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Wind speed trends over the contiguous United States

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[1] A comprehensive intercomparison of historical wind speed trends over the contiguous United States is presented based on two observational data sets, four reanalysis data sets, and output from two regional climate models (RCMs). This research thus contributes to detection, quantification, and attribution of temporal trends in wind speeds within the historical/contemporary climate and provides an evaluation of the RCMs being used to develop future wind speed scenarios. Under the assumption that changes in wind climates are partly driven by variability and evolution of the global climate system, such changes should be manifest in direct observations, reanalysis products, and RCMs. However, there are substantial differences in temporal trends derived from observational wind speed data, reanalysis products, and RCMs. The two observational data sets both exhibit an overwhelming dominance of trends toward declining values of the 50th and 90th percentile and annual mean wind speeds, which is also the case for simulations conducted using MM5 with NCEP-2 boundary conditions. However, converse trends are seen in output from the North American Regional Reanalysis, other global reanalyses (NCEP-1 and ERA-40), and the Regional Spectral Model. Equally, the relationship between changing annual mean wind speed and interannual variability is not consistent among the different data sets. NCEP-1 and NARR exhibit some tendency toward declining (increasing) annual mean wind speeds being associated with decreased (increased) interannual variability, but this is not the case for the other data sets considered. Possible causes of the differences in temporal trends from the eight data sources analyzed are provided.

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1. Motivation and Objectives

[2] Wind speed time series have been subject to far fewer trend analyses than temperature and precipitation records [*Gower*, 2002; *Keimig and Bradley*, 2002; *McAvaney et al.*, 2001; *McVicar et al.*, 2008; *Pirazzoli and Tomasin*, 1999, 2003; *Pryor and Barthelmie*, 2003; *Tuller*, 2004; *Brazdil et al.*, 2009], in part because of data homogeneity issues [*Thomas et al.*, 2008; *Tuller*, 2004; *DeGaetano*, 1998]. However, understanding how evolution of the global climate system has been manifest as changes in near-surface wind regimes in the past and how near-surface wind speed regimes might alter in the future is of great relevance to the insurance industry [*Changnon et al.*, 1999; *Thornes*, 1991], the construction and maritime industries [*Ambrose and Vergun*, 1997; *Caires and Sterl*, 2005; *Caires et al.*, 2006], surface energy balance estimation [*Rayner*, 2007], the community charged with mitigating coastal erosion [*Bijl*, 1997; *Viles and Goudie*, 2003], the agricultural industry [*O'Neal et al.*, 2005], forest and infrastructure protection communities [*Jungo et al.*, 2002], and the burgeoning wind energy industry [*Pryor et al.*, 2006b]. With respect to the latter, it is worth noting that during 2005–2008 over 18,000 MW of wind energy developments came online in the continental United States, increasing installed capacity to over 25 GW (AWEA wind energy fact sheets: Another record year for new wind installations, American Wind Energy Association, 2009, available at http://www.awea.org/pubs/factsheets/Market_Update.pdf). Many factors dictate the deployment and success of wind farm developments [*Barthelmie*, 2007], but because energy density is proportional to the cube of the wind speed, comparatively small changes in the wind speed at turbine hub height have large consequences for power production and hence for the overall economics of wind projects. In the context of wind energy applications, it is necessary to estimate the power output over the 20–30 year lifetime of the wind farm for economic feasibility [*Pryor et al.*, 2006a]. Thus questions that arise that can be paraphrased as "what is the current energy density and interannual variability in

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likely power production and will nonstationarities in the global climate system cause that variability or magnitude of a normal wind year to evolve on timescales of relevance to wind energy developments?'' [*Pryor et al.*, 2005a, 2005b, 2005c].

[3] Studies that have analyzed wind speed data from terrestrial anemometers have generally found declines over the last 30–50 years (see summary in the work of *McVicar et al.* [2008] and *Brazdil et al.* [2009]), the cause of which is currently uncertain. In part because of the difficulties in developing long, homogeneous records of observed near-surface wind speeds, reanalysis data have also been used to quantify historical trends and variability in near-surface wind speeds either in conjunction with in situ observations or independent thereof [*Hundecha et al.*, 2008; *McVicar et al.*, 2008; *Pryor and Barthelmie*, 2003; *Trigo et al.*, 2008]. However, temporal trends in these data sets are not always in agreement in terms of the presence, magnitude, or even sign of temporal changes. In one study of near-surface wind speeds over Australia from 1979 to 2001, *McVicar et al.* [2008, p. 2] report wind speed (u) trends from observations were ''poorly captured'' by data from the ERA-40, NCEP/NCAR, and NCEP/DOE reanalyses, leading the authors to remark ''This suggests: (i) changes in the reanalysis data assimilation have acted to mask the observed u changes; and/or (ii) an inadequate representation of key boundary-layer parameters in the reanalysis systems that govern u estimation.'' Further, comparisons of the NCEP and ERA-40 reanalysis near-surface winds with satellite and buoy derived wind speeds over oceans showed that reanalysis output was biased low, and temporal trends in in situ ship-based observations were of larger magnitude than those from the reanalyses [*Thomas et al.*, 2008]. Results from a recent study over the Netherlands also concluded that [*Smits et al.*, 2005, p. 1331]

> moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year) indicate a decrease in storminess over the Netherlands between 5 and 10%/decade. This result is inconsistent with National Centers for Environmental Prediction-National Center for Atmospheric Research or European Centre for Medium-Range Weather Forecasts reanalysis data, which suggest increased storminess during the same 41 year period.

These previous analyses motivated, in part, the current research which seeks in part to evaluate and intercompare an extensive range of wind speed data sets over the contiguous United States. Additionally, cognizant that the principal tools available for generating future scenarios of wind speed climates are empirical downscaling transfer functions applied to output from coupled atmosphere-ocean general circulation models [*Pryor et al.*, 2006b] or regional climate models (RCMs) [*Pryor et al.*, 2005a], here we also evaluate the consistency of temporal trends derived for the historical/contemporary climate using RCMs and assess the degree of similarity to statistics from observational data. If RCMs exhibit skill in reproducing variability and trends in the historical period this will increase confidence in future wind climate projections developed with these tools.

[4] In addition to seeking to quantify historical trends in wind speeds over the contiguous United States, and specifically the consistency of temporal trends derived from in situ observations, reanalysis data sets, and output from RCMs, we also examine a possibly related change, alterations in the interannual variability of near-surface wind speeds. This low-frequency variability of wind speeds is a key parameter for linking to climate evolution and is important in the context of wind energy because it may influence the economics by altering the long-term power generation capacity and/or the consistency of electricity supply. This component of the research derives from questions that have been raised regarding whether a temporal trend in the central tendency of the probability distribution of a geophysical variable will be, or is, associated with a change in variability [*Meehl et al.*, 2000]. One can envisage three cases for a normally distributed variable: (1) a change in the mean without a change in variance, (2) solely a change in variance, and (3) a change in mean and variance (which may or may not show the same sign). Annual mean wind speeds at a given site or grid cell fairly closely approximate a Gaussian distribution and hence it is appropriate and meaningful to compute a variance. Since wind speed is zero-bounded, there might reasonably be an expectation that increases in annual mean wind speed would be associated with increased interannual variability. Hence in this research we focus on annual mean wind speeds and ask the question, have changes in the annual mean wind speed (if present in the data sets considered) been associated with changes in variability?

[5] Herein we analyze 10-m wind speeds from a variety of observational data sets, reanalysis products, and regional climate model (RCM) simulations of the historical period.

[6] 1. We use these data to quantify the magnitude and statistical significance of historical trends in wind speeds and the consistency (or not) of trends derived using different data sets, direct observations, reanalysis products, and output from RCMs. As a component of this analysis we provide preliminary diagnoses of possible causes of temporal trends in the in situ observations. Specifically, we examine trends in terms of their temporal and spatial signatures and the role that major instrumentation changes may have played in dictating those trends.

[7] 2. We analyze these data to address whether trends in the mean wind climate (represented by the annual mean wind speed) at given stations or in specific grid cells in the various data sets have been associated with changes in the variance of annual mean wind speeds (i.e., interannual variability).

2. Data and Methods

2.1. Data

[8] Wind speed time series from eight sources are analyzed here:

[9] 1. Observations of near-surface wind speeds from two National Climate Data Center (NCDC) data sets containing land-based sites across the contiguous United States. Although the observational data records are nominally hourly, at least in the initial part of the study period at many sites the data were actually archived at three hourly intervals or only during daylight hours. Accordingly throughout this analysis we focus on wind speeds from 0000 UTC and 1200 UTC and initially analyze data from these two observation times separately to examine if there is any ''time of observation'' bias in observed temporal trends.

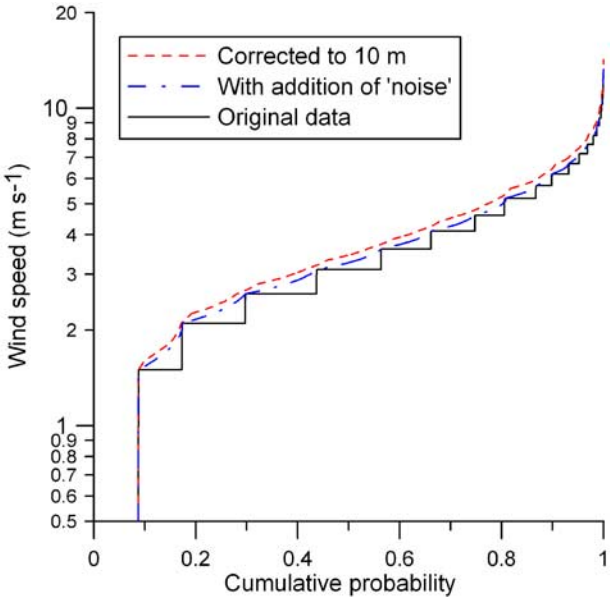

Figure 1. Cumulative probability distribution of wind speeds for 0000 UTC observations at site 724320 (Evansville regional airport in southwestern Indiana) in the raw data from the DS3505 data set, with lognormally distributed white noise added and then adjusted to a nominal measurement height of 10 m.

