NCEP–DOE AMIP-II REANALYSIS (R-2)

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An updated NCEP–NCAR reanalysis, covering 1979–present, features newer physics and observed soil moisture forcing and also eliminates several previous errors

National Centers for Environmental Prediction –National Center for Atmospheric Research (NCEP–NCAR) reanalysis (hereafter R-1) was created by a complex system of programs, libraries, scripts, and datasets involving many steps including decoding, reformatting, quality control, analysis, prediction, postprocessing, and archiving. Consequently the process was prone to human errors. During and after the main production phase of the R-1, several human processing errors were discovered. Many errors were discovered and fixed during processing, but several were discovered after too many years had been processed to fully reprocess the data. For most studies the human processing errors would be a minor consequence; however, these limitations were affecting some important studies. Consequently, a reanalysis project was started in 1998 when the Program of Climate Model Diagnosis and Intercomparison (PCMDI) of the Lawrence Livermore National Laboratory provided the needed computer time at the National Energy Research Supercomputing Center (NERSC) of the Department of Energy (DOE). NCEP–DOE Atmospheric Model Intercomparison Project (AMIP-II) reanalysis (R-2) was needed for comparisons with the various AMIP-II simulations (AMIP Project Office 1996). Besides fixing the human processing errors, we incorporated upgrades to the forecast model and a diagnostic package that had been developed since the time the R-1 system was frozen.

Initially this project was intended for researchers who were not able to use R-1 due to the various errors and system shortcomings as well as to provide an estimate of analysis uncertainties. However, as the R-2 products began to show promising results, the production suite was modified to accommodate the special request from the international and national projects such as Analysis, Interpretation, Modeling, and Synthesis phases of the World Ocean Circulation Experiment and the International Satellite Land Surface Climatology Project II.

R-2 benefited greatly from the prior experience, infrastructure, and datasets from R-1, which made it possible to perform the project with minimal human resources (2.5 man hours per day on the average) within a reasonable timetable. While transferring the reanalysis system from NCEP to NERSC, NCEP dedicated a substantial effort to make the assimilation sys-

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tem transportable to other types of machines. The analysis system is now available to institutions who wish to use it for further research.

R-2 products are available to the public from NCAR, Climate Diagnostics Center in Boulder, Colorado and from a Web site described at the end of this paper. The analyses were produced at a rate of one year of analyses per 3–4 weeks. The first analysis (January 1979) was started in early 1998 and analyses for 2000 were complete in May 2001. Conversion to a near-real-time system is in progress for purposes of climate monitoring and numerical seasonal prediction.

The results from R-2 have been encouraging. The corrections to the human processing errors have yielded major changes in some fields. Moreover, changes made to the reanalysis system itself have led to other significant improvements, which are described below.

R-2 should not be considered as a next-generation reanalysis, but should be regarded as an updated and human error–fixed version of R-1. A next-generation reanalysis will have more focus on accuracy, resolution, and long-term trends by assimilating rainfall, satellite radiances, and other remote observations, using an improved assimilation procedure based on 4D-variational assimilation.

This article is written for users who are already familiar with the reanalysis projects, and therefore, it is fairly concise. Readers who are unfamiliar with the previous R-1 are encouraged to read papers by Kalnay et al. (1996) and Kistler et al. (2001).

SYSTEM DESCRIPTION. *Similarities between R-1 and R2:*

1) same spatial and temporal resolution as R-1—that is, T62, 28 levels, 6 hours;
2) similar raw observational data (some additional data after 1993);
3) Special Sensor Microwave Imager (SSM/I) data not used;
4) same dependence on NESDIS temperature retrievals; and
5) similar output variables and file formats (GRIB and BUFR).

The change in raw observational data (item 2) is due to the improvement and corrections to the system's data preprocessing since R-1. These updated datasets were sent to the European Centre for Medium-Range Weather Forecasts (ECMWF) and merged with their data for the in-progress ECMWF Reanalysis-40 (ERA-40) project (Simmons and Gibson 2000), which is aiming to reanalyze the period 1957–2001. Subsequently, these merged datasets will be sent to NCEP for our future reanalyses. Use of NESDIS temperature retrievals as in R-1 (item 4) greatly simplified the analysis since collection, and incorporation of the raw satellite radiances (which is currently done in the NCEP operational analysis) would have been a major undertaking. The extension of R-2 to the presatellite period (before 1979) is still under consideration, pending allocation of human resources.

Error fixes from R-1 to R-2 (after R-1 system was frozen):

1) fixed Southern Hemisphere bogus data (PAOBS) problem (1979–92),
2) fixed snow cover analysis error (1974–94),
3) fixed humidity diffusion to remove "spectral snow" problem,
4) fixed oceanic albedo (entire period),
5) removed discontinuities in relative humidity-cloudiness relationship table at 0° and 180° (entire period), and
6) fixed snowmelt term (entire period).

The PAOBS problem was caused by a mistake in the location of the data that shifted the observation location by 180°. The quality control system rejected a large fraction of the PAOBS in R-1, but there were occasions when incorrect data were accepted by the R-1 analysis. The impact of this mistake was not so significant in the monthly average statistics (Kistler

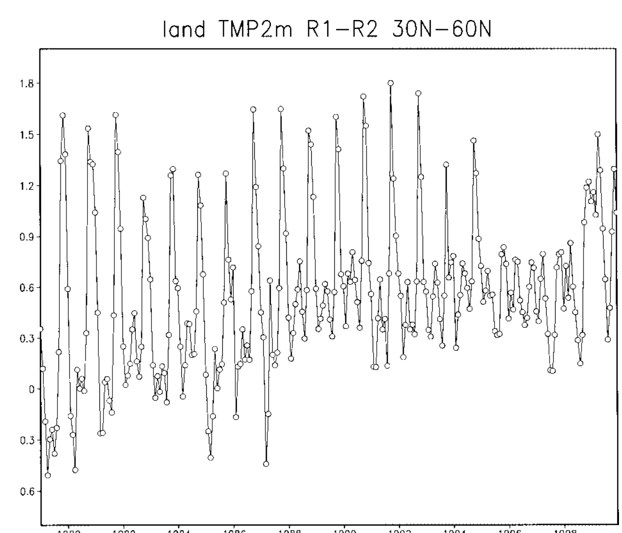


Fig. 1. Difference of monthly mean near-surface temperature (K) averaged over Northern Hemisphere middle latitude land (30°–60°N) between R-1 and R-2 during the period 1979–99.

