NORTH AMERICAN REGIONAL REANALYSIS

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The NCEP North American Regional Reanalysis (NARR) is a long-term, consistent, high-resolution climate dataset for the North American domain. It covers the 25-year period 1979-2003, and is being continued 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. Most of the remaining NARR tasks have subsequently been completed, including processing of the complete 25-year period. A few residual tasks are still in progress at the time of this writing, including the archiving activities.

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. 2004; Ek et al. 2003; Berbery et al. 2003).

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 representation of extreme events, such as floods and droughts, and should interface well with hydrological models.

Our results – first those of preliminary pilot runs at 80 km horizontal resolution and 38 layers in the vertical, and later those of most of the "production" results, at 32 km/45 layer resolution -- have been reported on in a sequence of conference papers. The last of those is Mesinger et al. (2004); note that its revised version is available at http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/index.html.

In all of these earlier reports, the assimilation of precipitation during the reanalysis was found to be very successful, obtaining model precipitation quite similar to the analyzed precipitation. 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. Significant improvements in the 2-m temperatures and 10-m winds were seen as well.

Subsequently, in addition to completing our 25-year production period, we have also built the system for and started the near real-time continuation of the NARR, following the practice of the “Climate Data Assimilation System”, the real time continuation of the GR. A basic requirement underlying reanalysis efforts is, of course, minimization of inhomogeneities as much as possible without detrimentally affecting the results. However, important inhomogeneities which we could not avoid are those in our precipitation input fields. One is the switch from the “unified” Climate Prediction Center (CPC) precipitation analyses over the Continental United States (ConUS) area, used until 1998, to observations from real-time gauges only, starting in 1999 (Higgins et al. 2000). Another is the change in precipitation analyses used over southern portions of the oceans starting in January 2003, when we switched to our current near real-time system. We give more details on the two new systems, CMAP and CMORPH, in the following sections.

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 (not reanalysis) lateral boundary conditions, in order to simulate the forecast skill that would be attainable in operational conditions using the same system.

The project has been supported for 6 years by the NOAA Office of Global Programs (OGP), with a reduced support in the (originally unplanned) sixth year. A Scientific Advisory Panel chaired by John Roads and reporting to OGP has provided valuable and continued guidance to the NARR project.

This is our first open literature documentation of the project, and the first report after the completion of the processing of the planned 25 years. In the section to follow we summarize the system and the data used. Subsequently, we give a description of the precipitation, upper air, near surface, and land-surface results obtained and compare the fits to observations with those of the global reanalysis. A brief summary of the near real-time continuation of the project, R-CDAS, is given next. We then briefly summarize the datasets produced, archiving systems established, and archiving activities in progress or planned. We end the main body of the text with concluding comments. Appendix A contains a more extensive documentation of the NARR datasets, and Appendix B a list of the acronyms used. A DVD accompanying this issue includes samples of results, and provides additional information useful to potential NARR users. A companion paper (Rutledge et al. 2005) will describe the data retrieval system in place at the main data distribution center, NCEP and NOAA's Climate Data Center (NCDC).

REANALYSIS SYSTEM AND DATA USED. The NARR System is essentially the same as the Eta Model and 3D-Var Data Assimilation System (EDAS), operational in April 2003 when the NARR system was frozen (Rogers and DiMego, ftp://ftp.ncep.noaa.gov/pub/emc/wd20er/caftimay01/v3_document.htm, and http://www.emc.ncep.noaa.gov/mmb/research/eta.log.html), except for a few differences. They include horizontal/vertical resolution, the use of the Zhao et al. (1997) -- as opposed to the later "Ferrier" -- cloud microphysics, and the use of a number of additional data sources (Tables 1 and 2). The system is fully cycled, with a 3-h 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 daily climatologies used are listed in Table 3.

A number of "fixed fields" are used as input to the land-surface model: land mask (land or water), vegetation type, soil type, surface slope type, snow-free albedo, maximum snow albedo, surface roughness, soil column bottom temperature, and the number of root zone soil layers (Ek et al. 2003; Mitchell et al. 2004).

The data used in the production runs includes most of the observations used in the Global Reanalysis, as listed in Table 1. The only GR data not used in the NARR are temperature retrievals since they were replaced by the use of radiances. Additional datasets used or improved in the NARR are summarized in Table 2 and discussed further below.

a. Precipitation. The assimilation of observed precipitation is by far the most important data addition to the NARR. The successful assimilation of these observations, converted into latent heat (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 ConUS area, Mexico, and Canada, the precipitation data assimilated are 24-h rain gauge data disaggregated into hourly bins. Over ConUS 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 the GR2 (Kanamitsu et al. 2002) forecasts of precipitation. 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 from full precipitation 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.

b. TOVS-1b radiances (instead of the NESDIS TOVS retrievals used in GR1 and GR2);

c. Profilers and Vertical Azimuth Display (VAD) winds;

d. Land surface wind (10 m) and moisture (2 m). We have made extensive tests on the impact of the assimilation of land surface data additional to surface pressure. In these tests, assimilation of land surface wind and moisture was found helpful, and thus was implemented in our production runs. Assimilation of land surface (2 m) temperature was found to be significantly detrimental to our tropospheric fits to rawinsondes, and therefore was not done. This issue is further discussed on the FAQ section in our NARR web page http://wwwt.emc.ncep.noaa.gov/mmb/rreanl.

e. Sea and lake ice. Over oceanic regions, until and including November 2002, ice values are based on the so-called satellite ice dataset (Grumbine 1996). This set's ice concentration values were interpolated to the RR grid, and rounded off to 1 or 0 (ice or no ice). As of December 2002, the RR ice values came from NESDIS' 25-km daily Ice Mapping System (IMS, http://www.ssd.noaa.gov/PS/SNOW/ims.html).

For the Great Lakes, ice data were available up to and including 2000 from the Great Lakes Environmental Research Laboratory (GLERL, R. Assel, personal communication). Subsequently, climatology was used, derived from the available GLERL values. Ice data for the Canadian lakes were obtained from the Ice Services Canada (ISC). The ISC data were provided on a per-lake basis, and did not contain data for every lake resolved by the RR. They were therefore supplemented, as needed, by using values of the nearest lake with data available. Also, the data mostly covered the period 1995 to November 2002; daily climatology was used for the times outside the periods of the availability of the ISC data.

f. Sea and lake surface temperatures. For most of our RR period, 1981 and onwards, ocean sea-surface temperatures (SSTs) were derived from the 1-degree so-called "Reynolds" dataset (Reynolds et al. 2002). Prior to 1981, our SSTs originate from a reconstructed SST dataset using COADS (Smith and Reynolds 2003). For the Gulf of California, in the absence of a more attractive alternative, monthly mean values valid near Guaymas, Mexico, were applied to the entire Gulf.

SSTs for the Great Lakes up to and including 2002 were provided by GLERL. For 2003, a 14-km GLERL analysis became available and was used. For the Great Salt Lake a climatological value was applied. For the Canadian lakes, when they were set to ice, the value of 273.15 was used. Otherwise, we used values interpolated between the Pacific and the Atlantic Ocean.

A more detailed discussion of the NARR data is presented in Shafran et al. (2004), also available on our web page.

RESULTS. 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 dataset over North America. We will now compare NARR precipitation monthly averages to observations, and the fit of NARR and GR to rawinsonde and near surface observations. The section will end with a brief look at the land surface data obtained.

