Sensitivity of Continental-Scale Climate Trend Estimates to the Distribution of Radiosondes over North America

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ABSTRACT

As part of its mandate to oversee the design of measurement networks for future weather and climate observing needs, the North American Atmospheric Observing System (NAOS) program hypothesized that replacing some of the existing radiosonde stations in the continental United States (CONUS) with another observing system would have little impact on weather forecast accuracy. The consequences of this hypothesis for climate monitoring over North America (NA) are considered here by comparing estimates of multidecadal trends in seasonal mean 500-mb temperature (T) integrated regionally over CONUS or NA, made with and without the 14 upper-air stations initially targeted for replacement. The trend estimates are obtained by subsampling gridded reanalysis fields at points nearest the 78 (126) existing CONUS (NA) radiosonde stations and at these points less the 14 stations. Trends in T for CONUS and NA during each season are also estimated based on the full reanalysis grid, but regardless of the sampling strategy, differences in trends are small and statistically insignificant. A more extreme reduction of the existing radiosonde network is also considered here, namely, one associated with the Global Climate Observing System (GCOS), which includes only 6 (14) stations in CONUS (NA). Again, however, trends for CONUS or NA based on the GCOS sampling strategy are not significantly different from those based on the current network, despite the large difference in station coverage. Estimates of continental-scale trends in 500-mb temperature therefore appear to be robust, whether based on the existing North American radiosonde network or on a range of potential changes thereto. This result depends on the large spatial scale of the underlying tropospheric temperature trend field; other quantities of interest for climate monitoring may be considerably more sensitive to the number and distribution of upper-air stations.

1. Introduction

In recent years, the weather research community has begun to explore the advantages that so-called adaptive observation strategies might yield for improving the skill of weather forecasts (Emanuel et al. 1995; Snyder 1996; Lorenz and Emanuel 1998; Morss 1999; Buizza and Montani 1999; Hirschberg et al. 2001). As originally conceived, these strategies envisioned measurements that are targeted over regions deemed likely to impact the subsequent development of synoptic events and would supplement the existing observational network. Because resources for any observational system are finite, however, and unnecessary redundancies ought to be eliminated, the question naturally arose as to whether targeted or other measurements could replace some of those from the existing conventional network. In more general terms, the discussion in the weather forecasting community has turned to the design of the optimal mix of conventional measurement systems and new technologies that will produce the best possible forecasts most economically.

Institutionally, such concerns within the United States have become the province of the North American Atmospheric Observing System (NAOS) program. As stated by NAOS (1996), its goal ‘‘is to provide the scientific, technical, and administrative basis for governmental decision processes on how to meet the evolving needs for atmospheric observations over the region of North America and adjacent ocean areas in support of the prediction and assessment of weather and of associated climate services.’’ Significantly, both weather and ‘‘associated climate services’’ are covered by the NAOS mandate, recognizing that climate monitoring efforts in this country are intimately linked to the observing network established for weather forecasting. Here, we investigate the effect of a potential observing system change considered by NAOS on estimates of climate trends over North America.

The weather research community has used observing system simulation experiments (OSSEs) and related observing system, or data sensitivity, experiments for many years to assess the potential impact of proposed observing system changes on weather analyses and forecasts. Errico (1999) advises care when evaluating results

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from OSSEs, however, because these are often dependent on the details of the data assimilation system and need not reflect the real information content of the data themselves. In the case of adaptive observation strategies, Morss and Emanuel (2002) caution that assimilated extra observations can sometimes degrade analyses and weather forecasts derived from them, depending on the sophistication of the assimilation system. Morss et al. (2001) suggest that one way to minimize the risk of this degradation is to adapt observations regularly and frequently. Partly in recognition that such approaches might require a redirection of resources, NAOS began OSSEs to test the impact on weather analyses and forecasts of scenarios in which half of the conventional radiosonde soundings are eliminated, either in space or time (Lord 1999). The consequences of such major observing system changes for climate monitoring need to be assessed as well.

