appears to be anthropogenic in origin. We investigate global temperature changes using surface as well as satellite measurements and show that lower tropospheric temperature trends for the period 1979–2001 are spatially correlated to anthropogenic surface CO_2 emissions, which we use as a measure of industrialization. Furthermore, temperature trends for the regions not spatially correlated with these CO_2 emissions are considerably smaller or even negligible for some of the satellite data. We also show, using the same measure, that two important climate models do not reproduce the geographical climate response to all known forcings as found in the observed temperature trends. We speculate that the observed surface temperature changes might be a result of local surface heating processes and not related to radiative greenhouse gas forcing. *INDEX TERMS:* 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 1620 Global Change: Climate dynamics (3309); 1630 Global Change: Impact phenomena; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; *KEYWORDS:* surface temperature, lower tropospheric temperature, climate change, CO_2 emissions. **Citation:** de Laat, A. T. J., and A. N. Maurellis (2004), Industrial CO_2 emissions as a proxy for anthropogenic influence on lower tropospheric temperature trends, *Geophys. Res. Lett.*, *31*, L05204, doi:10.1029/2003GL019024.

1. Introduction

[2] During the last 200 years the average earth surface temperature has increased by approximately 1 K.[1] This increase has been related to an increase in the solar constant, natural variability and human activities. The standard explanation is that increases in greenhouse gas concentrations, notably CO_2, CH_4 and O_3, are primarily responsible for increases in tropospheric temperature [*IPCC*, 2001], the so-called enhanced greenhouse effect. However, there exist a number of apparent discrepancies between the various kinds of temperature measurements. Tropospheric trends, which have been monitored intensively during the last couple of decades, show that surface temperatures increase faster than free tropospheric temperatures [*IPCC*, 2001; *Angell*, 1999; *Bengston et al.*, 1999; *Parker*, 2000; *Santer et al.*, 2000; *Jones and Moberg*, 2003]. The mean surface trends over the least two decades have been estimated at +0.2 K/decade [*IPCC*, 2001; *Folland et al.*, 2001; *Jones and Moberg*, 2003]. Lower tropospheric trends measured by satellites and radiosondes are smaller or even negative for the same period, with estimates varying between −0.02 and +0.06 K/decade [*Christy et al.*, 2003] The differences between surface-measured and satellite-measured trends have lead to some doubt being cast on the consistency of the different sets of measurements [*Santer et al.*, 2003].

[3] Certainly, the different types of observations would not be in disagreement if the heating were to occur only in the atmospheric boundary layer (hereafter ABL), i.e., the observed surface temperature changes were to arise primarily from surface- or ABL-related processes. In a recent study, *Kalnay and Cai* [2003] analyzed surface temperature measurements over the eastern United States and concluded that a significant portion of surface temperature increase over the last century (0.27 K) was related to surface processes such as urbanization and land-use. In addition, if industrial processes were to drive surface temperature changes, then the most important expected observable should be that these changes occur primarily in regions with the largest industrial surface CO_2 emissions.

[4] In this letter we find that measurements of surface and lower tropospheric temperature change give a very different picture from climate model predictions and show strong observational evidence that the degree of industrialization is correlated with surface temperature increases as well as lower tropospheric temperature changes.

2. Data and Analysis Overview

[5] We have analyzed temperature measurements both from satellite (Microwave Sounding Unit, MSU [*Christy et al.*, 2003; *Mears et al.*, 2003]) and surface (Climate Research Unit, CRU) sources and correlated them with surface CO_2 emissions using a thresholded trend technique described here and in an appendix. The global distribution of industrial surface CO_2 emissions is derived from the EDGAR CO_2 emissions database [*Van Aardenne et al.*, 2001] which includes emissions from biofuel combustion, fossil fuel use and biomass burning totalling approximately 8000 Tg carbon/year. The technique was applied to temperature measurements (and later model predictions) as follows. Global temperature data were divided into two regions for a range of CO_2 emission threshold values, according to whether the CO_2 emissions were higher or lower than the threshold value. Mean linear temperature trends were then calculated for all gridpoints in both regions yielding what we refer to hereafter as thresholded trend curves. The results for four temperature datasets are shown in Figure 1 (curves with shaded regions of uncer-

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL019024.