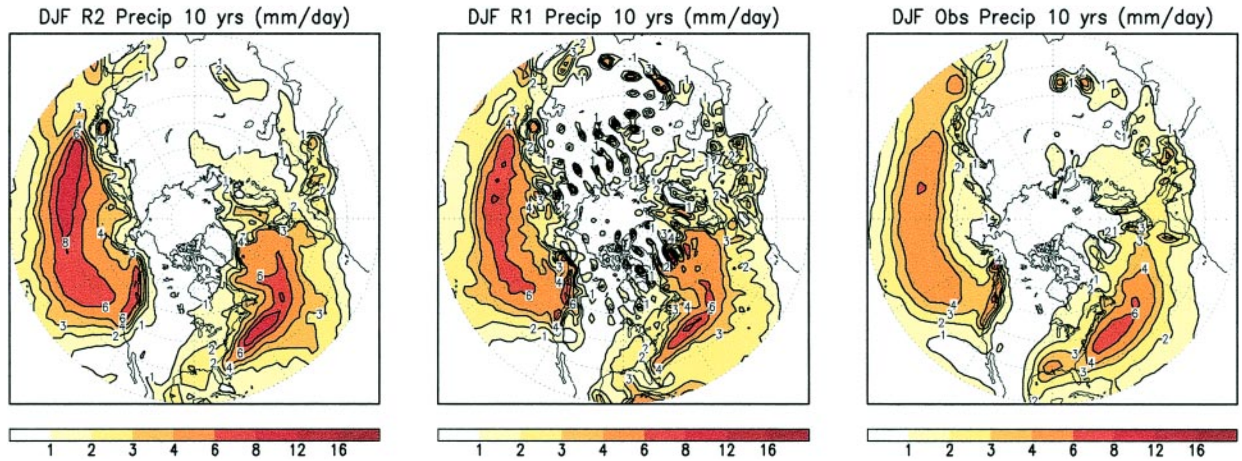


FIG. 2. Comparison of the Northern Hemisphere, 10-yr mean (1979–88) precipitation rate (mm day^{-1}) between (left) R-1, (center) R-2, and (right) Xie–Arkin analysis of observation during winter [Dec–Jan–Feb (DJF)].

et al. 2001), but some day-to-day analyses were significantly contaminated. For this reason, R-1 was considered to be unsuitable for Southern Hemisphere extratropical case studies for the affected years. A comparison between R-1, R-2, and the ECMWF Reanalysis (ERA-15) by Gibson et al. (1997) indicates that the difference in Southern Hemisphere, midlatitude 100-hPa height between R-2 and ERA-15 is less than the difference between R-1 and R-2, particularly over the southeastern Pacific. This implies that the fix was properly incorporated.

The R-1 error in the snow cover analysis involved repeated use of the 1973 data for the entire 1974–94 period. This error had its largest impact on the near-surface land temperatures during transition seasons when the snow cover shows its greatest variability. Figure 1 shows the difference of near-surface temperature averaged over the Northern Hemisphere mid latitude land areas between R-1 and R-2. The R-2 temperature tends to be warmer during September–November by 1.6 K.

The so-called spectral snow problem was caused by a simplification of the diffusion equation, which was intended to diffuse moisture and temperature on pressure surfaces instead of sigma surfaces. In order to speed up computations, the vertical gradient of specific humidity was assumed to be constant over the globe. This resulted in an unexpected fictitious source and sink of moisture in mountainous regions in high latitudes, where spectral representation of moisture resulted in unnatural spatial distribution due to the Gibbs phenomenon. This effect is most apparent during winter. In R-1, a special precipitation product was created by applying numerical filtering to remove the spectral noise. In R-2, this problem is greatly reduced despite an inadvertent removal of pressure coordinate correction (there was an error in an attempt to make more general pressure surface correction, which resulted in the removal of corrections). Figure 2 compares precipitation rates of R-1, R-2, and CPC Merged Analysis of Precipitation (CMAP) observed precipitation rates (Xie and Arkin 1997).

The albedo over the ocean was unrealistically large (around 0.15) in R-1 due to a programming error. The albedo in R-2 now has more realistic values of 0.06–0.07. Figure 3 shows the averaged albedo for the two analyses over ocean. The variation in the polar regions is due to the difference in specified sea-ice cover between R-1 and R-2 (which followed AMIP-II sea-ice specifications).

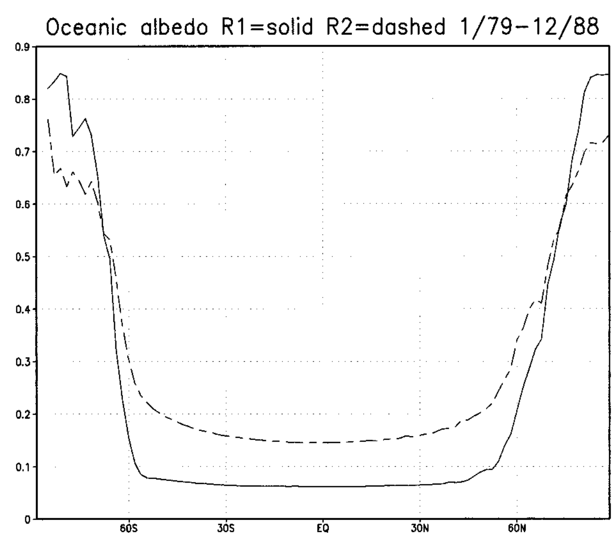


FIG. 3. Comparison of 10-yr mean (1979–88) zonally averaged albedo over ocean between R-2 (solid) and R-1 (dashed). Unit is in fraction.

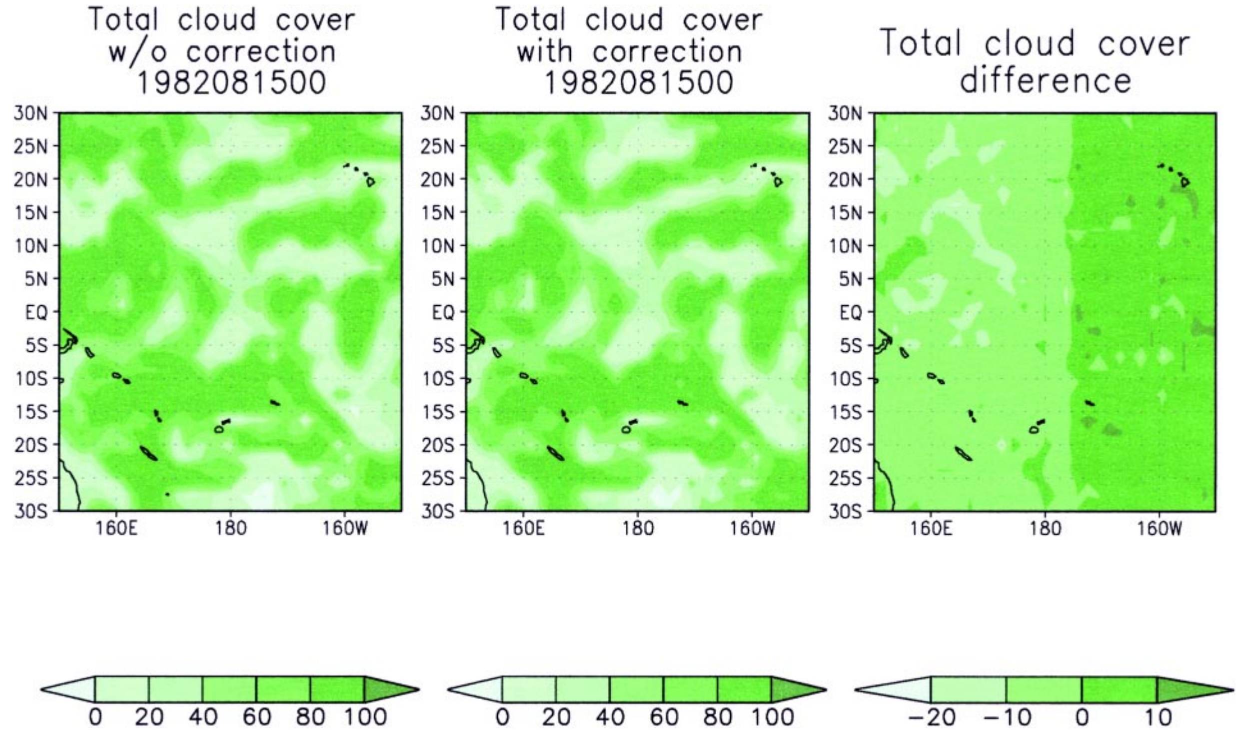


FIG. 4. An example of total cloud cover (15 Aug 1982). (left) From use of independent Western and Eastern Hemisphere cloudiness table. (center) From use of merged table, and (right) the difference of the first two. Note that the discontinuity is enhanced in the difference figure (%).