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. For illustration, we present winter and summer examples of particular interest, in which extreme events occurred. These are January results for a year of a strong El Niño, 1998, and the difference between flood months in 1993, and drought months in 1988 (e.g., Altshuler et al. 2002).

In Fig. 2 we compare the NARR precipitation for January 1998, the El Niño case, with the analyzed precipitation. The 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 recalled 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 not as good. The tendency of the NARR to generate visibly weaker maxima over cyclonic regions of the northern Atlantic, or even fail to generate a maximum as seen in Fig. 2, has been found to be also characteristic of other months. Given that the NARR was clearly meant to address primarily the North American land, this is not seen as a critical weakness. On the other hand, the satellite-based precipitation over oceans, as stated, should not be fully trusted either.

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 not only for the Midwestern maxima, but for the details of minor maxima and minima over land. Over oceans, the agreement is also very good, since systematic underestimations such as those shown in the winter if any are not apparent as they are canceled out when taking the difference between two summers. The figure indicates a high degree of reliability in the NARR estimation of interannual variability in precipitation.

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. In Mesinger et al. (2004), we compared 24-year January and July averages of temperature and vector wind rms fits to rawinsondes as functions of pressure, with those of the GR. We found that the advantage of the NARR over the GR was quite large, especially for winds, and greater for the analysis than for the first guess. However our temperature plots were affected by an inadvertent temperature “de-virtualization”. Corrected plots for only the latest 5 of the 24 years are shown in the revised version of that paper, available on our web site.

We now have averages of rms fits to rawinsondes for both temperatures and vector winds for all of the 25 years, and they are shown in Fig 4. In the figure, 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. 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 in addition to ConUS almost all of Mexico to the south and roughly the southern tier of the Canadian provinces to the north. But one should note that rms fits shown are not averages over the domain but over the observations available, so that regions with more observations have a larger weight. Typically, regarding rawinsonde reports, about 105-109 sites would have reports on any one day within the grid 212. Of those, most, about 90, would come from the ConUS area, with about 60 from its eastern and Plains areas, and about 30 from the predominantly mountainous U.S. west.

NARR fits to rawinsondes are seen to be considerably better than those of the GR for both temperatures and winds, and in both January and July. The advantage of the NARR is greater in January than in July, and larger for winds than 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 better the weaker the balance constraint imposed in the analysis scheme. The fit of the first guess to the observations is for that reason 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. We have accordingly produced the so-called “merged” NARR files, a mix of the two, as described in Appendix A.

The NARR first guess fits to rawinsondes for our 25 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. Generally, improvements are large near the surface and at the tropopause levels, and are somewhat smaller in the lower troposphere. Specifically, for the temperature, the NARR first guess fits in January at 700 mb are only marginally better than those of the GR, and in July between about 500 to 750 mb they are even slightly worse. This appears to be caused by somewhat of a bias problem of the NARR (not shown), reaching a value on the order of –0.5°K at 700 mb, compared to hardly any bias in the lower troposphere of the GR. The fits of the first guess winds in the NARR, on the other hand, are significantly better than in the GR at all levels, especially in January, and in particular at the upper troposphere – same as the analyses.

With respect to near-surface variables, 2-m temperatures and 10-m winds, we show January and July 1988. Only the first guess results are presented, because there are no GR analyses available for these fields. Recall that over land surface winds but not temperatures are assimilated. 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, especially in winter; 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 large rms advantage of more than 1 m/s of the NARR over the GR in January. In July, despite no obvious bias advantage, the NARR rms is still smaller than that of the GR.

One advantage of the NARR compared to GR is its higher temporal resolution, 3 vs 6 h. Not only are analyses and first guess fields available at shorter time intervals, but also a considerable fraction of the data are being assimilated at times closer to the observation time. But two additional factors should also be considered: the shorter 3-h interval reduces the time for model errors to grow (an advantage) but also allows less time for the gravity waves created by the initial imbalance to settle down (a disadvantage). The two factors can have an opposite effect in terms of the NARR first guess fitting better the observations. We run experiments aimed at finding out which of the two effects might be dominant: January, April, July and October 2002 were 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. The 3 and 6-h fits were remarkably similar, but in most cases the 6-h fits were slightly smaller. Thus, as far as the comparisons with the GR first guess fits of Fig. 5 are concerned, the 3 vs 6-h difference appears to have a negligible impact.

The realistic precipitation patterns produced in the NARR by the assimilation of observed precipitation provide vastly improved precipitation forcing for the Noah LSM component compared to the GR's. The Noah LSM used in NARR closely follows that described and evaluated in both the coupled Eta/Noah study of Ek et al. (2003) and the uncoupled North American Land Data Assimilation System (NLDAS) study of Mitchell et al. (2004). The Noah LSM simulates soil temperature and soil moisture (including frozen) in four soil layers of 10, 30, 60, and 100 cm thickness. The surface infiltration scheme accounts for subgrid variability in soil moisture and precipitation. The surface evaporation includes evaporation from the soil, transpiration from the vegetation canopy, evaporation of dew/frost or canopy-intercepted precipitation, and snow sublimation. The Noah LSM simulates snowpack states of water content, density and fractional coverage via the processes of sublimation, snowfall, and snowmelt and the snowpack surface energy fluxes of radiation, sensible/latent heat flux, subsurface heat flux, and phase-change heat sources/sinks. In the NARR, the snowpack depth is updated daily from the daily global snow depth analysis (47-km) of the U.S. Air Force, known as SNODEP. This daily update increment is the minimum needed to achieve a NARR snow depth within a factor of two of the Air Force snow depth. Being conscious of the notoriously slow spin-up time of soil moisture, in setting up the four stream processing of the NARR we have been careful to allow for the first stream's initial time of 3 months prior to the official beginning of the NARR dataset, and for a long, 15-months, overlap spin-up time at the junctures of the streams. All of these should have contributed to the generation of a high quality land-surface subset of the NARR; this has been confirmed by our inspection of various LSM NARR results.

Finally, it should be noted that a wealth of additional summary-type NARR results is available on our web site within the CPC-produced "climatology" of the NARR, and also, in particular as it concerns moisture transport processes, in Mo et al. (2005).

WORK IN PROGRESS: R-CDAS, AND DATA ARCHIVING ACTIVITIES. The NARR project originally aimed to produce a "retrospective" reanalysis of 25 years, 1979-2003, and to have it continue as a near-real time system starting with 1 January 2004. After we finished the retrospective processing to the end of November 2002, we faced a number of obstacles due to the fact that some of the datasets that we used were no longer available. Two major obstacles were unavailability of CMAP precipitation analysis over oceans, and unavailability of gauge precipitation observations over Canada. Other datasets that we were not able to procure in the same form as used retrospectively were specially processed ("Grumbine") sea ice and GLERL Great Lakes ice, beyond November 2002; and Great Lakes SSTs, beyond December 2002. Yet another problem was unavailability of data on the ice cover of the Canadian lakes.

We have therefore decided to process 2003, and for most of the variables listed above also December 2002, using our real-time system. This system, R-CDAS, Regional Climate Data Assimilation System, is identical to the one used in the retrospective NARR except for the following: For precipitation analyses over oceans we use the newly developed precipitation monitoring system CMORPH (Joyce et al. 2004). As a replacement of precipitation observations from Canada starting in January 2003 we use the model produced precipitation north of the area analyzed by CPC in real time which is an area somewhat greater than ConUS; at the northern boundary we use a blending similar to that used in the retrospective mode over oceans. For ocean ice cover as of December 2002 we use the daily NESDIS Interactive Multisensor Snow and Ice Mapping System (IMS) data. And finally, for the Great Lakes and Canadian lakes ice we use climatology.

