COMPARING STATION DENSITY AND REPORTED TEMPERATURE TRENDS FOR LAND-SURFACE SITES, 1979-2004

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Abstract

Three primary datasets are used to assess globally-averaged surface temperature trends. There are questions about the degree of overlap among these datasets and the corresponding independence of their separate trend estimates, particularly for lower station densities. Station densities are examined for 1979-2004 to investigate the independence of these primary datasets. Heating trend estimates will be more robust in areas having greater station densities. Station densities were generally highest in most areas in the 1980s but various events in the 1990s have contributed to station density decreases. These include the collapse of the Soviet Union and the surface station modernization programs in the United States. Temperature trends are warmest in the Northern Hemisphere, particularly at higher latitudes. Trends become cooler towards the south. Station densities are highest in the Northern Hemisphere, providing more confidence in the trends for this region. Robust surface temperature trend estimates cannot necessarily be expected between the available datasets at other regional scales. Tropical regions have sparse surface temperature data. Until further information can be obtained, the robustness of warming estimates in tropical region should be questioned. Networks such as GLOBE may improve station density in areas with very few stations.

1. Introduction

The assessment of a globally averaged surface temperature trend is emphasized in investigations of human- and natural- climate change (e.g., IPCC, 1995; IPCC, 2001; Brohan et al., 2006; CCSP, 2006). This paper assesses the independence of the surface data sets which are used to calculate the trend.

As reported in CCSP (2006), "…there are three main groups creating global analyses of surface temperature…differing in the choice of available data that are utilized as well as the manner in which these data are synthesized." These three groups are NOAA's National Climatic Data Center, NASA's Goddard Institute for Space Studies, and the Climatic Research Unit of the University of East Anglia, and the Hadley Centre of the UK Met Office.

The CCSP report discusses these three data groups to assess the robustness of the trend assessments as summarized in Jones (1995). These are i) "using 'frozen grids' where analysis using only those grid boxes with data present in the sparsest years is used to compare to the full dataset results from other years (e.g., Parker et al, 1994)"; ii) "sub-sampling a spatially complete field…only where in situ observations are available"; and iii) "comparing optimum averaging, which fills in the spatial field using covariance matrices, eigenfunctions or structure functions, with other analyses."

The question of the degree of overlap among the three analyses has not been assessed however. To the extent there is overlap in the observation sites, the analyses are not independent, and the three procedures referred to in the last paragraph are not independent tests. Biases in the raw surface temperature data will be carried through into the analyses. Newly recognized biases include those due to microclimate exposure (Davey and Pielke, 2005); neglect of the role of humidity on the temperature trends (Pielke et al., 2004; Davey et al., 2006), and a warm bias due to combining surface air temperature data from light and strong wind nights (Pielke and Matsui, 2005). However the focus of this paper is specifically on the surface density of the observing sites that are used to compute long-term temperature trends.

Our paper investigates the independence of the data by determining the station density used in the NOAA analysis used over land, and also the density of land data sites where the largest temperature trend anomalies have been reported. Vose and Menne (2004) show that the data density within the contiguous USA is quite good, but that this needs to be extended globally. Janis et al. (2004) discuss why station density is an important issue in monitoring long-term temperature trends.

In our paper, in order to add to the analysis of station densities, global temporal variations in temperature and station density are compared for the period 1979-2004. If there are a number of observing sites in a land grid analysis box, the anomaly would be more robust than if just one or no stations were present during the analysis period. If a significant number of the land analysis grid boxes have just one or no observing sites, the analyses of the three groups do not provide an independent assessment of the globally- averaged land-surface temperature trend.

2. Data and Methods

Monthly Climatic Research Unit (CRU) station density (n) information was obtained for the years of 1979-2004 from Russell Vose at the National Climatic Data Center (NCDC). These data were available as global 5°×5° grids. We also obtained annual surface temperature trend grids for the years 1979-2004 from NCDC's Global Climate at a Glance (GCAG) mapping server: http://www.ncdc.noaa.gov/gcag/gcag1b.html. The surface data that were used to construct these maps came from the merged Global Historical Climate Network and extended reconstructed sea surface temperature (GHCN-ERSST) dataset. These data were available at a global grid resolution of 5°×5°.