Efforts to test the dependence of large-scale upper-air statistics on measurement density have been undertaken at various times in the past. Even as the first set of general circulation statistics began to emerge from the Massachusetts Institute of Technology General Circulation Project and elsewhere in the 1960s (e.g., Starr et al. 1970), concerns were raised about the adequacy of the upper-air station network to determine these statistics properly. To address these concerns, Oort (1978) used the numerical output from a global climate model as a means for testing the sensitivity of results to sampling the output in ways that mimic the observations. By subsampling time series at individual model grid points or by subsampling the full model output just at grid points near existing radiosonde stations, Oort was able to simulate the effects of temporal or spatial gaps in the radiosonde network on hemispheric-scale climate statistics.

More recently, Yarosh et al. (1999) use a similar approach on a regional scale to determine that closing the moisture budget over the central United States is strongly dependent on adequate temporal and spatial sampling. Comparing output from the National Centers for Environmental Prediction (NCEP) Eta model analyses at full resolution with that at selected grid points bounding the domain, the authors determined that most of the bias in this moisture budget can be attributed to undersampling the diurnal cycle, and the remaining error is due mainly to gaps in the current radiosonde network. Further thinning of that network or a reduction of the sampling to once daily (one of the ‘‘half-raob’’ NAOS OSSE scenarios) would introduce errors on the order of 100% into the atmospheric moisture budget estimates for some months of the year (C. Ropelewski and E. Yarosh 1998, personal communication). On the other hand, Angell (1999) suggests that tropospheric temperature trends for North America obtained from 11 stations in his 63-station global network generally agree well with the trends based on all 120 radiosonde stations in North America. One might also conclude from the large-scale nature of the humidity trends over North America displayed by Ross and Elliott (1996) that some spatial undersampling of the current radiosonde network could be tolerated in computing continental trends in this quantity.

Elliott and Ross (2000) consider the effect on climate records of a proposed NAOS scenario in which measurements at the standard radiosonde stations are reduced during fair weather. Simulating this scenario by omitting observations from 12 North American stations when the surface pressure exceeds a certain threshold, the authors compare trends in monthly mean temperature and humidity during 1973–95 using this subsample with trends from the full set of observations. Although dependent on the methodology used, the comparison illustrates that the systematic biases introduced by such a sampling strategy can lead to important differences in the computed trends for some stations and seasons. Elliott and Ross (2000) conclude that, in general, these biases would contaminate the upper-air climatology of North America and complicate the calculation of climate trends.

Depending on the scenario, quantity, and methodology considered, therefore, the impact of observing strategies on upper-air climate statistics can span a broad range. Here, we combine elements of the sensitivity experiments referenced above to examine the consequences for climate monitoring of the so-called NAOS El hypothesis, namely: ‘‘It will be possible to reduce the number of radiosondes in the U.S. network without noticeably reducing forecast accuracy provided the sites removed have substitute observing systems in place’’ (NAOS 2000). As a metric for the impact of this scenario on climate monitoring, we focus on the multidecadal trend in 500-mb temperature integrated regionally over the continental United States (CONUS) and over North America (NA). Differences in trends during the last 20 years between surface and midtropospheric temperatures (NRC 2000) have raised awareness about the importance of monitoring the latter and make it a relevant choice here. Our approach, described more fully in the next section, is based on subsampling gridpoint values of 500-mb temperature produced by the NCEP–NCAR (National Center for Atmospheric Research) reanalysis (Kistler et al. 2001) to mimic the distribution of radiosonde stations over North America that would result from implementing the El hypothesis. As we illustrate, the effect of the El scenario on estimates of the regionally integrated trends in 500-mb temperature (and in two other quantities we also consider) is small, because of the large spatial scales that characterize the trend field.

2. Data and methodology

a. Data

Initial testing of the El hypothesis by NAOS (NAOS 2000) focused on the assertion that unnecessary redun-

TABLE 1. Stations associated with the NAOS E1 hypothesis. Grid points in the NCEP–NCAR reanalysis nearest these stations have been deleted in going from the SONDE to E1 sampling strategies.