We have compared the new system to 2002 for continuity and are running it as R-CDAS. The system has been ported to the current NCEP mainframe computer system, with responsibility for its daily running taken over by CPC.

During the intensive effort to complete the 23+ years of the NARR processing on the NCEP IBM supercomputer previously used for production, 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 NARR data followed and was completed 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 different 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 NOAA Operational Model Archive Distribution System (NOMADS) facility at NCDC a major distributor of NARR data. To handle the data volumes, the next version of the NOMADS software should allow subsetting by user specification of 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 have been produced, containing analysis and some of the first guess fields (Appendix A).

Additional outreach efforts are in progress or planned. Several NARR papers (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) are available on our web page, http://wwwt.emc.ncep.noaa.gov/mmb/rreanl. About 1000 copies of a CDROM with 24 years of NARR maps were distributed at the AMS 2004 Annual Meeting, and a NARR Users Workshop is scheduled to be held at the 2005 Annual Meeting. Additional information is available at the web page above, including instructions how to access the data that have been posted at various archiving centers. Yet more information along with a selection of NARR results, such as a set of monthly means, a set of daily means, a set of model-produced soundings, a sample free-forecast, and additional miscellaneous fields, is present on the DVD accompanying this Bulletin issue.

Comments on the NARR results posted or other related questions are most welcome and are hereby solicited.

CONCLUDING COMMENTS. The results summarized we believe confirm that the objectives set out at the beginning of the Regional Reanalysis project, to create a long-term, consistent, high-resolution climate dataset for the North American domain, as a major improvement upon the earlier global reanalysis datasets in both resolution and accuracy, have been fully met. Regarding accuracy, not only have the near-surface temperatures and winds been shown to be closer to the observations than those of the GR, as could probably be expected, but clear and quite significant improvements in winds and temperatures throughout the troposphere have been demonstrated as well.

With respect to the magnitude of improvements, given that the RR has assimilated the 10-m winds while the GR did not, one could expect the observed improvements in the 10-m winds. But the 2-m temperatures, which neither of the two reanalyses assimilated, can be looked upon as an independent verification of the reanalysis skill, so that improvements, quite considerable in winter, are worth noting. But perhaps the strongest indication of the overall quality of the product are the winds in the upper troposphere. Improved fits to raobs by about a third of that of the GR throughout the troposphere, including those at the jet stream levels, are well above our expectations. Given that jet stream level winds if anything describe primarily the largest atmospheric scales, this could be seen as a result going beyond the widespread downscaling concept when it comes to the use of limited area models. Another result worth noting is that the improvements over the GR are greater in winter than they have been in summer.

On the other hand, some of the RR features failed to be confirmed as beneficial. While no harm was documented from direct assimilation of radiances, no evidence of benefit was noted either. It is suspected that this is due to the relatively low top of the Eta Model used, of 25 mb. Higher temporal analysis frequency of the RR compared to that of the GR, 3 vs 6 h, respectively, has also not been demonstrated to increase the accuracy of the RR. Issues such as these should be understood better as studies of the system components and features are presumably advanced in years to come.

There have also been a few weaknesses found that require study to understand their origin. The most conspicuous of these is the systematic excessive strength of the Gulf of California low level jet (GCLLJ) in summer (Mo et al. 2005), with large differences compared to various observational evidence over the northern Gulf of California. This is an important issue in view of the North American Monsoon Experiment (NAME) activities and is at the time of this writing under investigation. We have also become aware that our precipitation analysis over Canada, due to a relatively small number of gauge observations we had, is not as good as we had hoped for. Our precipitation over northern Atlantic (e.g., Fig. 2) is also not as good as desired, and we do not expect our simulation of Atlantic hurricanes to be our strong point either. Yet, our overall accuracy, as illustrated by the four-panel plots of Fig. 4, makes us confident that our NARR datasets produced will keep yielding valuable results for numerous research and application purposes for years to come.

We are encouraged by the widespread use of the RR data for a variety of applications already at this early time, and hope to be able to learn from as well as be helpful to users and their projects. At the time of this writing we are looking forward to the first NARR Users Workshop at the coming AMS Annual Meeting in San Diego, in January 2005.

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APPENDIX A: NARR OUTPUT. The complete NARR archive is approximately 75 TB and includes the following:

input observations;

input observations with quality control (QC) marks and differences from analyses and first guess;

input analyses: sea surface temperature, snow, sea ice, observed precipitation;

plots of observations locations, QC;

plots of fits of analyses to observations;

plots of fits to global reanalysis;

plots of analyses;

fixed fields such as land-sea, vegetation, soil type, orographic height;

3 day forecasts every 2.5 days;

analyses and 3 hour forecasts (first guess) in three different sets of files (model restart, GRIB format on model grid, GRIB format on Lambert conformal grid)

The bulk of the 75 TB is taken by the model restart files, analyses and first guess fields. The format of the model restart files is binary, while that of the analyses and first guess fields is GRIB. The analyses and first guess fields are each saved on two grid types, model and Lambert conformal (so-called grid 221). The model grid is unsupported by many visualization programs as the wind and mass points are staggered. The binary restart file has a non-standard format and is much larger than the GRIB files because it contains all information needed for restarting the model. Consequently the Lambert conformal (AWIPS) GRIB data is considered the best suited for most users. Experience from earlier reanalyses suggests that a majority of users are mostly interested in the analyses and flux quantities (e.g., precipitation, latent heat, OLR) from the first guess. Demand for the forecasts is expected to be small, at least initially. A 'merged' dataset was thus formed based on the analyses supplemented by fluxes on the AWIPS grid. It is approximately 5 TB (60 MB every 3 hours). We expect that this merged dataset (contents to be given below) along with some of the smaller datasets will satisfy most users.

The data in the merged file is similar to that from the operational Eta model; the data is in GRIB format, on a Lambert-conformal grid and most of the fields are common to both the operational Eta and NARR datasets. However, there are some subtle differences. In the operational Eta, the wind components are grid relative and need to be rotated to produce the usual earth-relative winds. In the NARR, the rotation has already been done. Another difference is that NARR uses only one GRIB table because some software does not support multiple GRIB tables. (The operational Eta uses three GRIB tables.)

There are many software packages that handle GRIB files. We have tested and use the following, for tasks as given below.

GrADS: http://grads.iges.org/grads/

visualization and calculation tool (linux, windows, etc);

grib2ctl: http://wesley.ncep.noaa.gov/grib2ctl.html

makes control files for GrADS, updated for NARR (linux, windows, etc)

copygb: ftp://wesley.ncep.noaa.gov/pub/copygb/copygb-g95-linux.tgz

convert lambert-conformal grids to other grids, port for NARR (linux)

wgrib: http://wesley.ncep.noaa.gov/wgrib.html

inventory and decode GRIB files, updated for NARR (linux, windows, etc)

Distribution of Data. NCAR (National Center for Atmospheric Research), NCDC (National Climatic Data Center) and SDSC (San Diego Supercomputer Center at UCSD) have agreed to distribute the NARR merged dataset. These centers have their communities that they support; however, NCDC is using NOMADS (Rutledge et al. 2005) for distributing the data over the internet making the data freely and widely available. Of course bandwidth limitations are factor in such an approach, so one needs to avoid the mindset of "how do I get all the data" to "how do I use the web services to only get the data that I need." (See Rutledge et al. (2005) and Ebisuzaki et al. (2004) for more details.)   In order to keep the resources used per request at a manageable amount, NCDC-NOMADS set policies to limit requests that use large amounts of disk space, CPU time and I/O time. For current information, see the NARR home page, http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/index.html.

