NORTH AMERICAN REGIONAL REANALYSIS

BY FEDOR MESINGER, GEOFF DIMEGO, EUGENIA KALNAY, KENNETH MITCHELL, PERRY C. SHAFRAN, WESLEY EBISUZAKI, DUŠAN JOVIĆ, JACK WOOLLEN, ERIC ROGERS, ERNESTO H. BERBERY, MICHAEL B. EK, YUN FAN, ROBERT GRUMBINE, WAYNE HIGGINS, HONG LI, YING LIN, GEOFF MANIKIN, DAVID PARRISH, AND WEI SHI

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, is presented.

The NCEP (see appendix C for a list of acronyms) NARR is a long-term, dynamically consistent, high-resolution, high-frequency, atmospheric and land surface hydrology dataset for the North American domain. It covers the 25-yr period of 1979–2003 and is being continued in near–real time as the R-CDAS. Essential components of the system used to generate NARR are the lateral boundaries from and the data used for the NCEP–DOE Global Reanalysis, the NCEP Eta Model and its Data Assimilation System, a recent version of the Noah land-surface model, and the use of numerous datasets additional to or improved compared to those of the global reanalyses. In particular, NARR has successfully assimilated high-quality and detailed precipitation observations into the atmospheric analysis. Consequently, the forcing to the land-surface model component of the system is more accurate than in previous reanalyses, so that NARR provides a much-improved analysis of land hydrology and land–atmosphere interaction. The overall atmospheric circulation throughout the troposphere has been substantially improved as well.

Exploration of a regional reanalysis effort as a follow up to the NCEP–NCAR Global Reanalysis project was recommended by the November 1997 meeting of the advisory committee of the project. Opinion was expressed by the committee that "the proposed regional reanalysis is an exciting new idea which has considerable potential value, particularly if the RDAS is significantly better than the global reanalysis at capturing the regional hydrological cycle, the diurnal cycle and other important features of weather and climate variability."

AFFILIATIONS: MESINGER AND EK—NCEP/Environmental Modeling Center, Camp Springs, Maryland, and University Corporation for Atmospheric Research, Boulder, Colorado; DIMEGO, MITCHELL, ROGERS, GRUMBINE, LIN, MANIKIN, AND PARRISH—NCEP/Environmental Modeling Center, Camp Springs, Maryland; KALNAY, BERBERY, AND LI—Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland; SHAFRAN, JOVIĆ, AND WOOLLEN—NCEP/Environmental Modeling Center, Camp Springs, Maryland, and Science Applications International Corporation, San Diego, California; EBISUZAKI, HIGGINS, AND SHI—NCEP/Climate Prediction Center, Camp Springs, Maryland; FAN—NCEP/Climate Prediction Center, Camp Springs, Maryland, and RS Information Systems, McLean, Virginia
CORRESPONDING AUTHOR: Fedor Mesinger, NCEP/Environmental Modeling Center, 5200 Auth Road, Room 207, Camp Springs, MD 20746-4304
E-mail: fedor.mesinger@noaa.gov

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The NARR project was subsequently formed and has been supported for 6 years by the NOAA OGP. A scientific advisory panel chaired by John Roads of the Scripps Institute of Oceanography (La Jolla, California), reporting to OGP, has provided valuable and continued guidance to the NARR project.

Following the 25-yr period of 1979–2003, the NARR is being continued in near–real time as the R-CDAS. As specified in more detail below, this is done with a maximum effort to minimize changes in R-CDAS compared to the retrospective NARR system, so that the only changes in place are those that were forced by either unavailability in near–real time of some of the data sources or discontinuation of a data source.

After several years of development, most of the NARR production was successfully completed during May–September 2003, taking advantage of the window of availability of a previously "production" NCEP IBM 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-yr period.

The NARR was developed as a major improvement upon the earlier NCEP–NCAR GR1 (Kalnay et al. 1996; Kistler et al. 2001) in both resolution and accuracy. The NCEP–DOE GR2 (Kanamitsu et al. 2002) is used to provide lateral boundary conditions. The NARR takes advantage of the use of a recently operational version of the NCEP regional Eta model (Mesinger et al. 1988; Black 1988; Janjić 1994; for an overview, see Mesinger 2000) and data assimilation system (Rogers et al. 2001), including the many advances that have been made to this regional system since the GR system's vintage of 1995.

Some of the most important improvements are the 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 initiatives in hydrological research, such as assimilation of precipitation and improvements to the Noah land surface model, which is the land model subcomponent 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 model) 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 and 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 online at the NARR Web site (www.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 input. Temperature and vector wind rms fits to rawinsondes were considerably improved over those of the GR2 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.

In addition to completing our 25-yr production period, we have also built the system for and started the near-real-time continuation of the NARR, following the practice of the NCEP global Climate Data Assimilation System, the real-time continuation of the GR. A basic requirement underlying reanalysis efforts is, of course, minimization of technical inhomogeneities in the system. However, inhomogeneities in the input data are unavoidable, and the most important of these we faced are in the input precipitation fields. One such change, introduced into the processing as of 1999, is the switch from the use of both real-time and non-real-time precipitation observations to the use of only real-time observations in the gauge-only precipitation analyses over the CONUS. Another is the change in the type of CPC precipitation analyses used over the low- and lower midlatitude oceans, starting with January 2003, when we switched to our current near-real-time system. In the following sections, we give more details on these two systems of ocean precipitation analysis—namely, the CMAP, used in the retrospective NARR, and the CMORPH, used in the real-time R-CDAS.

As was the case with the GR, the NARR includes free forecasts performed at regular intervals, which are 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 should be useful to estimate or eliminate spinup 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.

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 2. A brief summary of the near-real-time continuation of the project, R-CDAS, is given next. We then summarize the datasets produced, archiving systems established, and archiving activities in progress or planned. Appendix A contains a more extensive description of the NARR datasets. A DVD accompanying this issue includes samples of results and provides additional information useful to potential NARR users. Appendix B summarizes the contents of the DVD in some more detail. Appendix C is a list of the acronyms used. A companion paper (Rutledge et al. 2006) will describe the data-retrieval system in place at the NCDC data distribution center.

TABLE 1. Data used in both the NCEP–DOE Global Reanalysis and in the North American Regional Reanalysis.

Dataset	Observed variable	Source
Rawinsondes	Temperature, wind, moisture	GR2
Dropsondes	Same as above	GR2
Pibals	Wind	GR2
Aircraft	Temperature and wind	GR2
Surface	Pressure	GR2
Geostationary satellites	Cloud drift wind	GR2

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	NESDIS
NCEP surface	Wind, moisture	GR2
MDL surface	Pressure, wind, moisture	NCAR
COADS	Ship and buoy data	NCEP/EMC
Air Force snow	Snow depth	Air Force Weather Agency
SST	1° 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

REANALYSIS SYSTEM AND DATA USED.

The NARR system is essentially the same as the EDAS operational in April 2003 when NARR was frozen [see Rogers (2005) for evolution of Eta and its 3DVAR-based EDAS], except for a few differences. They include horizontal/vertical resolution, the use of the Zhao et al. (1997) cloud microphysics that are used in the NCEP operational Eta model until November 2001, and the use of a number of additional data sources (Tables 1 and 2). (The Zhao et al. cloud microphysics were retained because the methodology for precipitation assimilation applied in the NARR had a longer track record for this choice of microphysics at the time at which the NARR configuration had to be frozen.) The NARR assimilation system is fully cycled, including the prognostic land states, with a 3-h forecast from the previous cycle serving as the first guess for the next cycle. A schematic illustrating the sequence of steps in this analysis–forecast system is shown in Fig. 1. In the figure, the funnel-shaped border of the 3-h observa-

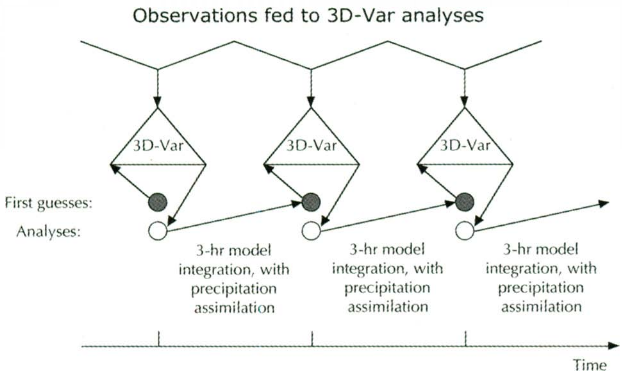

Fig. 1. A schematic illustrating the sequence of analysis–forecast steps of the NARR system.

tion segments feeding into the 3DVAR steps is meant to imply collection of data over the 3-h intervals centered at the analysis times. For the near-surface data assimilated we used a narrower time interval of 1 h (not shown in the figure).