Station name	Lat (°N)	Lon (°W)
Brookhaven, NY	40.9	72.9
Buffalo, NY	42.9	78.7
Denver, CO	39.8	104.9
Desert Rock, NV	36.6	116.0
Ft. Worth, TX	32.8	97.3
Miami Florida International University, FL	25.8	80.4
Minneapolis, MN	44.8	93.6
Oakland, CA	37.8	122.2
Peachtree City, GA	33.4	84.6
Salem, OR	44.9	123.0
Salt Lake City, UT	40.8	112.0
Santa Teresa, NM	31.9	106.7
Slidell, LA	30.3	89.8
Topeka, KS	39.1	95.6

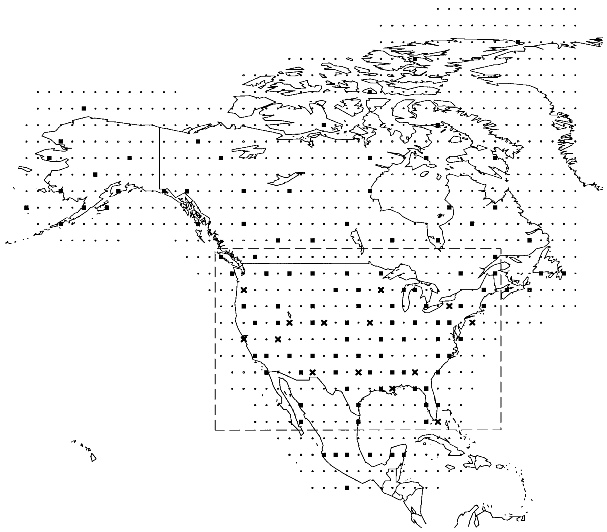

FIG. 1. Distribution of grid points drawn from the NCEP–NCAR reanalysis at the 2.5° lat × 2.5° lon resolution used to compute averages over North America or the continental United States (bounded by the dashed-line rectangle). Points lying nearest a radiosonde station are indicated by boxes or crosses, the latter further indicating the 14 stations associated with the El hypothesis. All other grid points are indicated by a small circle.

dancy may exist between radiosonde observations and measurements taken by instrumented commercial aircraft during their ascent or descent at airports as part of the Meteorological Data Collection and Reporting System (MDCRS). Vertical profiles of wind and temperature from MDCRS at 14 U.S. airports that are within ~100 km of radiosonde stations (see list in Table 1) were substituted for those from the latter to examine whether such a replacement would adversely impact weather forecasts. Here we examine whether eliminating these 14 radiosonde stations, without replacement, would adversely impact continental-scale estimates of midtropospheric temperature trends. In doing so, we assume that the heterogeneities between the conventional radiosonde and MDCRS measurements preclude easily mixing the two in future trend detection studies, inasmuch as homogeneity and continuity of observing systems are central tenets of climate monitoring (NRC 1999).

Data for assessing the impact of removing 14 upper-air stations from the North American network on estimates of large-scale trends could be obtained directly from archived records of station soundings. Calculating trends averaged over CONUS or NA with and without the 14 stations would require that considerable attention, however, be given to the quality of the radiosonde data themselves (Gaffen et al. 2000; Free et al. 2002). We have chosen instead to use the NCEP–NCAR reanalysis as our source of data, taking advantage of this product's lengthy record of gridded fields produced by an unchanging, sophisticated data assimilation system. Subsampling the full grid at points near the current array of radiosonde stations, and also at this array less the 14 stations, is easily accomplished. Importantly, this approach allows us to address not only the impact of removing the 14 stations, but also the adequacy of the existing upper-air network to estimate trends over North America, given that this network is sparser than the full reanalysis grid. For both of these purposes, we choose to ignore the reality that the reanalysis fields depend themselves on observations from radiosondes and other platforms; rather, we take these fields to represent a ''ground truth'' or control, independent of their source. We do require the reanalysis fields over North America to display realistic features, but as we demonstrate below, this condition is likely satisfied.