Merged Dataset. The merged dataset consists of two files containing 8 times per day analyses. The main ("a") file contains the analyses, accumulations and averages. The "b" file contains a few 3 hour forecast files that are meant to be helpful in doing hydrological budget calculations. We next list the variables included in the "main" and in the "b" merged files. Please note that the time and level/layer abbreviations are defined after the list. "Same but x" indicates that the same field is also saved at level x.

Main Merged File

Name	Valid time	Level/ layer	Comments
4LFTX	anl	180	Best (4-layer) lifted index
ACPCP	acc	sfc	Convective precipitation
ALBDO	anl	sfc	Albedo
APCP	acc	sfc	Total precipitation
APCPN	acc	sfc	Total precipitation (nearest grid point)
BGRUN	acc	sfc	Subsurface runoff (baseflow)
BMIXL	anl	hl1	Blackadar's mixing length scale
CAPE	anl	180	Convective available potential energy
			Same, but sfc
CCOND	anl	sfc	Canopy conductance
CD	anl	sfc	Surface drag coefficient
CDCON	ave	col	Convective cloud cover
CDLYR	ave	col	Non-convective cloud
CFRZR	3hr	sfc	Categorical freezing rain

CICEP	3hr	sfc	Categorical ice pellets
CIN	anl	180	Convective inhibition
			Same, but sfc
CLWMR	anl	prs	Cloud water
CNWAT	anl	sfc	Plant canopy surface water
CRAIN	3hr	sfc	Categorical rain
CSNOW	3hr	sfc	Categorical snow
DLWRF	ave	sfc	Downward longwave radiation flux
DPT	anl	2m	Dew point temperature
DSWRF	ave	sfc	Downward shortwave radiation flux
EVP	acc	sfc	Evaporation
FRICV	anl	sfc	Surface friction velocity
GFLUX	ave	sfc	Ground heat flux
HCDC	3hr	hcl	High level cloud cover
HGT	anl	prs	Geopotential height
			Same, but 0C, hl1, mwl, trop, cld base, cld top, max wind
HLCY	anl	3000	Storm relative helicity
HPBL	anl		Planetary boundary layer height
ICMR	anl	prs	Ice mixing ratio
LCDC	3hr	lcl	Low level cloud cover
LFTX	anl		Surface lifted index
LHTFL	ave	sfc	Latent heat flux
MCDC	3hr	mcl	Middle level cloud cover
MCONV	anl	slay	Horizontal moisture divergence
MCONV	anl	hl1	Horizontal moisture divergence
MSLET	anl		Mean sea level pressure (Eta model)
MSTAV	anl	100	Moisture availability
PEVAP	acc	sfc	Potential evaporation

POT	anl	10m	Potential temperature
			Same, but 30m, hl1, sfc
PRATE	3hr	sfc	Precipitation rate
PRES	anl	2m	Pressure
			Same, but 30m, cld base, cld top, cond. level, hl1, max wind, sfc, trop.
PRESN	anl	sfc	Pressure (nearest grid point)
PRMSL	anl	MSL	Pressure reduced to MSL
PWAT	anl	col	Precipitable water
RCQ	anl	sfc	Humidity parameter in canopy conductance
RCS	anl	sfc	Solar parameter in canopy conductance
RCSOL	anl	sfc	Soil moisture para. canopy conductance
RCT	anl	sfc	Temperature para. canopy conductance
RH	anl	0C	Relative humidity
			Same, but 2m, hl1
SFEXC	anl	sfc	Exchange coefficient
SHTFL	ave	sfc	Sensible heat flux
SNOD	anl	sfc	Snow depth
SNOHF	ave	sfc	Snow phase-change heat flux
SNOM	acc	sfc	Snow melt
SNOC	anl	sfc	Snow cover
SOILL	anl	soil	Liquid volumetric soil moisture (non-frozen)
SOILM	anl	soil	Soil moisture content
SPFH	anl	prs	Specific humidity
			Same, but 2m, 10m, 30m, slay, hl1
SSRUN	acc	sfc	Surface runoff (non-infiltrating)
TCDC	3hr	col	Total cloud cover
TKE	anl	hl1	Turbulence kinetic energy
			Same, but prs (only 1000-600 hPa)

TMP	anl	prs	Temperature
			Same, but 2m, 10m, 30m, slay, hl1, sfc, trop
TSOIL	anl	soil	Soil temperature
UGRD	anl	prs	Zonal wind (earth relative, AWIPS grid)
			Same, but 10m, 30m, slay, hl1,max wind, trop
ULWRF	ave	top	Upward longwave radiation flux
			Same, but sfc
USTM	anl	6000	u-component of storm motion
USWRF	ave	top	Upward shortwave radiation flux
USWRF	ave	sfc	Upward shortwave radiation flux
VEG	anl	sfc	Vegetation
VGRD	anl	prs	Zonal wind (earth relative on AWIPS grid)
			Same, but 10m, 30m, slay, hl1, max wind, trop
VIS	anl	sfc	Visibility
VSTM	anl	6000	v-component of storm motion
VVEL	anl	prs	Pressure vertical velocity
			Same, but slay, hl1
VWSH	anl	trop	Vertical speed shear
WCCONV	acc	2l	Water condensate flux convergence
WCINC	acc	2l	Water condensate added by precipitation assimilation
WCUFLX	acc	2l	Water condensate zonal flux
WCVFLX	acc	2l	Water condensate meridional flux
WEASD	anl	sfc	Accumulated snow
WVCONV	acc	2l	Water vapor flux convergence
WVINC	acc	2l	Water vapor added by precipitation assimilation
WVUFLX	acc	2l	Water vapor zonal flux
WVVFLX	acc	2l	Water vapor meridional flux

"B" Merged File

Name	Valid time	Level/ layer	Comments
DLWRF	fcst	sfc	Downward longwave radiation flux
DSWRF	fcst	sfc	Downward shortwave radiation flux
GFLUX	fcst	sfc	Ground heat flux
LHTFL	fcst	sfc	Latent heat flux
PWAT	fcst	col	Precipitable water
SHTFL	fcst	sfc	Sensible heat flux
ULWRF	fcst	sfc	Upward longwave radiation flux
USWRF	fcst	sfc	Upward shortwave radiation flux
WEASD	fcst	sfc	Accumulated snow [kg/m^2]

Definition of abbreviations of time validity and level or layer:

0C = Freezing level

100 = 0-100 cm below ground

10m = 10 m above ground

180 = 0-180 hPa above ground

2l = atmospheric column, top of atmosphere-700 hPa

2m = 2 m above ground

3000 = 0-3000 m above ground

6000 = 0-6000 m above ground

acc = accumulation from a 0-3 hour forecast

anl = analyses

ave = average from a 0-3 hour forecast

col = atmospheric column

fcst = 3 hour forecast

hcl = high cloud layer

hl1 = hybrid level 1

prs = 1000, 975, 950, 925, 900, 875, 850, 825, 800, 775, 750, 725,700, 650,

```
      600, 550, 500, 450, 400, 350, 300, 275, 250, 225, 200, 175, 150, 125,
      100 hPa
slay = 0-30, 30-60, 60-90, 90-120, 120-150, 150-180 hPa above ground
soil = 0-10, 10-40, 40-100, 100-200 cm below the surface
top  = nominal top of the atmosphere
trop = tropopause
```