The 32-km and 45-layer resolution used for the NARR production runs is the same as that of the operational Eta model prior to September 2000, but the domain is larger and equal to that of the current operational Eta model. The NARR domain and topography are shown in Fig. 2 and the climatologies used are listed in Table 3.

A number of the following fixed fields are used as input to the land surface model: land mask (land or water), vegetation type, soil type, surface slope category, maximum snow albedo, 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 include most of the observations used in the global reanalysis and its updated version GR2, as listed in Table 1. The only NARR domain GR2 data not used are satellite temperature retrievals because they were replaced by the use of satellite radiances. Assimilation of radiances affects both temperature and moisture, but, as used in the Eta model 3DVAR, over land the assimilation of radiances contains almost no moisture information. Additional datasets used or improved 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 observed precipitation, converted into latent heat (Lin et al. 1999; see also the next section), ensures that the model precipitation during the assimilation is close to that observed, and therefore, hopefully, ensures that the hydrological cycle is more realistic than if the model was free to forecast precipitation. All of the precipitation analyses ingested in NARR are ultimately disaggregated into hourly analyses on NARR's computational grid, but the starting point and methodology of this disaggregation is different whether over land or oceans.

Over CONUS, Mexico, and Canada, the hourly precipitation analyses are obtained by disaggregating a 24-h analysis derived solely from rain-gauge data. Over Mexico and Canada, the 24-h analysis is a 1° analysis of rain-gauge data using the Cressman successive-scan analysis technique. This 24-h analysis is disaggregated to hourly using the GR2 1-hourly precipitation forecasts. Over CONUS, the 24-h analysis is a 1/8° analysis obtained using the analysis method of J. Schaake (2001, personal communication), which applies an inverse-square-distance weighting scheme and an orographic enhancement technique known as PRISM (Daly et al. 1994). This 24-h CONUS analysis is disaggregated to hourly using temporal weights derived from a 2.5° analysis of hourly rain gauge data.

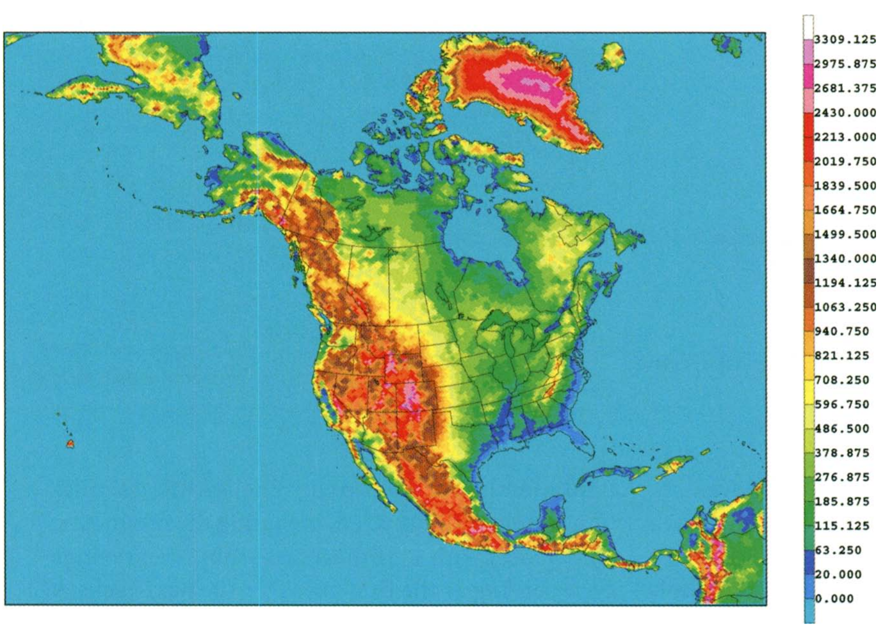

Fig. 2. The NCEP Regional Reanalysis domain and its 32-km topography. Terrain elevation (m) is indicated by the color scale at the right.

TABLE 3. Climatologies used in the North American Regional Reanalysis.

Dataset	Use details	Source
Green vegetation fraction	Specification of vegetation cover extent, monthly interpolated to daily	NESDIS
Baseline snow-free albedo	Specification of land albedo, quarterly interpolated to daily	NASA

Over the oceans, south of 27.5°N, and over land areas south of Mexico, the CMAP 5-day (pentad) global 2.5° precipitation analysis (Xie and Arkin 1997) is assimilated after it is disaggregated to hourly using the GR2 1-hourly precipitation forecasts. North of 42.5°N, where the CMAP data are known to be increasingly less reliable, there is no assimilation of precipitation over oceans. Over a 15° latitude belt centered at 35°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 because CMAP pentad data do not have adequate time and space resolution to be useful for very heavy precipitation. We had encouraging results in attempts to assimilate associated synthetic winds, but a decision was arrived at that no resources were available for testing as were felt to be required for these data to be assimilated with confidence.

TOVS-1b radiances. Instead of the NESDIS TOVS retrievals used in GR1 and GR2, TOVS-1b radiances were assimilated directly using almost the same code used in both the regional and global assimilation systems then operational at NCEP. For details of the general procedure, as applied to the global system, see Derber and Wu (1998) and McNally et al. (2000). The regional application was adapted directly from the global.

Near-surface wind (10 m) and moisture (2 m) over land. Extensive tests were conducted on the impact of assimilating near-surface ("surface") atmospheric observations in addition to surface pressure. "Off time" observations were found to be detrimental and were turned off by applying a narrow time window of 30 min centered on the analysis time to all surface observations over land. The assimilation of surface wind and moisture observations over land was found to be marginally helpful, and thus was used in our production runs. Assimilation of 2-m temperature over land was found to be significantly detrimental to our forecast fits to tropospheric rawinsondes, and therefore was not used. It is our belief that this latter problem stems from the inability of the Eta model 3DVAR to limit the vertical influence of surface mass observations. In NCEP's operational EDAS, off-time surface data and all surface temperature observations over land were turned off in September 2003. Only recently (May 2005) have the on-time 2-m temperature observations over land been turned back on with the use of 2DVAR at the surface. This solution came well after the NARR had to go into its production phase. This issue is further discussed on the FAQ page in our NARR Web site (online at www.emc.ncep.noaa.gov/mmb/rreanl/faq.html).

Sea and lake ice. Over oceanic regions, through 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 NARR grid and rounded off to 1 or 0 (ice or no ice). Subsequently, the ice values came from the NESDIS 25-km-daily IMS (information online at www.ssd.noaa.gov/PS/SNOW/ims.html).

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

Sea and lake surface temperatures. For most of our NARR period (1981 and onward), ocean SSTs were derived from the 1° 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. Beginning in 2003, a 14-km GLERL analysis became available and was used. For the Great Salt Lake, climatological values

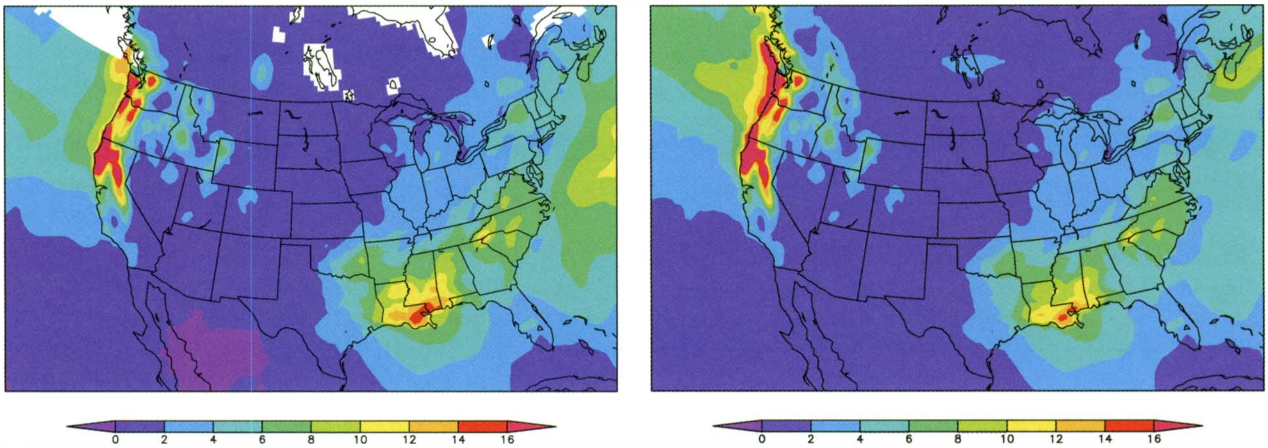

Fig. 3. (left) Observed (analyzed) precipitation assimilated by the NARR over land and over low- and lower midlatitude oceans and (right) NARR precipitation, averaged for January 1998 (in. month^{-1}). White indicates no available observations.

were applied, derived from monthly averages. For all other lakes resolved by the NARR (e.g., the Canadian lakes), we used SST values interpolated between the Pacific and Atlantic Oceans. However, once sea ice is specified as being present over any water point, a sea-ice branch in the land-surface physics calculates the surface temperature of the ice cover by solving the energy balance equation at every physics time step.