We start with 6-hourly archives of the NCEP–NCAR reanalysis at its 2.5° × 2.5° resolution for January 1958–December 1996. The main quantity for which trends are analyzed is 500-mb temperature, although we also consider the submonthly variance of 500-mb temperature defined by Iskenderian and Rosen (2000) and precipitable water. In the case of temperature, daily averages are created at each grid point from the 6-hourly values, and these in turn are averaged to create seasonal means for each of the four seasons: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). To create equal record lengths, we truncate the original reanalysis time series to span December 1958–November 1996 and calculate the seasonal mean temperature (T) for each of the 38 DJF, MAM, JJA, and SON.

b. Subsampling and spatial averaging approaches

Because the 14 stations involved in the El hypothesis are all located within the continental United States, we isolate results for CONUS, defined here as the reanalysis land and near-shore grid points in the region bounded by 25°–50°N and 67.5°–127.5°W (Fig. 1). Results are also presented for NA, which are those points shown in Fig. 1 lying within 15°–90°N and 50°–170°W. We

TABLE 2. Trends in seasonal mean 500-mb temperature (upper entries) for each of four sampling strategies over (top) North America and (bottom) the continental United States. Units are K $(\text{decade})^{-1}$, and trends in boldface are statistically significant at the 5% level. Lower entries, in italics and parentheses, give 95% confidence intervals about the trends. Results are based on NCEP–NCAR reanalysis fields during Dec 1958–Nov 1996. Number of grid points used in each averaging strategy is indicated in brackets.

	ALL	SONDE	E1	GCOS
		North America		
	[931]	[126]	[112]	[14]
DJF	0.130	0.158	0.160	0.162
	(0.40)	*(0.40)*	*(0.39)*	*(0.44)*
MAM	**0.252**	0.249	0.248	**0.266**
	(0.23)	*(0.26)*	*(0.26)*	*(0.25)*
JJA	0.131	0.129	0.130	0.136
	(0.24)	*(0.22)*	*(0.23)*	*(0.23)*
SON	0.086	0.079	0.081	0.054
	(0.21)	*(0.20)*	*(0.20)*	*(0.22)*
		Continental United States		
	[256]	[78]	[64]	[6]
DJF	0.269	0.279	0.283	0.232
	(0.32)	*(0.35)*	*(0.35)*	*(0.31)*
MAM	**0.280**	**0.270**	0.268	**0.280**
	(0.26)	*(0.27)*	*(0.27)*	*(0.27)*
JJA	0.168	0.162	0.164	0.159
	(0.28)	*(0.27)*	*(0.27)*	*(0.28)*
SON	0.068	0.077	0.079	0.067
	(0.35)	*(0.37)*	*(0.37)*	*(0.28)*

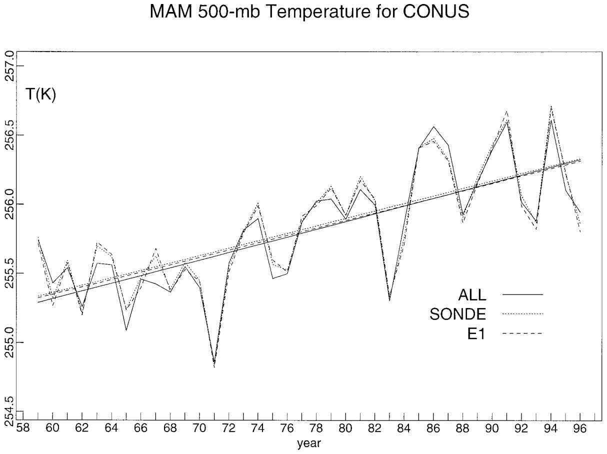

FIG. 2. Time series of seasonal mean 500-mb temperatures averaged over the continental United States during MAM 1959–96 using each of the three sampling strategies: ALL, SONDE, and El. The best-fit linear trend line associated with each time series is also shown; values of the trend are included within Table 2.

refer to the set of 256 points in CONUS as CONUS-ALL and the set of 931 points in NA as NA-ALL.