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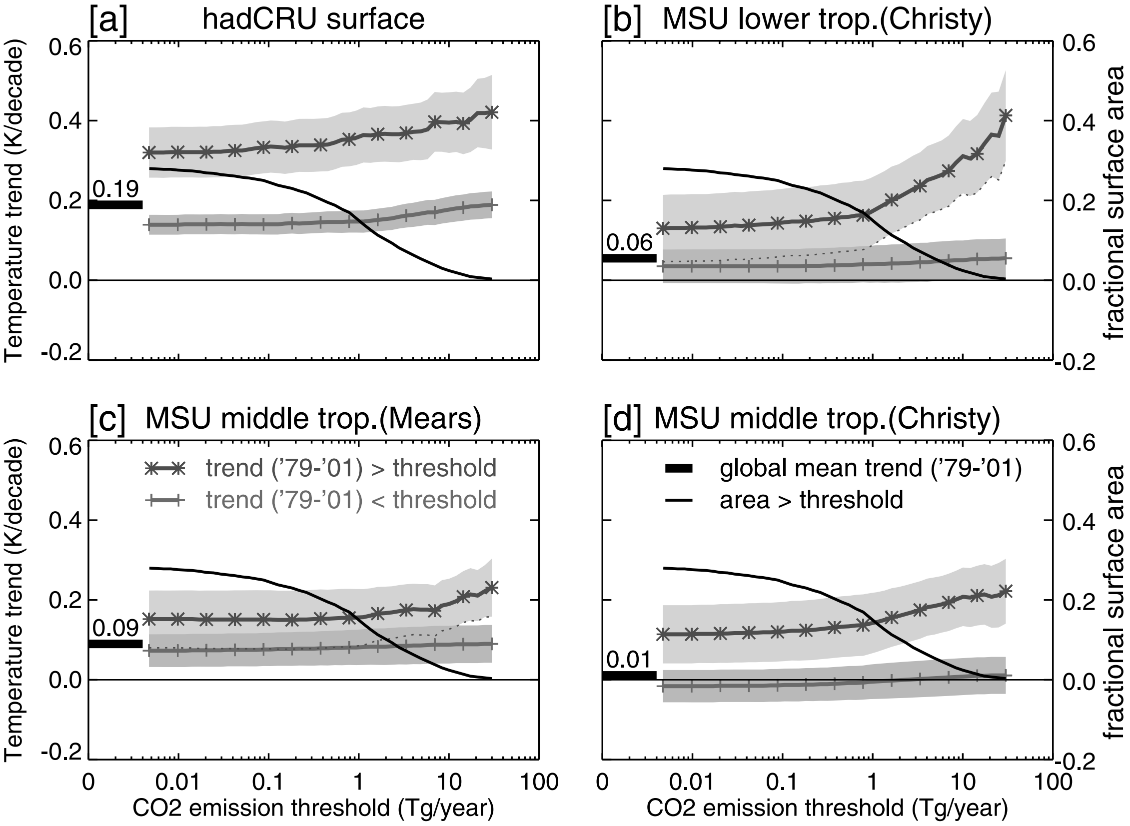

Figure 1. Mean temperature trends (K/decade) for the period 1979–2001 for different industrial CO_2 emission (Tg carbon/year) thresholds for: lower tropospheric MSU satellite temperature trends (upper right panel); surface temperature trends from the Hadley Center/Climate Research Unit data set (upper left panel); MSU satellite mid-tropospheric temperature trends from two different sources (lower panels). Industrial surface CO_2 emissions are taken from the EDGAR 1990 database. Each datapoint corresponds to the temperature trend of a selected subset (above (stars) or below (plus signs) the CO2 emission threshold) of the dataset. The shaded areas denote the mean 1-sigma uncertainties of the linear regressions which do not include measurement errors. Also shown in each panel is the fractional surface area (thick solid line) for which industrial surface CO_2 emissions are larger than the threshold emissions value. See color version of this figure in the HTML.