The stratiform cloud cover in the R-1 model was diagnosed from an empirical relative humidity–cloud cover relationship (Campana et al. 1994). This relationship was assumed to be a function of latitude band, surface type (land or water), and location of clouds in the Eastern or Western Hemisphere. The hemispheric division resulted in discontinuities in the cloud cover near the date line and the Greenwich meridian. The difference figure at the right in Fig. 4 magnifies the discontinuity. This problem was fixed in R-2 by making the empirical relationship independent of Eastern and Western Hemispheres.

We also corrected an error in the expression of the snowmelt term in the model, in which the conversion of snow to water was overestimated by a factor of 1000 in R-1. This error affects soil wetness evolution, but since the treatment of snowmelt and soil wetness change is crude and imprecise in R-1, as discussed later, the effect of the snowmelt error on the soil wetness in the resulting analysis was uncertain. In R-2, we corrected the snowmelt term and added more useful snow budget diagnostics. As discussed in the next section, the soil wetness evolution is treated completely differently in R-2 and is expected to be more accurate, including the effect of melting snow.

New system components:

1) simple rainfall assimilation over land surfaces for improved soil wetness,
2) smoothed orography, and
3) treatment of snow.

Roads et al. (1999) pointed out that the amplitude of the annual cycle of soil wetness over the continental United States in R-1 was too large, but its interannual variation was too small. The root of the problem is considered to be 1) deficiencies in the model precipitation and 2) the nudging term used in the soil wetness equation to prevent soil wetness drifting too far from climatology. Our first intention was to remove the nudging term, which also yields the benefit of closing the hydrological budget, by removing an artificial sink–source of soil moisture. However, repeated experiments with 1-year pilot analysis cycles and companion free forecast runs indicated that the model tended to have a pronounced drying tendency over tropical continents. We concluded that the model precipitation was deficient and unable to maintain a reasonable soil wetness without an alternative approach. Consequently we decided to replace the model precipitation at the land surface with an observed 5-day mean "pentad" precipitation based on a newly available NCEP/CPC global precipitation analysis that merges satellite and gauge measurement on a 2.5° × 2.5° latitude–longitude grid in a similar manner to CMAP by Xie and Arkin (1997). This retrospective global precipitation analysis, which is described further in Gruber et al. (2000), had just become available when the R-2 project started in 1998. Using the CMAP pentad precipitation prevented long-term climate drift of soil wetness in the R-2 analyses.

The procedure used in the analysis system is as follows. First, pentad average model generated precipitation is computed. This average is compared with the corresponding observed pentad precipitation. If the model-generated precipitation is greater (less) than the observed precipitation, the difference is subtracted from (added to) soil moisture at the topsoil layer (first of two soil layers of thickness of 10 and 190 cm, respectively) during the following pentad. For example, if the model precipitation at a point was low by 1 mm day^{-1} then 1 mm day^{-1} was added to the topsoil layer during the next pentad (0.25 mm would be added 4 times daily over the next pentad). However, when there is runoff, the critical quantity is the amount of model precipitation seeping into the soil; that is, model precipitation minus runoff. When this quantity is less than the observed precipitation, no correction is necessary as any precipitation errors are assumed to have affected the runoff rather than the soil moisture. When the observed precipitation is less than the model precipitation minus runoff, then the soil moisture is reduced by the difference of these two quantities. The soil moisture correction scheme adds to (removes from) the bottom layer when the top layer is saturated (lacks available soil moisture) and is not used when the ground is frozen. This correction method is equivalent to using observed precipitation in the hydrological calculations except that the correction is delayed by five days. This delay could be reduced to one day by using daily precipitation; however, only pentad-mean precipitation was available for the entire period of the reanalysis when the R-2 project was started in 1998. For the convenience of users examining the hydrology budget, the correction to the top layer soil wetness is kept as an additional diagnostic variable.

Another approach would be to discard the model predicted precipitation and replace it with the observed pentad precipitation for the corresponding period during the model integration. With this approach, it would be necessary to partition the observed pentad precipitation into 40-min (model time step) precipitation, but without prior knowledge of the high-frequency variability, the only reasonable assumption is to use constant rate during the 5-day period. This approach would avoid the delay between the observed and analysis precipitation, but would lack the temporal variability in the precipitation. A 5-day drizzling precipitation would have a different runoff than a 1-h shower even with the same total precipitation. Thus we have decided to use the first approach. Maurer et al. (2000) found that soil moisture and land surface water balance of R-2 was dramatically better than those of R-1. More detailed comparison will be shown later.

The orography was smoothed to prevent Gibbs phenomena–like precipitation (especially over the Amazon basin) and sensible and latent heat fluxes over ocean near steep orography. Figure 5 shows a comparison of the orography used in R-1 and R-2 at 20°S. The influence of the smoothing is apparent (see the Amazon basin, 70°–50°W).

Water equivalent snow depth is handled differently in R-2 from R-1. For R-1 and R-2 only a weekly Northern Hemisphere analysis of snow cover (without snow depth) was available for ingest. Consequently snow depth needs to be specified in some manner. In R-1, snow depth was computed based on an empirical formulation that set the maximum snow depth to 100 mm (liquid water equivalent), and the model predicted snow accumulation was ignored. This procedure made the R-1 snow depth practically useless. In R-2, the model snow depth was used (including model predicted snow accumulation) where it was consis-