APPENDIX B: List of Acronyms

3DVAR	3-Dimensional Variational Analysis
AWIPS	Advanced Weather Interactive Processing System
CMAP	CPC Merged Analysis of Precipitation
CMORPH	CPC Morphing Technique
COADS	Comprehensive Ocean-Atmosphere Dataset
COLA	Center for Ocean, Land, and Atmospheric Studies
CONUS	Continental United States
CPC	Climate Prediction Center
DOE	Department of Energy
DVD	Digital Versatile Disc
EDAS	Eta Data Assimilation System
EMC	Environmental Modeling Center
GCIP	GEWEX Continental-Scale International Project
GEWEX	Global Energy and Water Cycle Experiment
GLERL	Great Lakes Environmental Research Laboratory
GRIB	Gridded Binary
FAQ	Frequently Asked Questions
GCLLJ	Gulf of California Low Level Jet
GR	Global Reanalysis
GR2	Global Reanalysis 2 (Kanamitsu et al. 2002)

HPD	Hourly Precipitation Data
ISC	Ice Services Canada
IMS	Ice Mapping System
LSM	Land-Surface Model
NAME	North American Monsoon Experiment
NARR	North American Regional Reanalysis
NESDIS	National Environmental Satellite, Data, and Information Service
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCDC	National Climate Data Center
NLDAS	North American Land Data Assimilation System
NOAA	National Oceanic and Atmospheric Administration
NOAH	NCEP, Oregon State University, Air Force, and Office of Hydrology LSM
NOMADS	NOAA Operational Model Archive and Distribution System
PRISM	Parameter-elevation Regressions on Independent Slopes Model
R-CDAS	Regional Climate Data Assimilation System
OGP	NOAA Office of Global Programs
SDSC	San Diego Supercomputing Center
SNODEP	Snow Depth dataset from Air Force
TDL	Techniques Development Laboratory
TIROS	Television Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
VAD	Vertical Azimuth Display

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Figure captions

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

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 1998 (inches/month). White indicates no available observations.

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 1991-2003 for temperature, and over 1979-2003 for wind. NARR: dashed lines, GR: solid lines.

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

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.

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

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

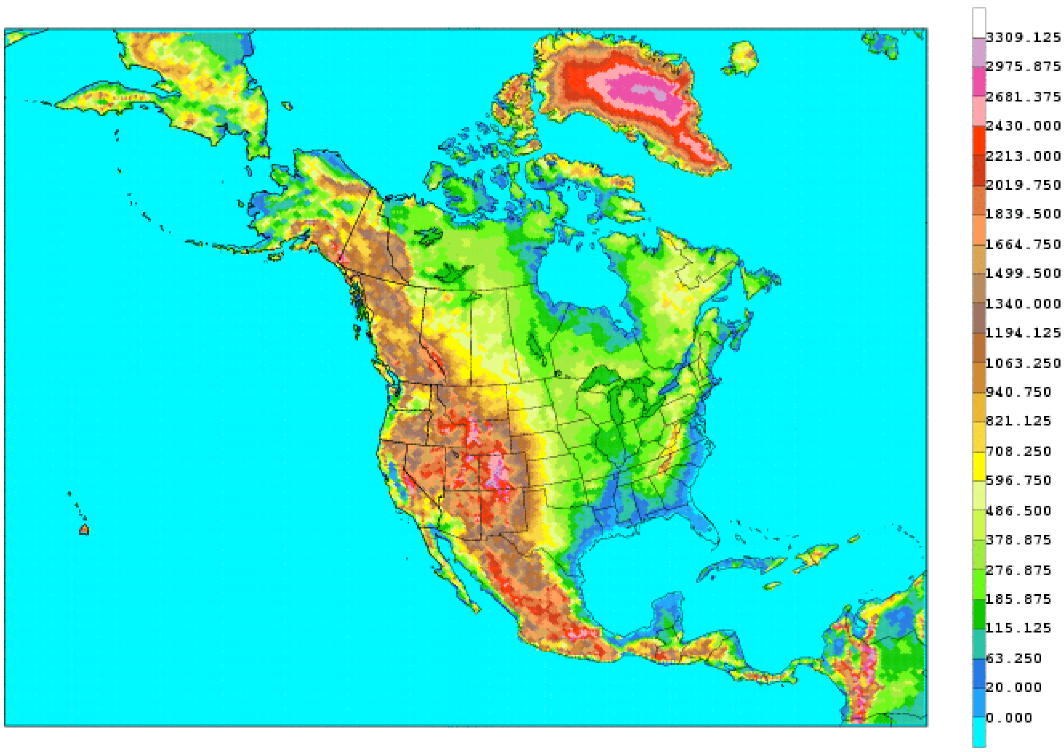
Dataset	Observed variable	Source
Rawinsondes	Temperature, wind, moisture	NCEP/NCAR Global Reanalysis (GR)
Dropsondes	Same as above	GR
Pibals	Wind	GR
Aircraft	Temperature and wind	GR
Surface	Pressure	GR
Geostationary satellites	Cloud drift wind	GR

Table 2. Data added or improved upon for the North American Regional Reanalysis

Dataset	Details	Source
Precipitation, disaggregated into hours	CONUS (with PRISM), Mexico, Canada, CMAP over oceans (<42.5°N)	NCEP/CPC, Canada, Mexico
TOVS-1B radiances	Temperature, precipitable water over oceans	NESDIS
NCEP Surface	Wind, moisture	GR
TDL Surface	Pressure, wind, moisture	NCAR
COADS	Ship and buoy data	NCEP/EMC
Air Force Snow	Snow depth	COLA and NCEP/EMC
SST	1-degree Reynolds, with Great Lakes SSTs	NCEP/EMC, GLERL
Sea and lake ice	Contains data on Canadian lakes, and Great Lakes	NCEP/EMC, GLERL, Ice Services Canada
Tropical cyclones	Locations used for blocking CMAP precipitation	Lawrence Livermore National Laboratory

Table 3. Daily climatologies used in the North American Regional Reanalysis

Dataset	Used for	Source
Green vegetation fraction	Initialization of vegetation	GR
Baseline snow-free albedo	Initialization of albedo	GR