tainty corresponding to left-hand scale) along with global mean trends for each data set (small solid block and number on left hand side) and the area corresponding to CO_2 emissions above the threshold emission value (solid line corresponding to right-hand scale). Clearly above-CO_2 emission threshold regions (asterisks) have significantly larger trends than both the global means and the below-threshold regions (plus signs). The trends also increase with increasing CO_2 emissions threshold. For example, the surface measurements show an above-threshold trend (see left-most edge of curve) of about 0.13 K/decade larger than the global mean trend and 0.18 K/decade larger than the below-threshold temperature trend. Satellite-measured trends for the above-threshold regions are about 0.06–0.10 K/decade larger than the global mean trends and 0.08–0.13 K/decade larger than below-threshold regions. Note that the CRU surface dataset does not cover the Antarctic, which shows a cooling trend for the period 1979–2001 according to the satellite observations. The global mean trend from the MSU lower tropospheric measurements for the same surface coverage as the CRU data is 0.09 K/decade, compared to 0.06 K/decade for all the surface MSU data. This implies that the "real" global mean surface temperature trend is very likely to be considerably smaller than the temperature trend in the CRU data (0.2 K/decade). It is clear that temperature trends for both satellite and surface measurements generally increase with increasing CO_2 emissions threshold. Evidently, areas with larger temperature trends (corresponding to higher CO_2 emissions) cover a considerable part of the globe. For instance, CO_2 emissions above 1 Tg/year, coinciding with a rapid increase in temperature trends in the MSU lower tropospheric data, cover about 15% of the globe. The differences between the MSU mid-tropospheric and MSU lower-tropospheric trends are consistent with the observation that surface temperature trends are larger than free tropospheric temperature trends. Evidently, the temperature trends are larger for higher surface CO_2 emissions (and increase more strongly with increasing CO_2 emissions threshold) in the lower-tropospheric case than in the mid-tropospheric measurements. This is consistent with the CRU surface data which shows even higher global temperature trends as well as a similar increase with increasing CO_2 emissions threshold. In passing we note that the differences between the two mid-tropospheric MSU datasets are largely explained by data merging procedures for the 1984–1987 period [*Mears et al.*, 2003]. We also note that the

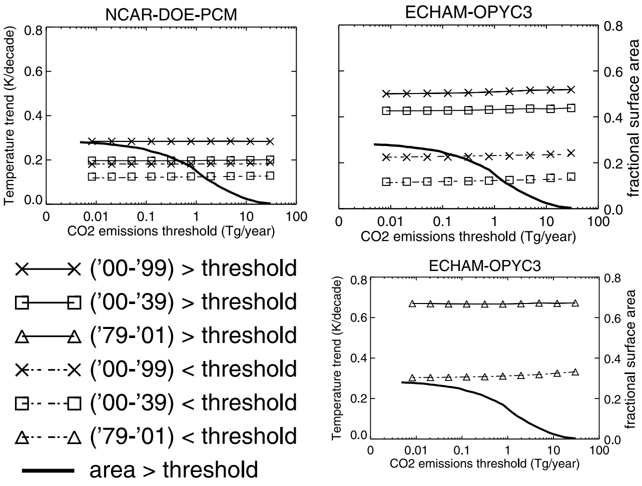

Figure 2. Average climate model-simulated 2-meter temperature changes as a function of industrial CO_2 emissions, applying the same method as used for Figure 1. The temperature trends (K/decade) are calculated for the periods 1979–2001 (triangles), 2000–2039 (squares) and 2000–2099 (crosses) for the IPCC-IS92a emission scenario ("business as usual") using the NCAR-DOE-PCM and ECHAM4-OPYC3 climate models. The thin solid lines indicate the modeled temperature trend for regions with industrial CO_2 emissions larger than the threshold value, the dashed-dotted lines indicate the modeled temperature trend for regions with industrial CO_2 emissions smaller than the threshold value. Fractional surface area (thick solid line) is as in Figure 1.

