Consistency Check for Trends in Surface Temperature and Upper-Level Circulation: 1950–1992

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ABSTRACT

A time series of 43 years of observed monthly mean air temperature at 109 sites in the 48 contiguous United States is compared to monthly mean air temperature specified from hemispheric gridded 700-mb heights. Because both upper-air and surface data have problems that may limit their use in climate change studies, this comparison could be considered a mutual consistency check. Cooling (by about 0.5°C) from 1951 to about 1970 and subsequent warming (also by 0.5°C) that continues through the present are found in both datasets, indicating that these interdecadal changes are probably real.

In the last several years the specified temperatures were often colder than those observed. This prompted an investigation of whether the "residual" (specified minus observed) has recently been large (and negative) compared to the earlier part of the record. It was found that for the same 700-mb height field, surface temperatures were almost a degree Celsius warmer in the last few years than they were in the early 1950s, but considering the variability of the residuals over the 1950–92 period, the recent cold residuals may not yet be strikingly unusual.

By comparing the full set of 109 stations to a "clean" subset of 24, the impact of common problems in surface data (station relocation, urbanization, etc.) was found to be quite small. The rather favorable comparison of observed surface temperatures and specified surface temperatures (which suffer from upper-air analysis/observation changes over the years) indicates that their respective data problems do not appear to invalidate their use in studies of interdecadal temperature change.

1. Introduction

There is certainly no lack of interest in the question of climate change. Both professionals and laymen are studying climatological records to detect the "first signs" of this change, whatever they may be. As long as climate change is not overwhelmingly large, it will be difficult to separate its signal from noise due to natural variability. For example, it is impossible to determine whether the warmth in 1990–91 over the United States (as well as over most of the Northern Hemisphere landmasses) was a feature of the natural variability of an essentially unchanged climate, or a sign of climate change. The never-ending stream of record-breaking temperatures (on both the warm and the cold side) may well indicate that we have not measured temperature for very long. Also, there is always doubt about the accuracy of our measurements and their representativeness for climate (change) studies. Figure 1 shows a 13-month running mean of the monthly temperature anomaly averaged over the continental United States for 1950–92. Below we will discuss which stations were used, and how reliable they are. By way of introduction, however, it suffices to say that while 1990–91 was a warm period indeed (NOAA 1992), the temperature was not much higher than in 1953.

The question of climate change came up from a somewhat different perspective at the National Meteorological Center's Climate Analysis Center (CAC) when we noticed during 1990 and 1991 that our forecast tools (upper-level maps) indicated consistently colder surface conditions than were actually observed. This was true even when the tools were retroactively furnished with the perfect forecast, that is, when observed 700-mb height analyses were used to specify surface conditions. In addition to simple questions about the climate getting colder or warmer, we here ask whether the relation between upper-level flow and surface weather has changed. Is it possible that for the same 700-mb height map the surface temperatures in 1990 were higher than they were in 1960? And if so, why?

For a better understanding we will explain first how surface temperatures are "specified" from a given up-

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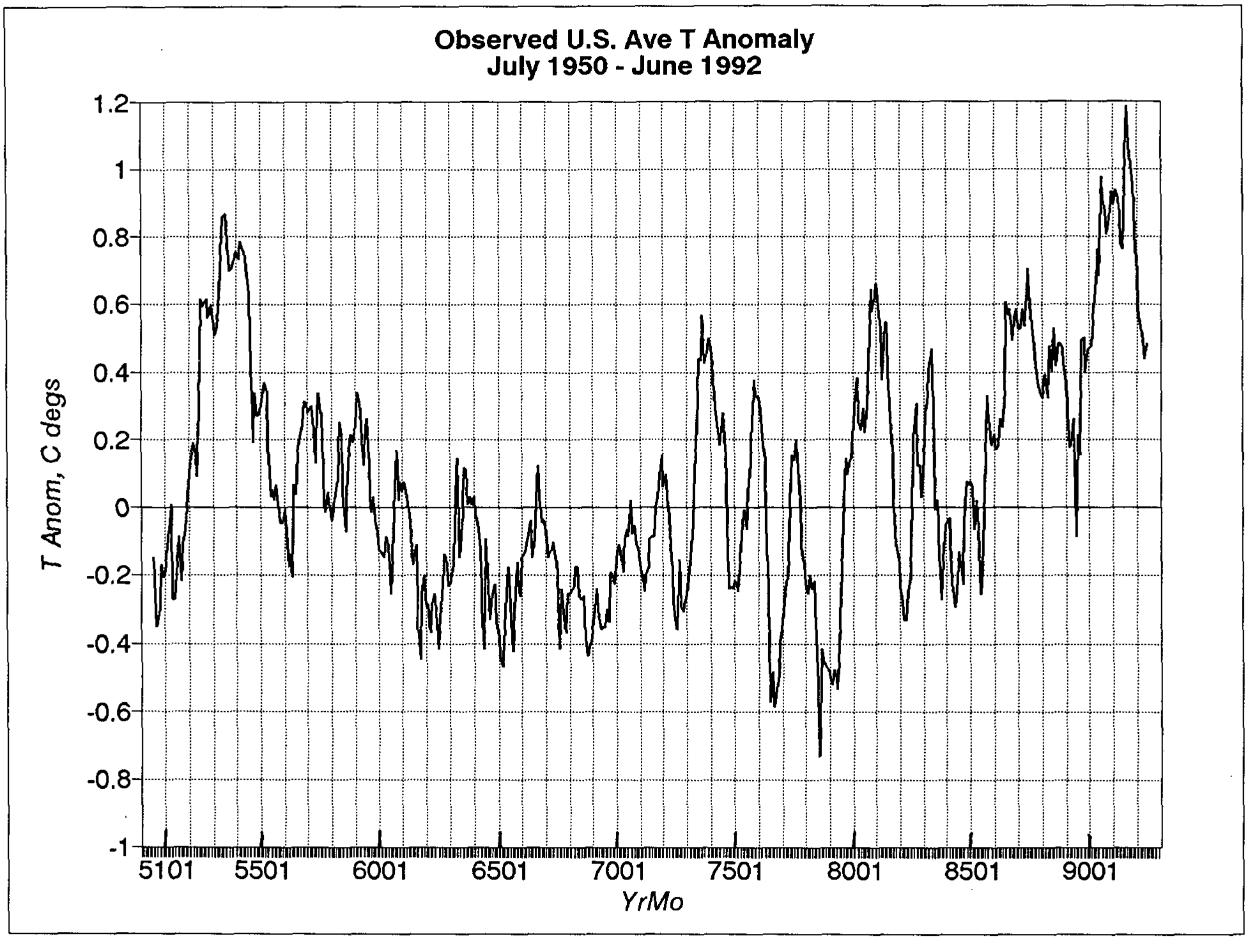