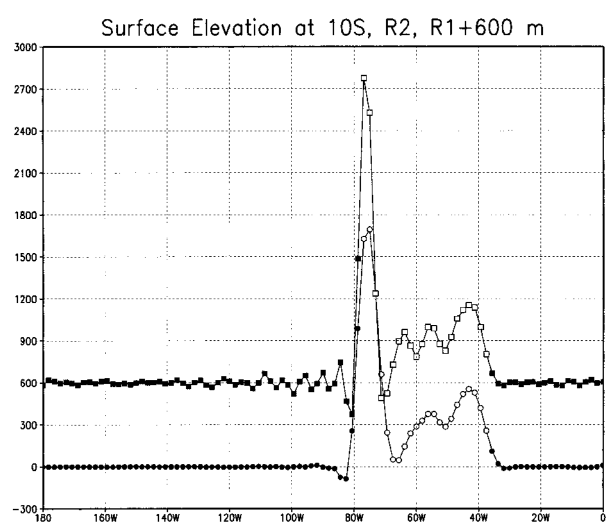
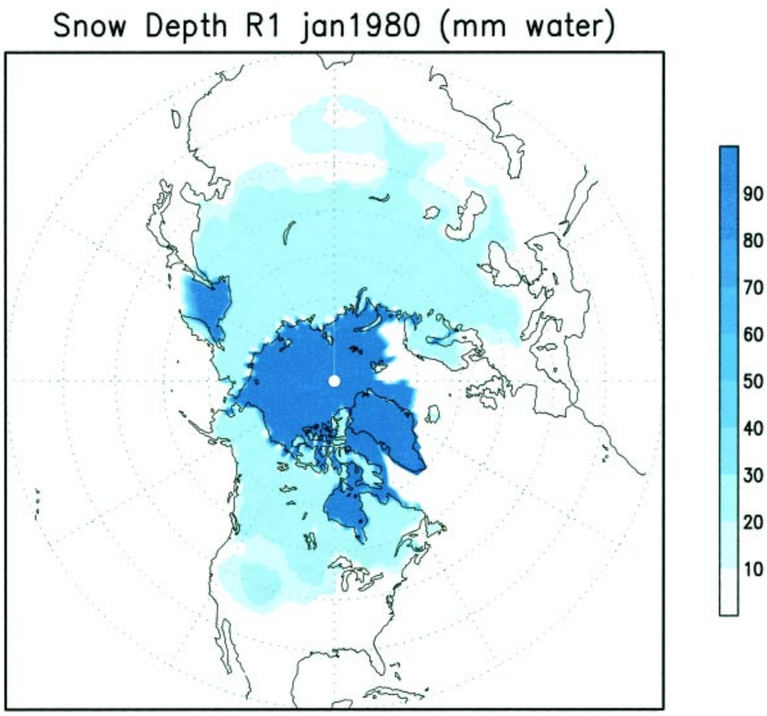


Fig. 5. Comparison of the zonal cross section of surface elevation at 20°S between R-1 (square) and R-2 (circle): 600 m is added to R-1 for contrast. The filled symbols indicate ocean points.

tent with the input snow cover analysis. When model snow cover disagrees with observation, the model snow depth was adjusted to the snow cover analysis by either removing the model snow without affecting the soil moisture or by adding snow using the empirical formulation of R-1. In regions of persistent observed snow cover in the input analysis, the R-2 scheme can build up deep snowpacks. This scheme is more realistic than those in R-1 and this procedure thus has the potential of providing more reasonable snow depth. Figures 6a and 6b compare the two water equivalent snow depth fields and demonstrate the distinct tendency for deeper and more spatially variable snow depth.

a)



b)

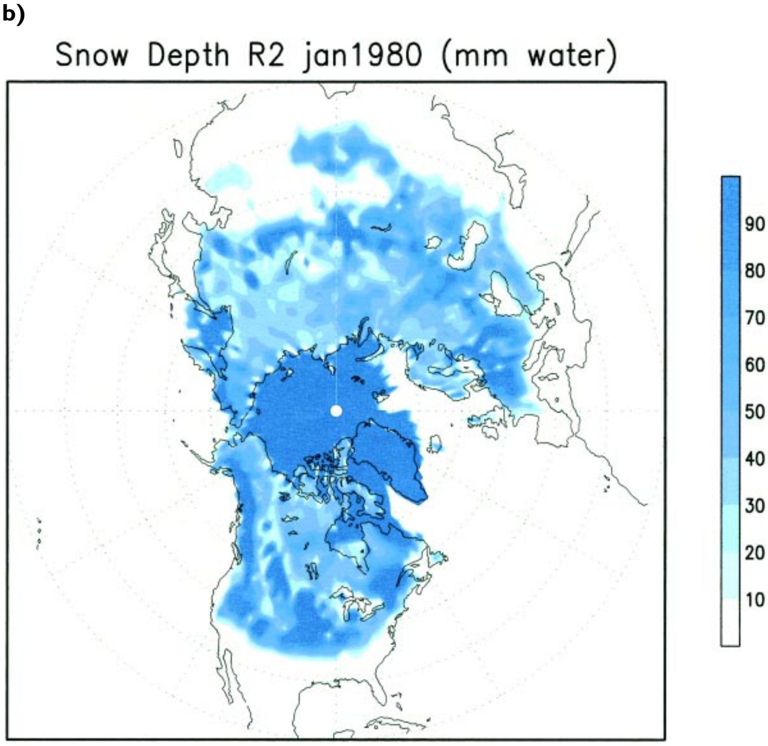


Fig. 6. Monthly averaged snow depth (equivalent water) of (a) R-1 and (b) R-2 for Jan 1980 (mm).

Model physics improvements:

1) implementation of the Hong–Pan planetary boundary layer that utilizes nonlocal diffusion (Hong and Pan 1996);
2) new shortwave radiation (Chou 1992; Chou and Lee 1996);
3) minor tuning of convective parameterization;
4) more realistic cloud-top cooling by removing vertical smoothing of heating in the cloud;
5) updated cloud-tuning coefficients for stratus clouds using preproduction, 1-yr analysis.
6) radiation calculation on full Gaussian grid; and
7) radiation code run once an hour as opposed to 3 h in R-1.

Many of these improvements to the model physics were based on the NCEP operational model upgrades during 1992–98, and others were based on experience with R-1. The Hong–Pan nonlocal vertical diffusion scheme is introduced to avoid undesirable vertical eddy flux convergence of heat, moisture, and momentum within the planetary boundary layer, which arose from the use of a local Richardson number for the evaluation of the local diffusion coefficient. The new scheme assumes a smooth vertical profile of diffusion coefficient based on the height of the boundary layer and the stability of the surface layer. The new shortwave radiation scheme by Chou

(1992) and Chou and Lee (1996) replaced the Lacis and Hansen (1974) scheme to ameliorate the excessive insolation at the surface found in R-1. The minor tuning to the convective parameterization includes the way the cloud top was computed, and the handling of absolutely moist unstable layer. The longwave radiation cloud-top cooling was enhanced by removing the empirical smoothing of vertical heating profile in the cloud layer. The stratiform cloud cover in the R-1 model was diagnosed from an empirical relative humidity–cloud cover relationship (Campana et al. 1994) based on short-range predictions with the operational version of the model. This relationship was reevaluated by comparing relative humidity from a 1-yr pilot R-2 analysis and the "RTNEPH" global cloud cover analysis of the U.S. Air Force (Hamill et al. 1992). Consequently, the R-2 cloud cover became more realistic (although not completely) and the shortwave fluxes better resembled observations. In addition, radiation and cloudiness were computed on a full Gaussian grid of 192 by 94 in R-2. In the R-1, radiation was computed on a linear grid of 128 × 64 to save computer time and interpolated to a full Gaussian grid for diagnostic output. This interpolation introduced undesirable smoothing and inconsistencies with the quantities computed on a full Gaussian grid (such as surface latent and sensible heat fluxes). Finally, the interval of the radiation calculation was increased from 3-hourly to hourly to increase the accuracy of the radiation–cloudiness feedback.