CRU dataset is derived from point measurements which consists of surface measurements binned on a 5° × 5° degree grid. If surface warming is closely related to industrialization, one could generally question how representative surface temperature measurements are of global warming as they are often conducted in the vicinity of human (industrial) activity.

[6] *Bengston et al.* [1999] have shown that model-predicted surface temperature trends are much larger (by about a factor of two) than what has been observed over the last two decades. This observation prompted us to apply the CO_2 emissions thresholding technique used above to climate model predictions. Figure 2 shows three sets of decadal temperature trends as simulated by each of two climate models (ECHAM4/OPYC3; NCAR-DOE-PCM) used by the IPCC [*IPCC*, 2001]. The temperature trends are calculated for the periods 1979–2001 (ECHAM only), 2000–2039 and 2000–2099 (both ECHAM and NCAR) from the IPCC-IS92A "business as usual" scenario study [*IPCC*, 2001]. It is very clear that modeled surface temperature trends subjected to the industrial surface CO_2 emissions thresholding technique are principally different from what is observed (cf. Figure 1). Instead of an increase in temperature trends with increasing industrial surface CO_2 emissions, the temperature trend is constant or even decreases slightly. IPCC-2001 predicts temperature trends of 0.2–1 K/decade (surface and free troposphere), much larger than what is observed for the surface (0.2 K/decade) and the free troposphere (0–0.1 K/decade). The models also predict that the temperature trends should be larger at higher latitudes, and strongest around the poles. This is somewhat in contradiction with the data, since regions with higher CO_2 emissions (and, as we have shown, larger temperature trends) correspond to fewer locations at high latitudes than lower CO_2 emissions regions.

[7] Other kinds of observations can also be explained within the industrialization framework. The majority of the industrial CO_2 emissions occur at northern mid-latitudes, so both hemispheres should show different temperature trends. According to IPCC-2001 the NH temperature land-surface-air temperature (LSAT) trend for the period 1976–2000 is 0.31 K/decade, significantly higher than the 0.13 K/decade for the southern hemisphere. Moreover, the LSAT differences between northern hemisphere and southern hemisphere are considerably larger for the period 1976–2000 (0.18 K/decade) compared to previous periods (differences of 0.06 K/decade for both 1910–1945 and 1946–1975). Interestingly, the differences over sea are smaller. This concurs with the rapid increase in industrialization that has occurred in the northern hemisphere during the last two to three decades.

[8] Certainly one does not necessarily expect that the same degree of greenhouse-related warming will occur simultaneously in the troposphere and at the surface as the oceans' heat capacity will introduce significant, possibly decadal, delay in the sea surface temperature response [*Lindzen and Giannitsis*, 2002]. Differences between ocean and land surface warming are therefore likely to occur regardless of the exact warming mechanism. However both the higher temperature trends at the surface than in the troposphere as shown in Figure 1 and a lack of agreement with climate models as shown in Figure 2 suggest a hitherto-overlooked driver of local surface temperature increases, which is linked to the degree of industrialization. This lends strong support to other indications that surface processes (possibly changes in land-use or the urban heat effect) are crucial players in observed surface temperature changes [*Kalnay and Cai*, 2003; *Gallo et al.*, 1996, 1999]. Although the exact mechanisms have yet to be determined our findings show that a significant part of the observed surface warming is related to processes other than enhanced greenhouse warming.

[9] In this letter we have laid out a new framework for understanding global lower tropospheric temperature trends and shown that measured temperature changes over the last two decades are locally or regionally related to CO_2 emissions in a way that is not at all consistent with climate model predictions. One of the reasons for this choice of proxy is that CO_2 emissions are basically free of decadal trends, since they have been increasing continuously for the last two decades and do not have any dependence on natural temperature changes occurring on decadal or smaller timescales (such as El Niño, La Niña or volcanoes). We therefore expect that temperature changes caused by natural events affect the absolute values but not the correlations shown here.