A more detailed discussion of the NARR data is presented in Shafran et al. (2004), in an updated version 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 obtaining a higher resolution, was to provide a more realistic and accurate dataset over North America. Therefore, after comparing NARR precipitation monthly averages to observations, we will here look at the fit of NARR compared to that of GR2 to rawinsonde and near-surface observations. We shall continue with a short discussion of moisture budget issues and will end with an overview of the NARR land surface treatment.

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 GR2. We have found an excellent agreement of the NARR with the analyzed precipitation over areas with assimilation in January and July for all of the years that we examined (Mesinger et al. 2004). Here we present winter and summer examples of particular interest, in which extreme events occurred. These are

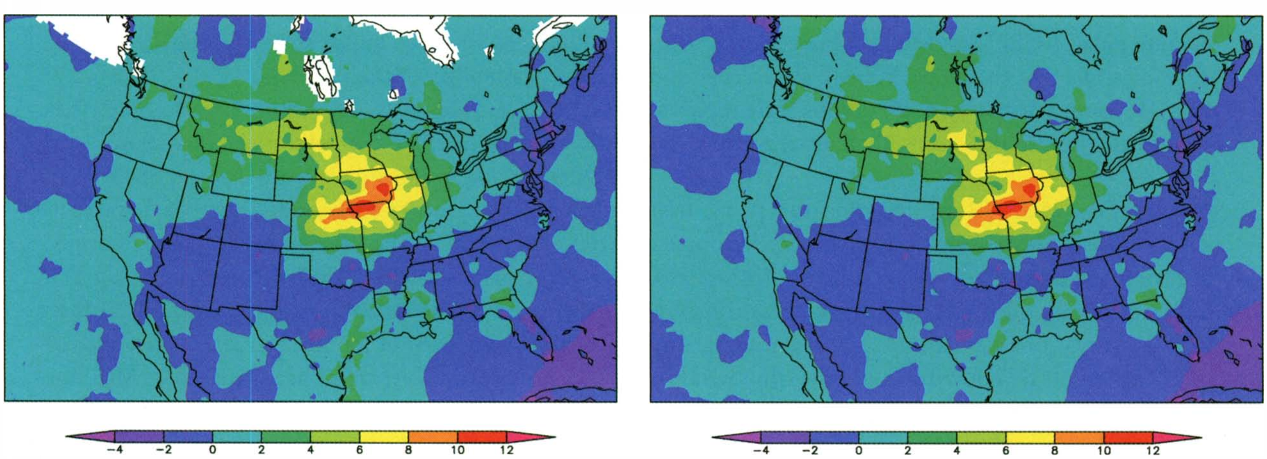

Fig. 4. Difference between 1993 and 1988 of the monthly average precipitation over June–July (in. month^{-1}) for (left) the observed precipitation, assimilated by the NARR over land and over low- and lower midlatitude oceans, and (right) the NARR precipitation.

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. 3, 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 derives vertical latent heating profiles from precipitation analyses 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. 3, has been found to also be characteristic of other months. Given that the NARR was clearly meant to primarily address 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 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. 4. 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, though systematic underestimations, if any, such as those cited earlier for winter, are not apparent because they are canceled out when taking the difference between the two summers. The figure indicates a high degree of reliability in the NARR estimation of interannual variability in precipitation.

One can wonder what the value is, if any, of the NARR precipitation compared to analyzed fields for potential users. While there possibly may be some in terms of model-produced precipitation being, to a degree, space–time filtered so as to conform to other data and the model itself, the main benefit undoubtedly is not in the NARR precipitation fields themselves but in the space–time consistency of various other precipitation-dependent NARR variables obtained.

While the realistic precipitation will in this way be very helpful for hydrologic and near-surface variables

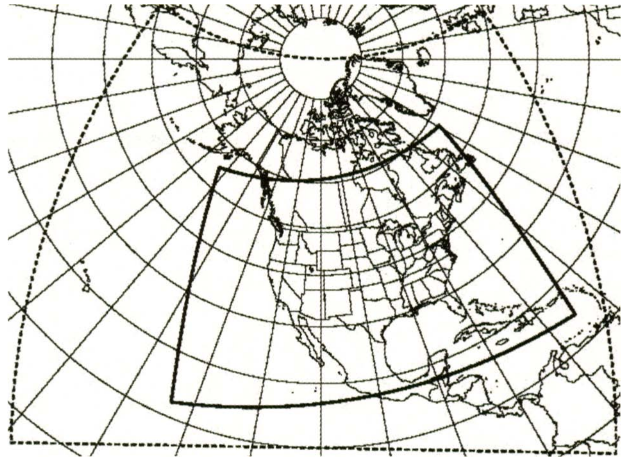

Fig. 5. Verification domain (heavy solid line) used to obtain the verification results in Figs. 6–9, in comparison with the NARR domain (dashed line).

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-yr January and July averages of temperature and vector wind rms fits to rawinsondes, as functions of pressure, with those of the GR2. We found that the advantage of the NARR over the GR2 was quite large, especially for winds, and was greater for the analysis than for the first guess. However, the temperature plots we showed in that paper were affected by an inadvertent temperature "devirtualization"—a conversion from virtual to regular temperatures that was wrong, the temperatures not having been virtual but regular already. Corrected plots for only the latest 5 of the 24 years are shown in the revised version of that paper, available on the NCEP NARR Web site (mentioned earlier).

Before we move to displaying our upper-air and near-surface results, in Fig. 5 we show the domain (heavy solid line) used for these verifications, in comparison with the NARR domain (dashed line). One should also note that the rms fits to be shown are not averages over the domain but over the observations available, so that regions with more observations have a greater weight. Typically, regarding rawinsonde reports, about 105–109 sites would have reports on any one day within the verification domain shown in Fig. 5. Of those, most (about 90) would come from the CONUS area, including about 60 from its eastern and Plains areas, and about 30 from the predominantly mountainous U.S. West. By design, all portions of the verification domain in Fig. 5 are far from the lateral boundary of the NARR domain, because the obvious desire in a regional modeling system that model vari-