FIG. 1. The surface temperature anomaly over the United States for 1950–1992, averaged over 109 stations. Units are °C. Each tick mark pointing down along the *x* axis represents a month; heavier labels pointing upward are for January of 1951, 1955, 1960, etc. A 13-month running mean has been applied. The first point in the graph is the average over January 1950–January 1951 plotted at its center, July 1950. The last point is the December 1991–December 1992 average. Anomalies are relative to the 1951–80 base period.

per-level map (section 2). In the same section the datasets are described. We then proceed in section 3 by giving an example of the cold bias alluded to above. The 1950–1992 time series of both specified and observed temperatures over the United States will be discussed in section 4. Time series of temperature averaged over a relatively large set of U.S. stations, as well as a "clean" subset (no known bias, no relocation, etc.), will be presented. In section 5 we present conclusions in light of unresolved discrepancies between trends in surface air temperature (Jones and Wigley 1990) on the one hand, and trends (or absence thereof) in free atmosphere temperature as measured by radiosondes (Angell 1988; Oort and Liu 1993) or vertically averaged tropospheric temperature as measured by satellite (Spencer and Christy 1992) on the other.

Both surface and upper-air data have problems that may limit their usefulness in climate change studies. It is important to note that (i) problems in surface and upper-air data are largely or entirely unrelated, and (ii) these problems (examples: urbanization, change in upper-air analysis) are very hard to quantify. The present comparison may reveal just how serious these problems are.

2. Specification of monthly mean surface air temperature

a. Method

The general purpose of specification is to determine local surface weather conditions given one or more upper-level maps. This question has traditionally come up in an operational forecast setting, that is, what the surface weather will be given large-scale prognostic fields that are known to have some forecast skill (generally midtropospheric fields). One example of such a technique is the so-called model output statistics approach used extensively in day-to-day forecasting (Klein and Glahn 1974). In the present work we apply a "perfect prog" approach; that is, we specify the monthly mean surface temperature given the observed monthly mean 700-mb height field.

Following Klein (1983), who developed the specification equations for this particular application, we use a training dataset for the 1948–81 period consisting of (i) monthly mean gridded 700-mb height anomalies (Z), and (ii) monthly mean surface air temperature (MMAT) anomalies at 109 stations in the United States. For each station we seek a specified MMAT anomaly (T_s) that matches the observed MMAT anomaly (T_o) as closely as possible by minimizing the expression

$$\sum_{j=48}^{81} [T_o(j, m) - T_s(j, m)]^2 \qquad (1a)$$

where

$$T_s(j, m) = \sum_{n=1}^{N} a_n Z_n(j, m) \qquad (1b)$$

and n is an index for the admitted grid points in order of selection (the first explaining the most temperature variance, etc.), j is the year index, m is the month, and N is the total number of grid points admitted. Equations (1) describe a linear multiple regression specifying MMAT at individual stations from Z_n at selected grid points (n). Klein (1983) selected the grid points ($n = 1, N$) by a forward-screening method and truncated at N by testing the additional explained variance for statistical and synoptic significance. Usually N is 3, 4, or slightly higher. The first grid point selected is almost always nearby (anomalously high/low heights often imply high/low temperature), while the next ones are consistent with known teleconnection and advection patterns (high heights over Alaska generally imply often cold weather in winter in the northern plains, etc). To enhance stability, three months of data were pooled; that is, to derive March equations, data for February, March, and April are used (Klein 1983). The March equations are applied here to March only.

The following features of the specification equations are important in the context of the present paper:

1) The average explained variance of Eq. (1) is up to 70% in winter, and around 50% in summer. These values vary over the country [see Klein (1985) and Kline and Klein (1986)] and may be lower for the independent data (1982–present).

2) There is no mean bias; that is, stationwise, the time-mean value of T_s must equal the time mean of T_o for each month, at least over 1948–81. This is by design. We will see below whether a bias develops beyond 1981.

3) It is in the nature of regression to produce T_s that are, generally, closer to the mean (zero) than is T_o. Therefore the residual ($T_s - T_o$) will often be of a sign opposite to T_o, particularly when T_o (anomaly) is large. To alleviate this built-in tendency, and to generate T_s with a standard deviation equal to that of T_o, we inflate T_s by

$$T'_s(j, m) = T_s(j, m)/\rho \qquad (1c)$$

where ρ is the linear multiple correlation coefficient between Z_n and T_o. Henceforth the prime is dropped from T'_s for convenience.

4) Note that (1b) depends on concurrent heights only. In Klein (1983) the previous month's temperature was included as a potential predictor on the rhs of (1b). Here we purposely work with the "height-only" specification method.

5) Several factors known to influence the temperature are left out of Eq. (1), at least in explicit form. The temperature is certainly sensitive to snow cover for example, and to the extent that the concurrent 700-mb height anomaly does not properly represent the snow-cover anomaly, $T_s(j, m)$ will contain an error.