[10] Surface processes are expected to have a very different impact on climate than the enhanced greenhouse effect: their impact is not global, but much more local; hence the possible changes in climate related to these processes will also occur on regional scales. By focussing

future study on local, surface heating processes rather than global, free-tropospheric heating processes we may come closer to elucidating the actual mechanisms driving the observed temperature increases. Such a change in focus may well have far-reaching implications for the socioeconomics of climate policy which would have to be considerably reevaluated.

Appendix A: Data and Analysis

[11] We used Microwave Sounding Unit temperature channel 2 measurements from 1979 to 2001 for the calculation of satellite temperature trends. The MSU channel 2 measurements are representative for the middle troposphere (surface to about 15 km altitude [*Christy et al.*, 2003; *Mears et al.*, 2003]). There are currently two datasets available, one from the University of Alabama at Huntsville (UAH) [*Christy et al.*, 2003], and one from the Remote Sensing Systems in Santa Rosa, California (RSS) [*Mears et al.*, 2003]. The MSU datasets consist of observations obtained from several (consecutive) different satellite platforms (TIROS-N, NOAA 06-12,14). These datasets have been put together to form a continuous dataset. The differences between the calculated trends between the RSS and UAH datasets are due to the different methods used to merge the two datasets [*Mears et al.*, 2003].

[12] In addition to the MSU channel 2 dataset we also used the UAH MSU lower tropospheric temperature (MSUlt) measurements, which are based on channel 2 trends that have been temperature-corrected for stratospheric temperature using a multi-view angle retrieval process. All satellite datasets are available on a $2.5° \times 2.5°$ degree horizontal resolution. The satellite data cover about 92% of the globe, only missing small parts of the polar caps. Both UAH datasets and the RSS datasets are publicly available: UAH: http://www.nsstc.uah.edu/public/; RSS: http://www.ssmi.com/msu/.

[13] We also used the surface temperature dataset from the Climate Research Unit at the Hadley Centre. This dataset consists of $5° \times 5°$ gridded surface measurements and covers about 71% of the globe, missing out large parts of the Antarctic. This dataset is publicly available at http://www.cru.uea.ac.uk/cru/data/temperature/.

[14] The industrial CO_2 emissions are obtained from the EDGAR database, which is a $1° \times 1°$ resolution data set of historical anthropogenic emissions for the period 1890–1990 for several trace gases [*Van Aardenne et al.*, 2001]. The higher resolution CO_2 emission data is rebinned onto the lower resolution satellite temperature measurements grid ($2.5° \times 2.5°$), the surface temperature measurements grid ($5° \times 5°$) and the climate model horizontal grid ($3° \times 3°$). The EDGAR dataset is publicly available at ftp://ftp.rivm.nl.

[15] The climate model-simulated surface temperature trends are for the IPCC-2001 IS92A scenario study [“business as usual” scenario, no reductions in greenhouse gas emissions for the period 2000–2099]. The results of most of the climate model simulations for the IPCC 2001 report are publicly available at http://ipcc-ddc.cru.uea.ac.uk/. The IPCC 2001 report is also publicly available at http://www.ipcc.ch/.

[16] As discussed in the text we use a thresholding technique, which involves calculating mean temperature trends of regions for which a certain quantity (in this case: industrial CO_2 emissions) are below or above a certain threshold value of this particular quantity. The temperature trends are calculated by applying a linear regression to the monthly mean temperatures for the period 1979–2001. The mean trends may be determined either: (1) by first calculating the trends and then averaging them or (2) by first calculating the average temperature and then the trend. Differences between both procedures were less than 2%. We therefore chose the first approach: calculation of mean temperatures for the two sub-regions, and then calculated the temperature trend of the mean temperatures. From this approach the 1-sigma uncertainties for the trend of the mean temperatures could also be determined, which are shown in Figure 1 by the shaded areas. Note that no measurement errors have been taken into account in the 1-sigma uncertainty calculations. The measurements error estimate for the UAH satellite measured temperature trends is 0.05 K/decade [*Christy et al.*, 2003].

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