The 2.5° × 2.5° resolution of the NCEP–NCAR reanalysis product is sufficiently fine to allow a simple mapping from each of the 78 (126) radiosonde stations in CONUS (NA) to a nearby reanalysis grid point. The mapping is achieved by assigning a station to its nearest grid point using a great circle distance. We refer to the set of grid points closest to all CONUS and NA station locations as CONUS-SONDE and NA-SONDE, respectively (Fig. 1). The subset of grid points formed by deleting the 14 El hypothesis points (shown by crosses in Fig. 1) from CONUS-SONDE and NA-SONDE are, in turn, referred to as CONUS-El and NA-El.

To form regional averages of T for each sample of grid points (ALL, SONDE, and El), we first divide CONUS and NA into 5° latitude-wide zonal bands and arithmetically average the values of T at the appropriate grid points in each band, in a manner similar to the technique described by Angell (1999, 2000) to obtain zonal average temperature anomalies from station data. The band averages are then weighted here according to the relative area of the band within CONUS or NA. In mathematical terms, we calculate

$$\langle T \rangle = \sum_y a_y \left[\frac{1}{n_y} \sum T(\varphi, \lambda) \right],$$

where $\langle T \rangle$ is the seasonal mean temperature for CONUS or NA, a_y is the ratio of the area of zonal band y to the total area of CONUS or NA, and n_y is the number of values of T at grid points with latitude φ and longitude λ in band y for a given sampling strategy (ALL, SONDE, or El). Note that this approach to computing $\langle T \rangle$ helps mitigate the problem of translating information from the irregular network of SONDE or El points into regional averages.

Finally, from the time series of $\langle T \rangle$ for each region and sampling strategy, we determine the least squares best-fit linear trend in $\langle T \rangle$. We examine its statistical significance with respect to a null trend using a Student's t test that compares the mean of the squared residuals from the trend line with the mean of the squared residuals from the mean, zero-trend line. In addition, we establish an error in a trend estimate by determining the value that is significantly different from the best-fit trend at the 95% level of confidence, according to Student's t distribution.

3. El hypothesis results

Trends in 500-mb temperature averaged over CONUS and NA for each sampling strategy (ALL, SONDE, and El) are reported in Table 2 for each season. Time series of T averaged over CONUS for MAM during 1959–96 and associated linear trends are plotted in Fig. 2 for illustration. In concert with expectations about the increase in greenhouse forcing over this period, all the trends reported in Table 2 are positive, although only those during MAM for some of the samples are significantly so. The trends over North America seem reasonable in light of estimates by Angell (1999) or Lanzante et al. (2003) from radiosonde records, but we avoid overinterpreting the entries in Table 2 in light of the caution offered by Kistler et al. (2001) about the accuracy of trends from reanalysis products. Our interest here, after all, is not in the fidelity of the reanalysis trend values per se, but rather in using the reanalysis to test the sensitivity of trend estimates to spatial sampling. For this purpose, the reanalysis trends appear suitably realistic.

The differences among the sampling strategies in Table 2 are small. Comparing first the difference between SONDE and ALL, in all but one case (NA for DJF) trends for these two samples lie within 0.01 K (decade)$^{-1}$ of each other, suggesting that the current radiosonde network over CONUS and NA is adequate for estimating midtropospheric temperature trends for these regions. The relative sparseness of stations over the northern part of the continent may account for the larger trend difference during DJF for NA, but even this value [0.03 K (decade)$^{-1}$] is modest, representing some 20% of the NA-SONDE trend. Reducing the station distribution further—that is, in going from SONDE to El—has very little additional impact on the trend estimates, according to the differences between the SONDE and El columns in Table 2. Note that because the 14 El stations all lie within CONUS, the impact of removing these stations from the network is relatively larger in CONUS than in NA. The small reduction in the CONUS MAM trend associated with adopting the El sampling strategy is sufficient to cause the value to dip below that nominally required for statistical significance; Nicholls' (2001) argument that such thresholds are artificial is relevant here. More importantly, none of the trends for any strategy over NA or CONUS (including GCOS; see next section) differ significantly from each other in any season, as determined by Student's *t* tests and evident from the error estimates in Table 2.

