P1.1 NORTH AMERICAN REGIONAL REANALYSIS

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1. INTRODUCTION

The NCEP North American Regional Reanalysis (NARR) is a long-term, consistent, high-resolution climate data set for the North American domain. It covers the 25-year period 1979-2003, and it will be continued later in near-real time as the Regional Climate Data Assimilation System, R-CDAS. After several years of development, most of the production was successfully completed during May-September 2003, taking advantage of the window of availability of the previously "production" NCEP IBM ASP supercomputer, and using four parallel streams to carry it out during this limited time. The NARR tasks still to be completed are described later.

The NARR was developed as a major improvement upon the earlier NCEP/NCAR Global Reanalysis (GR1, Kalnay et al, 1996; Kistler et al, 2000), in both resolution and accuracy. The NCEP/DOE Global Reanalysis (GR2, Kanamitsu et al, 2002) is used to provide boundary conditions, but the NARR takes advantage of the use of the regional Eta model including the many advances that have been made in the Eta regional modeling and data assimilation systems since the GR system's starting time of 1995. Some of the most important improvements are direct assimilation of radiances, the use of additional sources of data (Table 2), improved data processing, and several Eta model developments, particularly those associated with the GCIP-funded initiatives in hydrological research, assimilation of precipitation, land-atmosphere coupling, and improvements to the Noah land surface model, which is the land-model sub-component of the Regional Reanalysis (Mitchell et al. 2003; Ek et al. 2003; Berbery et al. 2003).

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The NARR should help answer questions about the variability of water in weather and climate, in particular as it concerns U.S. precipitation patterns. To that end, a special effort was made to output all "native" (Eta) grid time-integrated quantities of water budget. We expect that the NARR should have a good handle on extreme events, such as floods and droughts, and should interface well with hydrological models.

Results of preliminary pilots, produced at 80 km horizontal resolution and 38 layers in the vertical have been reported earlier (Mesinger et al. 2002). We have also reported on our preliminary "production" results, at 32 km/45 layer resolution (Mesinger et al. 2003). In all of these tests, the assimilation of precipitation during the reanalysis was found to be very successful, obtaining model precipitation quite similar to the analyzed precipitation, especially during the warmer seasons. Temperature and vector wind rms fits to rawinsondes were considerably improved over those of the GR throughout the troposphere, both in January and in July, and in the analyses as well as in the first guess fields. Improvements in the 2-m temperatures and 10-m winds were seen as well. Following final tests and having "frozen" the system we run most of the NARR production during the past summer. We report here on the production NARR results as they are available to us at the time of this writing, and provide additional information deemed to be useful to potential NARR users.

The period that still remains to be processed as part of the planned 25 years, consists of December 2002 and all of 2003, and requires a number of special processing tasks because not all the necessary input data is available in near real time and can be processed in the same manner as the data used so far. The plans include efforts to minimize inhomogeneities and to build a system enabling the NARR to continue to be run in real-time, like the "Climate Data Assimilation System" is being run as a real-time continuation of the GR.

As was the case with the GR, the NARR includes free forecasts performed at regular intervals, useful for predictability studies. We have chosen to do these forecasts every 2.5 days, out to 72 h in order to have free forecasts alternatively initialized at 0000 and 1200 UTC, with a 12-h overlap period. This would be useful to estimate spin-up in the first 12 h. The free forecasts use GR2 forecast lateral boundary conditions, which simulates the forecast skill attainable in operational conditions with the same system.

The project has been supported for 5 years by the NOAA Office of Global Programs (OGP), as originally planned, and will continue with reduced support for one more year, in order to complete the tasks summarized above. A Scientific Advisory Panel chaired by John Roads and reporting to OGP has provided valuable and continued guidance to the NARR project.

2. REANALYSIS SYSTEM AND DATA

The NARR System is similar to the Eta Model and 3D-Var Data Assimilation System (EDAS), operational in April 2003, at the time when the NARR system was frozen, (Rogers and DiMego, ftp://ftp.ncep.noaa.gov/pub/emc/wd20er/caftimay01/v3_document.htm), except for the resolution and for the use of a number of additional data sources (Tables 1 and 2). It includes most (but not all) of the model changes implemented on October 2001 (see http://www.emc.ncep.noaa.gov/mmb/research/eta.log.html), and in particular, the cloud microphysics of Zhao et al. (1997). The system is fully cycled, with a 3-hr forecast from the previous cycle serving as the first guess for the next cycle. The 32 km/45 layer resolution used for the NARR production runs is the same as that of the operational Eta prior to September 2000, but the domain is that of the current operational Eta, including North America and parts of Atlantic and Pacific, and encompassing 106° x 80° of rotated longitude x latitude. The NARR domain and topography are shown in Fig. 1, and the fixed fields used are listed in Table 3.

The data used in the production runs, includes all the observations used in the Global Reanalysis (Table 1). The additional data sets used in the NARR are summarized in Table 2 and discussed further below:

- Precipitation. The assimilation of observed precipitation is by far the most important data addition to the NARR. The successful assimilation of these observations (Lin et al. 1999, see also section 3) ensures that the model precipitation during the assimilation is close to that observed, and therefore that the hydrological cycle is more realistic than it would be otherwise. Over the continental United States (ConUS), Mexico, and Canada, precipitation data assimilated are 24-h rain gauge data disaggregated into hourly bins. Over the ConUS area, the disaggregation is performed based on hourly precipitation data (HPD), using an inverse distance scheme, and the Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly et al, 1994) known as "mountain mapper". Over Mexico and Canada, the disaggregation is based on GR2 (Kanamitsu et al. 2002) forecasts. Over the oceans, south of 27.5^{o}N, CPC Merged Analysis of Precipitation (CMAP) pentad data (Xie and Arkin, 1997) are used, also disaggregated into hourly using the GR2 precipitation forecasts. North of 42.5^{o}N, where the CMAP data is known to be increasingly less reliable, there is no assimilation of precipitation. Over a 15^{o} latitude belt centered at 35^{o}N there is a linear transition of the assimilation of precipitation, from full assimilation south of this blending belt, to no assimilation north of it. Moreover, over tropical cyclones, with locations prescribed from Fiorino (2002), there is no assimilation of precipitation since CMAP pentad data do not have adequate time resolution to be useful for very heavy precipitation.
- TOVS-1b radiances (instead of the NESDIS TOVS retrievals used in GR1 and GR2);
- Profilers and Vertical Azimuth Display (VAD) winds;
- Land surface wind and moisture. In Mesinger et al. (2003) we stated that we were also assimilating land surface temperature; we have subsequently found out that this was not correct, and that, if we do, our results – tropospheric fits to rawinsondes – are visibly worse. This issue is further discussed on the FAQ section in the NARR webpage http://wwwt.emc.ncep.noaa.gov/mmb/rreanl.
- Lake surface: Ice cover (Grumbine, personal communication), and lake temperature, to the extent available, as opposed to the global SST used in the GR. For lakes for which temperature is not available, the temperature was assumed to be the same as that of nearby lakes.
- SST and sea ice: these data were used in the GR but improved processing was developed for the NARR (Stokes, Grumbine, personal communications).