6) The specification approach will only be successful on 1982–present (independent) data if the temperature–height relationship that prevailed during the training period holds beyond 1981.

7) The present work deviates from previous uses of the specification equations in one particularly important aspect: the time and space scale. The equations have been derived to explain, stationwise, the sometimes large changes in monthly weather as they relate to the upper-air flow. We are studying here long-term biases between specified and observed temperature *averaged over* the entire continental United States, that is, we eliminate much of the temperature variations that are the prime target for the variance-explained maximizing equations.

Any long-term biases found between T_s and T_o could be attributed to any of the following causes: (i) long-term changes in lower-boundary conditions, (ii) long-term changes in the practice of measuring temperature, (iii) increased urbanization near observational sites, (iv) gradual shifts in the height–temperature relationship through the appearance of flow types not (or insufficiently) included in the 1948–81 training period, and v) changes in the analysis method for gridded 700-mb height data.

There are many earlier studies in which specification was used to detect the effect of some process. Defining the residual as

$$R(j, m) = T_s(j, m) - T_o(j, m) \qquad (2)$$

one can link $R(j, m)$ in a particular month to snow cover (Namias 1963; Walsh et al. 1985), soil moisture (Walsh et al. 1985; Van den Dool et al. 1986), and sea surface temperature (Van den Dool et al. 1986). As an example, Namias (1963) applied five-day-mean specification equations to show that February/March 1960 was colder than expected from the 700-mb height field because of the extensive positive snow cover anomaly. Using essentially the same technique,

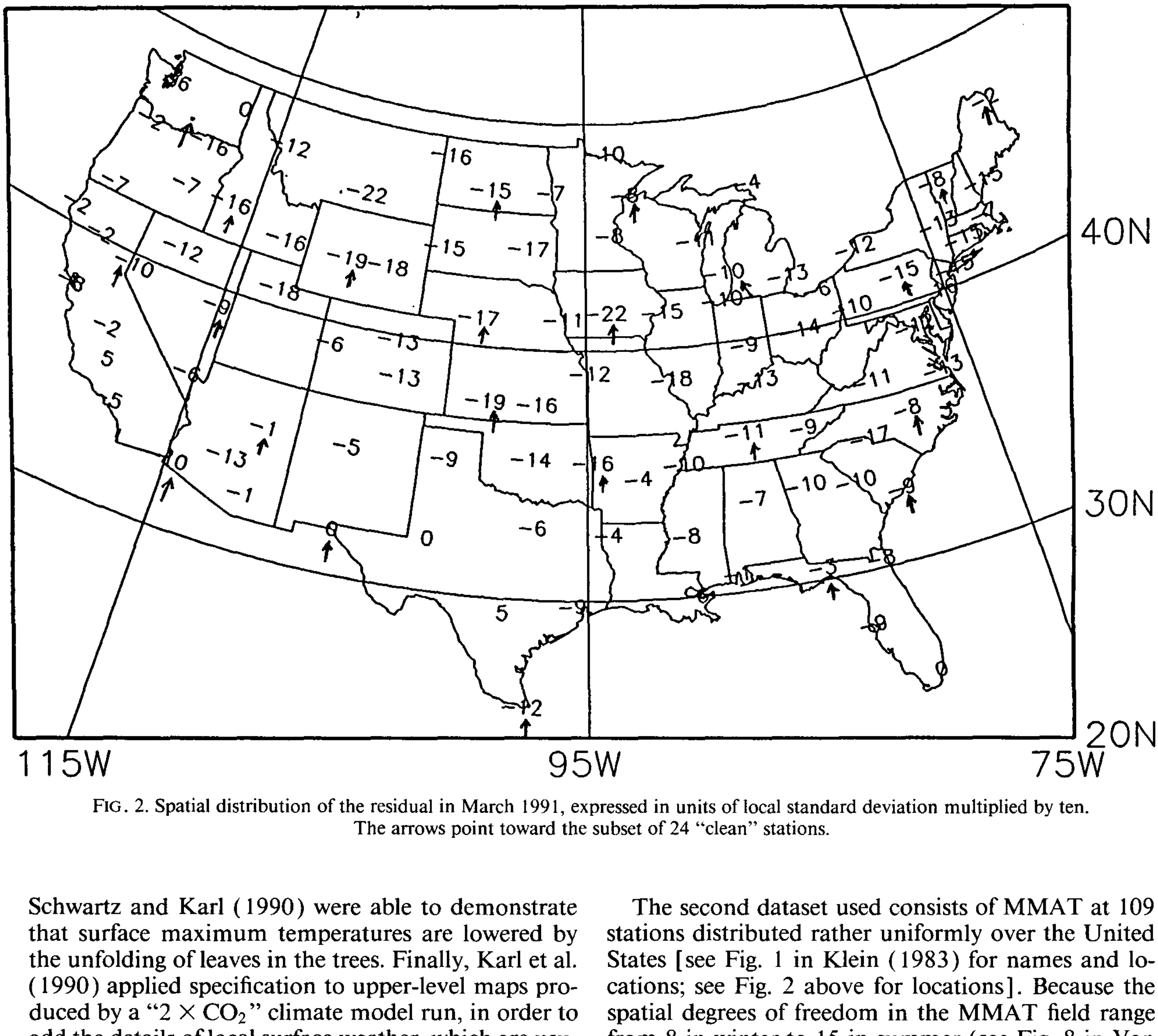

FIG. 2. Spatial distribution of the residual in March 1991, expressed in units of local standard deviation multiplied by ten. The arrows point toward the subset of 24 "clean" stations.