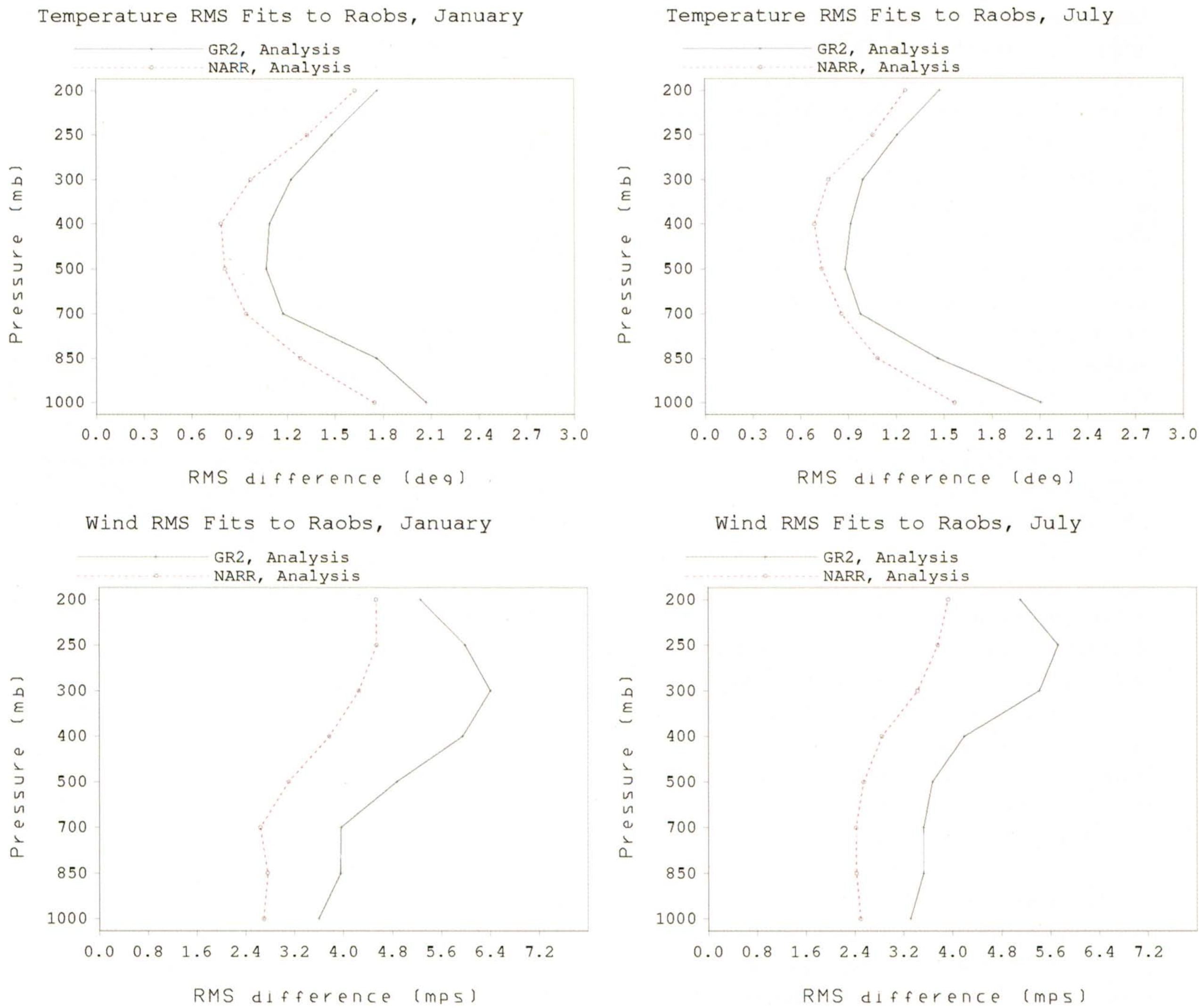

FIG. 6. RMS fits to rawinsondes as a function of pressure for (top) temperature and (bottom) vector wind for (left) January and (right) July averages over 1979–2002. NARR: dashed lines; GR: solid lines.

ables yield a significant improvement over the lateral boundary source (GR2 in this case) clearly cannot be realized close to the lateral boundaries, except for topographically forced near-surface variables.

Averages of the rms fits to rawinsondes for both temperatures and vector winds for the first 24 years of NARR are shown in Fig. 6. We have omitted the 25th year, 2003, because of an error discovered in our processing of CMORPH precipitation; at the time of this writing this year is being reprocessed. In Fig. 6, NARR rms fits to rawinsondes as functions of pressure are shown as dashed lines for temperature (top panels) and vector wind (bottom panels), for January (left panels) and July (right panels). The same fits for the GR2 are shown as solid lines.

NARR fits to rawinsondes are seen to be considerably better than those of the GR2 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 our attention to the first-guess fits, we note that the fits of the analysis to the observations, shown in Fig. 6, are influenced by both the estimation of the background and observation error covariances, and by the degree of balance imposed on the analyses. The fit will be better the weaker the balance constraint imposed in the analysis scheme is, because, as a result, the scheme will draw to the observations more. Therefore, 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 model 3DVAR in May 2001 that are included in our system (Rogers et al. 2001) resulted

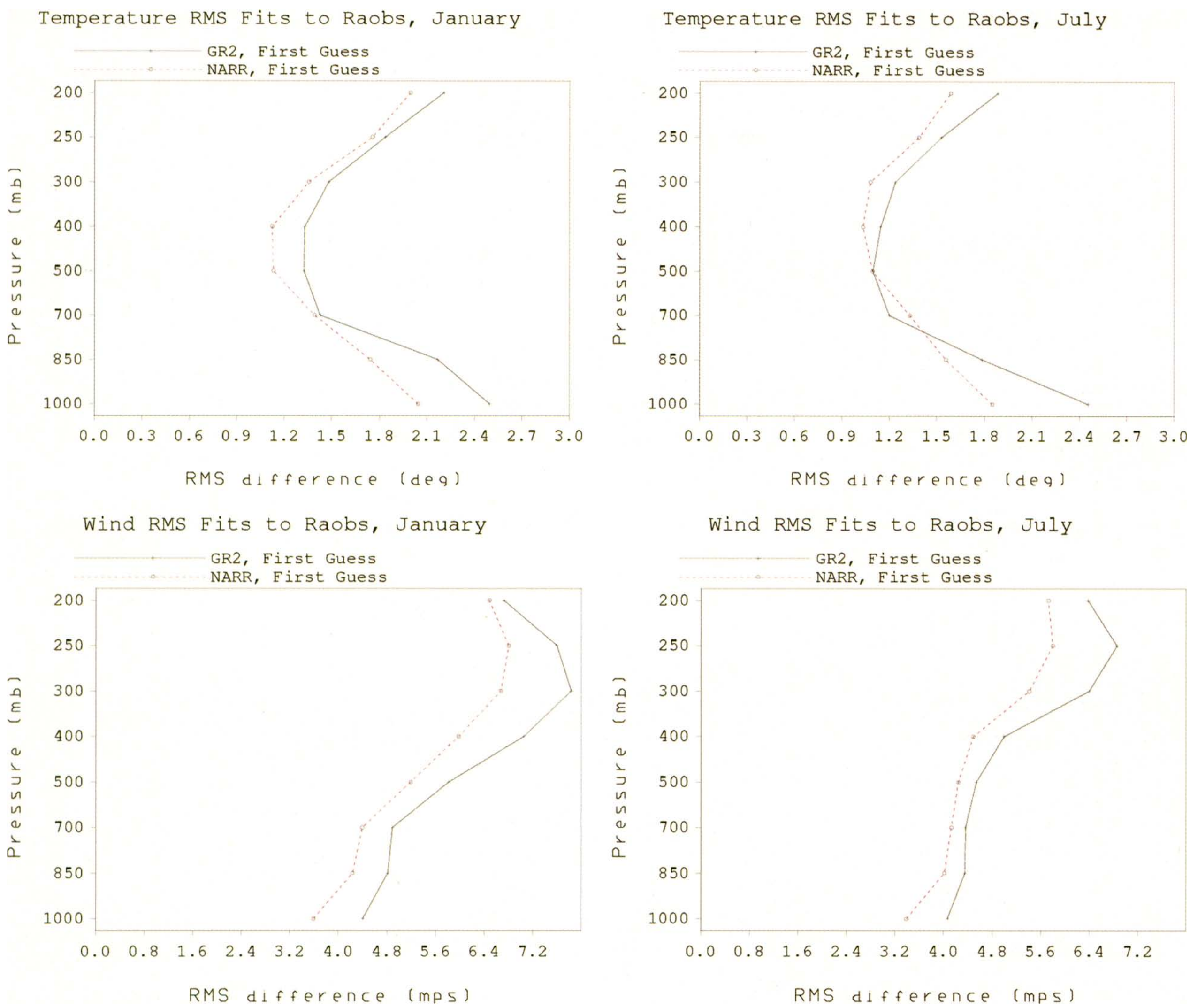

FIG. 7. Same as Fig. 6, but for the first guess.

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 GR2 first-guess fits to data, prior to entering the 3DVAR 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 nonanalyzed 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 24 years (shown in Fig. 7) are overall still considerably better than those of the GR2, 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 GR2, and in July, between about 500 and 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 –0.5K at 700 mb, compared to hardly any bias in the lower troposphere of the GR2. The fits of the first-guess winds in the NARR, on the other hand, are significantly better than in the GR2 at all levels, especially in January, and particularly in the upper troposphere, which is the same as in the analyses.