Table 1. Data used in both the NCEP/NCAR Global Reanalysis (GR) and in the North American Regional Reanalysis (NARR)

Dataset	Observed variable	Source
Rawinsondes	Temperatures, wind, moisture	GR
Dropsondes	Same as above	GR
Pibals	Wind	GR
Aircraft	Temperature and wind	GR
Surface	Pressure	GR
Cloud drift	Winds from geostationary satellites	GR

Table 2. Data added or improved upon in the North American Regional Reanalysis (a star indicates data not assimilated)

Dataset	Details	Source
Precipitation, disaggregated into hours	CONUS (with PRISM), Mexico, Canada, CMAP over oceans (<35^{o}N)	NCEP/CPC, Canada, Mexico
TOVS-1B radiances	Temperature, precipitable water over oceans	NESDIS
Surface	Temperature*, wind, moisture	GR
TDL surface	Pressure, temperature*, wind, moisture	NCAR
COADS	Ship and buoy observations	NCEP/EMC
Air Force snow	Snow depth	COLA and NCEP/EMC
SST	1-deg. Reynolds, with Great Lakes surface temperature	NCEP/EMC, GR
Sea and lake ice	Includes data on Canadian and Great Lakes	NCEP/EMC, GLERL, Canadian Ice Center
Tropical cyclones	Locations used for blocking CMAP precipitation	LLNL

Table 3. Fixed fields and initial/boundary conditions

Dataset	Use	Source
Green vegetation fraction	Initialization of vegetation	GR
Baseline snow-free albedo	Initialization of albedo	GR
Sigma-level data	Lateral boundary conditions	GR
Surface binary files	Initialization of land states; option exists to initialize with NARR data	GR

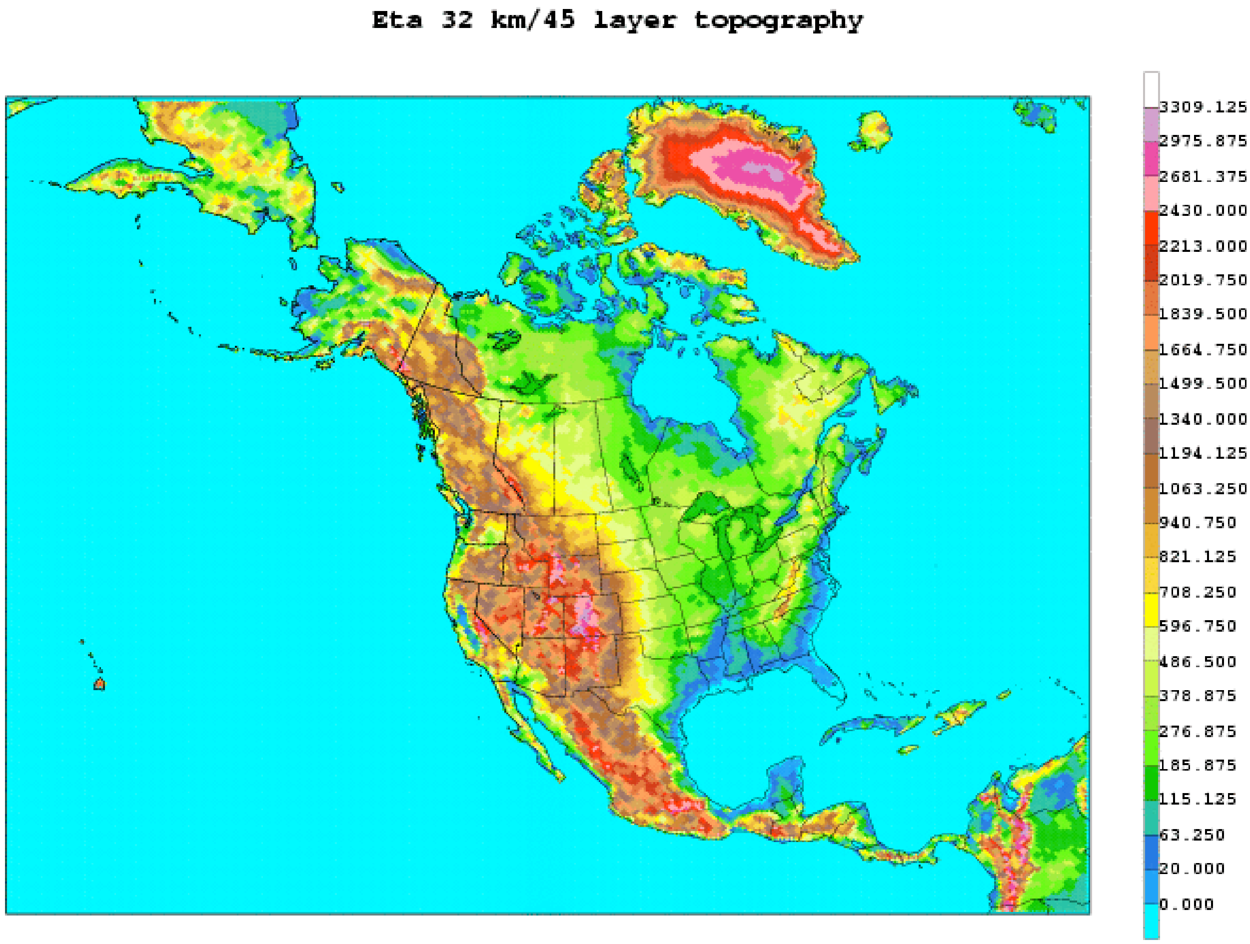

Fig. 1. The NCEP Regional Reanalysis domain and its 32 km/45 layer topography.