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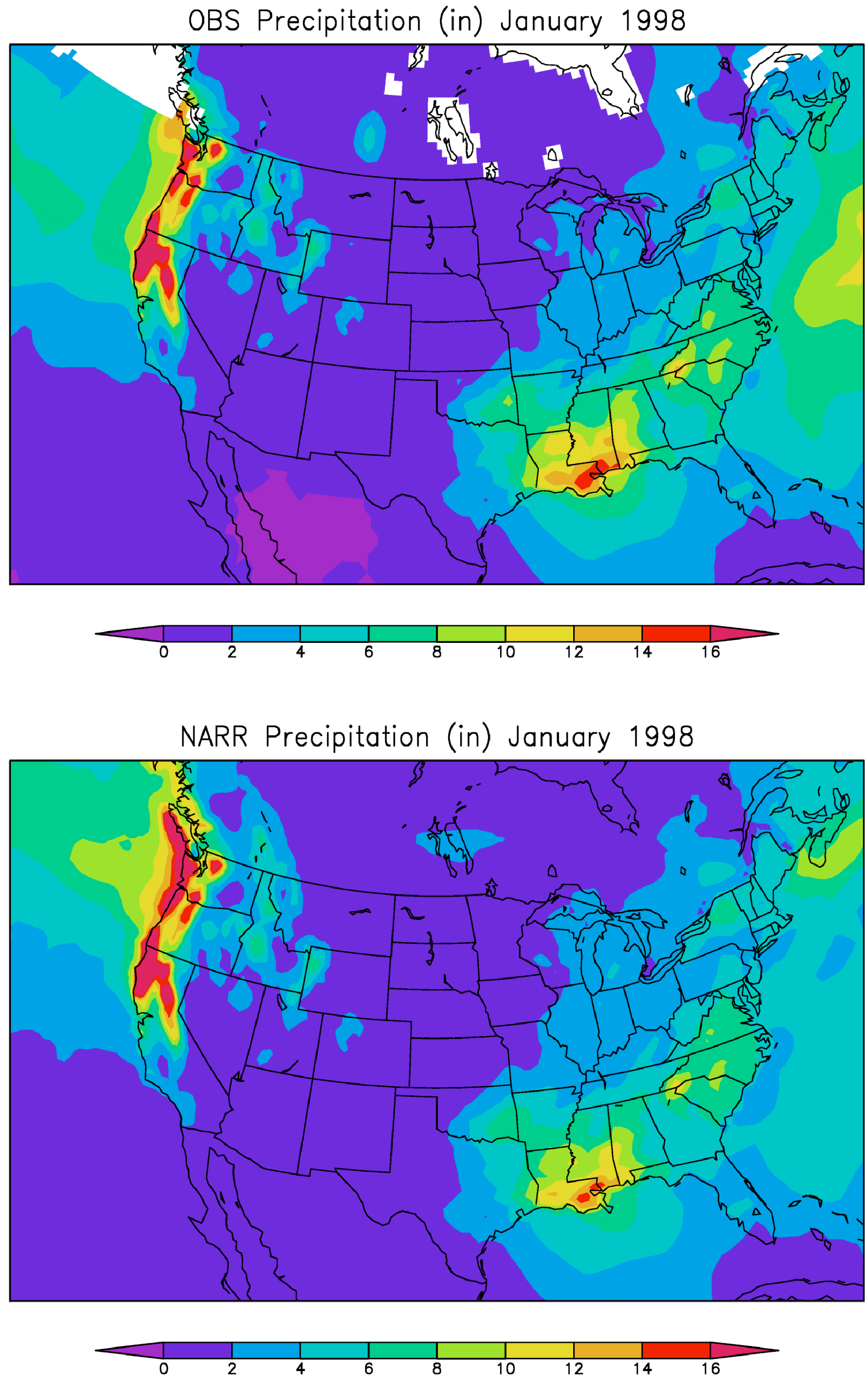


Fig 2. "Observed" (analyzed) precipitation assimilated by the NARR over land and over southern parts of the oceans (see text), and NARR precipitation, averaged for January 1998 (inches/month). White indicates no available observations.

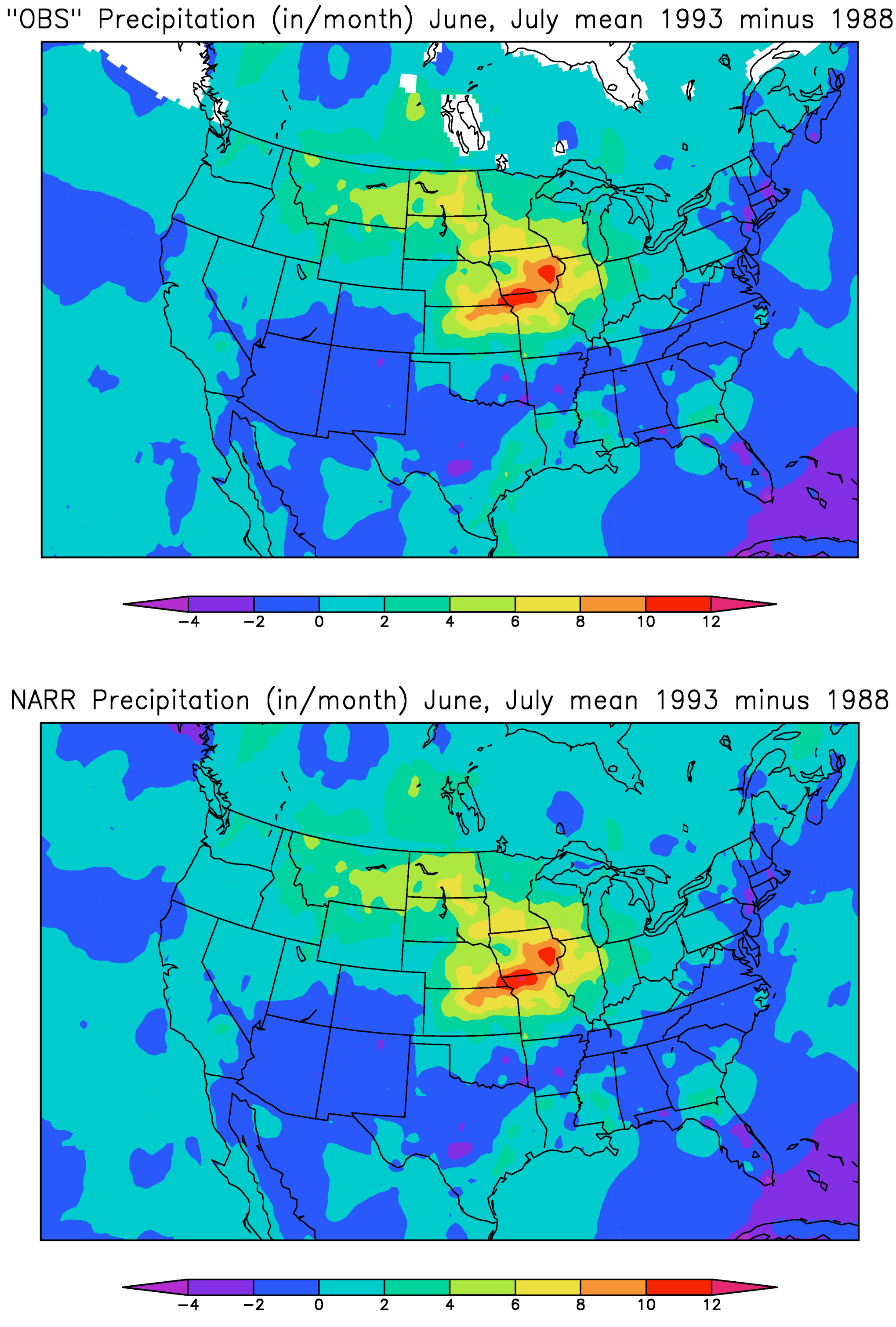
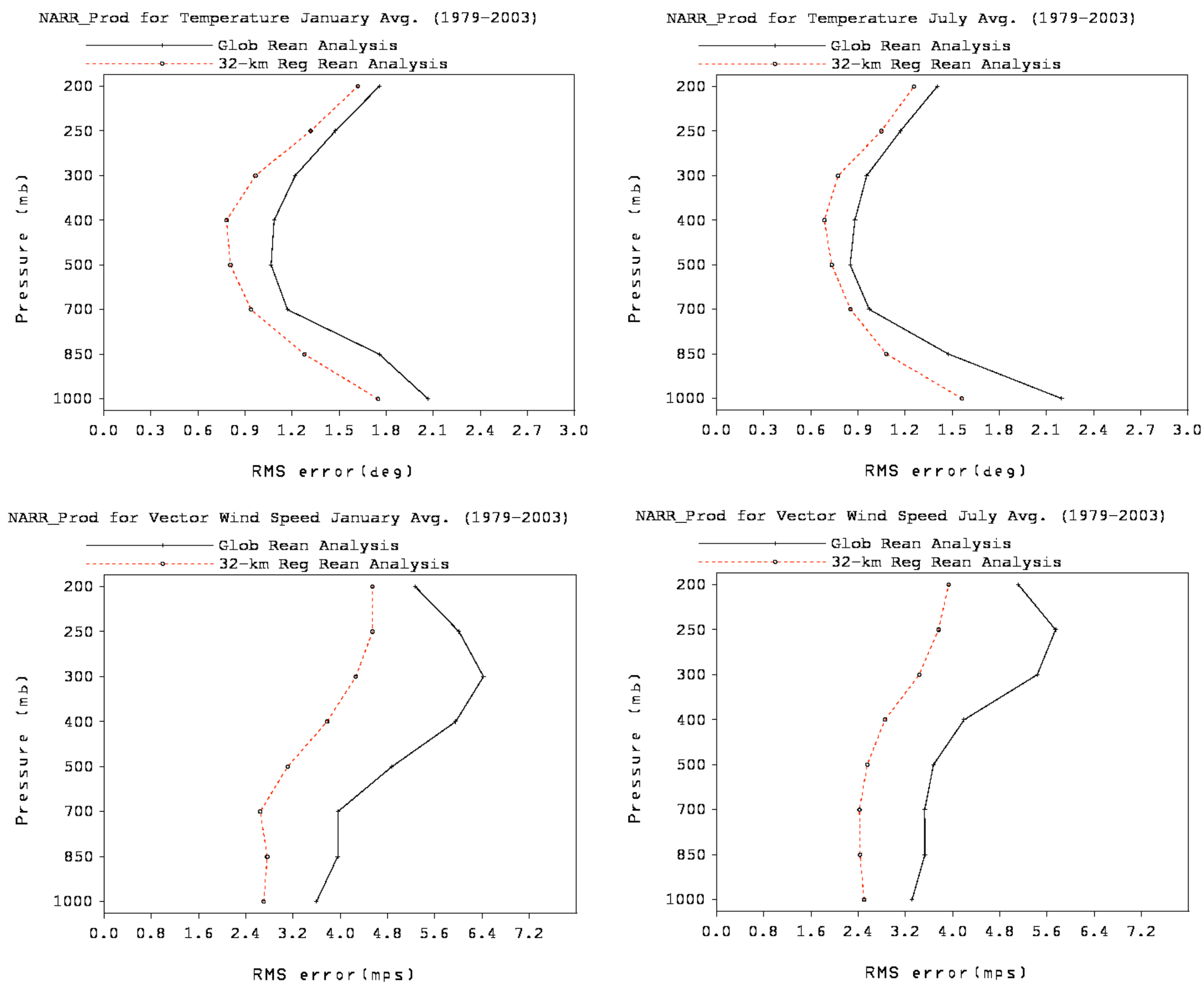