As mentioned above, observational records of wind speed are subject to data inhomogeneities associated with the introduction of new measurement technologies or protocols. One such example is the deployment of the Automated Surface Observing System (ASOS) which commenced in the early 1990s. The frequencies with which extreme and calm winds were reported significantly altered with the introduction of ASOS instrumentation. An analysis of 12 stations showed ASOS derived wind speeds were an average of 0.2 m s^{-1} lower than with the prior observing system, with a range of -0.65 m s^{-1} to 0.15 m s^{-1}, though the higher wind speeds were higher from the ASOS instrumentation [*McKee et al.*, 2000]. In the data description accompaniment to one of the two observational data sets used herein (NCDC-6421) *Groisman* [2002, p. 14] notes "we recommend excluding these data from any possible assessments that involve extreme and low wind analyses." We did not attempt to correct for these inhomogeneities, but their presence strongly argues for use of the other data sets considered herein. A further characteristic of note that pertains to both observational data sets is that wind speed data are reported in whole knots (the ASOS anemometers are rated to ±2 knots from 0 to 125 knots, http://www.nws.noaa.gov/asos/pdfs/aum-toc.pdf). The result is that the wind speed data are not continuous (but rather categorical with an approximate interval of 0.5 m s^{-1}). Wind speed time series are also frequently discontinuous in the time domain. In both observational data sets we consider only sites/grid cells where over 300 possible observations are present in every year of record for the analyses based on the 0000 and 1200 UTC, and 600 observations are present for analyses using data from both 0000 and 1200 UTC. In both cases a further constraint was applied: that more than two thirds of valid observations are available in each climatological season of each year. The two NCDC data sets are as follows:

[10] The first data set is the NCDC-6421 data set "Enhanced hourly wind station data for the contiguous United States" [*Groisman*, 2002]. In the documentation for this data set Groisman indicates that data from 1655 stations over the contiguous United States were homogenized to a nominal measurement height of 10 m above ground level (agl) using local knowledge of the surface roughness length around the site and land cover (i.e., the presence or absence of snow) in combination with the logarithmic wind profile. The data were also scrutinized based on knowledge regarding station moves and data control flags. Observations from this data set are used as provided and were extracted for the period 1973–2000, inclusive, owing to the increase in the number of stations with valid data from fewer than 500 to over in 800 in 1973 [*Groisman*, 2002]. After applying our data selection criteria described above, records from 336 stations were subject to the trend analyses.

[11] The second data set is the near-surface wind speeds from land-based sites across the contiguous United States extracted from the online data archive held by NCDC (http://www.ncdc.noaa.gov/oa/mpp/freedata.html, DS3505 surface data, global hourly). Data were obtained by the authors for all land based sites that have records from 1973 to 2005, along with comprehensive station histories. Valid data that passed all NCDC data quality control procedures were selected for sites where the station histories (including anemometer height) were available and indicated the station had not moved more than 5 km over the study period. The data selection criteria resulted in time series from 193 stations being available for analysis. All stations are airports (190) or military installations (3). One hundred and eighty of these stations are also represented in the NCDC-6421 data set. As mentioned above, the data as stored in the NCDC archive are not continuous. This can result in problems with use of linear trend analyses; hence lognormally distributed random numbers were added to the time series to "recover" some of the missing variability inherent in wind speeds but lost when the data were stored at a resolution of 1 knot (Figure 1). Additionally, not all wind speed data were collected at 10 m above the ground and several anemometer heights changed during the study period, so we corrected the data to a common measurement height of 10 m based on the recorded anemometer heights and the power law wind profile using an exponent (α) of 1/7 [*Manwell et al.*, 2002]. Application of this approximation assumes near-neutral stability and a flat relatively smooth surface around the sites [*Emeis*, 2005], and hence will vary with time and station location. However, the correction to 10 m is relatively small for most measurement heights encountered in the data records, so this correction was deemed adequate (Figure 1).

[12] 2. Near-surface (10-m) U (west–east) and V (south–north) components of the flow were extracted from four reanalysis data sets. Reanalysis projects such those used herein draw data from a range of sources, which are quality controlled and assimilated with a consistent data simulation system (models). These reanalysis products are thus a hybrid of the observations that are assimilated and "background" information used to provide complete representations of the atmosphere that are derived from a short-range

forecast initiated from the most recent previous analysis. The data and forecasts are integrated using error statistics, and the reanalysis products thus comprise four-dimensional, homogenized, and systematic data sets. The degree of dependence on (and to some degree, association with) observations depends on the density and relative accuracy of the observations, the error statistics which map the observations onto the model state variables, and the dynamics and physics of the forecast model and thus is variable with geophysical parameter [*Kalnay et al.*, 1996; *Kanamitsu et al.*, 2002; *Kistler et al.*, 2001; *Uppala et al.*, 2005]. The reanalysis output and observational station wind speed time series are analyzed separately herein, and the results are intercompared because while the reanalysis procedures integrate surface observations (other than surface terrestrial wind speeds) they also assimilate data from other sources. The reanalysis products have been extensively evaluated and intercompared both by the groups that derive them and independent researchers [*Cooter et al.*, 2007; *Dell'Aquila et al.*, 2007; *Kanamitsu et al.*, 2002; *Song and Zhang*, 2007; *Wang et al.*, 2006; *Zhao and Fu*, 2006]. Three key aspects of the reanalysis systems in terms of their depiction of near-surface wind speeds: the formulation (and spatial resolution) of the numerical model, assimilated data, and the method of vertical extrapolation from the lowest model level to winds at 10-m height are described below for each of the reanalysis products used herein:

[13] First is the NCEP-NCAR reanalysis data archive (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html) for 1948–2006, inclusive [*Kalnay et al.*, 1996]. This data set is referred to as NCEP-1. The reanalysis system characterizes surface fields at a spatial resolution $\sim 2.5 \times 2.5°$ and at 28 vertical levels. Of particular relevance to the simulation of near-surface wind speeds, the surface roughness length over land used in the model system is derived from climatology. The wind components at 10 m is designated in the B classes of variables by *Kalnay et al.* [1996, p. 426] which indicates that "although there are observational data that directly affects the value of the variable, the model also has a very strong influence on the analysis value." However, observed land-based surface winds are not among the variables assimilated. Rather, surface winds are obtained from a downward extrapolation of lowest model winds by use of Monin-Obukhov similarity theory. The model has five levels within the lowest 100 mb with the lowest being at sigma level 0.995. Surface roughness lengths are seasonally dependent as described by *Dorman and Sellers* [1989] but do not account for species changes or interannual phenological changes.

[14] Second is the NCEP-DOE reanalysis data (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html) for 1979–2006 (the data record starts in 1979), inclusive [*Kanamitsu et al.*, 2002]. This data set is referred to as NCEP-2 and the 10-m wind components used herein have a resolution $\sim 1.9 \times 1.9°$. NCEP reanalysis 2 was undertaken in response to several issues and errors in the NCEP/NCAR reanalysis 1 model and products. This reanalysis product has the same resolution as NCEP/NCAR (T62 with 28 vertical sigma levels) and relies on assimilation of the same raw observations, although certain improvements were made. Those that have principal importance for near-surface flow are smoothed orography, different boundary layer parameterizations (see http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm), and changes in the parameterization of soil moisture. The 10-m winds are derived from the wind components at the lowest model level, a surface roughness length from climatology, and the surface layer formulation based on Monin-Obukhov similarity theory (M. Kanamitsu, personal communication, 2008).

[15] Third is the ERA-40 reanalysis data set [*Uppala et al.*, 2005]. This data set is referred to as ERA-40, and the 10-m wind components used herein have a resolution of $\sim 2.5 \times 2.5°$. Although the ERA-40 reanalysis products are available for the period 1957 to 2002 (the reanalysis product ends in the middle of 2002), data were only extracted for 1973–2001, inclusive, owing to a major change in assimilated data that occurred in 1973, and a dramatic increase in the number of wind observations assimilated over the Northern Hemisphere between 1967 and 1972 and 1973–1978 [*Uppala et al.*, 2005]. It also is noteworthy that for the ERA-40 derived wind speeds there was no variation over time in the model's land cover characteristics, but a coupled wind-wave model was implemented [*Uppala et al.*, 2005]. Only the surface wind observations from the ocean are used in the data assimilation for ERA-40, owing to concerns regarding the representativeness of land-based observations. Thus as for the NCEP reanalysis products described above, the near-surface winds within in ERA-40 are most strongly dependent on the assimilated upper air wind and temperature observations, surface pressure observations, and, of course, the boundary layer scheme including land description. Over land, surface roughness lengths are assumed to be fixed climatological fields derived from land-use maps, with an extra contribution dependent on the variance of subgrid scale orography (see description in chapter 9 of http://www.ecmwf.int/research/ifsdocs/PHYSICS/). Post-processing to generate the 10-m wind components over land takes the wind speed at a height of 75 m and interpolates it vertically assuming a roughness length of 0.03 m and applying a stability correction based on the Monin-Obhukov length scale. As a consequence "10 meter u and v fields can be characterized as "B" variables" (S. Uppala, personal communication, 2008). As mentioned above, a key issue in the use of wind components from reanalysis products is that there is tremendous evolution in the number and nature of assimilated data sources over the period of record considered here [see, e.g., *Uppala et al.*, 2005, Figure 1]. Near-surface wind speeds are inherently difficult to model due to the high spatial variability, influence of local obstacles, and relative scarcity of observations. As just one example, previous analyses of ERA-15 near-surface wind speeds indicated a negative bias over oceanic surfaces. According to *Uppala et al.* [2005, p. 2974],

> [these] deficiencies were subsequently corrected by changes to the assimilation system. Unrepresentative island wind observations were no longer used, and ship winds were applied at the anemometer height where known and otherwise as a more representative height than 10 m…Surface winds in the later years of ERA-40 also benefit directly from the assimilation of scatterometer and SSM/I data, and indirectly from interaction with the ocean-wave model that in turn benefits from the assimilation of altimeter measurements of ocean-wave height.

Accordingly, wind speeds over ocean surfaces are generally higher in ERA-40 than ERA-15 [*Uppala et al.*, 2005] although, as in our prior analysis of wind speeds over Europe, there is a substantial negative bias in ERA-40 wind speeds over the contiguous United States relative to the NCEP reanalyses (see below for an example of the mean wind speeds during the period of overlap). This finding may be explained by prior research that found ‘‘significantly weaker cyclone activity over the leeside of the Rocky Mountains in all seasons,’’ a feature the authors attribute to ‘‘the subgrid scale orographic parameterization used in ERA-40’’ [*Wang et al.*, 2006, p. 3149].