A more detailed discussion of our data used and data processing is presented in Shafran et al. (2004, this CD-ROM).

3. COMPARISONS WITH OBSERVATIONS AND WITH THE GLOBAL REANALYSIS

Given that the Global Reanalysis data have been available for almost a decade, an obvious goal of the NARR, in addition to higher resolution, was to provide a more realistic and accurate data set over North America. We will now compare NARR precipitation monthly averages to observations, and the fit of NARR and GR to rawinsonde and other observations using results of the available production runs. In presenting the results we are somewhat hampered by the time constraint, given that at the time of this writing only a few weeks have elapsed since the 23+ years of the NARR were generated, and that during the production time, all of the available computer and manpower resources were fully engaged in the production effort, limiting our ability to inspect the results.

In presenting the precipitation results of our pilot and preliminary runs, we compared monthly totals for January and July of the NARR precipitation with those of the "observed" (i.e., analyzed) precipitation assimilated into the NARR, as well as with those of the GR. We have found an excellent agreement of the NARR with the analyzed precipitation over areas with assimilation in the January and July months for all the years that we examined, an agreement better than previously reported for the pilot runs. For illustration, we present winter and summer examples of particular interest, in which extreme events occurred. In Fig. 2 we compare the NARR precipitation in January 1997, a time of a strong El Niño, with the analyzed precipitation based on observations, and in Fig. 3 the difference between flood months in

1993, and drought months in 1988 (e.g., Altshuler et al. 2002). The January 1997 comparison shows that over land there is an extremely high agreement between NARR and observed precipitation, even over the complex western topography. It should be noted that the model does not assimilate precipitation directly but instead latent heat information derived from observations, and that from this forcing the model produces the NARR precipitation (Lin et al. 1999). Thus, it was not obvious that it was possible to achieve such exceedingly good agreement over land. Over the oceans, the agreement is very good in southern latitudes, and toward more northerly latitudes where the assimilation is gradually transitioned out, the agreement is still reasonable in magnitude, but not in the detailed distribution. The tendency of the NARR to generate visibly weaker maxima over cyclonic regions of the northern Atlantic, seen in Fig. 2, has been found to be typical of other months. Given that the NARR was clearly meant to address primarily the North American land, this is not seen as a serious problem.

For a summer example of precipitation we present the difference between the June, July of the flood year of 1993, and the drought year of 1988. The monthly average of this difference for observations and NARR is shown in Fig. 3. Once again, the agreement over land is extraordinarily good, down to very small-scale detail. This is true for the Midwestern maxima, just as it is for the detail of lesser significance at various other places over land. Over oceans, the agreement is also good, this time – note that we are looking at a difference -- in all of the oceanic areas shown.

While the realistic precipitation will be very helpful for hydrologic and near surface variables, and in particular soil wetness, the accuracy of model variables in the troposphere, especially winds and temperatures, is a primary indication of the performance of the overall system. Mesinger et al. (2003) displayed temperature and vector wind rms fits to rawinsondes as functions of pressure, for January and July of our 1988 preliminary run, in comparison with those of the GR, both for the analysis and for the first guess. The advantage of the NARR over that of the GR was seen to be greater for the analysis than for the first guess, and to be considerable, especially for winds. The 32 km results available at the time, however, were inadvertently obtained without precipitation assimilation. We here present a similar set of plots, but for January and July averages over 24 years, 1979-2002. As before, our verification domain for these upper-air plots as well as for the near-surface plots to follow is the so-called grid 212, encompassing most of Mexico to the south and up to a considerable fraction of Canada to the north. For this period and region, in Fig. 4, NARR rms fits to rawinsondes as functions of pressure are shown, dashed lines, for temperature (upper panels), and for vector wind (lower panels), for January (left panels) and July (right panels). The same fits for the GR are shown as solid lines. The results displayed are similar to those obtained for the single year of Mesinger et al. (2003). NARR fits to rawinsondes are seen to be considerably better than those of the GR for both temperature and winds, and in both January and July, except for temperature at lower troposphere in July, at 700 and 850 mb, where the two are about the same. The advantage of the NARR is greater in January than in July, and it is greater for winds than it is for temperatures.

Before turning attention to the first guess fits, we note that the fits of the analysis to the observations, shown in Fig. 4, are influenced by both the estimation of the background and observation error covariances, and by the degree of balance imposed on the analysis. The fit will be worse the stronger the balance constraint imposed in the analysis scheme. The fit of the first guess to the observations is generally considered a better independent validation of the quality of the analysis system. For example, the changes implemented in the operational Eta 3D-Var in May 2001 (web site given in section 2) resulted in improved NARR fits to rawinsondes in the first guess (3-h forecasts) but made them worse in the analysis. We therefore compare the NARR and GR first guess fits to data, fits prior to entering the 3D-Var analysis. From a practical point of view, most users of the NARR will want to use the analyses for the variables that are analyzed, but will use the first guess for non-analyzed fields such as surface fluxes.

The NARR first guess fits to rawinsondes for our 24 years, shown in Fig. 5, are overall still considerably better than those of the GR, even though the improvement is smaller than for the analysis fields. For the temperature, the NARR first guess fits are better than those of the GR except at 700 mb in January, and in July they are better except between 500 and 850 mb. The fit of the first guess winds in the NARR, on the other hand, are significantly better than the GR at all levels, especially in January, and in particular at the upper troposphere – both just as it was for the analyses.