With respect to near-surface variables (2-m temperatures and 10-m winds), we show results for January and July 1988 in Figs. 8 and 9. In both the NARR and GR2 systems, these are postprocessed variables, based on the land surface and lowest midlayer (NARR) or lowest level (GR2) values. Only the first-guess results are presented, because there are no GR2 analyses available for these fields. Recall that over land, 10-m

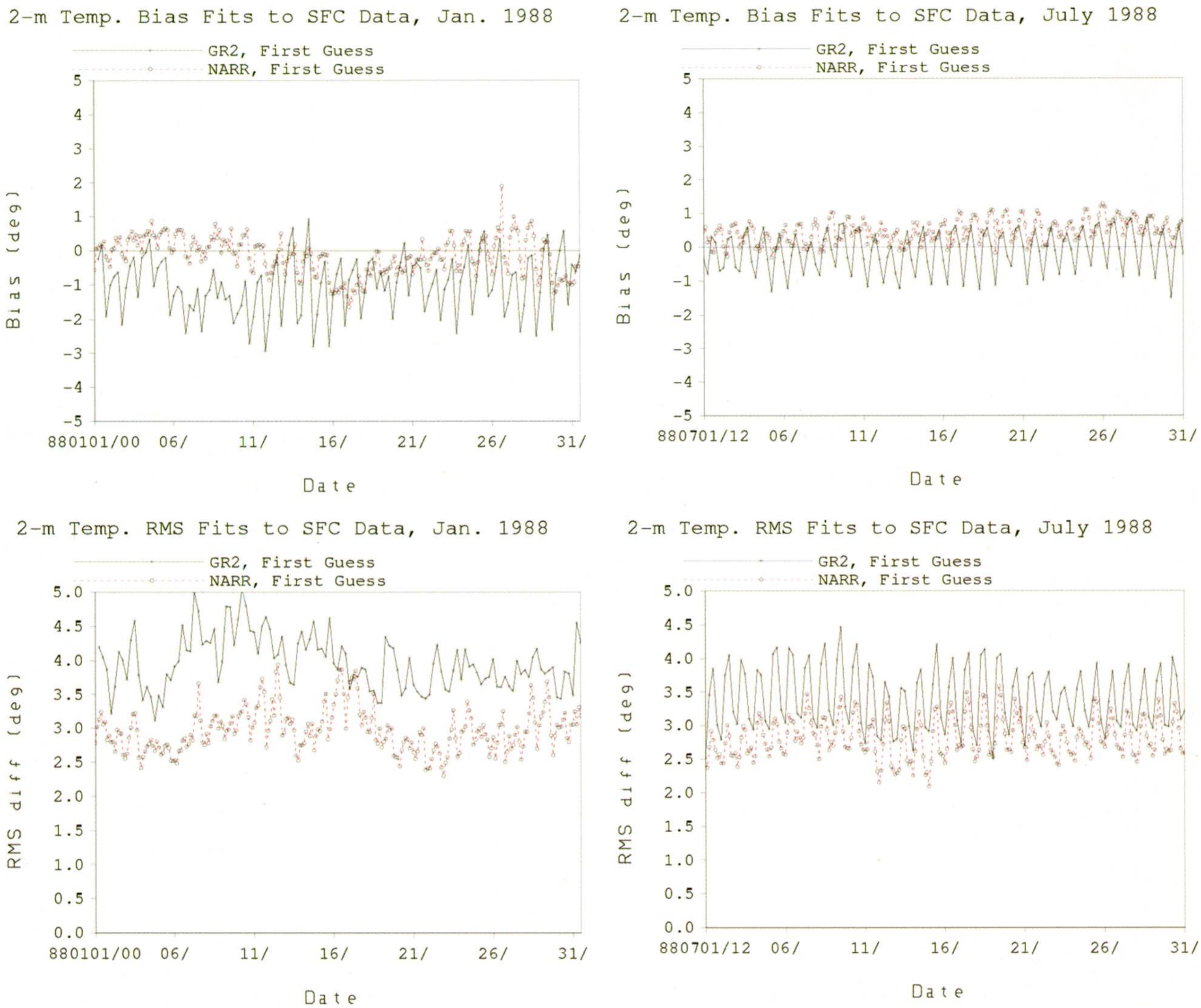

FIG. 8. (top) Bias and (bottom) rms of the first-guess 2-m temperatures fits to observations for the NARR (dashed lines) and the GR (solid lines), for (left) January 1988 and (right) July 1988 as functions of time.

winds but not 2-m temperatures are assimilated. We display in Fig. 8 the bias and the rms fits of the first-guess 2-m temperature for both the NARR (dashed lines) and GR2 (solid lines) as a function of time. The results shown are averages for all of the surface stations of the verification domain (Fig. 5) that have passed the quality control test. Typically, this would be about 450 stations, most of them within the CONUS area. The results indicate that the NARR 2-m temperature biases are generally smaller, with smaller diurnal variations in the bias than in GR2, in both winter and summer, indicating a more improved diurnal cycle behavior in NARR than in GR2. The rms errors are also smaller for the NARR than for the GR2, especially in winter; and the diurnal amplitude in the rms fit to observations—a problem for the GR2 in July—is also considerably smaller.

Figure 9 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 GR2 in January, on the order of 1–2 m s^{-1}. This carries over into the rms results, contributing to a large rms advantage of more than 1 m s^{-1} of the NARR over the GR2 in January. In July, despite no obvious bias advantage, the NARR rms error is still smaller than that of the GR2.

As a final example of results, we turn our attention to the moisture budget, which is an aspect of considerable interest and also one in which the NARR, in view of its precipitation assimilation and spatial resolution, should achieve results significantly improved relative to the GR2. As motivation, the investigation of Roads et al. (2003) of various water budget com-

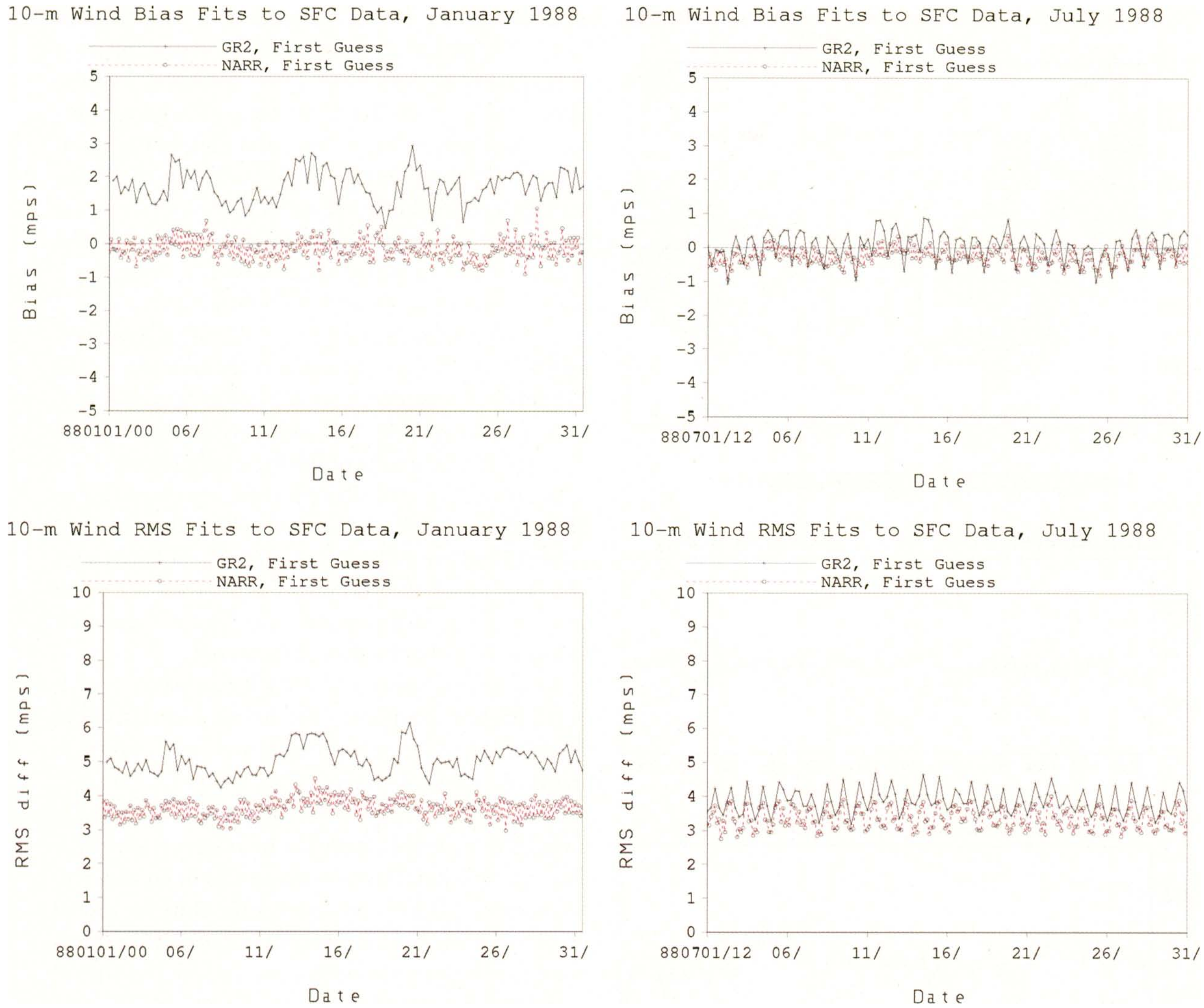

FIG. 9. Same as Fig. 8, but for the 10-m winds.

ponents in a number of models and analyses points out the qualitative agreement among the models and available observations, but also stresses numerous outstanding issues, such as needing to better close the budgets. An indication of the degree to which budget closure is achieved is given by the overall magnitude of the residual R of the main terms of the atmospheric water budget,

$$\frac{\partial Q}{\partial t} + P - E - \mathrm{MFC} = R, \qquad (1)$$

where Q is the total column vertically integrated moisture (precipitable water); t, time; P, precipitation; E, surface evaporation; and MFC, vertically integrated moisture flux convergence. Roads et al. (2003) include a summary of 4 years of the NCEP Eta model operational analyses and point out the encouraging fact of the Eta model budget residuals being significantly smaller than those of the GR1 and GR2, but at the same time being hard to interpret in the area of the all-important interannual variations, because of the operational Eta model and EDAS systems of NCEP being affected by analysis and model changes. NARR's hallmark of course is production of a regional-scale dataset in which such changes are absent.