Schwartz and Karl (1990) were able to demonstrate that surface maximum temperatures are lowered by the unfolding of leaves in the trees. Finally, Karl et al. (1990) applied specification to upper-level maps produced by a "2 × CO_2" climate model run, in order to add the details of local surface weather, which are usually missing in coarsely resolved simulated climates.

b. Datasets

Two datasets are used here. Both consist of monthly mean data for the period 1948–1992. The first is 700-mb height, for the current application, represented at a network of 133 grid points (see Fig. 2 in Klein 1983). The area covered is from 180°W to 50°W, and 20° to 80°N. This dataset is and has been maintained at CAC and its predecessors. Certain known problems with the data are discussed in Barnston and Livezey (1987). From a climate point of view, it is important to remember that the analysis scheme used to obtain grid-point values (note that we do not use direct height observations) has changed over the years from hand analysis to increasingly more sophisticated machine analyses.

The second dataset used consists of MMAT at 109 stations distributed rather uniformly over the United States [see Fig. 1 in Klein (1983) for names and locations; see Fig. 2 above for locations]. Because the spatial degrees of freedom in the MMAT field range from 8 in winter to 15 in summer (see Fig. 8 in Van den Dool et al. 1986), the area-averaged temperature could be calculated, without any loss of accuracy, from far fewer than 109 stations. Discussion of trends in surface air temperature focuses often on reliability and representativeness of observations, and we therefore decided to use, in parallel, a subset of 24 stations that are as "clean" as possible. This subset, listed in the Appendix and shown in Fig. 2 by arrows pointing toward the station, was decided upon with the advice of Pamela Hughes at the National Climatic Data Center in Asheville, North Carolina. The clean set has been chosen to include only stations that 1) experienced no (or minimal) changes in location, 2) were not near large population centers, and 3) contained no changes in time of observation. The 24 chosen provide reasonable coverage of the United States.

One factor not used in the choice of 24 is a change in instrumentation. At nearly all 109 stations, the type of thermometer has changed twice. Over the periods 1959–64 and 1983–89, respectively, the so-called HO6x and HO8x were installed. We cannot rule out that the impact of these changes (Gall et al. 1992) will show up in results based on either the clean 24 stations or all (109) stations.

Figure 1 shows the area-averaged temperature based on 109 stations. A 13-month running mean has been applied to smooth the higher frequencies. The departures are relative to the 1951–80 mean.

Both surface temperatures and upper-level data have problems that might limit their usefulness in climate studies, but these problems are of a totally different nature and largely, if not totally, unrelated. Therefore, comparing observed and 700-mb specified temperature could provide a useful mutual consistency check to see just how serious these data problems are.

3. Recent bias? 1982–present

Figure 2 gives a pronounced example of the recent bias, that is, specification indicates much colder conditions than were observed. Shown is a map of R [see Eq. (2)] for March 1991. The values are expressed in units of (local) standard deviation multiplied by 10. (The standard deviation is calculated for each month and station using monthly data over 1951–80.) As can be seen, R is negative at virtually all 109 stations, with magnitudes reaching two standard deviations in some areas. This negative "bias" occurred both in the east, where observed temperatures were above normal, and in the west, where observed conditions were colder than normal.

Figure 3 shows a 13-month running mean of the area-averaged residuals R for the independent years 1982–92. The last point in the graph is the average over December 1991 through December 1992. Two features should be noted in particular in Fig. 3. One is that, overall, over the ten years, the bias is small. The second is an eight-year downward trend from positive values in 1984 to the current negative values. The magnitude of the change during these eight years is $-1°C$.

The downward change in R in Fig. 3 would be consistent with any of the following physical causes: (i) increased urbanization, (ii) increased drought condition, (iii) lack of snow, (iv) upwardly biased thermometer reading, (v) a real increase in surface temperature representing only a shallow near-surface layer (for instance by having less than the expected number of shallow cold-air outbreaks), and, therefore, barely reflected in 700-mb height, and, last but not least (vi) natural variability. By comparing the 109 to the 24 clean stations we believe we can rule out (i); see next section. Cause (ii) has not been observed—note that negative biases in March 1991 (see Fig. 2) occurred both over the drought-stricken land in the far west, as well as over the wetter-than-normal soil east of the Continental Divide. Cause (iii) cannot be ruled out. In fact, because it was so warm in 1990 and 1991, there was less snow than normal, which almost certainly contributes to negative R, at least in several winter months. Cause (iv) cannot be ruled out either.

The advantage of using independent data is that R is not constrained by methodology. However, it is impossible to tell from the ten years of data displayed in Fig. 3 whether the downward trend over 1984–92 is unprecedented or due to natural variability [cause (vi)] expressing itself in a secularly changing 700-mb height versus surface temperature relationship. To address the natural variability problem, we present in the next section a graph identical to Fig. 3, but now for 1950–92. Also, we compare 109 versus 24 stations to assess the impact of (mildly) suspect stations.

4. The 1950–92 time series

Figure 4 shows the residual R for the entire 1950–92 period, both for all 109 stations (solid line) and for the subset of 24 reliable stations (dotted). We first note a small detail in the computational procedure. The residuals were obtained by subtracting the observed and specified temperatures expressed as anomalies relative to the 1951–80 base period. The values of T_s was obtained by expressing height anomalies relative to the 1951–80 base period. This is slightly different from the 1948–81 period for which the equations were derived (Klein 1983), and so the time-mean residual in Fig. 4 is zero over 1951–80.

The prime result of Fig. 4 is that we are no longer inclined to believe that the 1984–92 decrease in R shown in Fig. 3 is so exceptional, or that a "climate change" explanation is inescapable. Despite the fact that R was constrained by methodology over 1950–81, there have been earlier decreases and increases of R of nearly the same magnitude as the one observed over the last few years. Fairly impressive changes in R on time scales of two to five years are seen in Fig. 4. Increases and decreases of 0.5°C up or down have occurred both in the dependent data (1955–58, 1977–81) and in the independent data (1983–84, 1984–91). In between, very quiet periods prevailed, where R was nearly constant.