[16] Fourth is the North American Regional Reanalysis. This data set is referred to as NARR. Reanalysis output for the two 10-m wind components at a resolution of $\sim$32 $\times$ 32 km were extracted for 1979–2006 from the NARR-A output. Lateral boundary conditions for NARR are derived from the NCEP–DOE Global Reanalysis (NCEP-2). Key modifications relative to other previous reanalyses pertain to the NCEP Eta Model and its Data Assimilation System, ‘‘and the use of numerous datasets additional to or improved compared to those of the global reanalyses’’ [*Mesinger et al.*, 2006, p. 343]. Key assimilated data sets in NARR that are not used in the NCEP-2 global reanalysis are NCEP surface wind from the GR2 data set and MDL surface pressure and wind from NCAR [*Mesinger et al.*, 2006]. Further, the topography was specified at the model resolution of 32 km, and atmosphere-surface interactions are specified using a recent version of the Noah land-surface model [*Radell and Rowe*, 2008; K. T. Mitchell, The community NOAH land-surface model user’s guide version 2.7.1, ftp://ftp.emc.ncep.noaa.gov/mmb/gcp/ldas/noahlsm/ver_2.7.1/Noah_LSM_USERGUIDE_2.7.1.htm]. Surface roughness length is time invariant and comprises a fixed value of 0.1 m plus a correction for orographic effects (D. Jovic, personal communication, 2008). The vertical extrapolation from the lowest of the 45 model layers to 10 m is stability corrected following the procedure outlined by *Lobocki* [1993] and is described by *Chuang et al.* [2001]. The resulting near-surface wind fields were subject to evaluation by the NARR team. Daily average 10-m wind speeds from about 450 stations across the continental United States for 2 months (January 1988 and July 1988) indicate daily average biases are mostly negative but below 1 m s^{-1} and the typical daily average RMSE is below 4 m s^{-1} [*Mesinger et al.*, 2006].

[17] 3. Near-surface (10-m) U (west–east) and V (south–north) components of the flow were extracted from two Regional Climate Models (RCMs) run for 1979–2004 as part of the North American Regional Climate Change Assessment Program (NARCCAP) using boundary conditions from NCEP-2 [*Mearns et al.*, 2005]. Output from two RCMs is used herein:

[18] First, MM5 [*Grell et al.*, 1995] is a nonhydrostatic incompressible grid point model. It represents coupling of energy and moisture flow between the atmosphere and land surface by use of the Noah land surface model with 16 classes of vegetation, each having its own surface roughness, as describe for the SiB model [*Dorman and Sellers*, 1989]. The model was run with a horizontal grid spacing of 52 km.

[19] Second, RSM [*Juang et al.*, 1997] is a hydrostatic incompressible spectral model that also uses the improved Noah land surface model [*Ek et al.*, 2003] with 13 vegetation classes. It was run with an equivalent grid spacing of 50 km.

[20] As shown herein, there are substantial differences in wind speeds and trends generated by these two RCMs for 1979–2004. In considering these discrepancies it is important to note that a fundamental difference between spectral and grid point models is that spectral models such as the RSM continuously use the large-scale fields of a global spectral model over the full regional domain and calculate the perturbation from this large-scale field to represent regional-scale processes. Grid point models such as MM5, by contrast, use large-scale fields only in the forcing frame at the lateral boundaries.

[21] Contrasting the three classes of 10-m wind speed data used herein, it is instructive to reflect on their individual strengths and weaknesses. Observational data are essentially free from parameterizations but are subject to inhomogeneities resulting from changes in instrumentation, instrument malfunction, station moves, changes in land use, or obstacles around the station and are limited by substantial missing data and the data resolution in the context of computing robust temporal trends. Additionally, observational sites may or may not be regionally representative. Conversely, the reanalysis simulation packages ensure the data sets are homogenous and complete, but near-surface wind speeds are, as discussed above, strongly influenced by model physics and data that are assimilated. The global reanalysis models are designed to run at much lower spatial resolution than can capture all the features that dictate near-surface flow fields. Resultant near-surface wind climates from these reanalysis products are likely to be ‘‘best’’ in contexts with strong synoptic forcing with little topographic forcing (e.g., over much of the eastern United States), and least skillful where thermotopographic effects are strongest (e.g., over much of the western United States). Last, RCM do not benefit from data assimilation (at least in the simulations presented here), but like NARR are run at higher spatial resolution than the global reanalyses. Naturally, both the RCMs and regional reanalyses are sensitive to the boundary conditions applied [*Pryor et al.*, 2005a].

2.2. Methodology

[22] Wind speed time series exhibit variability on multiple temporal scales (from seconds to millennia). Here we focus on the annual timescale. For the initial trend analysis, cognizant of the issues with low and very high wind speeds in the observational data sets (see discussion in section 2.1), we focus our analyses on the 50th and 90th percentiles of the wind speed distribution and the annual mean wind speed. In each case the percentiles are computed using the 0000 and 1200 UTC observations or model output from each day of each year. The resulting time series are analyzed for trends using linear regression and bootstrapping techniques to determine whether trends are robust to the stochastic effects in the time series. In brief, this involves bootstrap resampling of the residuals from the linear regression analysis of annual Xth percentile wind speed on year. These residuals are randomly selected using a bootstrapping technique and added onto the linear fit line from the trend analysis and the trend is reestimated [*Kiktev et al.*, 2003]. This procedure is repeated 1000 times to generate 1000

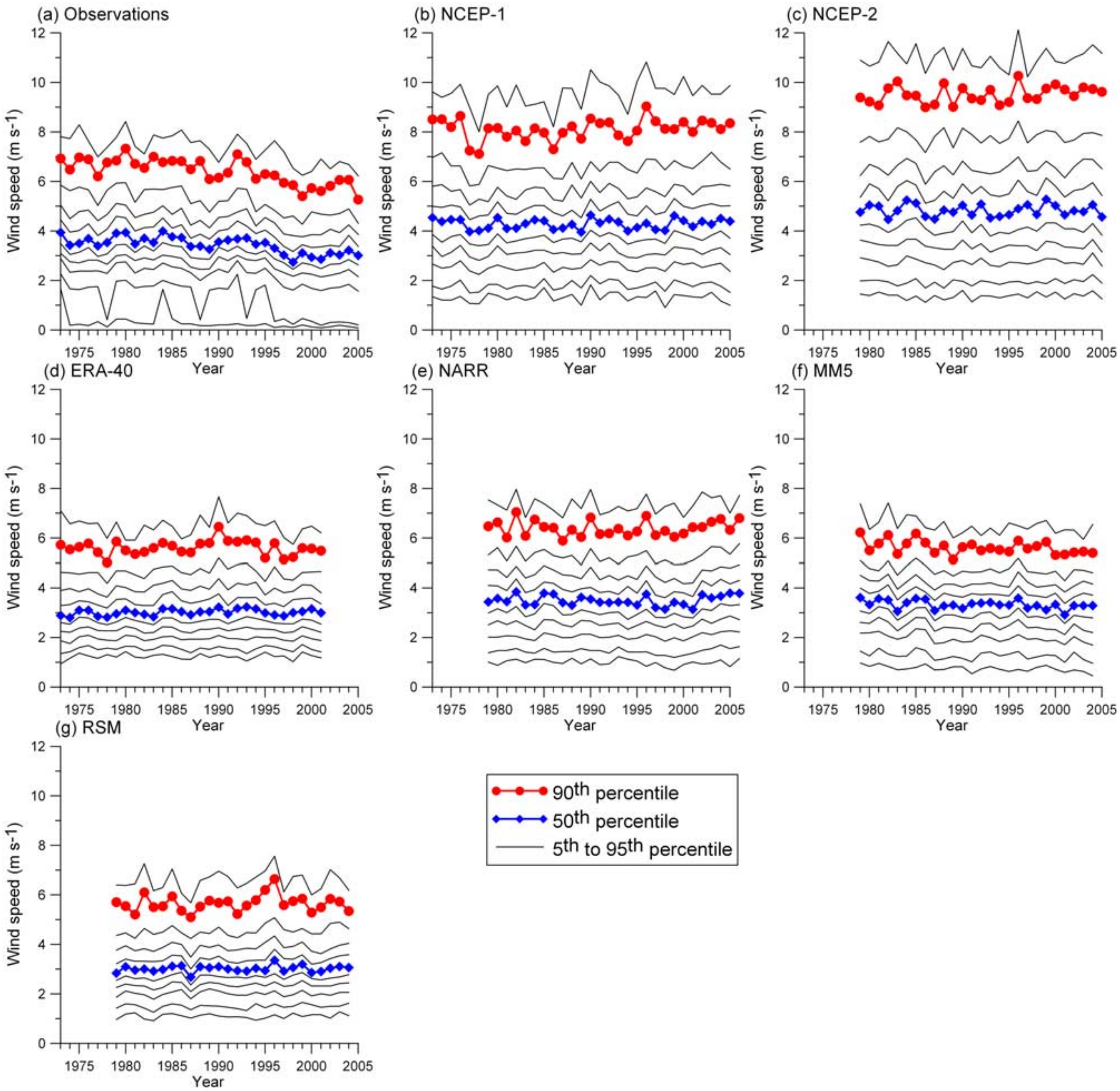

Figure 2. (a) Annual percentiles for 1200 UTC observations from site 724320 (5th, 10th, 20th . . . 90th, 95th percentile, where the 50th and 90th percentiles are shown in the blue and red, respectively). Despite considerable interannual variability, data from this station (in DS3505) exhibit a significant downward trend in both the 50th percentile (of approximately 0.7%/year) and the 90th percentile (of approximately 0.6%/year) wind speed. (b–g) Output from the other data sources used herein for the grid cell containing Evansville.

plausible trends for each station/grid cell. If a zero trend falls within the middle 900 values in an ordered sequence of the distribution of 1000 realizations the trend is not significant at the 90% confidence level. In each case the magnitude of the trend is evaluated as the slope term in the regression analysis determined using the original time series of annual percentiles (see the examples given in Figure 2).