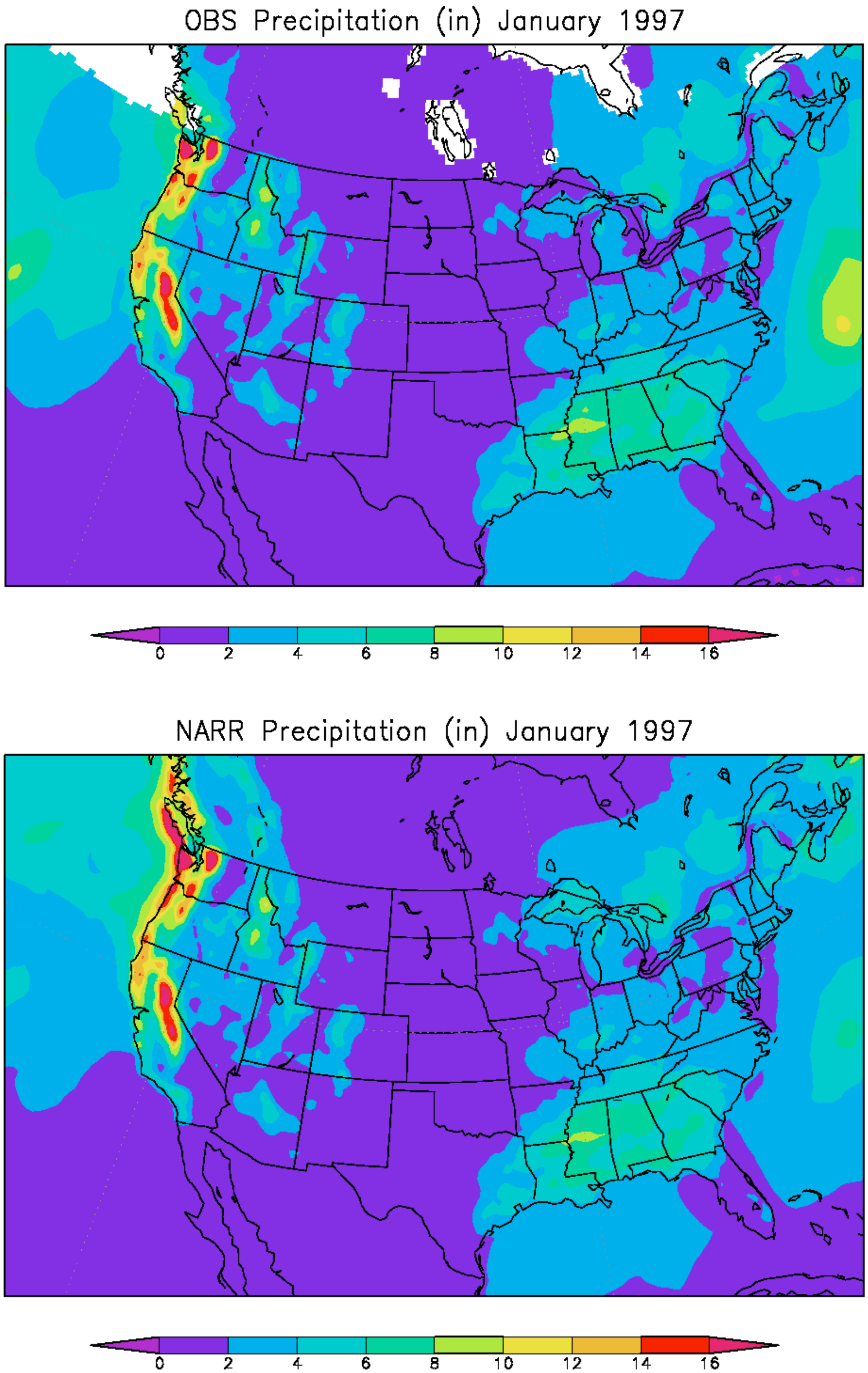

Fig 2. "Observed" (analyzed) precipitation assimilated by the NARR over land and over southern parts of the oceans (see text), and NARR precipitation, averaged for January 1997 (inches/month).