We also note that the impact of any suspect stations is, fortunately, rather small, the full and dotted lines in Fig. 4 agreeing generally to within 0.1°C. This is perhaps surprising, because increased urbanization alone ought to have made R increasingly negative. This is apparently either a small effect, large only at a few stations, or compensated by other factors.

For further discussion of the above, we show in Fig. 5 the specified temperature anomaly over the United States for 1950–92. Scales, base period, and the meaning of the graph are identical to Fig. 1, except that Fig. 5 is based on 700-mb height data. Note that the specified temperature during the 1990–91 warm period was

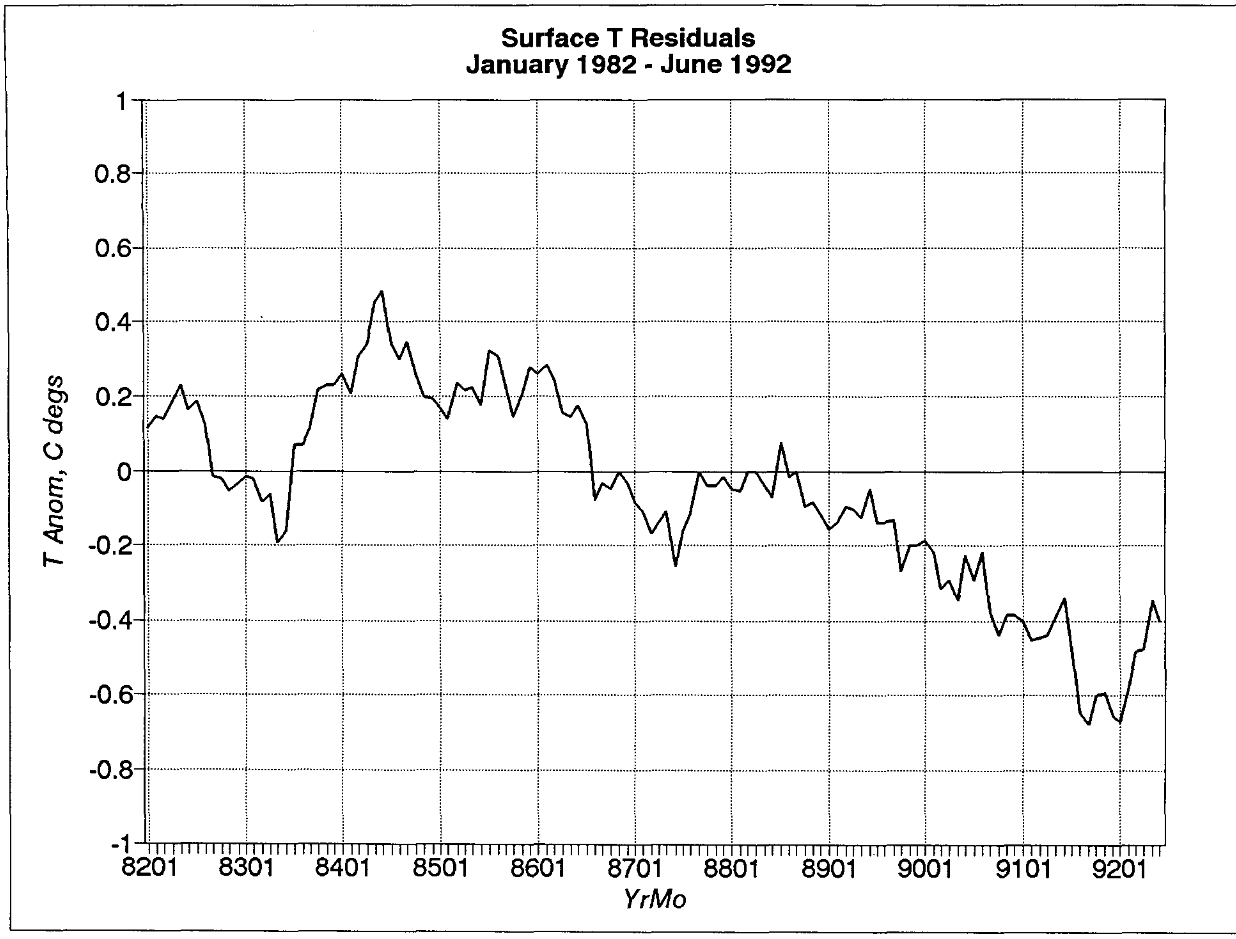

FIG. 3. Thirteen-month running mean of the residual, averaged over 109 stations, for the period of independent data, 1982–1992. Units are °C.

not exceptionally high, and less warm than 1953. It is this discrepancy with reality [1990–91 was the warmest period during the 1950–92 record (see Fig. 1)] that prompted this article.

Taken together, Figs. 1, 4, and 5 indicate by and large that the interdecadal trends in surface air temperature are consistent with changes in 700-mb height, particularly the cooling from the early 1950s to the late 1960s and the subsequent warming that continues through the present. Note that R is generally within + to -0.50°C (Fig. 4), while T_o and T_s vary between + and -0.80°C (Figs. 1 and 5). Therefore, observed surface air temperature and specified surface air temperature have many similarities, despite real and alleged problems associated with both surface and upper-air data and despite real discrepancies that must exist related to anomalies in snow cover, soil moisture, etc., which are unaccounted for, at least in explicit form, by the specification equations. This mutual consistency clearly indicates that the temperature changes shown in Fig. 1 are mostly real.

On the one hand it may not seem so remarkable that Fig. 1 and Fig. 5 are so similar, because the method has minimized R over 1948–81. On the other hand, the amount of variance in the spatially and temporally smoothed MMAT displayed in these figures is small and thus not the first direct target of the station- and calendar-month-specific explained variance-maximizing equations. Moreover, it is unlikely that the specification equations, consisting of only a few terms, would "explain" any real inconsistencies between heights and surface temperature, even when given a chance on dependent data.