[23] Note, as discussed above, the wind speed time series from the various data sets, reanalysis products, and the RCM cover different temporal windows. Rather than truncate all to a common time period (which would cover only a 22-year period, 1979–2000), in the trend analysis we analyze all data sets independently for their respective time periods and then use the NCEP-1 output to contextualize the shorter time periods.

[24] For the analysis of interannual variability, we compute the annual mean wind speed in each year of record from each individual station or grid cell, and then use a 7-year window to compute the interannual variability which is assigned to the central year. Thus for 1990 the mean wind speed is computed using all data from that year, and the interannual variability ascribed to 1990 is computed as the

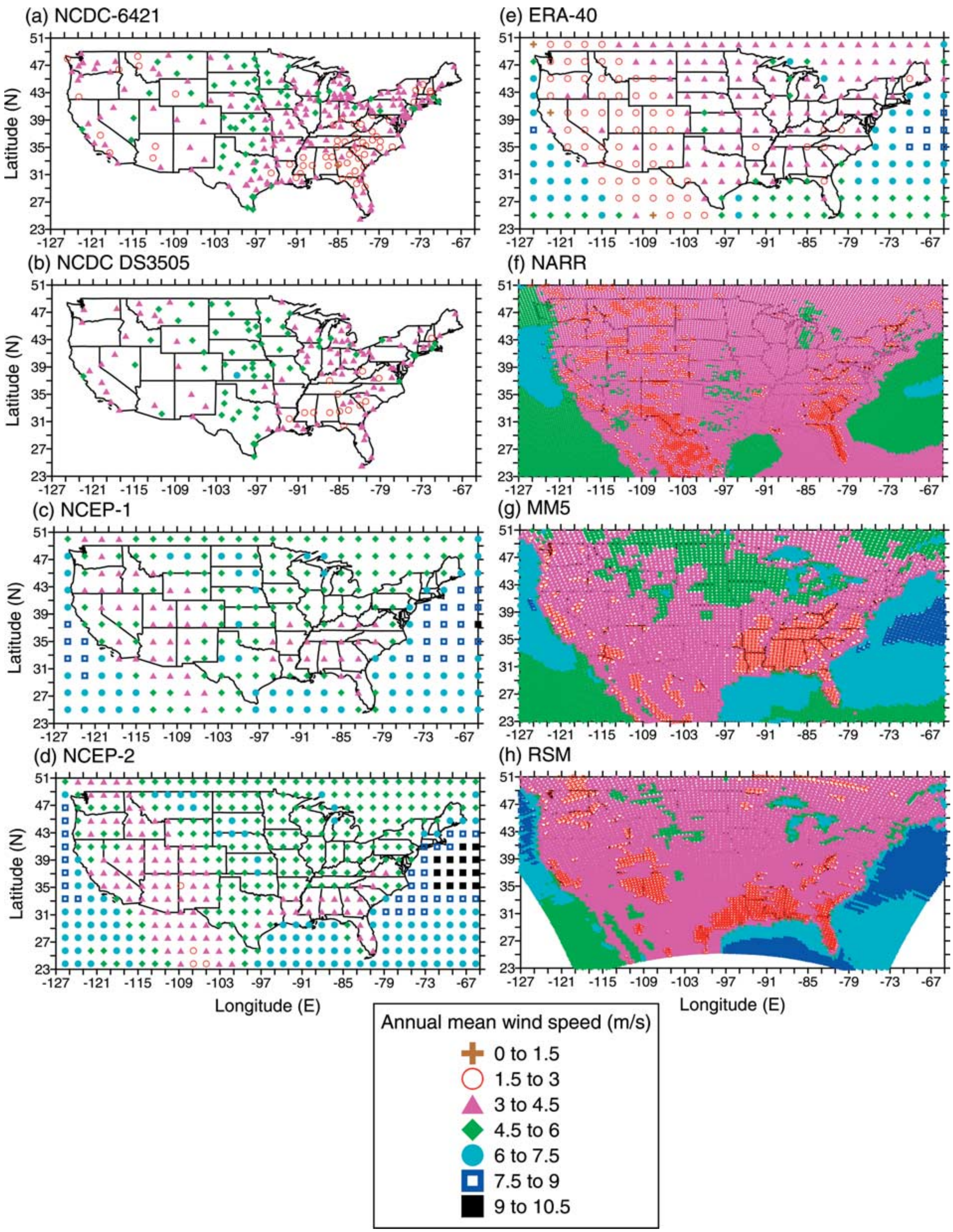

Figure 3. Average of annual mean wind speeds 1979–2000 from (a) NCDC-6421, (b) NCDC DS3505 (modified as described herein), (c) NCEP-1, (d) NCEP-2, (e) ERA-40, (f) NARR, (g) MM5, and (h) RSM.

standard deviation of the seven annual mean wind speeds from 1987 to 1993, inclusive. These estimates of variability and the time series of annual mean wind speed are then subject to a trend analysis similar to that described for the percentiles.

3. Results

3.1. Comparison of Mean Wind Speeds During the Contemporary Climate

[25] Even though a 22-year period is not sufficient to provide a stable climatology (even in the absence of climate nonstationarity), to provide an initial intercomparison of the data sets an average annual mean wind speed was computed for the period of overlap (1979–2000). As expected, the mean annual mean wind speed from the two observational data sets exhibit a high degree of correspondence as do the reanalysis output (Figure 3). However, there is evidence of a negative bias in the ERA-40 wind speeds relative to the other global reanalyses. Also, in accord with the analyses conducted by the NARR team [*Mesinger et al.*, 2006], the annual mean wind speeds from NARR appear negatively biased relative to the station observations. The RSM simulates lower wind speeds over the north central United States and Canada than are manifest in the MM5 simulation or the NCEP-2 simulation used to provide the large-scale fields used in the RCM simulations. The discrepancies in mean wind speed evident in Figure 3 derive from multiple sources such as differences in the orographic properties of the model fields, spatial resolution, and vertical interpolation of the wind speeds to 10 m. While they are noteworthy in their own right, these discrepancies do not preclude use of these wind speed data sources for trend analyses since it is a presumption of such analyses that if near-surface flow regimes have evolved as a consequence of a changing global climate, at least part of that signal will be due to changes in atmospheric dynamics at the synoptic or larger scale [*Gower*, 2002; *Pirazzoli and Tomasin*, 1999; *Pryor and Barthelmie*, 2003]. Such a change should be manifest in all data sets particularly in the eastern United States where the synoptic scale forcing typically dominates [*Hodges et al.*, 2003], the terrain is generally less complex and thermo-topographic flows are generally weaker.

3.2. Are There Temporal Trends in Annual 50th and 90th Percentile Wind Speeds Over the Contiguous United States?

[26] An example of the trend analysis as applied to observational time series from the NCDC DS3505 data set for a single station in southern Indiana (Evansville regional airport) is given in Figure 2a. As shown, there is considerable interannual variability in the magnitude of the percentile values, but at this site, as at the majority of those studied (Figures 4 and 5), both the 50th and 90th percentile wind speeds in both of the observational data sets exhibit statistically significant declines over the period 1973–2000 (NCDC-6421 data) or 1973–2005 (NCDC DS3505 data modified as described in section 2.1). Figure 2a also reemphasizes the change in low wind speeds associated with introduction of the ASOS instrumentation. At this site the 5th and 10th percentile wind speeds drop to almost zero after the introduction of the new firmware (Figure 2a). However, the discontinuity is considerably less evident in the higher percentiles. The downward trend in 50th and 90th percentile wind speeds that is evident in the in situ observations from this site is not observed in time series of grid cell average wind speeds from the reanalysis products or either RCM (Figure 2). In this grid cell as in the majority of those studied herein, the annual percentiles from the reanalysis products do not appear to be characterized by marked discontinuities within the 1973–2005 period (or indeed the periods of record from each reanalysis product), possibly indicating evolution of the reanalysis systems did not play a major role in dictating the temporal trends presented herein. For this station the wind speed percentiles from both RCMs and NARR exhibit closer accord with the observations than is evident in the NCEP-2 reanalysis that provides the boundary conditions for these models, possibly due to the higher spatial resolution, though the ERA-40 output also appears to replicate the wind speed distribution relatively well.

[27] When observations from the NCDC DS3505 data set are analyzed for trends at all 193 stations, 150 exhibit declines in the 0000 UTC 50th percentile values, 33 stations exhibit no trend, and only 10 stations exhibit increases. In the 1200 UTC time series 146 stations exhibit declines in the 90th percentile wind speeds, 36 stations exhibit no trend, and 11 stations exhibit increases (Figures 4 and 5). Similar results are found for the NCDC 6421 data set. These results thus indicate a prevalence of trends toward decreasing wind speeds over the period of study, 1973–2000 or 1973–2005. There is no evidence for substantially different trend signs or magnitude with hour of observation (cf. Figures 4 and 5). Additionally, the trends when expressed in percent per year are generally slightly larger for the 50th percentile than the 90th percentile values as might be expected if due to changes in the cut-in wind speed of the anemometers.

[28] Trends in the 50th and 90th percentile wind speeds derived independently for stations common to the NCDC 6421 and DS3505 data sets exhibit a high degree of similarity. Temporal trends in both percentiles from all the 180 stations common to the NCDC-6421 and NCDC DS3505 data sets exhibit correlation coefficients above 0.9. The average ratio of derived temporal trends is 0.85 ± 0.36 (mean ± 1 standard deviation) for the 50th percentile wind speeds and 0.84 ± 0.32 for the 90th percentile wind speeds, with the NCDC-6421 data exhibiting slightly higher magnitude trends on average. The differences in trend magnitudes from the two data sets may reflect the slightly different data periods, 1973–2000 (NCDC-6421) versus 1973–2005 (NCDC DS3505), and emphasize that the different treatment of the data in terms of extrapolation from the actual measurement height to 10 m, and corrections for data truncation have only a modest impact on the trend results.