Figure 10a presents our residual Eq. (1) over roughly the CONUS area and southern Canada; units on this as well as Figs. 10b and 10c are millimeters per day. The figure shows that over most of the central United States the atmospheric water budget is in near balance. However, over the complex terrain of the western United States, the imbalance may achieve values of about 1 mm day^{-1} and even higher over small areas.

To illustrate these differences and look at what the imbalance is for specific basins at subcontinental scales, we present the time series of the area-averaged

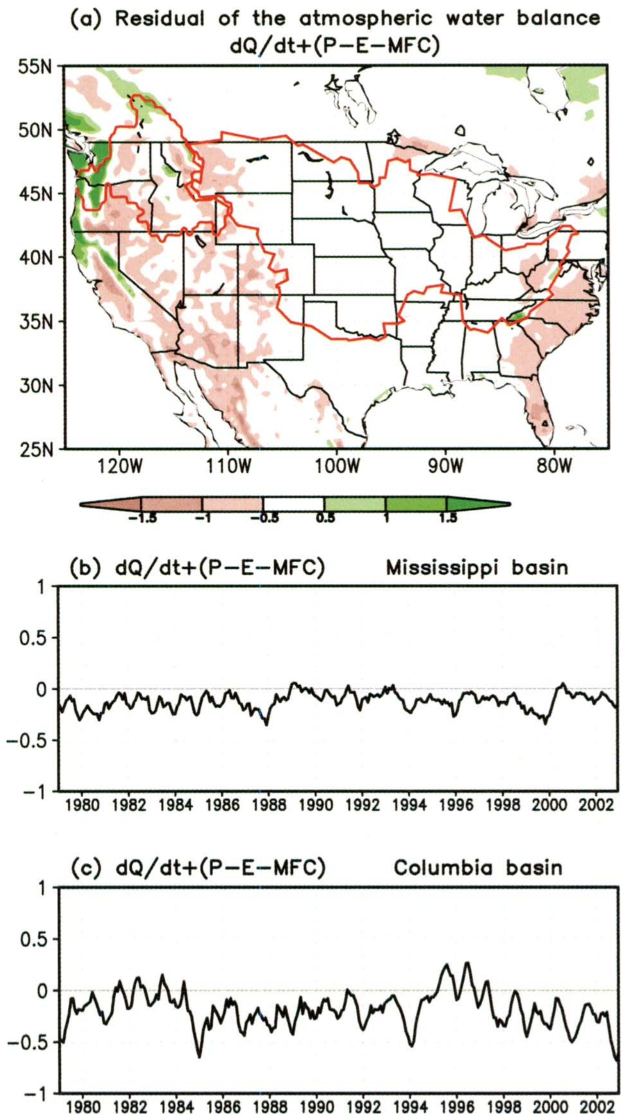

FIG. 10. (a) 25-yr NARR average (mm day^{-1}) of the residual of the main terms of the atmospheric water balance. (b) Same as (a) but as a function of time for the spatial averages over the Mississippi and (c) Columbia River basins. A 13-month running mean has been taken in the plotted time series to remove the annual cycle. Mississippi and Columbia basins of the lower two panels are depicted by solid red lines in (a).

residual term for the Mississippi and Columbia River basins in Figs. 10b and 10c, respectively. A 13-point running mean has been applied to remove the annual cycle and thus emphasize interannual variations (as in Fig. 19 of Roads et al. 2003). In the case of the Mississippi River basin, the residual term remains small and slightly negative throughout the 24-yr period. The overall average is −0.12 mm day^{-1}.

The Columbia River basin is chosen because it has important complex terrain effects where observations and the regional reanalysis become more uncertain [see Luo et al. (2005) for an analysis of precipitation data quality and its impact on the analysis of the Columbia basin surface water cycle]. The geographical anomalies are larger (Fig. 10a) than in the Great Plains, but they tend to compensate in the basin average; consequently, the residual time series, while displaying values of larger magnitude than in the Mississippi River basin, remains within 1 mm day^{-1}, with an overall average of −0.19 mm day^{-1}.

For a comparison against the GR2 values, 4-yr averages for the Mississippi basin and the time plot of the 13-month averages for the GR2 in Roads et al. (2003, their Table 2 and Fig. 19f, respectively) are available. The typical magnitude of the Mississippi River basin values of our Fig. 10b, after removing the overall mean of −0.12 mm day^{-1}, tends to be smaller than the GR2 values of Fig. 19f of Roads et al. (2003) by about a factor of 2. The mean itself is much smaller than the mean value of about −0.6 mm day^{-1} for GR2 of Table 2 in Roads et al. (2003) by about a factor of 5.

One advantage of the NARR compared to GR is its higher temporal resolution (3 versus 6 h, respectively). 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 the observations better. We ran 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 in every respect, but in a majority of cases the magnitudes of the 6-h fits were slightly smaller.

This is not a completely clean test because our 6-h forecast segments were in the test run starting from analyses produced by our regular 3-h forecast segments. But, we expect the impact of the difference to be negligible. Given the result of this test we cannot claim that the 3-h resolution of the NARR system has increased the accuracy of the result, though it did increase the time resolution of our data.

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 that of the GR. 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 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 state (SWE) is updated daily at the 0000 UTC analysis time from the daily global (47-km) SNODEP. This daily update is the minimum needed to achieve a NARR snow depth within a factor of 2 of the U.S. Air Force snow depth, assuming a 5:1 ratio of physical snow depth to SWE. Any analysis of the NARR surface water balance must account for this daily increment of SWE, which is derived by subtracting the 3-h NARR SWE forecast valid at 0000 UTC from the NARR SWE analysis of the same time.

Being conscious of the notoriously slow spinup 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-month) overlap spinup 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.

We have created a land surface subset of the NARR output and this subset is available from our NCEP NARR Web site. The size of this subset is about 0.7 TB, or about one-seventh the size of the merged NARR output described in appendix A. The subset includes near-surface atmospheric fields (e.g., the fields to drive offline uncoupled land models), surface fluxes and states, and soil column states.

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 the 25 years from 1979 to 2003 and to have it continue as a near-real-time system starting with 1 January 2004, with as few changes as possible—optimally, none. After we finished the retrospective processing to the end of November 2002, we faced a number of obstacles toward that end. Two major obstacles were unavailability in real time 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 the 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, December 2002, using our real-time system. This system, R-CDAS, is identical to the one used in the retrospective NARR, except for the following.

Over CONUS, because the spatial density of hourly rain gauge data available to NCEP in real time is relatively sparse, the temporal weights used for disaggregation to hourly are derived from hourly real-time 4-km WSR-88D radar-dominated precipitation analyses. Over Canada, no precipitation is assimilated.

Over the oceans and land areas south of Mexico, because CMAP analysis is unavailable in real time, the global 8-km 30-min satellite-based CMOPRH precipitation analysis (Joyce et al. 2004) is used instead, whereby two successive 30-min analyses are temporally averaged to 1 h. Otherwise, the same latitudinal-weighting treatment as described above for CMAP is applied, but unlike with CMAP, precipitation assimilation is retained over tropical cyclones.

For ocean ice cover as of December 2002, we use the daily NESDIS IMS data. And finally, for the Great Lakes and Canadian lakes ice, we use climatology.