All of these changes impacted precipitation, surface fluxes, radiation fluxes, and the land hydrology budget. The reduction of the spin-down in summertime precipitation over the southeast United States, which was apparent in R-1, was drastically improved by the use of the nonlocal vertical diffusion. Changing the shortwave radiation significantly improved the surface radiation fluxes. Some of the apparent impacts of these changes are discussed later in the paper.

Fixed field improvements:

1) improved desert albedo (Briegleb et al. 1996),
2) sea-ice and SST fields (AMIP-II, provided by PCMDI),
3) new ozone climatology (Rosenfield et al. 1987),
4) Northern Hemisphere snow cover analysis (interpolated from weekly to daily values), and
5) CO_2 set to 350 ppmv (AMIP-II specified constant).

These changes improved radiation fluxes at the surface and made the analysis more consistent with the AMIP-II specification (AMIP Project Office 1996). The albedo over desert areas is greater than in R-1. The AMIP-II SST made the analysis consistent with the AMIP-II boundary conditions, and also improved the SST near the polar ice boundaries. The ozone climatology is thought to be better than the old climatology. The snow cover analysis (produced operationally by the National Snow and Ice Data Center) was interpolated from weekly to daily values by interpolating the latitude and longitude of snow cover boundary in time. In R-1, the snow cover analysis changed discontinuously every seven days (until the daily snow analyses became available in September 1998).

Improvement to the diagnostics:

1) better diagnostic fields of clouds, and
2) fixed snow–water budget diagnostics.

In R-2, the model cloud cover at 28 model layers for both stratiform and convective clouds are archived. In R-1, only high, middle, and low cloud cover for both types of clouds were archived. The R-2 snow budget includes snowfall, snowmelt, and snow sublimation, and is more complete than R-1.

Archive, distribution, monitoring, and prediction:

1) data kept in the NERSC mass storage;
2) no CD-ROMs (however, plan exists at NCAR);
3) analysis distributed through the Internet;
4) NCAR and Climate Diagnostics Center (Boulder, CO) also distributes the analyses;
5) only 2.5 NCEP scientists making production runs;
6) only two PCMDI scientists and other external scientists involved in monitoring; and
7) unlike R-1, no medium-range prediction is performed during the analysis.

Errors found in R-2. Unfortunately, R-2 also suffered from human errors. The analyses and postprocessing were repeated several times in the production phase due to these errors. However, some of the errors needed to be left alone since they were found after too many analyses were complete. Four such errors, all of them related to programming problems, should be mentioned. The first is the zonally averaged seasonal climatological ozone used in the radiation computation; the latitudinal orientation was reversed north to south. Limited experiments revealed only a minor impact, but problems in the radiation fluxes in the stratosphere may be expected. The second is in the formulation of countergradient flux formulation in the surface-layer physics. The error allowed a countergradient flux to occur anywhere over the entire globe even though it was intended to occur only over oceans. The effect of this error was found to be quite small. The third involved the positive soil-moisture correction when the topsoil layer was saturated. Instead of adding the correction to the second layer, the correction was added to the top layer. Once in the top layer, the correction would either seep into the second layer or disappear as runoff, not an unreasonable fate for the correction. The fourth problem was in the units of model runoff when applied to the soil-moisture correction. The effect of this error is to stop the reduction of soil moisture in cases of model runoff and when the observed precipitation is less than (model precipitation–model runoff). For all other cases, this units problem had no impact. Unfortunately we have not yet completed sufficient analyses to say anything concrete about the effects of the units problem. However, after three months of test assimilation, the effects are found to be relatively minor.

There may also be errors discovered after a more thorough examination by the research and user community.

ANALYSIS COMPARISONS BETWEEN R-1 AND R-2. In this section, key differences between R-1 and R-2 are presented. Due to the system improvements, fixes of errors, and improvements to model physics and fixed fields, many features are improved significantly.

Improvements. Soil wetness fields, especially the interannual variability, are dramatically improved due to the use of observed pentad-average precipitation for soil wetness evolution. In order to demonstrate this, the soil moisture of R-1, R-2 was compared with observation over Illinois where a long time series of measurement is available. The direct comparison revealed that the soil moisture content of R-2 is much less (about 450 mm on the average) than that of observation (about 700 mm) but the amplitude and annual variation are in reasonably good agreement. On the other hand, soil moisture content of R-1 (about 600 mm on the average) is closer to observation during the winter season but much less in summer, and the amplitude of annual variation is too large and has very little interannual variation. In practice, a direct comparison of model and observed soil moisture can be misleading as different models and observations can have different values of unavailable soil moisture. The variations in available soil moisture are more physically relevant, and these variations can be estimated by removing the minimum value obtained from a long time series (approximating the minimum value as the unavailable part of soil moisture). When this was done, the results (Fig. 7) show more clearly that R-2 and observations have many similarities to the observations. By contrast, R-1 is wetter, has a much stronger annual cycle, and has little interannual variability. The improved forcing (observed precipitation versus model precipitation) and the removal of the climatological nudging were largely responsible for the improved R-2 soil moisture variations.

The unrealistically large interannual variation of soil wetness found at the beginning of the R-2 assimilation (1979–80) is due to two reasons. The first is the spindown of soil wetness from R-1 soil wetness, which was used to initialize R-2 on 1 December 1978. The second is a possible problem in the pentad precipitation analysis in which missing rain gauge observations were mistakenly reported as zero in the earlier periods. Thus, the use of R-2 soil wetness in the earlier period (1979–81) is cautioned.

Over land, wintertime precipitation, surface air temperature, and surface fluxes in high latitudes are improved (not shown), due to the correction of the "spectral snow" problem and the corrections to snow cover and snow depth. The changes in boundary layer and convective and radiation parameterizations seem to have improved the tropical precipitation, but only very slightly (not shown).

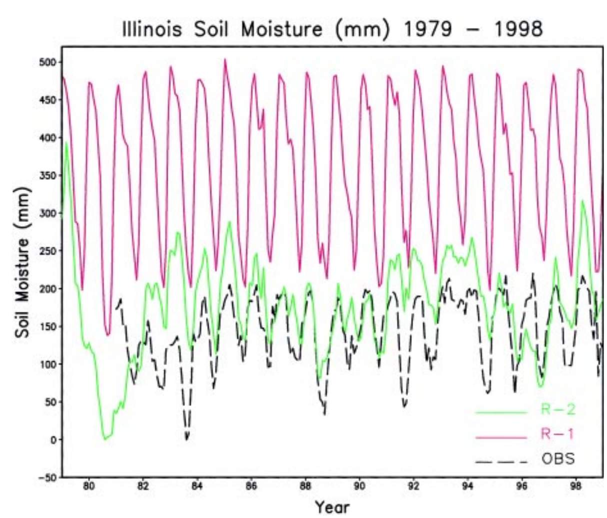


FIG. 7. Comparison of available monthly averaged deep layer (200 cm) observed (solid), R-1 (short dashed), and R-2 (long dashed) soil wetness over Illinois, spatially averaged in each case for the period 1979–99 (mm).