[29] There is considerable spatial variability across the contiguous United States in terms of the season characterized by highest wind speeds [*Klink*, 1999a], but trends in the 50th and 90th percentile observed wind speeds do not exhibit well-defined seasonality (see the example given in Figure 6 for data from the NCDC 6421 data set). Downward trends dominate both percentiles computed for all seasons and are of comparable magnitude in all seasons. This uniformity of temporal trends across percentiles, time (seasonally), and space does not preclude a dynamical cause(s)

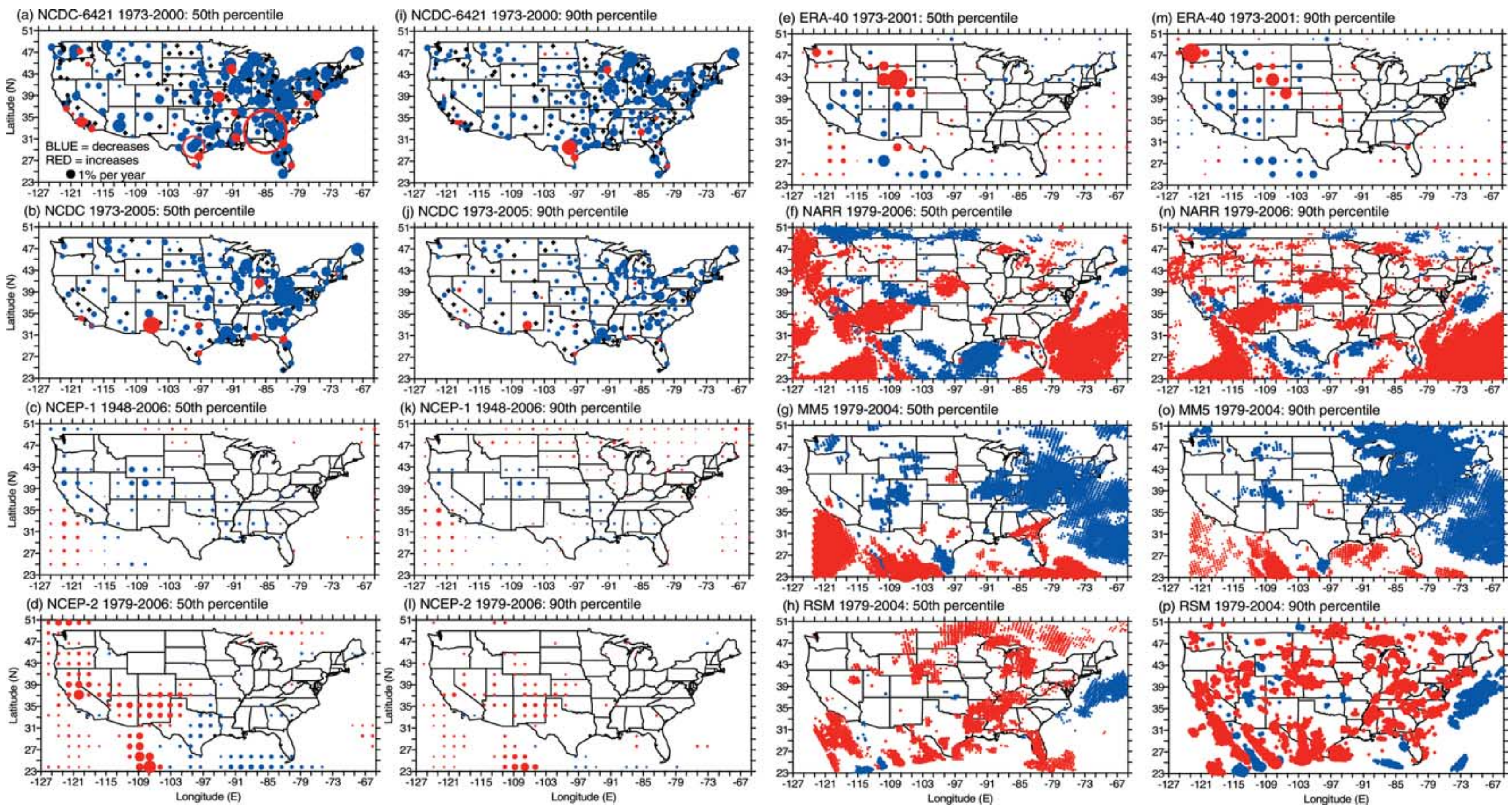

Figure 4. Results of the trend analysis applied to data from 0000 UTC. The individual frames show results for the 50th percentile wind speed from (a) NCDC-6421 (1973–2000), (b) NCDC DS3505 (1973–2005), (c) NCEP-1 (1948–2006), (d) NCEP-2 (1979–2006), (e) ERA-40 (1973–2001), (f) NARR output (1979–2006), (g) MM5 output (1979–2004), (h) RSM output (1979–2004), and the 90th percentile wind speed from (i) NCDC-6421 (1973–2000), (j) NCDC DS3505 (1973–2005), (k) NCEP-1 (1948–2006), (l) NCEP-2 (1979–2006), (m) ERA-40 (1973–2001), (n) NARR (1979–2006), (o) MM5 output (1979–2004), and (p) RSM output (1979–2004). In each frame the size of the dot scales linearly with the magnitude of the trend and the color of the dot indicates the sign of the trend (scale as shown in Figure 4a). To enhance the legibility of this figure, stations that exhibit a trend in excess of 2%/yr are shown by open circles. Where the station time series did not indicate a statistically significant trend a plus symbol is shown. Where time series from a reanalysis or RCM grid cell did not exhibit a trend no symbol is shown.

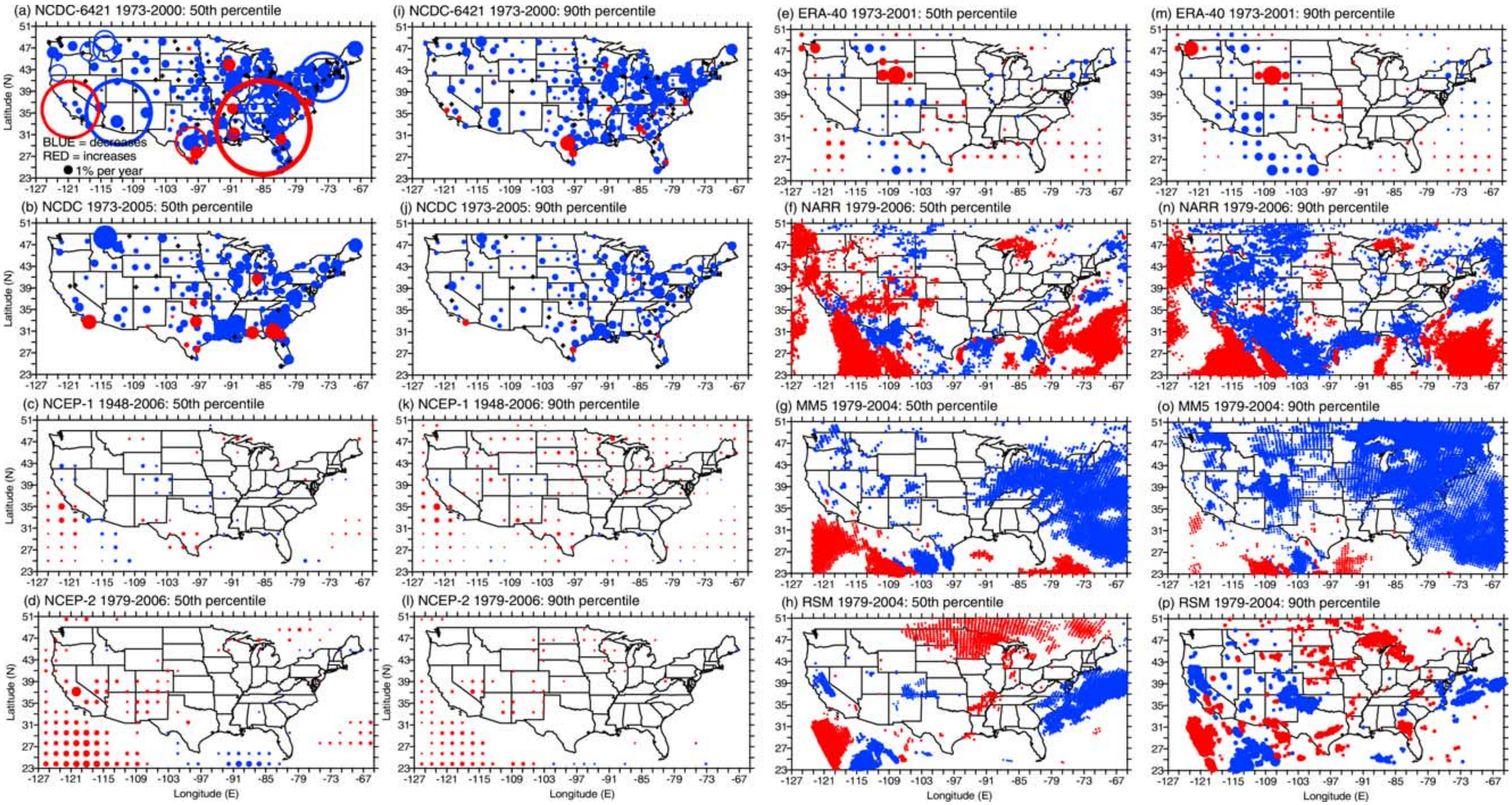

Figure 5. Results of the trend analysis applied to data from 1200 UTC. The individual frames show results for the 50th percentile wind speed from (a) NCDC-6421 (1973–2000), (b) NCDC *DS3505* (1973–2005), (c) NCEP-1 (1948–2006), (d) NCEP-2 (1979–2006), (e) ERA-40 (1973–2001), (f) NARR output (1979–2006), (g) MM5 output (1979–2004), (h) RSM output (1979–2004), and the 90th percentile wind speed from (i) NCDC-6421 (1973–2000), (j) NCDC *DS3505* (1973–2005), (k) NCEP-1 (1948–2006), (l) NCEP-2 (1979–2006), (m) ERA-40 (1973–2001), (n) NARR (1979–2006), (o) MM5 output (1979–2004), and (p) RSM output (1979–2004). In each frame the size of the dot scales linearly with the magnitude of the trend and the color of the dot indicates the sign of the trend (scale as shown in Figure 5a). To enhance the legibility of this figure, stations that exhibit a trend in excess of 2%/yr are shown by open circles. Where the station time series did not indicate a statistically significant trend a plus symbol is shown. Where time series from a reanalysis or RCM grid cell did not exhibit a trend no symbol is shown.