To further elaborate on the consistency of heights and surface temperatures we have plotted in Fig. 6 five-yr running means of observed MMAT (thin dashed), along with the spatially averaged U.S. 700-mb height anomaly (thick full line), denoted by Z. All 16 grid points (of the 358-diamond grid; Barnston and Livezey 1987) within the natural and political borders of the United States (lower 48 states) are averaged together to obtain the latter. This is perhaps a step toward the simplest physical specification of surface temperature imaginable, based on local heights only. No assumptions of any kind are made, nor has there been any fitting on a training period. Figure 6 is plotted such

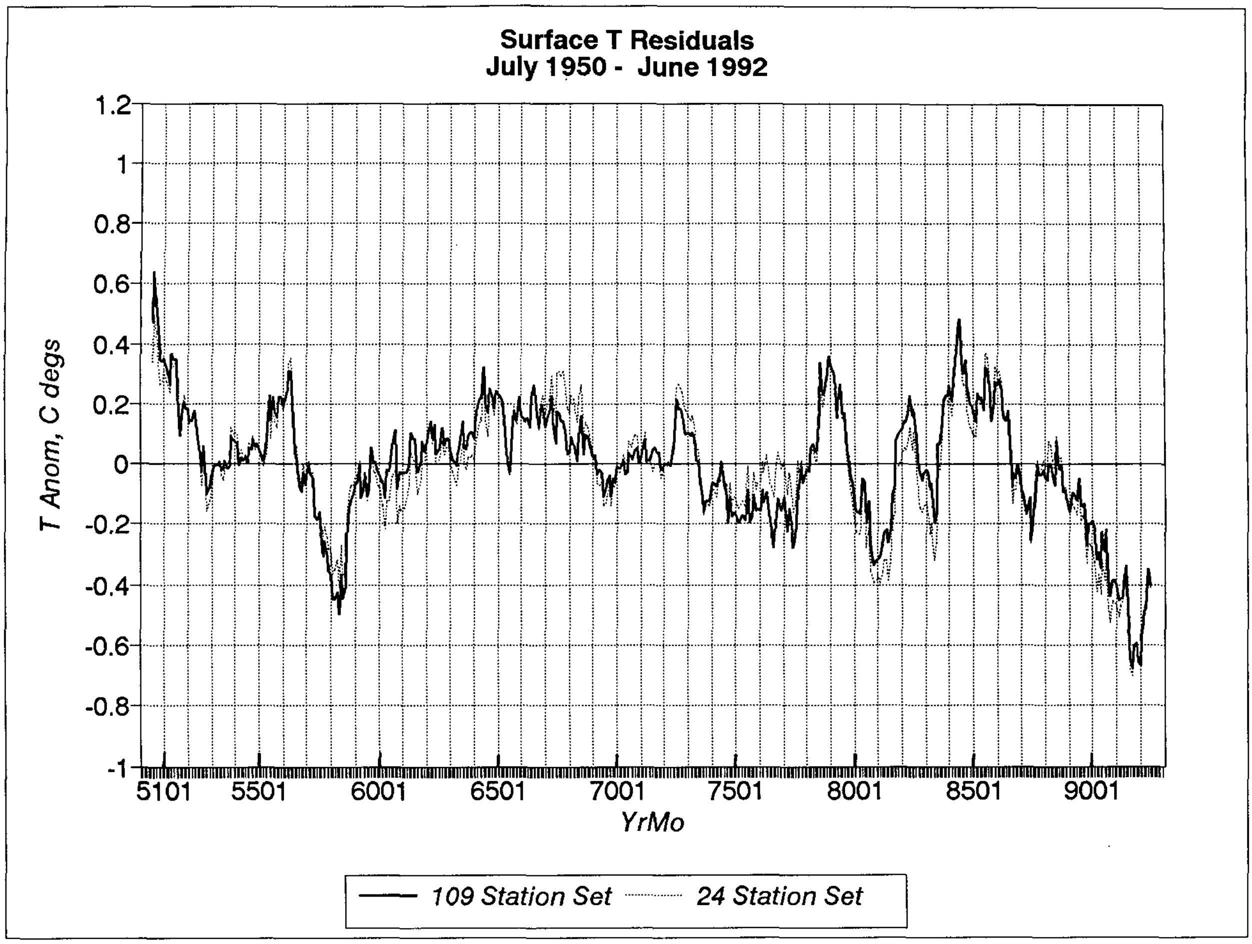

FIG. 4. As in Fig. 3 but now for the full 1950–1992 period. The full (dotted) line is for 109 (24) stations.

that a 10-m height anomaly (left-hand scale) corresponds to 1°C temperature anomaly (right-hand scale) on the rationale that a 10-meter 1000–700-mb thickness anomaly would be close to a 1° layer average temperature anomaly. It is clear from Fig. 6 that the variation of Z and T_o is fairly consistent on the interdecadal time scale and to the best of our knowledge the data entering these curves are measured entirely independent from each other.

In Fig. 6 we have also plotted the 5-yr running mean of specified MMAT (thin full line). It is quite obvious that the T_o and T_s curves are much closer to each other than either of them is to the Z curve, both on dependent and independent data. It therefore seems that useful detail and calibration is added by using the full specification equations even for 5-yr running means of nationwide temperatures. Therefore, local 700-mb heights cannot substitute for a quantitative specification method. As described before, the specification equations usually take the local (or nearby) height with positive regression constant as the first term, but the regression constant varies widely with space and season. The remaining terms in the specification equations describe advection, and it appears that advection remains nonnegligible even when a large spatial/temporal average is taken.