Land-based grid cells were identified in the global 5°×5° grid. These cells were then classified by continent, hemisphere, and latitudinal band. For continents, the following regions were defined: North and South America, Europe, Africa, Asia, and Australia/Oceania (Figure 1a). Antarctica was not considered explicitly, as it is considered in the latitudinal band analysis (>50S, see below). Five latitudinal bands were designated corresponding to the polar (>50N,>50S), temperate (20N-50N,20S-50S, and tropical (20N-20S) regions of the world (Figure 1b).

Then, for each region defined in Figure 1, annual averages of monthly station densities were computed. Station densities were initially organized into 7 classes (Table 1) for each of the regions in Figure 1.

We investigated yearly variations in *n* for the years 1979-2004. It is during the last two to three decades that surface warming has been the most prominent (Chase et al., 2000). The intention here is to investigate the percentages of the total number of land-based grid cells having station densities in each density class (Table 1). To accomplish this, time series of station density were constructed using the classes in Table 1 and results were compared between the geographical regions shown in Figure 1.

After completing this initial analysis, we were especially interested in those grid cells reporting either isolated or scattered (see Table 1) station densities. Of these grid cells, we identified those having the greatest temperature trends and identified the surface sites present within those grid cells.

3. Station Density

3.1 Latitudinal Bands

Station network densities categorized by latitudinal band during the period of 1979-2004 (Figure 2) show that during the early 1980s, station densities were generally at their highest values (fewest grid cells with zero sites, especially in temperate zones). A slight shift towards lower station densities can be seen in the northern temperate and high latitude zones during the early 1990s, possibly related to the USSR collapse around this time. Another reduction in n occurred for the northern temperate zones between the years of 1997-2000. This may be related to modernization efforts in governmental weather agencies, e.g., NWS, at this time. Outside the temperate zones, little changes in n occurred. During the period of 1979-2004, besides the high latitude regions, tropics have the lowest n values, with a majority of cells having < 1 station per cell. The limited density of observing stations is a significant issue, as this is a region where the CCSP (2006) report was unable to reconcile recent surface and tropospheric temperature trends. Specifically, they reported:

> *"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."*

The sparse observational sites in the tropics may also be a reason for the poor agreement.

3.2 Continents

A drop in *n* was expected in the early 1990s for Asia, corresponding with the decline of the USSR (also assumed to be behind the notable drops in *n* at this time in the 20-50N and >50N latitude belts). This, however, was not definitively observed, as shown in the temporal station density variations by continent (Figure 3). There is, however, a drop in *n* for Europe at this time. One can also see what might be the effects of the NWS modernization efforts in the late 1990s, as evidenced by sharp drops in the percent of grid cells having very dense station coverage in North America. Similar drops were also observed at this time for Australia/Oceania. At the beginning of the 21st century, it appears that Europe and South America have the densest station coverage of the continents considered here.

4. Temperature Trends and Site Coverage, 1979-2004

Most of the warming trends for grid cells with $n<1$ (Figure 4a) and $1<n<2$ (Figure 4b) are located primarily over land areas, and most of these are in the Northern Hemisphere. Most of the observed land-based cooling trends are in the Southern Hemisphere.

It appears that those grid cells where $1<n<2$ (Figure 4b) may have an average heating trend that is relatively warmer than that for the grid cells where $n<1$ (Figure 4a), as evidenced especially by the noticeably lower number of cells with cooling trends in Figure 4b compared to Figure 4a. This is in fact what the summary histograms of these two datasets suggest (Figure 5). The cells with $n>2$ sites per cell have the largest warming trends, with the greatest land-based warming occurring in Europe and China (see Figure 4c).

In fact, larger warming temperature trends at higher latitudes are also apparent by continent (Figure 6). For instance, North America (Figure 6a) and especially Europe (Figure 6c) show some of the strongest warming trends in temperature of all the continents. The least warming is occurring in the continents in the Southern Hemisphere, like South America (Figure

6b) and Australia (Figure 6f). Larger continents such as Asia (Figure 6e) show more variability in their reported temperature trends.