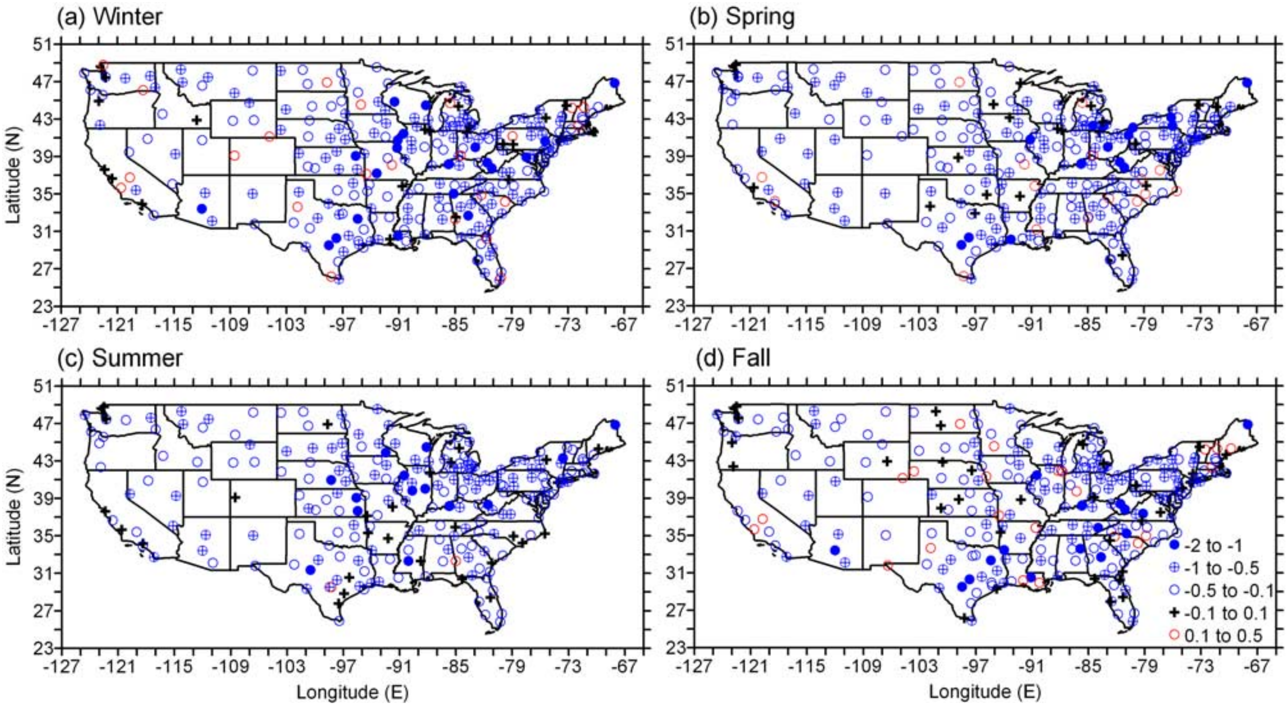

Figure 6. Temporal trends in the 90th percentile wind speed computed for each climatological season (a) winter (December to February), (b) spring (March to May), (c) summer (June to August), and (d) fall (September to November) expressed in percent per year using the scale shown in Figure 6d.

of the observed trends, and particularly east of the Rocky Mountains it may be related to changes in cyclone frequency [*Bierly and Harrington*, 1995; *McCabe et al.*, 2001]. However, these trends may also reflect data inhomogenities [*DeGaetano*, 1998]. To investigate the possible role of introducing the ASOS firmware, time series of annual percentiles from each station were analyzed to determine the year in which the largest discontinuity occurred. In this analysis a 5-year running mean was applied to the time series of the annual percentiles and used to determine the year in which the 5-year running mean exhibited the largest change relative to the mean computed using the 5 years computed up to that point. Discontinuities in the 50th and 90th percentile wind speeds from the 0000 UTC and 1200 UTC measurements at a given site generally occur in the same year, but as shown in Figure 7, while the ASOS deployment largely occurred between 1993 and 1998, the discontinuities in the 50th and 90th percentile annual wind speeds from the 193 stations are distributed throughout the entire data record (1973–2005). The dominant source of the temporal trends thus remains uncertain. It is possible that data inhomogenities other than introduction of the ASOS systems are responsible, such as increased urbanization and thus increased surface roughness lengths at the measurement sites or deterioration in anemometer performance over time [*DeGaetano*, 1998].

[30] Temporal trends identified in the current work are in accord with prior work in and around Minnesota that indicated a decline in the upper percentiles of observed annual mean daily wind speeds from about 1960 to 1995 [*Klink*, 2002] and the observed decrease in mean annual and winter wind speeds in western Canada [*Tuller*, 2004]. The results do not, however, replicate the results of an analysis of monthly maximum and minimum wind speeds from 1961 to 1990 which indicated a broadening of the distribution (declining minimum monthly wind speeds and increased

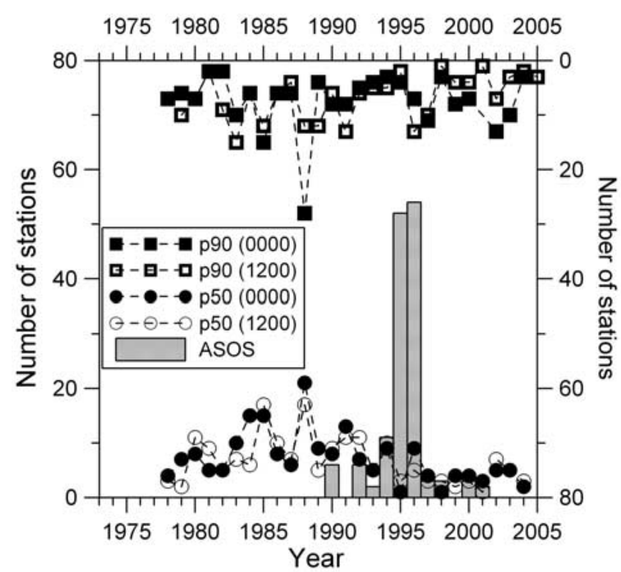

Figure 7. Time series of the number of stations in the NCDC DS-3505 data set that were reported as experiencing ASOS deployment in a given calendar year. Also shown are the number of stations for which 5-year running mean 90th and 50th percentile wind speeds computed using the 0000 UTC and 1200 UTC data exhibited the largest discontinuity.

maximum monthly wind speeds) [*Klink*, 1999b]. The implied ''stilling'' of wind speeds has been identified in a large number of observational data sets from midlatitude locations [*Roderick et al.*, 2007; *McVicar et al.*, 2008], but as in the research conducted in Australia [*McVicar et al.*, 2008; *Rayner*, 2007] these trends are largely not manifest in reanalysis data.

[31] The time periods used in the trend analyses presented in Figures 4 and 5 differ by data set. As emphasized above, and documented in prior research, trends need not be linear and there is substantial evidence for periodicities in wind speeds. An analysis of mean annual and winter wind speeds from four coastal stations in Canada indicated period-of-record declines but the majority of the trend was concentrated between late 1960s through to the mid-1980s [*Tuller*, 2004]. To assess the influence of the specific time window on the resultant trends the NCEP-1 data set was truncated to match the time periods of the other data sets, and the trends were recomputed using both the 0000 UTC and 1200 UTC data in a single analysis (Figure 8).

[32] Results from all the trend analyses indicate the following:

[33] 1. Magnitudes of trends in the observed wind speed records for 1973–2000 and 1973–2005 are substantial, up to 1%/year at multiple stations and much above that at a few. Trends in the reanalysis data sets and RCM output, where present, are generally of lesser magnitude (Figures 4, 5, and 8), and no other data source is as dominated by negative trends as the in situ observations. Temporal trends in the data sets from in situ measurements are of largest magnitude over the eastern United States but negative at the overwhelming majority of stations across the entire contiguous United States. The trends in wind speed percentiles from in situ observations do not exhibit strong seasonality (Figure 6) or a clear signature from the introduction of the ASOS instrumentation (Figure 7). Hence the cause(s) of the declines remains uncertain. However, it is worthy of note that simulations conducted with MM5 also exhibit coherent regions of reduced magnitude 50th and 90th percentile wind speeds over the eastern United States.

[34] 2. As in the observations, output from the NCEP reanalysis 1 data set for 1948–2006 generally indicates a tendency toward decreased values of the 50th percentile annual wind speeds, particularly in the central United States. However, the 90th percentile wind speeds exhibit statistically significant increases over the rest of the contiguous United States (Figures 4 and 5).

[35] 3. When the NCEP-1 data set is truncated to the period of the observational time series (1973–2000 or 1973–2005) (Figure 8), in contrast to the observations, NCEP-1 output imply substantial increases in 50th and 90th percentile wind speeds over much of the contiguous United States but particularly the Midwest. Also in contrast to the station observations, trends in the NCEP reanalysis 1 data set for 1973–2000 or 1973–2005 exhibit more statistically significant increases and are frequently of larger magnitude in the 90th percentile values when expressed as a percent change.

[36] 4. There are some similarities in wind speed trends in NCEP-1 and NCEP-2, for example the prevalence of upwards trends in the western United States when only 1979–2006 is considered (Figure 8), but there are also differences. While time series from NCEP-1 exhibit spatially consistent increasing trends in the 50th percentile over the Midwest over the period 1979–2006 (Figure 8), NCEP-2 output generally does not indicate significant trends in the 50th percentile wind speeds over the Midwest (Figures 4 and 5).

[37] 5. Comparable trends in the 50th and 90th percentile wind speeds from ERA-40 are almost evenly divided between increasing, decreasing, and no change over the contiguous United States (Figures 4 and 5), with declines over the southwestern United States and increases along the spine of the Rocky Mountains. In contrast to the NCEP-1 observations ERA-40 output does not indicate a tendency toward increased 50th and 90th percentile wind speeds over the Midwest during 1973–2001 (cf. Figures 4 and 5 and Figure 8).

[38] 6. Output from NARR for 1979–2006 indicate contrary trends in the 0000 UTC and 1200 UTC output with declining trends over much of the western United States in the 0000 UTC wind speeds but increases in the 1200 UTC output (cf. Figures 4 and 5).