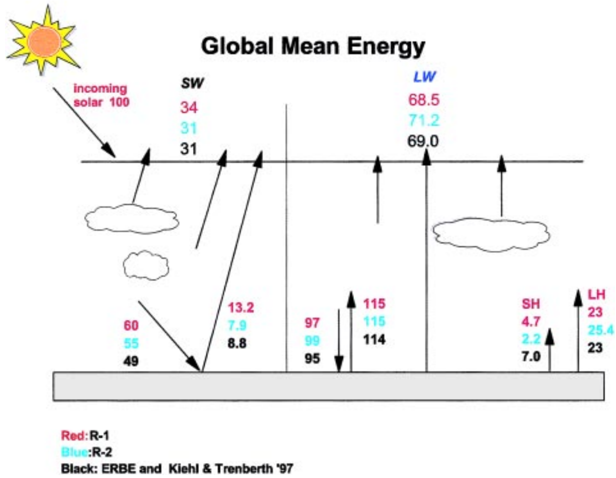


FIG. 8. Comparison of global radiation budget: SW stands for shortwave radiation fluxes, LW for longwave fluxes, SH for sensible heat fluxes, and LH for the latent heat fluxes. R-1 in red, R-2 in blue, and independent estimates (Kiehl and Trenberth 1997) in black. Units are in percent assuming the incoming solar radiation is 100.

One of the significant shortcomings that prompted NCEP to change the shortwave radiative transfer algorithm in R-2 was the excessive surface insolation found in R-1, as shown in Fig. 8. (Yang et al. 1998; Berbery et al. 1999). The general consensus from Kiehl and Trenberth (1997) indicates that the correct magnitude of surface insolation is about 49% of the solar constant over the annual mean. With the new shortwave radiative transfer algorithm of Chou (1992) and the refined cloud algorithm, R-2 substantially improves the ratio to about 55%, compared to 60% in R-1. Replacing the R-1 land surface albedo algorithm by that of Briegleb et al. (1996) in R-2 over land also greatly enhances the accuracy of surface albedo at various locations, particularly over the Sahara. The new albedo algorithm handles direct and diffuse components separately, and also divides the solar spectra into visible and near-infrared bands. This treatment successfully brightens the Sahara from 0.3 in R-1 (Yang et al. 1999) to beyond 0.4 (in albedo unit) in R-2, which is in good agreement with the estimate from Staylor and Wilbur (1990; see Fig. 9). Moreover, the combination of the new shortwave transfer algo-

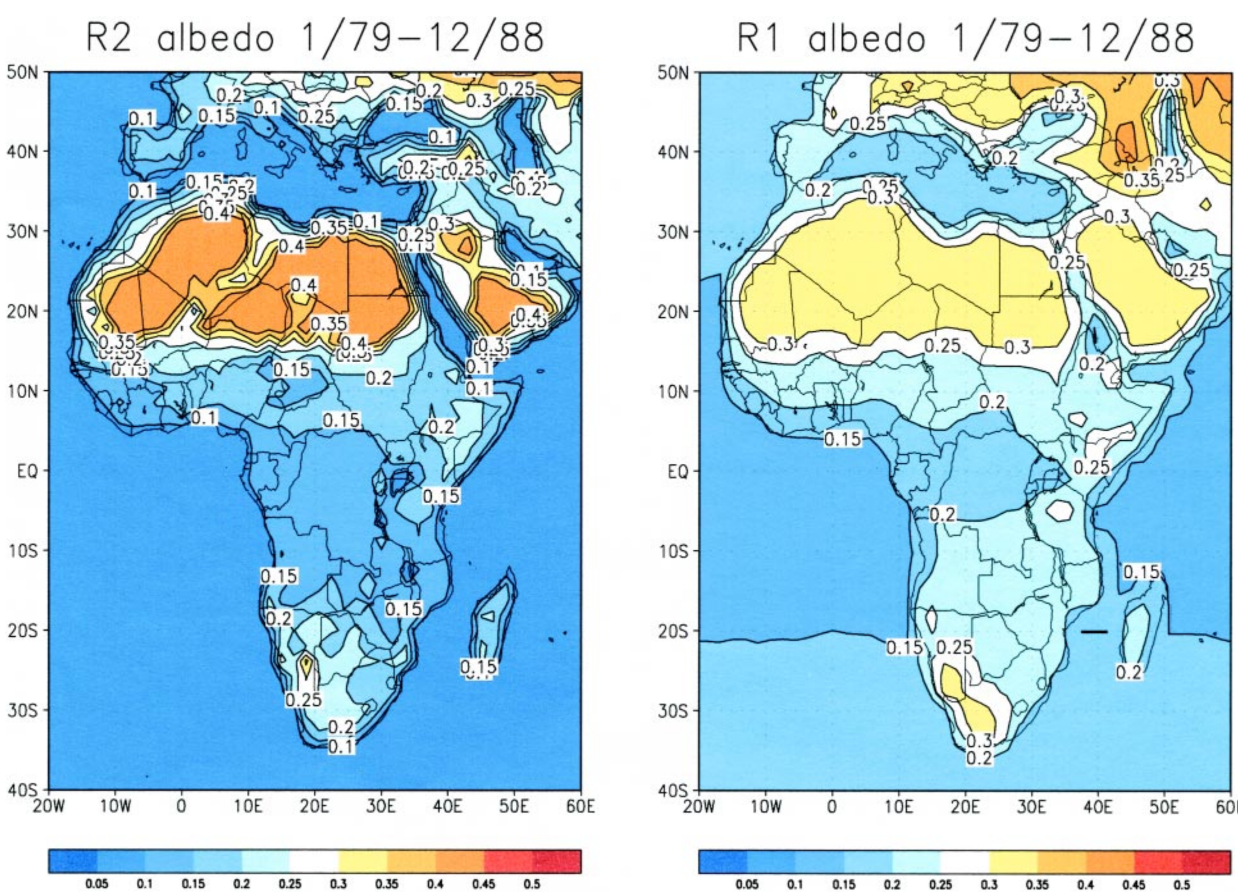


FIG. 9. Comparison of 10-yr average (1979–88) surface albedo over Africa between (left) R-2 and (right) R-1. Unit is in fraction.

rithm combined with the reduction of ocean surface albedo, from 0.15 in R-1 to 0.06~0.07 in R-2, reduced the R-1 high bias of planetary albedo. The annual global mean albedo for R-1 was 0.34 versus 0.31 for R-2. The corresponding reflected shortwave radiation at the top of the atmosphere was ~115 W m^{-2} for R-1 (Yang et al. 1999) and ~105 W m^{-2} for R-2, which compares well with 103 W m^{-2} of Earth Radiation Budget Experiment (ERBE; Barkstrom et al. 1989).

The changes in boundary layer and convection parameterizations significantly reduced the systematic spindown of tropospheric humidity over the southeast United States, especially Florida, during the summer season, and partially corrected the problem of excessive precipitation over the area in R-1. Furthermore, since the systematic spinup/down appears as a systematic tendency error in the budget equation, the reduction of large systematic spinup/down makes it easier to interpret the budget calculations. For more detail of the error and closure of the budget calculation of the reanalysis products, see Kanamitsu and Saha (1996) and Roads et al. (2002)

Major differences. In addition to the apparent improvements, there are several additional significant differences between R-1 and R-2 analyses. The soil temperature and 2-m air temperature are warmer for R-2 than for R-1. This is partly due to the fix in snow cover. The precipitable water in the Tropics is larger than in R-1 as a result of the change in the boundary layer and convective parameterizations.