5. Discussion and conclusions

We have compared 43 years (1950–92) of observed monthly mean air temperature (MMAT) at 109 stations in the United States to temperatures that are specified from concurrent monthly mean 700-mb height using the approach of Klein (1983). The focus of discussion is particularly on the following related issues. 1) Do the observed and specified interdecadal temperature changes agree? 2) Does the residual (defined as specified minus observed), which has been large and negative recently, show any trends? 3) How serious is the contamination of observed MMAT by problems such as urbanization? The answers are as follows. 1) In spite of problems in surface and upper-air data, it appears that observed and

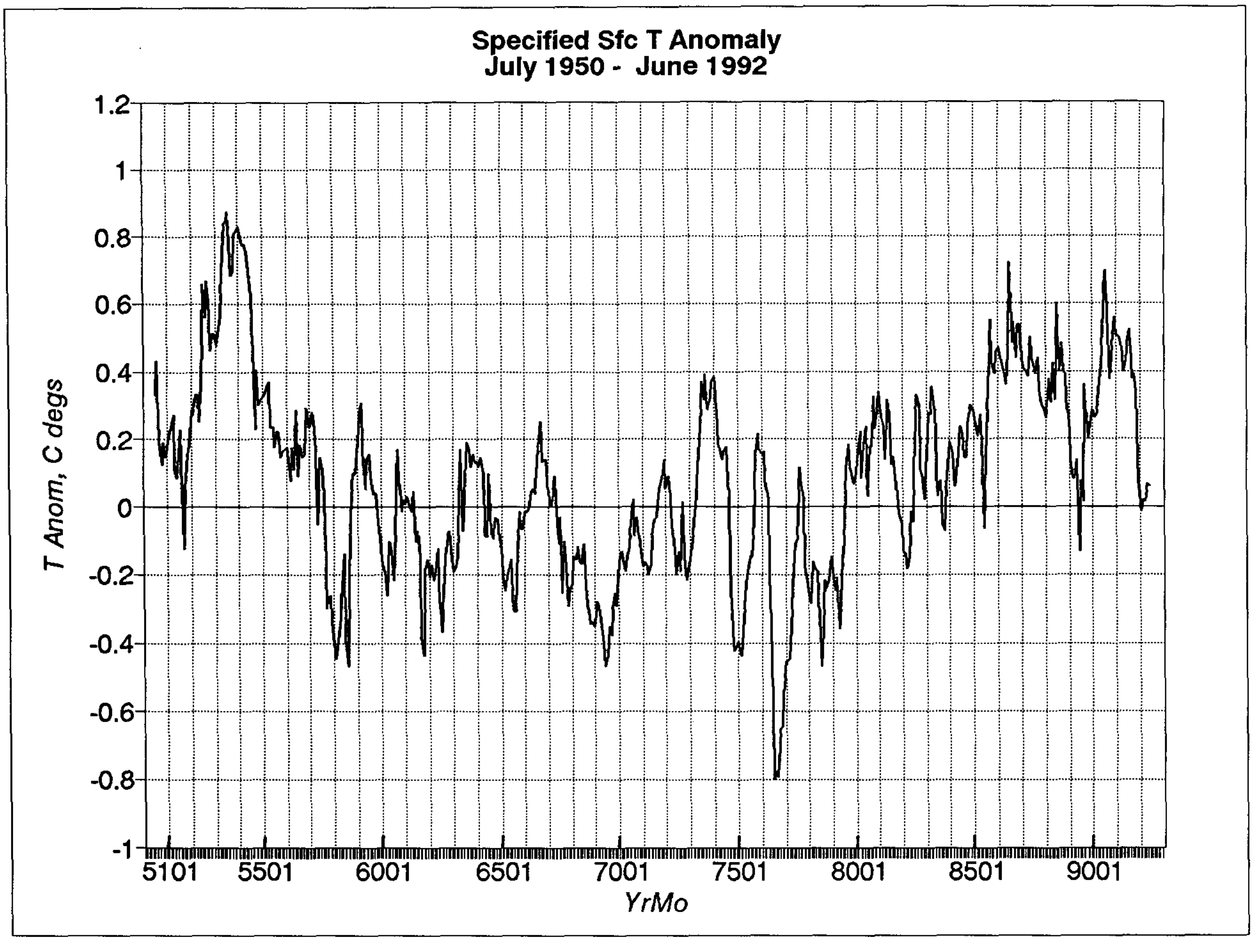

FIG. 5. As in Fig. 1 but now for specified temperature.

specified temperature anomalies are quite similar on the year-to-interdecadal time scale, indicating therefore that the variations seen in Fig. 1 are mostly credible. 2) The residual does show variations on all time scales, but it is generally less than 0.50°C (see Fig. 4). It would be premature to conclude that the recent tendency for exceptionally large negative residuals is beyond what can be expected from natural variability, but it is worth monitoring. 3) By using a clean subset of stations (24 out of 109), we found the problem of urbanization and station relocation to be only a small factor in the variation of United States–averaged temperature on time scales of one year and longer.

Extension of this analysis to areas other than the United States would be a useful step in validating temperature change elsewhere. Updating the results for the United States beyond 1992 will tell us whether the large negative residuals (example in Fig. 2) are to be taken seriously, or dismissed as just natural variability.

The overall consistency of heights and surface temperature over 1950–92 implies that the interdecadal temperature changes over this period are more likely due to changes in frequency of occurrence and amplitude of common circulation types than to the appearance of new flow patterns. The latter would be hard to handle by the specification equations. It is also possible that we are dealing with spatially nearly uniform height increases (decreases). In this case there would not be a change in the flow patterns, just a change in the overall height and temperature level. The specification equations are well trained for the latter climate change scenario, since at most cities the first term relates (with positive regression coefficient) to the height at a nearby grid point.