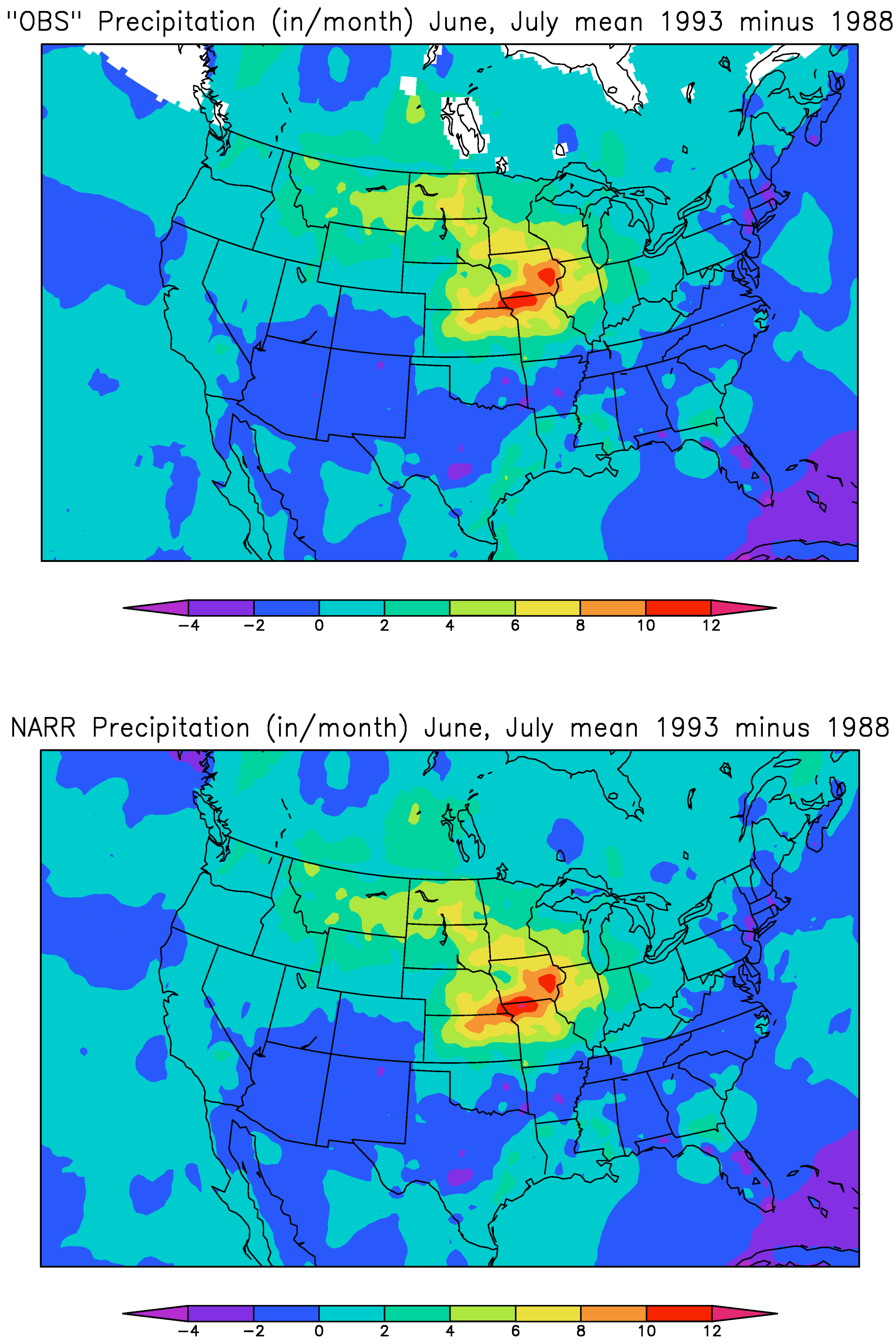

Fig. 3. “Observed” precipitation, assimilated by the NARR over land and over southern parts of the oceans (see text), and NARR precipitation, June, July 1993 minus June, July 1988 (inches/month)

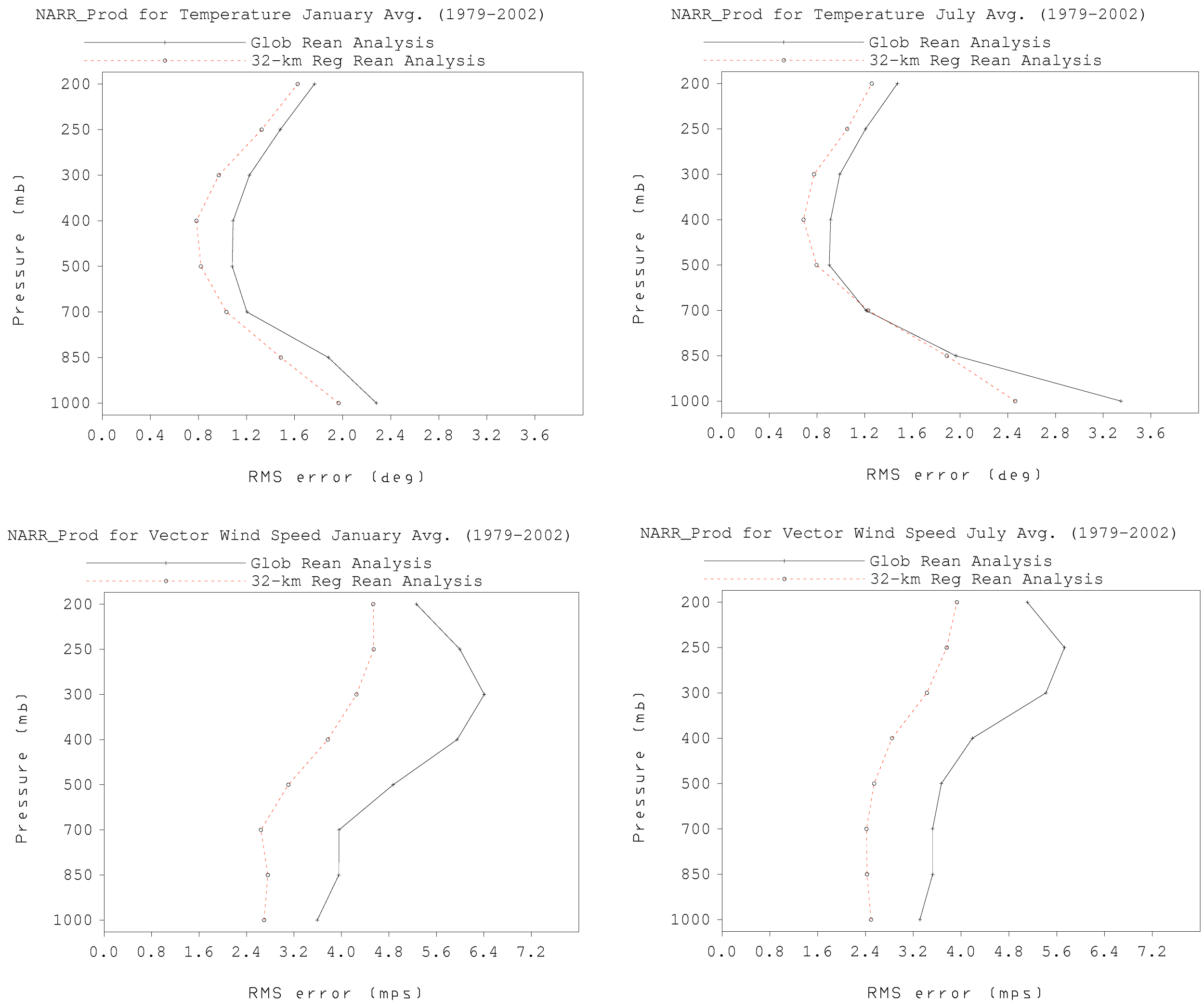

Fig. 4. RMS fits to rawinsondes as a function of pressure, for temperature (upper panels), and for vector wind (lower panels), for January (left panels) and July (right panels), average over 1979-2002. NARR: dashed lines, GR: solid lines.