The pattern we just described is also apparent when we illustrate temperature trends as a function of latitude band (Figure 7). The northern latitudes (Figure 7a,b) show the most warming. These trends show less warming, and sometimes even cooling, as one moves south (Figure 7d, e); however, station density also decreases further south, so these findings may not be robust.

Although station densities tend to be greatest in the northern latitudes, the highest northern latitudes also tend to have the highest counts of grid cells with no data, as evidenced by the counts for the continents of North America and Asia, along with the counts for latitudes >50N (Table 2). This may adversely affect the robustness of the temperature trend estimates in these regions. The southern polar regions have very sparse data, making it difficult to determine overall temperature trends there.

We also investigated maximum and minimum temperature (T_{max} and T_{min}, respectively) trends for the same period. For T_{max}, trends > +1.0°C/decade are observed for both n<1 (Figure 8a) and 1<n<2 (Figure 8b). These locations are generally in Mongolia and Siberia. For those grid cells having n>2 stations, all trends were under +1.0°C/decade. The summary histograms for T_{max} trends (Figure 9) show that the average trends for cells with either n<1 or 1<n<2 are greater than the average trends for cells with n>2. North America, Europe, and Asia show clear warming in T_{max} over time (Figure 10). These continents also have higher station densities compared to other continents, so these findings may be more robust. Warming trends in maximum temperatures aren't as clear on other continents (Figure 10). Many of these continents showing less warming in T_{max} also have lower station densities, causing these reported trends to be less credible. Trends in T_{max} as a function of latitudinal band (Figure 11) show the same tendencies as in Figure 10. Some of the northern latitudes have warmer trends, and higher station densities to support these findings. Towards the south, however, trends in T_{max} show less warming, but there are lower station densities, making these results less reliable.

As with T trends, some of the largest counts of grid cells with no data to calculate T_{max} trends are found in the higher latitudes (both north and south) and on continents such as North America (Table 2). Additionally, there are large counts of grid cells with no data in the tropical latitudes (20S-20N), which also increases the number of grids with no data on continents such as Africa and South America. Asia, to a lesser extent, also shows this increase.

Trends in T_{min} appear to follow the same patterns as for T_{max} (Figure 12), with more reports of trends > +1.0°C/decade for cells having either n<1 or 1<n<2 stations per cell, compared to those cells having more than 2 stations per cell. For n>2, however, there are reports of T_{min} trends> +1.0°C/decade in a couple of cells in northern China (Figure 12c). The average T_{min} trend for cells with n<1 stations is less than the average trends for cells having either 1<n<2 or n>2 stations per cell (Figure 13). The Northern Hemisphere shows the greatest warming trends in T_{min}, compared to regions that are further south (Figures 14 and 15). Again, the trends in the Northern Hemisphere are based on higher station densities in certain regions. Counts of grids with no data for estimating T_{min} trends have the same characteristics as those for T_{max} (Table 2).

Before concluding this section, it is important also to note that continents such as South America, Africa, and Asia have significantly more grid cells with no data for calculating T_{max} and T_{min} trends, compared to grid cells with no data for calculating T trends (Table 2). This lowers the credibility of the T_{max} and T_{min} trend calculations in these regions compared to the T trend calculations. This pattern is also evident in the tropics (20S-20N) and the temperature latitude bands (20N-50N, 20N-50S).

5. Conclusions

The analysis of surface station density presented in this paper indicates that at regional scales, surface temperature trends and anomalies cannot always be expected to be robust between the available surface temperature datasets since with zero, one or two available stations per analysis grid box, they cannot be independent assessments. Northern Asia, for example, has very low station densities in general. Recent social and political changes in the region such as the collapse of the USSR have contributed to decreases in station density and the resulting sparser coverage of stations in this region compared to other regions such as Europe. Northern Asia, despite its sparser station coverage, reported some of the highest temperature trends for the period of 1979-2004 (see Figures 6 and 8). Pielke and Matsui (2005) present a discussion as to why the surface minimum temperature trends in such high latitude regions can be amplified compared to similar lower-tropospheric warming at lower latitudes.