As illustrated by Fig. 10, the increase brings the tropical precipitable water closer to the National Aeronautics and Space Administration (NASA) water vapor project estimates (NVAP; Randel et al. 1996), which are based on satellite and conventional observations. Figure 11 displays the geographical distribution of the difference in the 10-yr average precipitable water between R-1 and R-2.

The cloud cover is larger in R-2. Globally, total cloud amount increased from 44% in R-1 to 56% in R-2. This change is a result of the new cloudiness–relative humidity table generated for R-2 as discussed in the section titled "Error fixes from R-1 to R-2 (after R-1 system was frozen)." The larger fraction seems to better agree with several observational sources. The increase of global cloud amount in R-2 appears to play certain roles in readjusting the global energy distribution, but the details have not yet been sufficiently analyzed.

Possible drawbacks and other changes. The changes in the physics of the model did improve the overall quality of the analysis but may have caused deterioration in some portions of the analysis. The following section lists the major differences found between R-1 and R-2 that may be associated with a deterioration. However, uncertainties in observations make it difficult to provide a conclusive judgment.

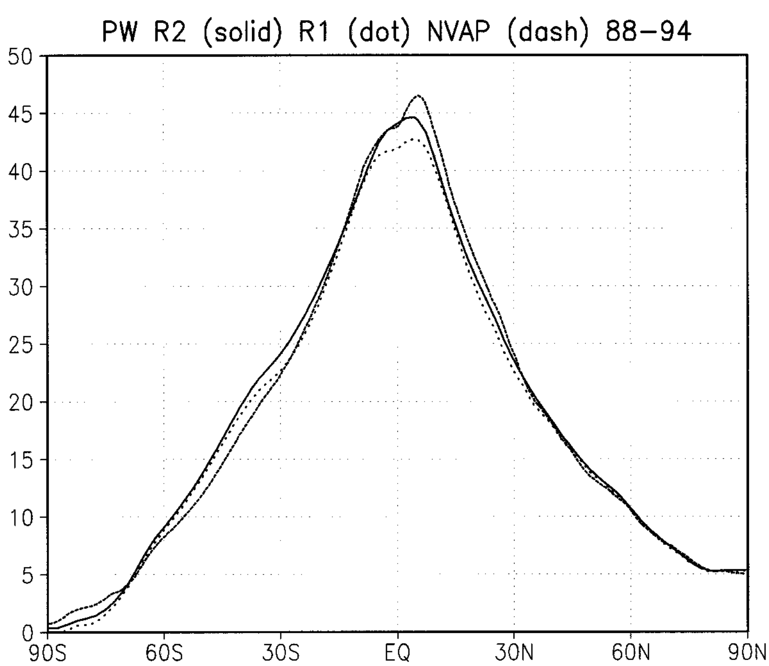


Fig. 10. Zonally averaged precipitable water for Jan 1988–Dec 1994 from R-2 (solid line), R-1 (dotted line), and NVAP (dashed line) (mm).

In the radiation budget, the improvement in shortwave radiation is somewhat offset by the increase of outgoing longwave radiation (see Fig. 8). R-1 is in very good agreement with ERBE; namely, with 237 and 234 W m^{-2} for R-1 and ERBE, respectively, for the global annual mean (Yang et al. 1999), while 242 W m^{-2} for R-2 is about 3% higher than ERBE. The overestimation is more substantial in the Tropics, where R-2 can be up to 15~20 W m^{-2} larger than ERBE and R-1. Much of this difference can be traced to the dryer humidity in the upper troposphere in R-2, to which outgoing longwave radiation (OLR) is sensitive (Yang et al. 2000).

In the Tropics, R-2 relative humidity at 300 hPa is about 10%–15% lower than that of R-1, and it can be

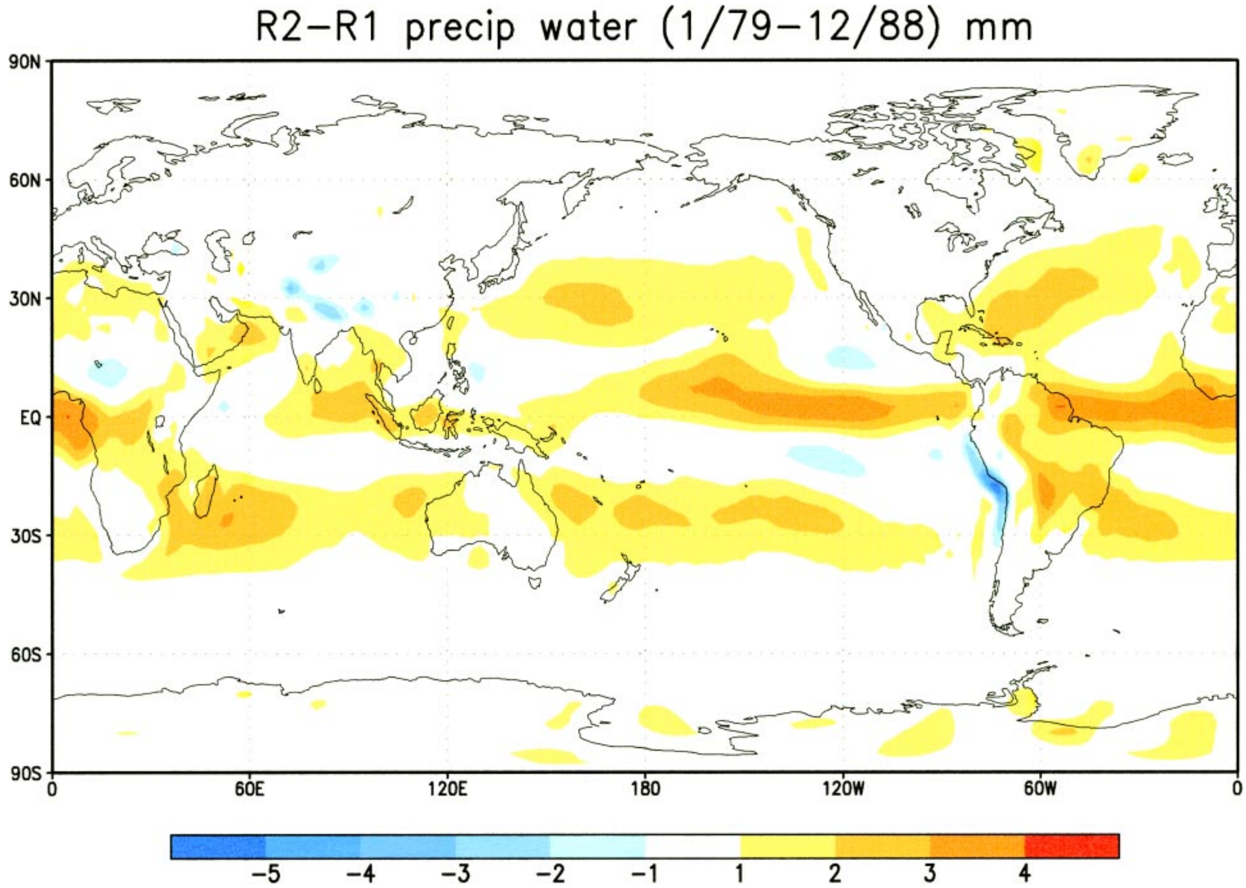


FIG. 11. Difference of 10-yr averaged (1979–88) precipitable water (mm) between R-1 and R-2.

up to 45% lower in the warm pool region of the western tropical Pacific (see Fig. 12). Since the total precipitable water from R-1 and R-2 are about the same, it is suspected that the water vapor profile in R-2 has more moisture in the lower atmosphere. Still further research is needed to understand the causes.