Inspection of Fig. 3 reveals the explanation for the relatively small differences in Table 2. The structure of the MAM-trend field plotted in the figure, based on the full set of reanalysis grid points (i.e., ALL), is of large enough scale to permit it to be well sampled by both the existing radiosonde network (SONDE) and El. A similar picture holds for the 500-mb temperature trend field in each of the other seasons (Henderson et al. 2002) and for the other two quantities (500-mb temperature variance and precipitable water) we consider but do not show here [see relevant trend maps in Iskenderian and Rosen (2000) and Ross and Elliott (1996), respectively]. We judge that the continental-scale trends in these last two quantities from the ALL, SONDE, and El sampling strategies do not differ significantly from each other during any season.

4. The GCOS strategy

Given the small change in trend estimates accompanying the modest reduction in upper-air stations over CONUS from 78 (SONDE) to 64 (El), the question arises as to the effect a more dramatic station reduction might have. The large spatial scale of the trend field in Fig. 3 suggests that one could adequately sample it with a significantly smaller number of stations and still produce reasonable continental-scale trend estimates. We examine this possibility by subsampling *T* at the 14 North American stations of the Global Climate Observing System (GCOS) Baseline Upper-Air Network (WMO 1996). The radiosonde stations in the GCOS Baseline Upper-Air Network were selected to be relatively evenly distributed over the globe to satisfy future climate monitoring needs, and Fig. 4 shows that, indeed, they are broadly spaced over the North American continent. In light of this distribution and the large-scale background trend field in Fig. 4, we do not expect GCOS estimates of the area-averaged trend to differ greatly from those based on the full radiosonde network.

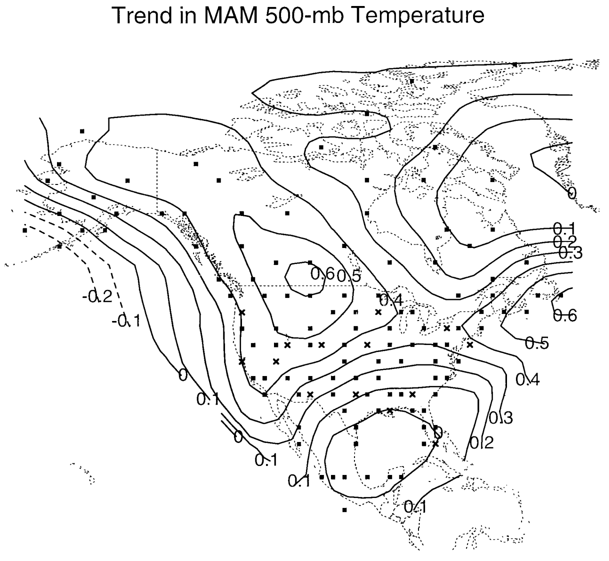

FIG. 3. Map of the trend in seasonal mean 500-mb temperature over North America during MAM 1959–96 based on the full NCEP–NCAR reanalysis (ALL). Isolines are drawn every 0.1 K (decade)$^{-1}$; negative contours are dashed. The boxes and crosses, indicating grid points associated with the SONDE and El station sampling strategies, are as shown in Fig. 1.