With respect to near-surface variables, 2-m temperatures and 10-m winds, we show January and July 1988, the months we have shown before. Only the first guess results are presented, because there are no GR analyses available for these fields. We display in Fig. 6 the bias and the rms fits of the first guess 2-m temperature for both the NARR (dashed lines) and the GR (solid lines), as functions of time. The results shown are averages for all the surface stations of the domain 212 that have passed the quality control test. The results indicate that the NARR 2-m temperature biases are generally smaller and have less of a diurnal cycle than the GR, both in the winter and in the summer. The rms errors are also smaller for the NARR than for the GR, and the diurnal amplitude in the rms fit to observations – a problem of the GR in July -- is also considerably smaller.

Fig. 7 displays the corresponding plots of the first guess 10-m vector wind biases and rms fits for the same two months. The NARR has a slight negative bias in both winter and summer. A considerable positive bias is displayed by the GR in January, on the order of 1-2 m/s. This carries over into the rms results, contributing to a very considerable rms advantage of the NARR over the GR in January, of more than 1 m/s. Also in July, despite no bias advantage, the NARR rms is somewhat smaller than that of the GR.

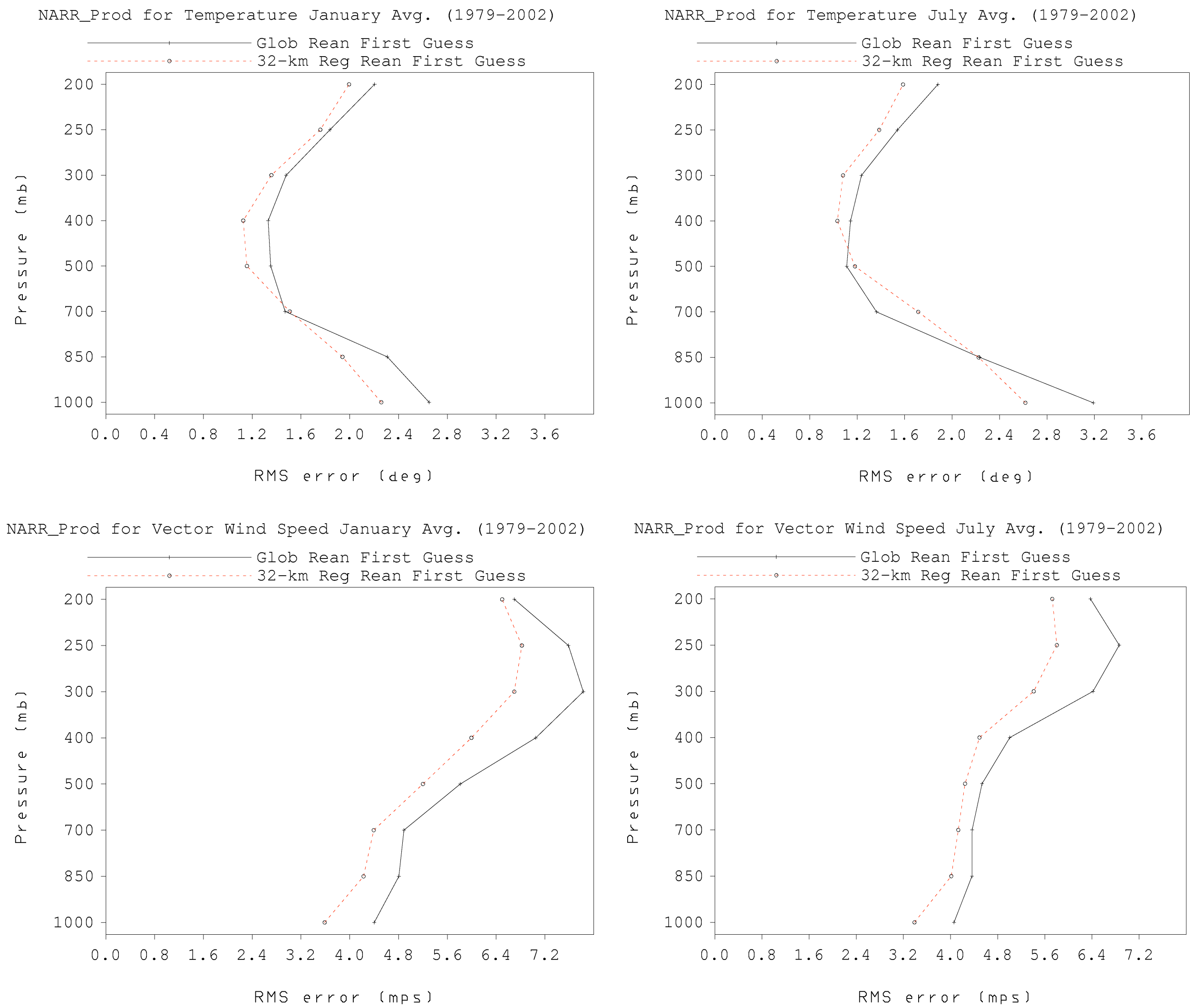

Fig. 5. Same as Fig. 4 but for the first guess.

One advantage of the NARR compared to GR is its higher temporal resolution, 3 vs 6 h. Not only are analysis and first guess fields available at shorter time intervals, but also a considerable fraction of the data are being assimilated at more correct times. But when comparing the NARR first guess fields with those of the GR as done in Figs. 5 to 7, two additional factors are involved: 3 h makes the first guess closer to the initialization time so that there is less time for the model error grows to take place, but then being closer to the initialization time also allows less time for the gravity waves created by the initial imbalance to settle down. The two factors have an opposite effect in terms of the NARR first guess being at an advantage, or at a disadvantage, in fitting the observations. We have run an experiment aimed at finding out which one of the two might be greater: July 2002 was rerun with each of the 3-h forecast segments extended to 6 h, and fits to rawinsondes of the thus obtained 6 h NARR first guess fields were then compared against those of the 3 h fits. There was exceedingly little difference between the two, but in most cases the 6 h fits were a little smaller than the 3 h ones. Thus, as far as the plots of Fig. 5 are concerned, the 3 vs 6 h difference appears to have had very little impact on the result.