[39] 7. As expected, the period of observation used in the trend analysis has a profound impact on the presence and absence of temporal trends and indeed the sign of trends. However, the NCEP-1 output exhibits a dominance of positive trends for all periods that commence in or subsequent to the mid-1960s and end after the early 1990s. A possible exception to this is the Pacific Northwest where, as in the analysis of *Tuller* [2004] based on direct observations, there is some evidence of declining wind speeds post-1970.

[40] 8. Analysis of output from the RCMs for 1979–2004 indicate that MM5 simulations are characterized by generally declining 50th and 90th percentile wind speeds over the course of 1979–2004, while output from the RSM generally imply a greater prevalence of positive trends, although those the increases are much less spatially coherent (Figures 4 and 5). The RSM output also appears to exhibit sensitivity to hour of the day which is not evident in the MM5 simulations. Positive trends in the 50th and 90th percentile wind speeds are more common and of larger magnitude in the 0000 UTC time period in the RSM simulations. This implies a possible link to the parameterizations of planetary boundary layer dynamics. Differences between the RSM and MM5 simulations likely derive from variations in the model physics from the two RCMs and/or the different ways in which data from NCEP-2 are used within the two model frameworks. NCEP-2 provides only lateral boundary conditions for the MM5 simulations, while the RSM is influenced by the reanalysis at all grid points. Since MM5 is only influenced on the lateral boundaries, it is possible that this model could drift away from the reanalysis in the interior of the model domain. Both models use the Noah land surface scheme to represent coupling with the surface, which includes the specification of vegetation (and hence grid point surface roughness) although MM5 uses slightly more vegetation classes. Differences in surface wind speed might be caused by differences in lowest-model wind speeds due to dynamical differences as previously described. They also might be caused by differences in cloudiness or precipitation, which would alter the grid point specific surface energy balance and low-level stability in the Monin-Obukhov similarity theory extrapolation process. Lack of spatial coherence in

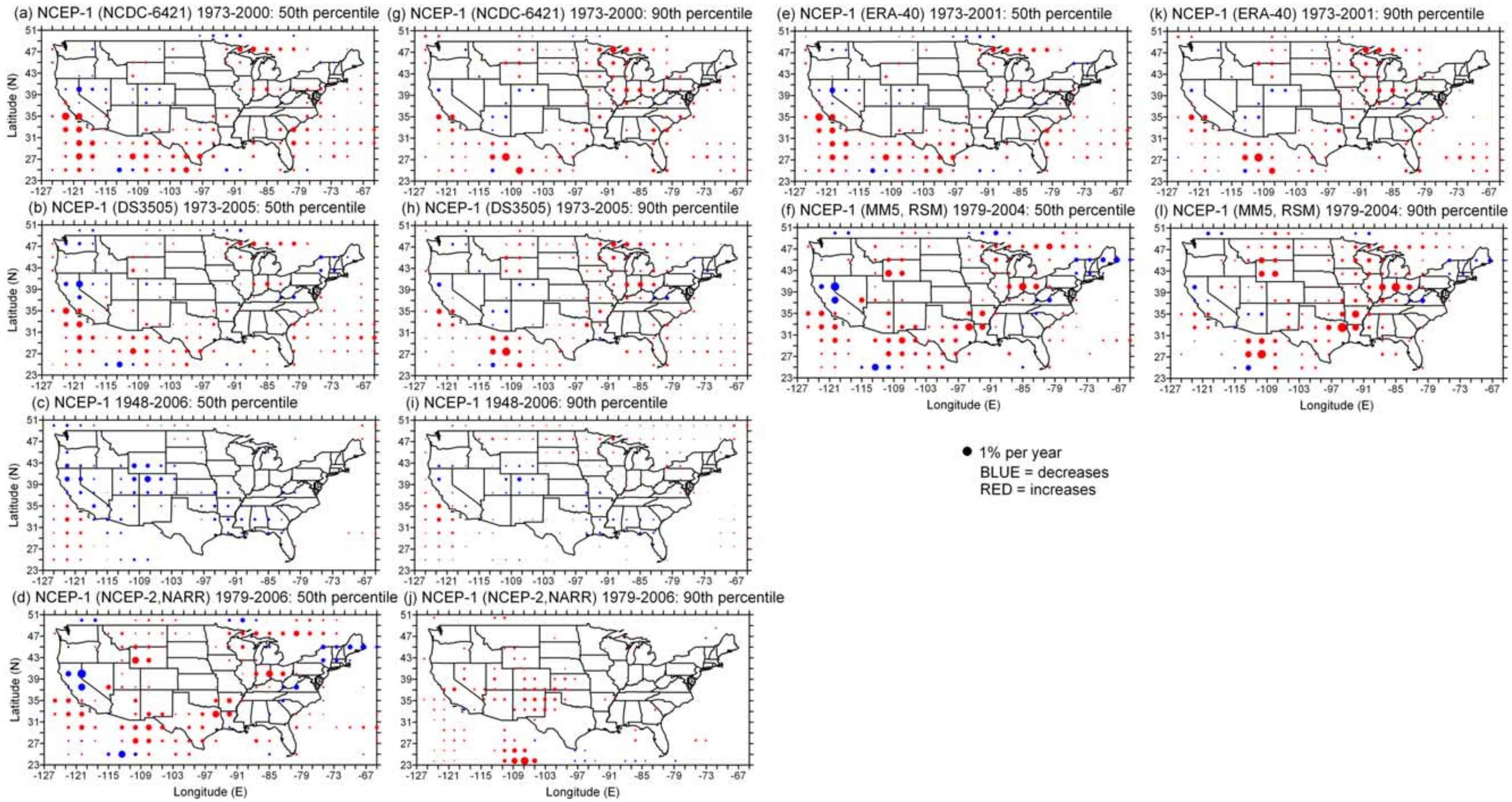

Figure 8. Results of the trend analysis applied to data from 0000 and 1200 UTC for the NCEP-1 wind speeds truncated to match the time period of each of the other data sets. As in Figures 4 and 5, the left plots show results for the 50th percentile and the right plots show the 90th percentile trends. The individual frames show (a and g) NCEP-1 truncated to replicate the data period used from NCDC-6421 (1973–2000), (b and h) NCEP-1 truncated to replicate the data period used from NCDC DS3505 (1973–2005), (c and i) NCEP-1 for the period 1948–2006, (d and j) NCEP-1 truncated to replicate the data period used from NCEP-2 and NARR (1979–2006), (e and k) NCEP-1 truncated to replicate the data period used from ERA-40 (1973–2001), (f and l) NCEP-1 truncated to replicate the data period used from the two RCM (1979–2004). In each frame the size of the dot scales linearly with the magnitude of the trend and the color of the dot indicates the sign of the trend (scale as shown below Figure 8f). Where time series from a reanalysis grid cell did not exhibit a trend no symbol is shown.

differences might give more credence to the latter explanation. In a very limited test of model diurnal heat fluxes [*Takle et al.*, 2007] RSM tended to produce somewhat higher than observed sensible heat flux over the diurnal cycle (MM5 was not a part of this intercomparison). This would support stronger daytime coupling of surface winds with the free atmosphere and a higher amplitude for the diurnal cycle.

[41] 9. When the NCEP-1 data set is truncated to replicate the period for which the RCM output is available, in contrast to the results of analyses of MM5 output, NCEP-1 shows significant positive trends over the Midwest.

[42] On the basis of the analyses presented herein we conclude there are substantial differences between trends derived from carefully quality controlled observational wind speed data, reanalysis products and RCMs, and indeed between wind speeds from different reanalysis data sets and RCMs. The source of the discrepancy between the eight data sets is demonstrably not solely a product of the different time periods. Our findings of disparate temporal trends in the historical period from in situ observations and reanalysis products are to some degree consistent with previous studies from Australia and Europe summarized above and prior research across the European continent in terms of the presence of quantitative differences in mean wind speeds [*Pryor et al.*, 2006a]. While these differences cannot be fully explained, they must be acknowledged and their presence strongly advocates for use multiple data sources in assessing near-surface wind climates. Additionally, as we propose in our prior work, such differences/discrepancies are "physically consistent with previous analyses of cyclone climatologies and might reasonably be invoked to provide a range of conditions (confidence bounds) for comparison with AOGCM simulations" [*Pryor et al.*, 2006a, p. 36].

3.3. Are Changes in the Annual Mean Wind Speed Associated With Increased Interannual Variability?

[43] To address questions regarding whether changes in the annual mean wind speed are associated with increased interannual variability, output from the data sets analyzed above were used to compute the annual mean at each station or grid cell and one metric of variability (the variance of 7-year windows of annual mean wind speed). Each metric was subjected to a trend analysis of the type described above. The results were then summarized in terms of the magnitude and sign (if significant at the 90% confidence level) of the (1) temporal trend in the mean and (2) temporal trend in variance. The results (Figure 9) can be summarized as follows:

[44] 1. They emphasize the overwhelming dominance of negative trends in annual mean wind speed when derived from the observational time series and that the other data sources exhibit greater variability in the sign of temporal trends. The results also indicate that stations or grid cells that exhibit a statistically significant trend in mean wind speed also tend to exhibit a statistically significant change in the interannual variability over the time periods of record. This is particularly the case for output from the two RCMs in which over 90% of grid cells that exhibit a statistically significant trend in annual mean wind speed also exhibit a significant change in interannual variability.

[45] 2. In the NCDC-6421 data set there is a tendency for stations that exhibit negative trends in the annual mean wind speed to also exhibit positive trends in the interannual variability. This inference is contrary to the a priori expectation that a decline in annual mean wind speed would be associated with a decrease in the interannual variability. This finding may be an artifact of the data issues discussed above and it is pertinent to note that this is not the case with the other observational data set. Analyses based on the NCDC DS3505 data (modified as discussed in section 2), indicate that stations that exhibit significant declines in annual mean wind speed have an almost equal probability of exhibiting increased or decreased interannual variability.

[46] 3. In the NCEP-1 data set there is a tendency for grid cells that exhibit increases in annual mean wind speeds to also exhibit an increase in interannual variability. Equally, there is a tendency for grid cells that exhibit decreases in annual mean wind speeds to exhibit a decrease in interannual variability. This is in broad accord with the a priori expectation that a decline (increase) in mean wind speed would be associated with a decrease (increase) in interannual variability. The NARR data set also exhibits a somewhat similar tendency with grid cells that exhibit a statistically significant decline in annual mean wind speeds also exhibiting declining variance (interannual variability), though this tendency is by no means uniform.