Trend results for NA and CONUS for the GCOS sampling strategy are included in Table 2. Aside from the results for SON, when trends for NA are smallest and less than 0.1 K (decade)$^{-1}$, the GCOS and SONDE trend estimates for NA are within 10% of each other. For CONUS, where only six GCOS stations sample the entire region, the largest difference between GCOS and SONDE trends, in DJF, is still less than 20%. It can be noted, however, that the trends from SONDE are closer to the ''truth'' (ALL) than are those from GCOS in six of the eight seasonal results for the two regions.

5. Concluding remarks

To the extent that the NCEP–NCAR reanalysis reproduces the structure of midtropospheric trend fields over North America, then the large-scale nature of these fields allows them to be adequately sampled by both the current radiosonde network and ones that are sparser.

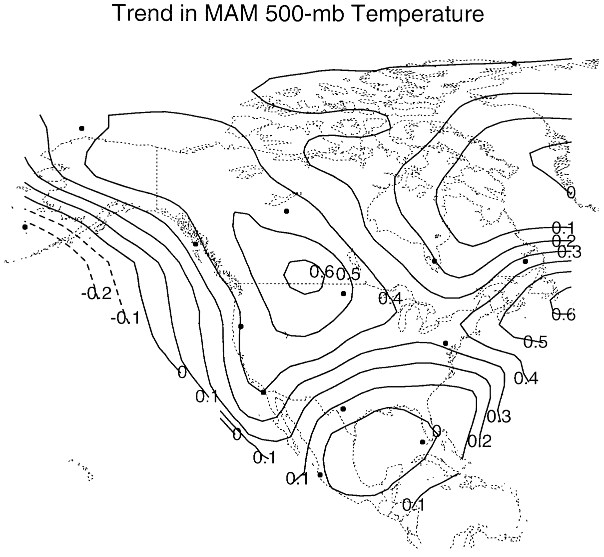

FIG. 4. As in Fig. 3, a map of the trend in seasonal mean 500-mb temperature over North America during MAM 1959–96 based on the full NCEP–NCAR reanalysis (ALL) with isolines drawn every 0.1 K (decade)$^{-1}$ and negative contours dashed. The closed circles indicate grid points lying nearest radiosonde stations in the GCOS network.

In the case of the 500-mb temperature trends highlighted here, differences in continental-scale averages associated with even the large network reduction from SONDE to GCOS remain modest, the largest difference between the two sampling strategies for CONUS amounting (in DJF) to less than 0.05 K (decade)$^{-1}$. Indeed, trends based on the various sampling strategies tested here cannot be distinguished statistically from each other. Note, however, that we did not consider the added impact of missing observations in time, which Trenberth and Olson (1991) warn could significantly amplify errors arising from spatial sampling.

Although our attention here has focused on the robustness of trend estimates, Fig. 2 also suggests that interannual signals in continental-scale averages of 500-mb temperature are not overly sensitive to spatial sampling, in that the three time series shown are correlated at values (when detrended) of 0.95 and higher. On the other hand, the rms difference between the detrended CONUS El and ALL series in the figure is 0.091 K, which is not insubstantial compared to the standard deviation in the detrended ALL series of 0.29 K. Reducing the station network as severely as GCOS can have an even larger impact on measures of interannual variability. Consider the plots similar to Fig. 2 produced by Henderson et al. (2002) for NA that include GCOS time series for each season. Although the NA-GCOS series during MAM, for example, is well correlated with that for NA-ALL ($r = 0.89$), the rms difference between the two detrended series then is 0.15 K compared to a standard deviation in the detrended NA-ALL series of 0.30 K. This difference may be important for certain climate monitoring purposes.

The robustness of continental-scale estimates of trends in 500-mb temperature depends on the large scale of the underlying trend field. Other quantities of interest to the climate research and monitoring communities may be considerably more sensitive, however, to the number and distribution of North American upper-air stations. Trends in regional moisture divergence are a likely example, in light of the results of Yarosh et al. (1999) mentioned in the introduction. The method used here of subsampling gridded analysis fields to simulate proposed reconfigurations of the North American radiosonde network could be applied to such fields so long as the scales involved are adequately represented in the analysis.

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