In conclusion it may be stated that while 700-mb height and surface temperature agreed quite well over 1950–89, the last three years (1990–92) featured much warmer surface temperature than would be expected from the concurrent 700-mb height, R running about −0.50°C in recent 13-month averages (latest data entry December 1992). If R remains large and negative in the near future, then the question of a physical explanation becomes more urgent. We have listed above several possible physical and measurement/analysis reasons why such biases may occur. But there is also the possibility that we are wit-

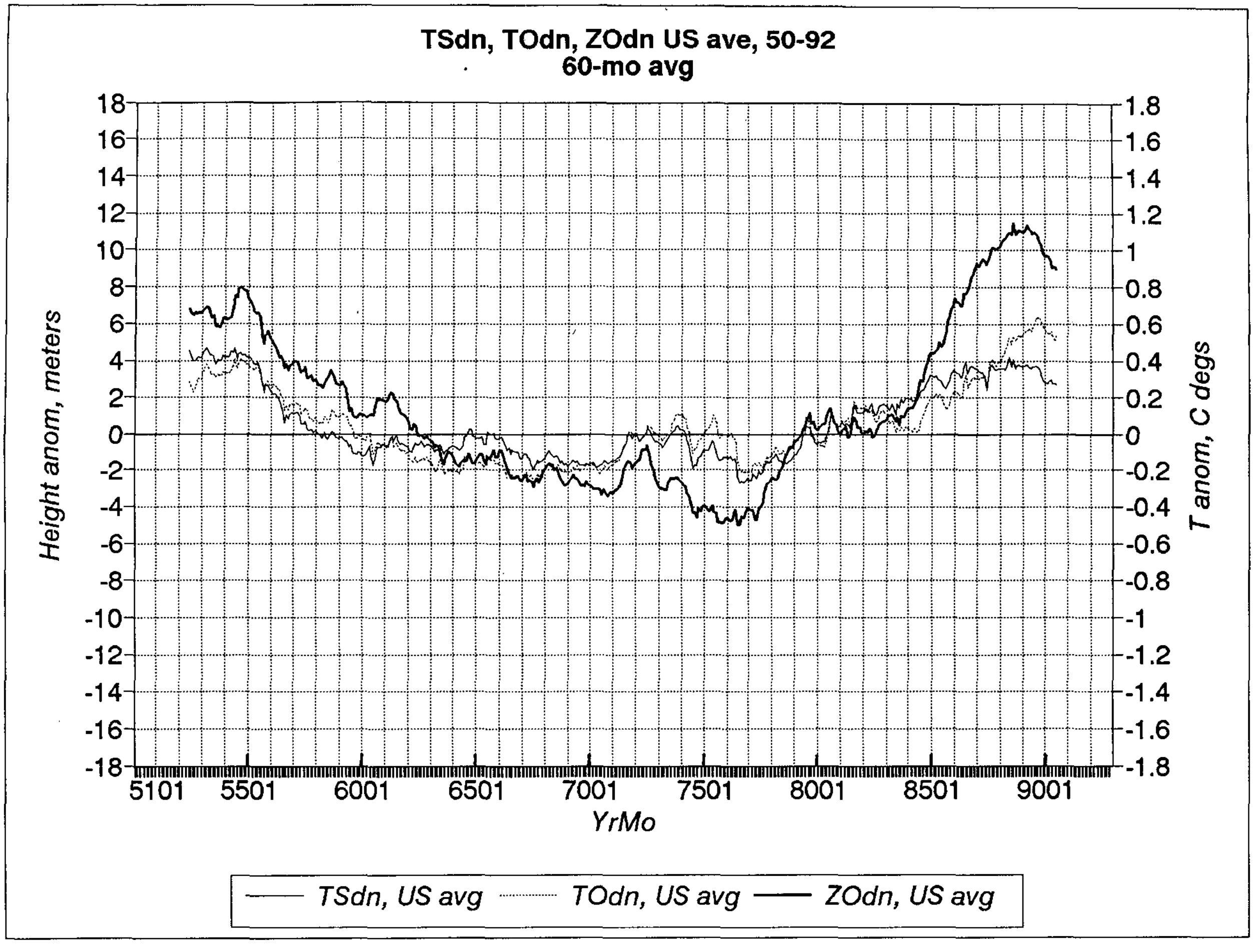

FIG. 6. As in Fig. 1. Dashed thin line: observed U.S.-averaged temperature anomaly. Thin full line: specified U.S.-averaged temperature anomaly. Thick full line: observed U.S.-averaged 700-mb height anomaly in geopotential meters. All series have been smoothed by a 5-yr running mean. Temperature scale on the right, height scale on the left.

nessing a methodological problem with the specification equations. Regardless of the cause, these large biases present a problem in operational applications since they amount to errors on the order of the local standard deviation. Various attempts are being made to improve matters, for instance by introducing a Kalman filter (Epstein 1992, personal communication).

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APPENDIX

The 24 Station Subset of the 109 U.S. Stations

Number	WMO number	State	Location
1	72208	South Carolina	Charleston Municipal
2	72214	Florida	Tallahassee Municipal
3	72250	Texas	Brownsville International
4	72270	Texas	El Paso International
5	72280	Arizona	Yuma International
6	72306	North Carolina	Raleigh–Durham

7	72327	Tennessee	Nashville Metropolitan
8	72344	Arkansas	Fort Smith Municipal
9	72374	Arizona	Winslow Municipal
10	72425	West Virginia	Huntington Tri-State
11	72451	Kansas	Dodge City Municipal
12	72483	California	Sacramento Executive
13	72486	Nevada	Ely, Yelland
14	72514	Pennsylvania	Williamsport–Lycoming County
15	72546	Iowa	Des Moines Municipal
16	72562	Nebraska	North Platte, Lee-Bird
17	72576	Wyoming	Lander, Hunt
18	72617	Vermont	Burlington International
19	72635	Michigan	Grand Rapids, Kent
20	72681	Idaho	Boise Municipal
21	72712	Maine	Caribou Municipal
22	72745	Minnesota	Duluth International
23	72764	North Dakota	Bismarck International
24	72781	Washington	Yakima Air Terminal

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