Fig. 3. "Observed" precipitation, assimilated by the NARR over land and over southern parts of the oceans (see text), and NARR precipitation, June, July 1993 minus June, July 1988 (inches/month).



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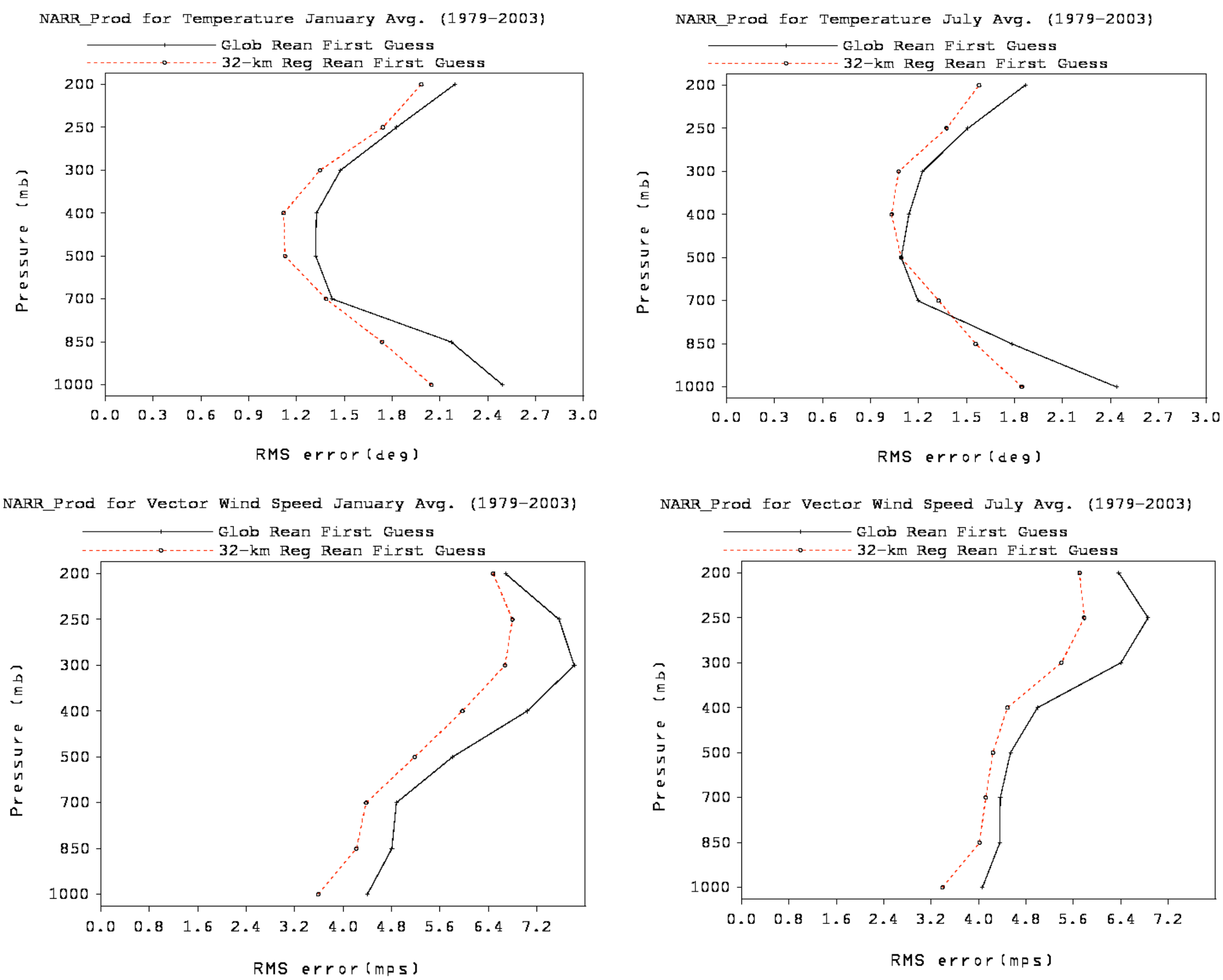
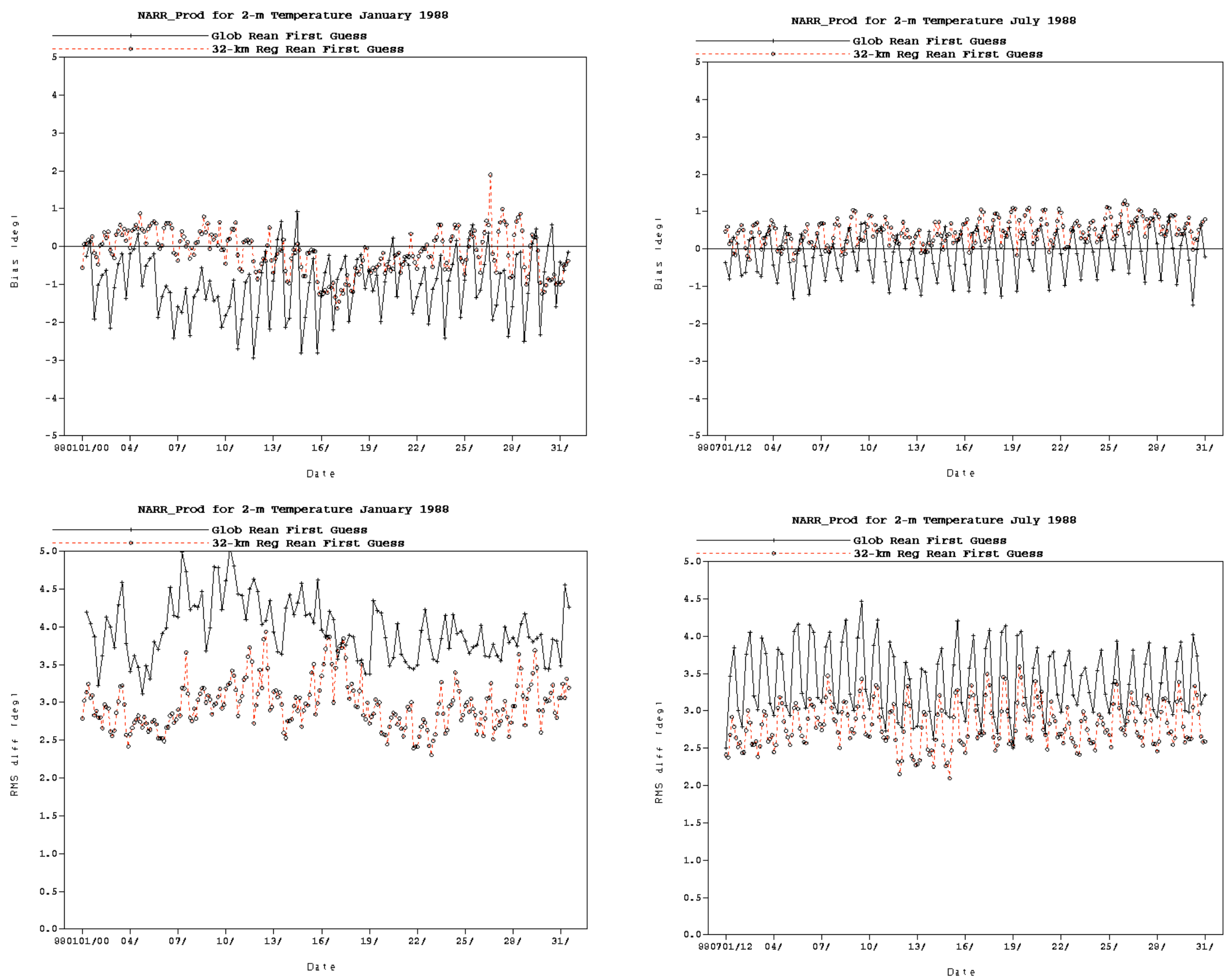