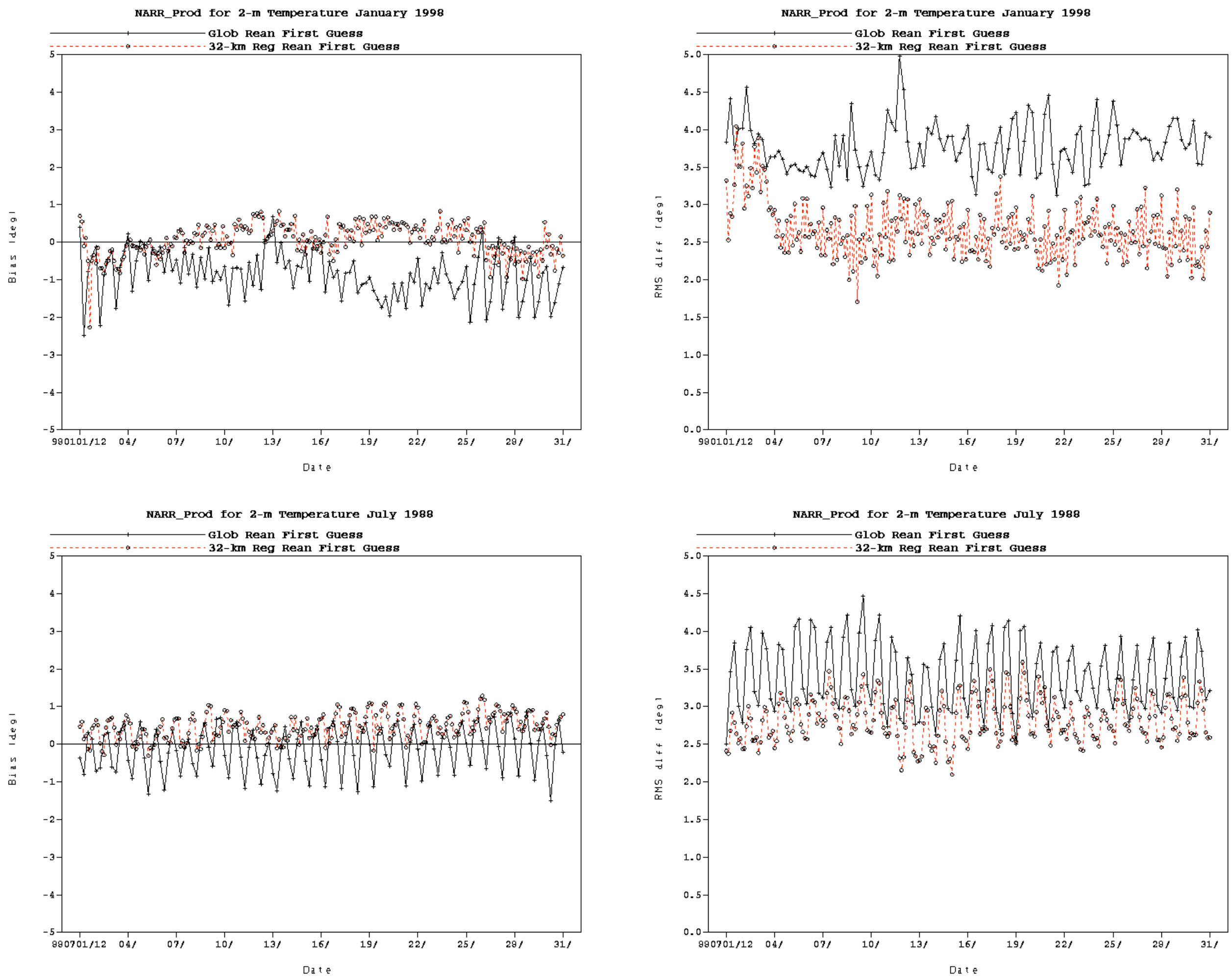

Fig 6. Bias (top) and RMS (bottom) of the first guess 2-m temperatures fits to observations for the NARR (dashed lines) and the GR (solid lines), for January 1988 (left) and July 1988 (right) as functions of time.

4. WORK IN PROGRESS AND PLANS

Several data preparation tasks remain to be completed before the period following November 2002 can be continued. Efforts will be needed to produce input data sets so as to minimize inhomogeneities compared to the 23+ years processed so far. Sea ice, ice cover for the Canadian lakes and the Great Lakes need to be produced, and some obstacles preclude doing these the same way as the 23+ years were done. CMAP precipitation and Canadian gauge data are not processed in real time or are not available at the time of this writing beyond December 2002. We plan to do all of these data preparation or processing tasks with a view to minimizing the changes required to transition to a real-time system, Regional Climate Data Assimilation System, R-CDAS.

Since CMAP is not available in real time, we are pursuing the use of the new precipitation monitoring system CMORPH (Joyce et al. 2004) instead. Since we have no real-time source of precipitation observations from Canada either, we plan to use the model produced precipitation north of the area to be analyzed by CPC in real time, which is an area somewhat greater than ConUS; with blending at the northern boundary similar to that done presently over oceans. The new system for precipitation required in order to replace the use of CMAP and Canadian gauge data in near real time will be built and applied to 2003. This new system will be compared to 2002 for continuity and will become the R-CDAS. It will have to be ported to the current NCEP mainframe computer.