The higher northern latitudes in general also exhibit this tendency towards lower station densities, casting some doubt on the robustness of the temperature trends that are reported there. Decreases in station coverage have been more common in many high-latitude locations, including sites in North America, which have been influenced by changes such as the station modernization programs in the United States. This is an issue that deserves more attention, considering the common knowledge/expectation in the scientific community that higher latitudes will have some of the largest warming trends around the globe.

Tropical regions have sparse coverage of surface temperature data. Until further information can be obtained in these regions, the robustness of warming estimates in this region should be questioned. Consequently, the CCSP (2006) finding that the "*the majority of observational data sets show more warming at the surface than in the troposphere,,, while " all model simulations show more warming in the troposphere than at the surface"* may be a result of the inadequate sampling of the tropical land areas.

The most robust results are obtained in temperate zones. It is in these zones where station densities are the highest.

To increase the station density in locations where there currently are less then 3 stations, the GLOBE network offers promise (http://www.globe.gov/globe_flash.html). Hiemstra et al (2006) has shown for a region in the USA the robustness of GLOBE data to enhance the spatial resolution of the surface air temperature information.

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Figure 3. 1979-2004 time series of the percentages of the total number of land cells represented by each category of n, classified by continent (see Figure 1a).

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Figure 6. Summary histograms of temperature trends for North America (a), South America (b), Europe (c), Africa (d), Asia (e), and Australia/Oceania (f). The number of grid cells with no stations is indicated for each panel. Continents are defined as in Figure 1.

Figure 7. Summary histograms of temperature trends for latitude bands of >50N (a), 20-50N (b), 20N-20S (c), 20-50S (d), and >50S (e), as defined in Figure 1. The number of grid cells with no stations is indicated for each panel.

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Figure 14. Summary histograms of annually-averaged T_{min} trends for North America (a), South America (b), Europe (c), Africa (d), Asia (e), and Australia/Oceania (f). The number of grid cells with no stations is indicated for each panel. Continents are defined as in Figure 1.

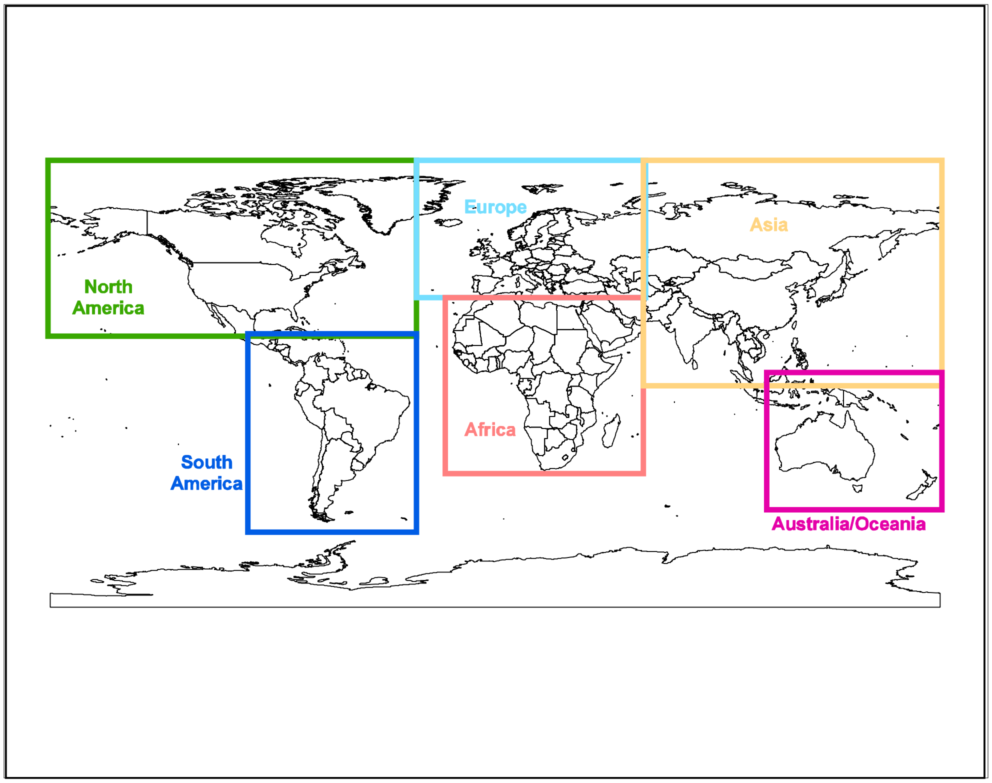
Figure 15. Summary histograms of annually-averaged T_{min} trends for latitude bands of >50N (a), 20-50N (b), 20N-20S (c), 20-50S (d), and >50S (e), as defined in Figure 1. The number of grid cells with no stations is indicated for each panel.