Fig. 5. Same as Fig. 4 but for the first guess.



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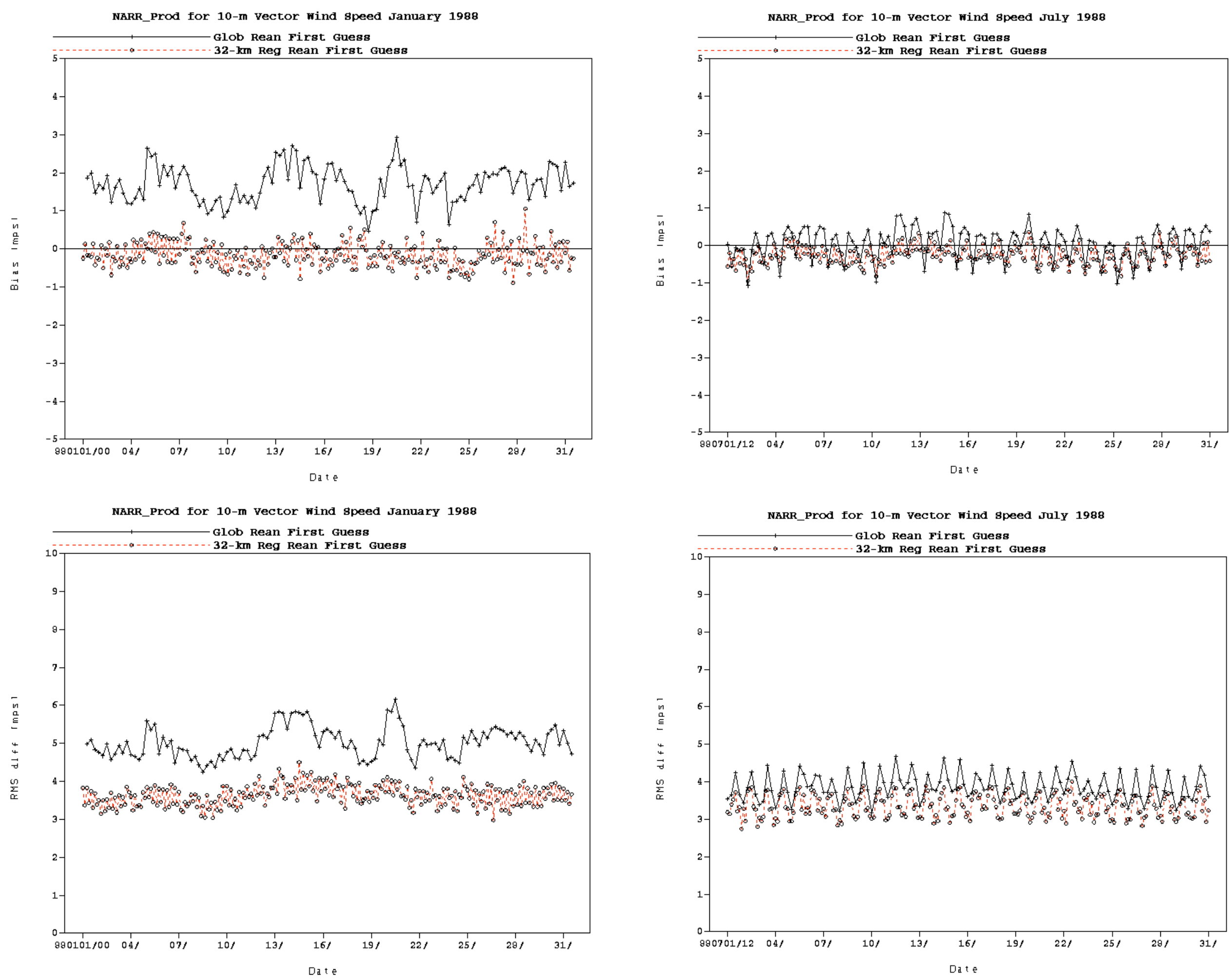

Fig. 7. Same as Fig. 6 but for the 10-m winds.