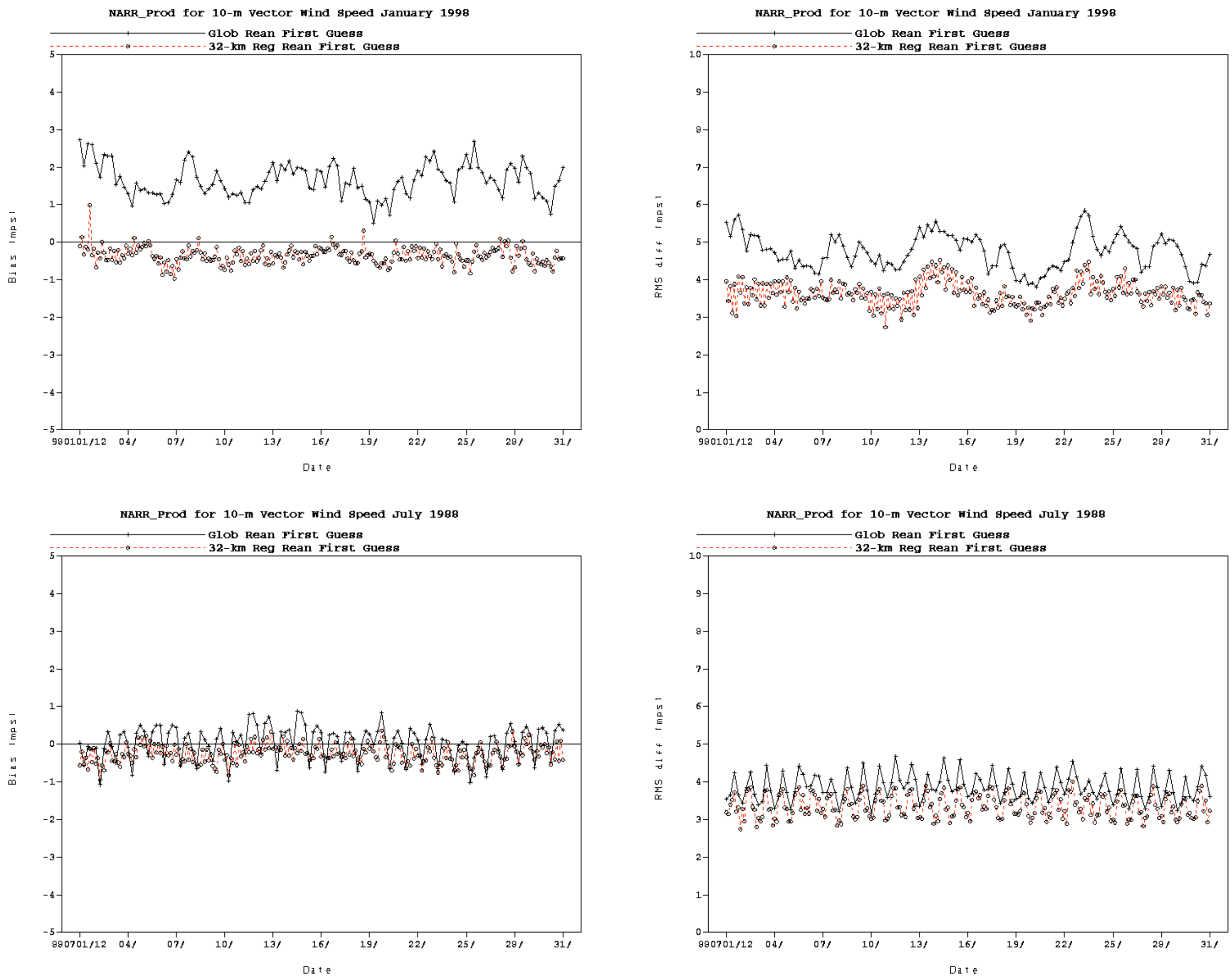

Fig. 7. Same as Fig. 6 but for the 10-m winds

During the intensive effort to complete the 23+ years of the NARR processing, datasets had to be moved directly into the mass-storage system at NCEP. The production of monthly means and other data forms that facilitate the use of the data will be done during this year and in early 2004. Four archiving centers plan to host various subsets of the NARR data. They are NCDC, NCAR, San Diego Supercomputing Center (SDSC) and the University of Maryland. These centers have a wide variety of storage resources at hand and will be making different portions of the total NARR database available at their institutions. Our plan is to make the so-called NOMADS facility at NCDC a major distributor of NARR data. To handle the data volumes, the next version of the NOMADS software is planned to allow subsetting by user specified: region, time, level, field, and resolution. This will likely require four unique processing streams to extract the proper data and prepare it to take maximum advantage of the individual storage possibilities available. Specifically, since none of the archiving centers have the ability to have on-line both the analysis and the first guess GRIB (also referred to as AWIPS) files, "merged" AWIPS files will be produced, containing analysis and some of the first guess fields. Discussion on which fields need to be included is in progress.

A number of additional outreach efforts are in progress or planned. Several NARR companion papers are being presented at this meeting (Shafran et al. 2004 on the data used; Ebisuzaki et al. 2004 on the archiving and data access, and Ek et al. on the land surface/ boundary layer issues). An article for the AMS Bulletin is planned, accompanied by a DVD including a sample of results. Finally, a Users Workshop is planned for 2004. Additional information is available at http://wwwt.emc.ncep.noaa.gov/mmb/rreanl, including instructions how to access results that have been posted for early evaluation and code testing by the expected user community. Comments on the NARR results posted or other related questions are most welcome and are hereby solicited.

Acknowledgements. Bringing a project of this magnitude to near-completion would not have been possible without the extraordinary NCEP work environment, and a strong support of the NCEP director, Louis Uccellini, and NCEP/EMC director, Stephen Lord. Their support, and moreover suggestions, some of which made their way into the NARR product, is gratefully acknowledged. No lesser credit should go to NOAA/OGP that funded and is funding the project, and their responsible program directors, Mark Eakin in the early stages, and Richard Lawford later on: their guidance in terms of the mechanics of the effort, and trust as well as foresight regarding the eventual high quality of the product to be obtained, were not only always helpful, but also an inspiration for our perseverance through the various steps behind us. The support of the NCEP/CPC director, Jim Laver, was just as well essential to enable the work presented to be accomplished.

The project's Scientific Advisory Committee, chaired by John Roads, and including Anna Barros, Lance Bosart, Mike Fiorino, Roy Jenne, Dennis Lettenmaier, Ed Miles, Roger Pulwarty, Eugene Rasmusson, and Greg Tripoli, repeatedly came up with useful suggestions, again with some of them finding their way into the product presented; and kept providing not only useful comments, but also strong support as well as encouragement for the effort.

Hugo Berbery, of the University of Maryland, with his careful and insightful studies of the EDAS as well as NARR preliminary results, enabled our awareness of numerous essential features of the product-to-be, and has much helped our accomplishing the results we have. Huug van den Dool, of NCEP/CPC, provided unfailing assistance with a variety of our precipitation processing efforts. Suru Saha, of NCEP/EMC, suggested the El Niño January we have chosen for the our Fig. 2. Numerous other colleagues, too many to mention, gave us useful advice, and are hereby acknowledged as well.

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