We have checked the new system for continuity by inspecting the magnitude of changes in monthly average plots of the type of Figs. 6 and 7 for 2003 compared to those of 2002, and have been running it as R-CDAS. The system has been ported to the current NCEP mainframe computer system, with responsibility for its daily execution taken over by CPC. However, as mentioned earlier, an error has been discovered in our processing of CMORPH precipitation, and consequently, at the time of this writing, reprocessing of our R-CDAS system data is in progress. The reprocessing has been completed for the period of January 2004 until near-real time; reprocessing of 2003 is expected to be finished by the end of the 2005 calendar year.

During the intensive effort to complete the 23-plus 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 2004. Two centers are at present archiving subsets of the NARR data, NCDC, and NCAR. SDSC has plans to archive some of the NARR data as well. These centers have different storage resources at hand and may eventually be making different portions of the total NARR database available to their local users and to the general public. Our plan is to have the NOMADS facility at NCDC be a major public distributor of NARR data (Rutledge et al. 2006). To handle the data volumes, the NOMADS software has been upgraded for quick access to specific fields.

Additional outreach efforts are in progress or planned. Several NARR papers presented at the 2004 AMS Annual Meeting are available on our Web page (e.g., Shafran et al. 2004 on the data used; Ebisuzaki et al. 2004 on the archiving and data access). About 1000 copies of a CD-ROM with 24 years of NARR maps were distributed at the same AMS meeting. A NARR Users' Workshop was held at the 2005 AMS Annual Meeting; numerous presentations made at that workshop are also available on our Web page. The Web page in addition includes instructions on how to access the data that have been posted at the two archiving centers that so far have downloaded NARR data: NCDC and NCAR. Yet more information, along with a selection of NARR results, such as a set of monthly means, a set of daily means, a sample free forecast, and additional miscellaneous fields, is present on the DVD accompanying this issue of *BAMS*.

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

CONCLUDING COMMENTS. We believe the results summarized here 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 NARR 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 GR2 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 were in summer.

It would be helpful to have an assessment of reasons that led to these improvements. Four major candidate reasons come to mind: better/more observations being assimilated, better assimilation schemes, enhanced resolution, and a better model. Provided that precipitation assimilation is included within better assimilation schemes, we are confident each of these four major features has contributed, and can point to supporting material in some cases; but we are not in a position to assess which of these aspects had contributed the most to the NARR improvements. For example, as to the fourth aspect listed (the model), or a combination of the third and the fourth aspects (resolution and the model), we can refer readers to the comparisons of the QPF skill of the then AVN/MRF model, run at T126 resolution, and the Eta model, during the mid-1990s, when the Eta model was run at 80- and then 48-km resolution (e.g., Mesinger 2000, Figs. 7 and 8). Recall that the GR2 was done using the T62 resolution.

On the other hand, some of the NARR features failed to be confirmed as beneficial. While no harm was documented from a direct assimilation of radiances, no evidence of benefit was detected either. It is suspected that this is due to the relatively low top of the Eta model used (25 mb). Higher temporal analysis frequency of the NARR compared to that of the GR (3 versus 6 h, respectively) has also not been demonstrated to increase the accuracy of the NARR. Issues such as these should be understood better as studies of the system components and features involved 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 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 NAME activities and is at the time of this writing under investigation. In contrast, the NARR's Great Plains low-level jet compares favorably with observations, both regarding its strength and its prominent diurnal cycle with a nocturnal maximum (Mo et al. 2005). As for other weaknesses, we have also become aware that our precipitation analysis over Canada, because of the relatively small number of gauge observations we had, is not as good as we had hoped for. In retrospect, having the model forecast precipitation as we are doing in R-CDAS might have been better. Our precipitation analysis over the northern Atlantic (e.g., Fig. 3) 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. 6, makes us confident that our produced NARR datasets will keep yielding valuable results for numerous research and application purposes for years to come.

We are encouraged by the widespread use of the NARR 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.

ACKNOWLEDGMENTS. We are most grateful to the team that carried out the GR1 project in whose footsteps we have followed. Bringing a project of this magnitude to completion would not have been possible without the extraordinary NCEP work environment, and the strong support and suggestions of the NCEP director, Louis Uccellini; the NCEP/EMC director, Stephen Lord; and the NCEP/CPC director, Jim Laver. No lesser credit should go to NOAA/OGP who funded the project, as well as much of the forerunner development of the precipitation assimilation and Noah land surface model within the EMC GAPP and GCIP projects, and whose program directors, Mark Eakin, Richard Lawford, Jin Huang, and Ken Mooney, provided us with guidance in terms of the mechanics of the effort, as well as trust regarding the eventual high quality of the product to be obtained. The project's Scientific Advisory Committee, chaired by John Roads, and including Ana Barros, Lance Bosart, Mike Fiorino, Roy Jenne, Dennis Lettenmaier, Ed Miles, Roger Pulwarty, Eugene Rasmusson, and Greg Tripoli, provided us not only useful guidance but also strong support and encouragement. Huug van den Dool of NCEP/CPC provided unfailing assistance with a variety of our precipitation processing efforts. John Schaake of NWS/OHD developed the algorithm, code, and testing for the gridded analysis over CONUS of the daily gauge-only precipitation observations. The internal EMC reviewers Michael Baker and Glenn White, and three anonymous reviewers, offered a wealth of excellent suggestions, thereby contributing much to the final shape of the manuscript and of the DVD included with this issue. Numerous other colleagues, too many to mention, gave us useful advice, and are hereby acknowledged as well.

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

- input observations;
- input observations with QC marks and differences from analyses and first guess;
- input analyses: sea surface temperature, snow, sea ice, observed precipitation;
- plots of observation locations, QC;
- plots of fits of analyses to observations;
- plots of fits to Global Reanalysis 2;
- plots of analyses;
- fixed fields such as land–sea mask, terrain height, vegetation type, soil type, and some key parameters applied in the land surface component, such as soil porosity and wilting point;
- 3-day forecasts every 2.5 days;
- analyses and 3-h 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 because the wind and mass points are staggered. The binary restart file has a nonstandard 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 are 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 selected 3-h averages, accumulations, and forecasts on the AWIPS grid. It is approximately 5 TB (60 MB every 3 h). We expect that this merged dataset along with some of the smaller datasets will satisfy most users.

The data in the merged dataset are similar to that from the operational Eta model; the data are in GRIB format on a Lambert-conformal grid and most of the fields are common to both the operational Eta model and NARR datasets. However, there are some subtle differences. In the operational Eta model, 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 model 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*: visualization and calculation tool (Linux, Windows, etc.; information online at http://grads.iges.org/grads);
- *grib2ctl*: makes control files for GrADS, updated for NARR (Linux, Windows, etc.; information online at www.cpc.ncep.noaa.gov/products/wesley/grib2ctl.html);
- *copygb*: convert Lambert-conformal grids to other grids, port for NARR (Linux; information online at www.cpc.ncep.noaa.gov/products/wesley/copygb.html);
- *wgrib*: inventory and decode GRIB files, updated for NARR (Linux, Windows, etc.; information online at www.cpc.ncep.noaa/gov/products/wesley/wgrib.html).

Distribution of data. NCAR, NCDC, and SDSC have agreed to distribute the NARR-merged dataset. These centers have their communities that they support; however, NCDC is using NOMADS (Rutledge et al. 2006) for distributing the data over the Internet, making the data freely and widely available. Of course, bandwidth limitations are a factor in such an approach, so one needs to avoid the mindset of "How do I get all of the data?" by asking instead, "How do I use the Web services to only get the data that I need?" [See Rutledge et al. (2006) 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.

Merged dataset. The merged dataset consists of two files containing eight-times-per-day analyses. The main ("a") file contains the analyses, accumulations, and averages. The "b" file contains a few 3-h forecast files that are meant to be helpful in doing hydrological budget calculations. For an explicit list and description of variables included in the a and b merged files, readers are referred to the attached DVD and to the NARR home page.

APPENDIX B: CONTENTS OF THE INCLUDED DVD.

The included DVD contains selected products from the NARR project. Some of the data were only meant to be a sample of the NARR products (e.g., the analyses and forecasts covering the "Storm of the Century," 12–14 March 1993). Other datasets, monthly means, and daily means contain selected fields spanning from 1979 to 2002 and provide a description of the evolving state of the atmosphere.

The data (forecasts and analyses) on the DVD are in GRIB format, which is a machine-independent WMO format. Included on the disk are GrADS control and index files so the data can be displayed using GrADS. The analyses and forecasts for this DVD were reduced in size by 1) reducing the domain size, 2) eliminating many fields, and 3) reducing the eight-times-daily frequency to daily and monthly means.