[47] 4. In the NCEP-2 and ERA-40 data sets grid cells characterized by both positive and negative trends in annual mean wind speed exhibit a tendency toward increased interannual variability of annual mean wind speed. The source of increased variability at the end of the data record in grid cells that exhibit declining annual mean wind speed is currently unknown but it is worthy of note that interannual variability in annual mean wind speeds is generally considerably smaller in the reanalysis data sets than in the observational time series or the RCM output.

[48] 5. In the RCM output grid cells characterized by both positive and negative trends in annual mean winds speeds exhibit a tendency toward decreased interannual variability with time. Further, in the case of MM5 output, grid cells characterized by decreasing annual mean wind speed exhibit larger magnitude declines in interannual variability than those that exhibit an increasing trend in annual mean wind speed.

[49] Thus as in the trend analysis of annual 50th and 90th percentiles of the wind speed there is no clear consensus in the data sets with regards to possible links between a change in the annual mean wind speed and interannual variability. Only the NCEP-1 output, and to some degree the NARR, exhibit evidence for the a priori assertion that increased mean annual wind speed would be associated with increased interannual variability and declining mean wind speeds with decreased interannual variability.

4. Concluding Remarks

[50] Near-surface wind speeds are of great importance in dictating possible impacts of global climate change and developing robust assessments of the contemporary wind climate have applications in multiple fields. Detection, quantification, and attribution of temporal trends in wind speeds within the historical and contemporary climate

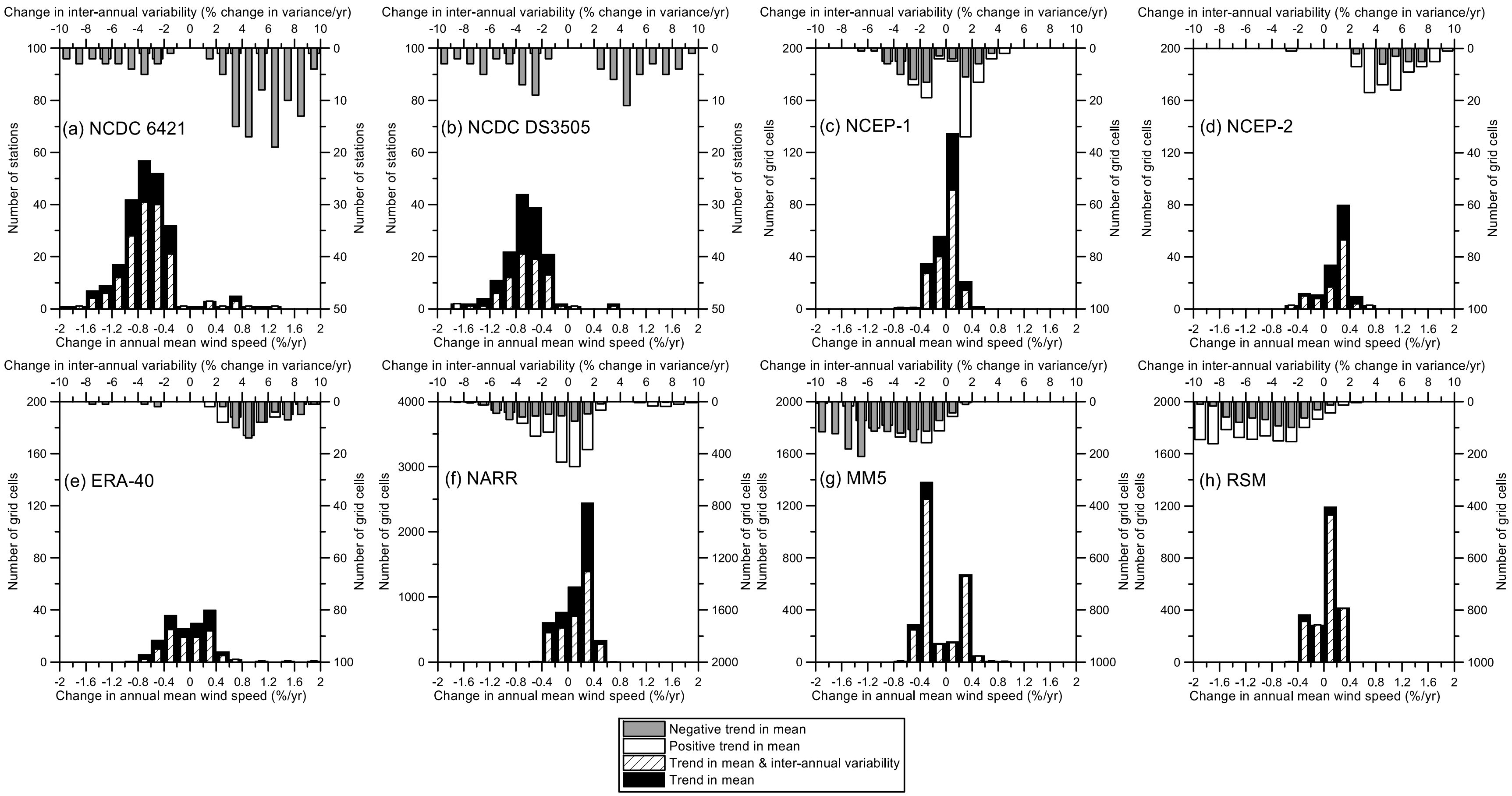

Figure 9. Synthesis of the trend analysis for annual mean wind speed and interannual variability. Each frame represents a different data source. In each frame the bottom two sets of bars represent the number of stations or grid cells (left-hand axis) that exhibit (1) statistically significant change in the annual mean wind speed (shown in the legend as "trend in mean") and (2) a statistically significant change in both the annual mean wind speed and interannual variability (shown in the legend as "trend in mean and interannual variability"). The two top bars show the grid cells or stations (right-hand axis) that exhibited a trend in the interannual variability of the specified sign and magnitude. This analysis includes only stations or grid cells that exhibited statistically significant changes in the mean wind speed. These data are conditionally sampled based on the sign of the trend in the annual mean wind speed (shown in the legend as "negative trend in mean" or "positive trend in mean"). Thus this second analysis (and the results shown by the top bars) illuminates whether a change in the variance (positive or negative) is associated with a given sign of trend in the annual mean.

provides a critical context for climate change research and a platform for evaluation of the models being used to estimate possible future wind speed regimes under global climate change scenarios. However, time series of wind speeds from in situ measurements are typically highly fractured and subject to large inhomogenities. Here we present a comprehensive intercomparison of wind speed trends over the contiguous United States during the end of the 20th century and early 21st century based on two observational data sets, four reanalysis data sets, and output from two RCMs formulated in the context of two principal objectives. The first objective is to quantify the magnitude and statistical significance of historical trends in wind speeds and the consistency (or not) of trends derived using different data sets and to provide a preliminary diagnosis of possible causes of temporal trends. The second objective is to address whether trends in the mean wind climate were associated with changes in the associated variability.

[51] Results presented herein indicate the following:

[52] 1. As in prior research across the European continent and Australia there are quantitative differences in mean wind speeds (Figure 3) and trends in wind speed percentiles between carefully quality controlled observational data, reanalysis data sets, and RCM output (Figures 2, 4, 5, and 8). Data from two observational data sets exhibit consistent negative trends across the entire contiguous United States during 1973–2000 and 1973–2005. These trends are of largest fractional magnitude over the eastern United States and particularly the Midwest. The observed temporal trends appear to be reproduced in part by the MM5 RCM nested within the NCEP-2 reanalysis. MM5 also performs relatively well in terms of reproducing the annual mean wind speeds. Negative trends in the in situ observations are present in all seasons and do not appear to be related to the introduction of the ASOS firmware. There is no strong evidence of substantial bias in temporal trends with the hour of the day in the observations or the global reanalysis data sets, though the NARR and the RSM simulations exhibit a greater prevalence of positive trends in the western United States in the 1200 UTC output (Figures 4 and 5). While the discrepancies between temporal trends from the different data sources (in situ observations, reanalyses, and RCMs) cannot be fully explained they must be acknowledged and their presence strongly advocates for use of multiple data sets in analyses of wind speed climates.

[53] 2. There is no clear consensus in the eight data sets with regards to the presence or absence of links between a change in the annual mean wind speed and interannual variability (Figure 9). In all data sources, stations or grid cells that exhibit a statistically significant trend in mean wind speed also tend to exhibit a statistically significant change in the interannual variability over the time periods of record. This is particularly the case for output from the two RCMs in which over 90% of grid cells that exhibit a statistically significant trend in annual mean wind speed over the period 1979–2004 also exhibit a significant change in interannual variability. In the NCDC-6421 in situ data set there is a tendency for stations that exhibit negative trends in the annual mean wind speed to also exhibit positive trends in the interannual variability; however, analyses based on observations from the NCDC DS3505 data set indicate that stations that exhibit significant declines in annual mean wind speed have an almost equal probability of exhibiting increased or decreased interannual variability. In the NCEP-1 and NARR data sets there is a tendency for grid cells that exhibit increases (decreases) in annual mean wind speeds to also exhibit an increase (decrease) in interannual variability, though this tendency is by no means uniform. In the NCEP-2 and ERA-40 data sets grid cells characterized by both positive and negative trends in annual mean wind speed exhibit a tendency toward increased interannual variability of annual mean wind speed. In output from both RCMs tend to indicate a decline in interannual variability over the simulation.

[54] Results presented herein, and similar research conducted in Europe and Australia, indicate that in contrast to temperature and precipitation, data sets of wind speed drawn from in situ measurements and reanalysis products exhibit substantial discrepancies both in terms of absolute magnitude and the sign of temporal trends over the last 30–50 years. Both RCMs presented herein exhibit some skill in reproducing the mean wind climate across the contiguous United States for the historical period, but MM5 appears to exhibit greater accord with historical trends derived from in situ observations.

[55] Given the importance of the wind energy industry to meeting Federal and State mandates for increased use of renewable energy supplies and the impact of changing wind regimes on a variety of other industries and physical processes, further research on wind climate variability and evolution is required, as are detailed analyses focused on reconciling the discrepancies illuminated herein.

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