Table 1. Station density classification scheme.

Class	*Values*
None	0
Isolated	$0 < n \leq 1.0$
Scattered	$1.0 < n \leq 2.0$
Light	$2.0 < n \leq 3.0$
Moderate	$3.0 < n \leq 4.0$
Dense	$4.0 < n \leq 5.0$
Very Dense	$n > 5.0$

Table 2. Total counts of grid cells having no data for trend estimates in temperature (T), maximum temperature (Tmax), and minimum temperature (Tmin). Counts are classified by continents and latitude bands, which are defined in Figure 1.

Continent	**T**	**T_{max}**	**T_{min}**
North America	81	94	89
South America	8	83	83
Europe	24	33	30
Africa	28	134	134
Asia	50	124	108
Australia/Oceania	18	37	33
Latitude Band	**T**	**T_{max}**	**T_{min}**
> 50N	164	191	182
20N-50N	3	63	64
20S-20N	21	202	194
20S-50S	6	44	42
>50S	303	311	307



b)

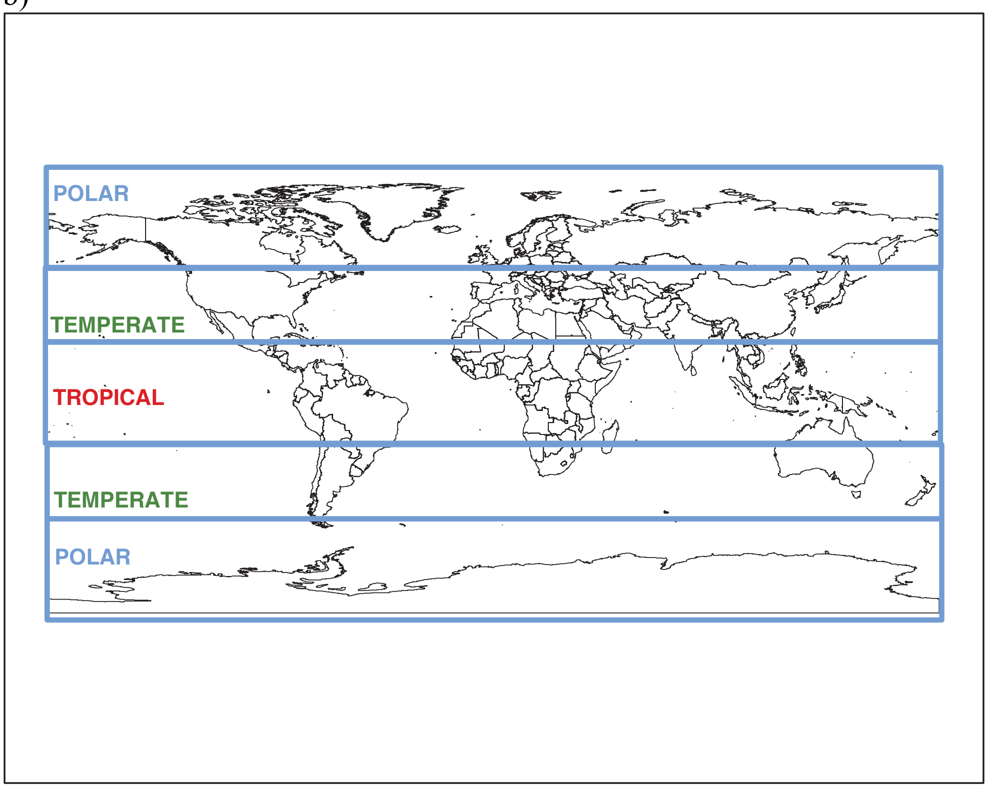


Figure 1. Continents (a) and latitude bands (b) discussed in this paper.