In addition to the above-mentioned data, the DVD contains a copy of PCGrADS and a demonstration program. To run the program, insert the DVD into a DVD reader of a computer running Windows XP. In the root directory of the DVD, run the program *demo.bat,* which starts a GUI program that allows access to selected fields on the DVD. The engine for this program is GrADS, and we would like to thank Brian Doty for permission to include it on this DVD.

APPENDIX C: LIST OF ACRONYMS

- 3DVAR: Three-dimensional variational data assimilation
- AMS: American Meteorological Society
- AVN: Aviation model
- 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–Atmosphere Studies
- CONUS: Contiguous United States
- CPC: Climate Prediction Center
- CPU: Central processing unit
- DOE: Department of Energy
- EDAS: Eta Model Data Assimilation System
- EMC: Environmental Modeling Center
- FAQ: Frequently asked questions
- GAPP: GEWEX Americas Prediction Project
- GCIP: GEWEX Continental-Scale International Project
- GEWEX: Global Energy and Water Cycle Experiment
- GLERL: Great Lakes Environmental Research Laboratory
- GR: Global Reanalysis
- GR1: Global Reanalysis 1 (Kalnay et al. 1996; Kistler et al. 2001)
- GR2: Global Reanalysis 2 (Kanamitsu et al. 2002)
- GrADS: Grid Analysis and Display System (online at http://grads.iges.org/grads)
- GRIB: Gridded binary
- GUI: Graphical user interface
- HPD: Hourly precipitation data
- IMS: Interactive Multisensor Snow and Ice Mapping System
- I/O: Input/output
- ISC: Ice Services Canada
- LSM: Land-surface model
- MRF: Medium-range forecast
- NAME: North American Monsoon Experiment
- NARR: North American Regional Reanalysis
- NASA: National Aeronautics and Space Administration
- NCAR: National Center for Atmospheric Research
- NCDC: National Climatic Data Center
- NCEP: National Centers for Environmental Prediction
- NESDIS: National Environmental Satellite, Data, and Information Service
- NLDAS: North American Land Data Assimilation System
- NOAA: National Oceanic and Atmospheric Administration
- NOMADS: NOAA Operational Model Archive and Distribution System
- NWS: U.S. National Weather Service
- OGP: NOAA Office of Global Programs
- OHD: Office of Hydrological Development
- OLR: Outgoing longwave radiation
- PCGrADS: Windows version of GrADS
- PRISM: Parameter-Elevation Regressions on Independent Slopes Model
- QC: Quality control
- QPF: Quantitative precipitation forecast
- R-CDAS: Regional Climate Data Assimilation System
- RDAS: Regional Data Assimilation System
- SDSC: San Diego Supercomputing Center
- SNODEP: Snow depth analysis (daily) of the U.S. Air Force Weather Agency
- SST: Sea surface temperature
- SWE: Snow-water equivalent
- TIROS: Television Infrared Observation Satellite
- TOVS: TIROS Operational Vertical Sounder
- WSR-88D: Weather Surveillance Radar-1988 Doppler

REFERENCES

Altshuler, E., M. Fennessy, J. Shukla, H. Juang, E. Rogers, K. Mitchell, and M. Kanamitsu, 2002: Seasonal simulations over North America with a GCM and three regional models. COLA Tech. Rep. 115, 66 pp.

Berbery, E., Y. Luo, K. Mitchell, and A. Betts, 2003: Eta model estimated land surface processes and the hydrological cycle of the Mississippi Basin. *J. Geophys. Res.*, **108,** 8852, doi:10.1029/2002JD003192.

Black, T. L., 1988: The step-mountain eta coordinate regional model: A documentation. NOAA/NWS National Meteorological Center, 47 pp.

Daly, C., R. P. Neilson, and D. L. Phillips, 1994: A statistical–topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteor.*, **33,** 140–158.

Derber, J. C., and W.-S. Wu, 1998: The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system. *Mon. Wea. Rev.*, **126,** 2287–2299.

Ebisuzaki, W., J. Alpert, J. Wang, D. Jovic, and P. Shafran, 2004: North American Regional Reanalysis: End user access to large data sets. Preprints, *20th Int. Conf. on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography and Hydrology,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, 8.2.

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *J. Geophys. Res.*, **108,** 8851, doi:10.1029/2002JD003296.

Fiorinio, M., 2002: Analyses and forecasts of tropical cyclones in the ECMWF 40-year Reanalysis

(ERA-40). Preprints, *25th Conf. on Hurricanes and Tropical Meteorology,* San Diego, CA, Amer. Meteor. Soc., 261–265.

Grumbine, R. W., 1996: Automated passive microwave sea ice concentration analysis at NCEP. NCEP/EMC/OMB Tech. Note 120, 13 pp.

Janjić, Z. I., 1994: The step-mountain Eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.,* **122,** 927–945.

Joyce, R. J., J. E. Janowiak, P. A. Arkin, and P. Xie, 2004: CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeor.,* **5,** 487–503.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kanamitsu, M., and Coauthors, 2002: NCEP/DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.,* **83,** 1631–1643.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

Lin, Y., K. E. Mitchell, E. Rogers, M. E. Baldwin, and G. J. DiMego, 1999: Test assimilations of the real-time, multi-sensor hourly precipitation analysis into the NCEP Eta model. Preprints, *8th Conf. on Mesoscale Meteorology,* Boulder, CO, Amer. Meteor. Soc., 341–344.

Luo, Y., E. H. Berbery, and K. E. Mitchell, 2005: The operational Eta model precipitation and surface hydrologic cycle of the Columbia and Colorado basins. *J. Hydrometeor.,* **6,** 341–370.

McNally, A. P., J. C. Derber, W.-S. Wu, and B. B. Katz, 2000: The use of TOVS level-1B radiances in the NCEP SSI analysis system. *Quart. J. Roy. Meteor. Soc.,* **126,** 689–724.

Mesinger, F., 2000: Numerical methods: The Arakawa approach, horizontal grid, global, and limited-area modeling. *General Circulation Model Development,* D. A. Randall, Ed., Academic Press, 373–419.

——, Z. I. Janjić, S. Nicković, D. Gavrilov, and D. G. Deaven, 1988: The step-mountain coordinate: Model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment. *Mon. Wea. Rev.,* **116,** 1493–1518.

——, and Coauthors, 2004: North American Regional Reanalysis. Preprints, *15th Symp. on Global Change and Climate Variations,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, P1.1.

Mitchell, K. E., and Coauthors, 2004: The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *J. Geophys. Res.,* **109,** D07S90, doi:10.1029/2003JD003823.

Mo, K. C., M. Chelliah, M. Carrera, R. W. Higgins, and W. Ebisuzaki, 2005: Atmospheric moisture transport over the United States and Mexico as evaluated from the NCEP Regional Reanalysis. *J. Hydrometeor.,* **6,** 710–728.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate,* **15,** 1609–1625.

Roads, J., and Coauthors, 2003: GCIP water and energy budget synthesis (WEBS). *J. Geophys. Res.,* **108,** 8609, doi:10.1029/2002JD002583.

Rogers, E., 2005: On-line documentation of major changes to EMC mesoscale modeling systems. EMC, NCEP. [Available online at www.emc.ncep.noaa.gov/mmb/mmbpll/eric.html#TAB4.]

——, M. Ek, Y. Lin, K. Mitchell, D. Parrish, and G. DiMego, 2001: Changes to the NCEP Meso Eta analysis and forecast system: Assimilation of observed precipitation, upgrades to land-surface physics, modified 3DVAR analysis. EMC, NCEP. [Available online at www.emc.ncep.noaa/gov/mmb/mmbpll/spring2001/tpb.]

Rutledge, G. K., J. Alpert, and W. Ebisuzaki, 2006: NOMADS: A climate and weather model archive at the National Oceanic and Atmospheric Administration. *Bull. Amer. Meteor. Soc.,* **87,** 327–341.

Shafran, P., J. Woollen, W. Ebisuzaki, W. Shi, Y. Fan, R. Grumbine, and M. Fennessy, 2004: Observational data used for assimilation in the NCEP North American Regional Reanalysis. Preprints, *14th Conf. on Applied Climatology,* Seattle, WA, Amer. Meteor. Soc., 1.4.

Smith, T. M., and R. W. Reynolds, 2003: Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997). *J. Climate,* **16,** 1495–1510.

Xie, P., and P. A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates and numerical model outputs. *Bull. Amer. Meteor. Soc.,* **78,** 2539–2558.

Zhao, Q., T. L. Black, and M. E. Baldwin, 1997: Implementation of the cloud prediction scheme in the Eta Model at NCEP. *Wea. Forecasting,* **12,** 697–712.