There are other minor but notable differences. For example, some differences exist in the upper-air height and temperature analyses over Northern Hemisphere oceans, where most of the observations are from satellites. It is worth noting that the reanalysis is a blend of model forecast and observations and, therefore, small differences arise between R-1 and R-2 due to model differences, even over the less data-sparse Northern Hemisphere. There are differences in the equatorial divergent wind and stratospheric temperature in the Southern Hemisphere, where in R-2 the upper branch of the Hadley circulation is lower and the Southern Hemisphere jet is located slightly farther north.

SUMMARY. In summary, NCEP–DOE AMIP-II Reanalysis (R-2) is an updated 6-hourly global analysis series from 1979–present, which fixes the known processing errors in the NCEP–NCAR reanalysis (R-1) and uses an improved forecast model and data assimilation system. It provides a better reanalysis and is recommended for users who are affected by known errors in R-1. Examples of studies include (i) analysis of transients in the Southern Hemisphere, particularly case studies; (ii) use of near-surface temperatures and snow cover over the Northern Hemisphere continents in winter, especially in high latitudes; (iii) analysis of soil wetness; (iv) analysis of the snow budget; and (v) sensitivity of analyses to changes in the assimilation model. The R-2 provides more accurate pictures of (i) soil wetness and near-surface temperature over land, (ii) the land surface hydrology budget, (iii) snow cover, and (iv) radiation fluxes over ocean. It should also be noted that R-2 might not necessarily provide better analyses than R-1. The OLR over the tropical warm pool and upper-level tropical moisture are known fields that may be less accurate than the R-1 analyses. The real reason for this deterioration is not known but seems to be related to the new boundary layer formulation and convection.

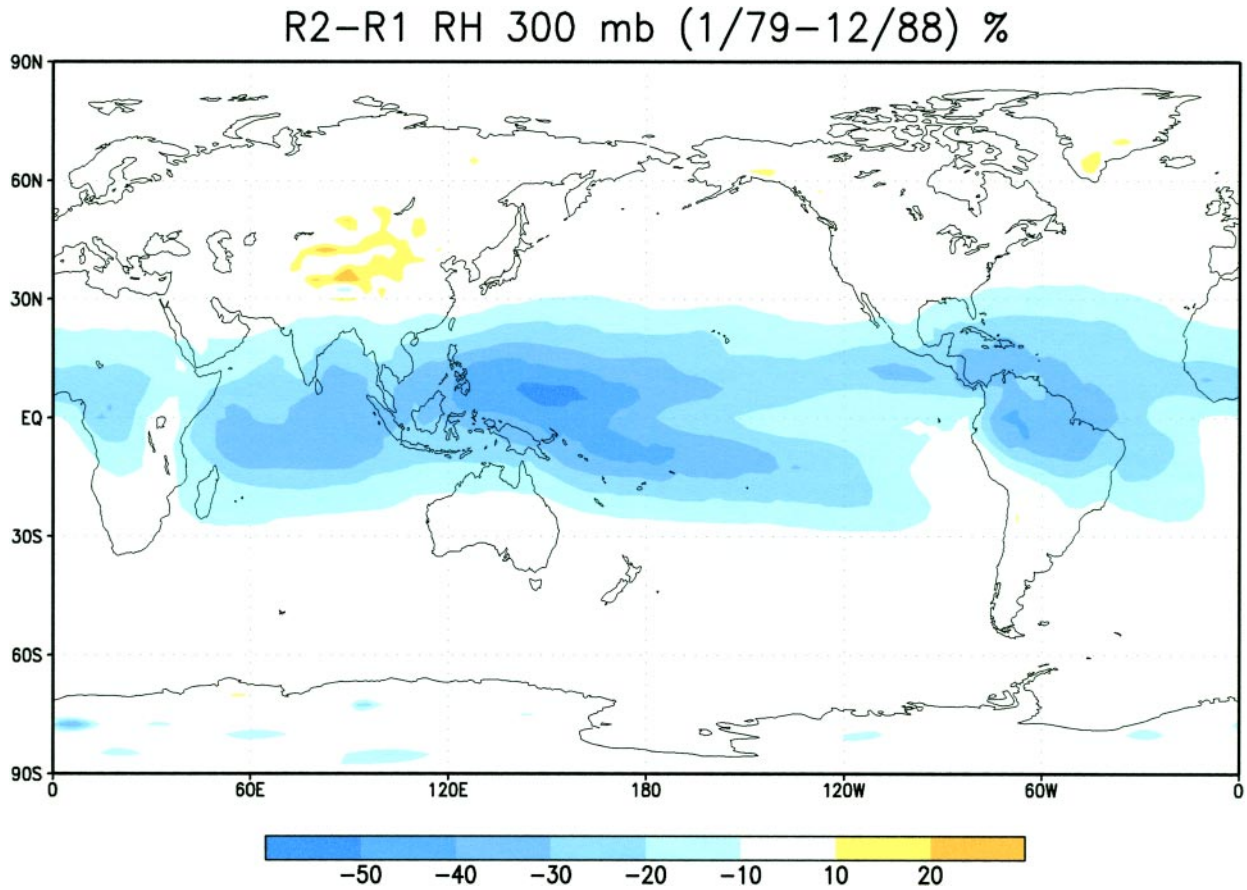


Fig. 12. Same as Fig. 10 but for 300-hPa relative humidity (%).

These changes improved the precipitation but inadvertently worsen the radiation budget. In this respect, R-2 can be used with R-1 to understand the sensitivity of the analysis to changes in the model parameterizations. Such sensitivity is one factor affecting the accuracy of the various reanalysis efforts.

Most of the monthly averaged files are available online at http://wesley.wwb.noaa.gov/reanalysis2. The site also contains a more detailed comparison between R-1 and R-2. Readers are also encouraged to look for a number of existing publications comparing R-1 and R-2, some of which are listed in the references (e.g., Arpe 2000; Yang et al. 2000; other articles in the Proceedings of the Second WCRP International Conference on Reanalyses; and Taylor 2001).

Again, R-2 should be considered as an updated R-1 and not as a next-generation reanalysis. Although R-2 has some significant improvements, a next-generation reanalysis would have much higher resolution, assimilation of rainfall and satellite radiances, a much improved forecast model, and finally, be based on both better theoretical techniques, such as 4D-variational assimilation and increased attention to long-term trends.

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