REGIONAL CLIMATE AND VARIABILITY IN NASA MERRA AND RECENT REANALYSES: US SUMMERTIME PRECIPITATION AND TEMPERATURE

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A Technical Report Submitted to NCA: 2/28/2012

1 INTRODUCTION

The characterization and understanding of climate variability at regional scales is important for both research and societal applications. Atmospheric retrospective-analyses (or reanalyses) integrate a variety of observing systems with numerical models to produce a temporally and spatially consistent synthesis of data for weather and climate variability studies.

In this report, we assess regional variability over North America, specifically the United States, from NASA's Modern-Era Retrospective analysis for Research and Applications (MERRA, Rienecker et al. 2011). Emphasis is placed on summertime precipitation because 1) it is a difficult parameter to capture in the most difficult season (Bosilovich et al. 2009) and 2) significant observational resources exist to benchmark comparisons. Surface air temperature is also assessed.

The report considers various regions across the contiguous United States. Furthermore, attention is given to potential connections with El Niño-Southern Oscillation (ENSO) variations as well as to the trends in the data. Precipitation and temperature are the initial foci, given their relative importance in societal applications, and some connections to broad climate dynamics will also be discussed. One aspect of this work is an initial evaluation of reanalyses uncertainties in the representation of regional climate variations over the United States from reanalyses.

2 DATA AND METHODS

2.1 Reanalyses

Reanalyses have a long track record for providing information on climate variations and for the evaluation of climate models. While reductions in model biases, improvements in data assimilation implementations and increases in resolution have improved the latest reanalyses, significant issues remain, so that some validation and background studies are required before interpreting results. Consider that variations in the observing system itself can cause spurious variations in the reanalysis time series (Bosilovich et al. 2011; Robertson et al. 2011). Such features have been noted in the three latest global reanalyses for the satellite era. While most of our assessment will focus on MERRA (Rienecker et al. 2011), we also make some comparisons with ERA-Interim (Dee et al. 2011) and CFSR (Saha et al. 2010). For this study, we have worked with the latest ERA-Interim data (at ¾ degree resolution), which begins in 1979 and continues forward in near-real-time. At the time of this report, CFSR has not been archived beyond 2009.

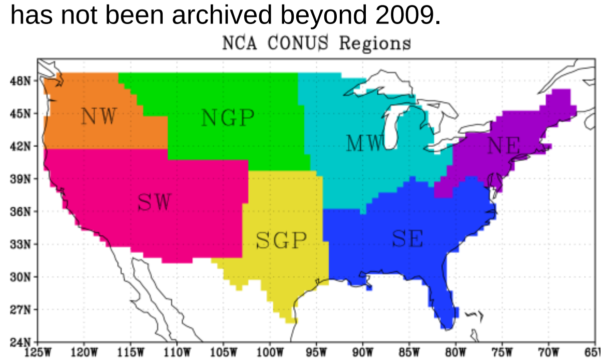

Figure 1 Continental US regions defined by the National Climate Assessment, with an additional split in the Great Plains states.

Bosilovich et al. (2009) evaluated radiative fluxes and precipitation from eight operational analyses and reanalyses systems. Over the Mississippi River basin, the quality of reanalyses seasonal precipitation degrades noticeably in summer, as has also been seen in numerical predictions. Total precipitation is governed more by local convective elements than large scale well-resolved dynamical processes. Yet, extreme summertime climate variability often manifests through devastating precipitation extremes (e.g. drought and flood). Given the importance of summertime precipitation and its uncertainty, this assessment of MERRA begins by evaluating the skill in summertime precipitation variability.

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2.2 Gauge Observations

The Climate Prediction Center (CPC) daily gauge analysis for CONUS provides the benchmark (Chen et al. 2008; Xie et al. 2008). Precipitation gauges have been analyzed to ¼ degree resolution over the continental United States. While reanalyses have slightly coarser spatial resolution, the spatial calculations and maps presented here maintain the higher resolution of the observations, as opposed to interpolating to the coarser grids. The daily data have been averaged to seasonal means for the time series analysis.

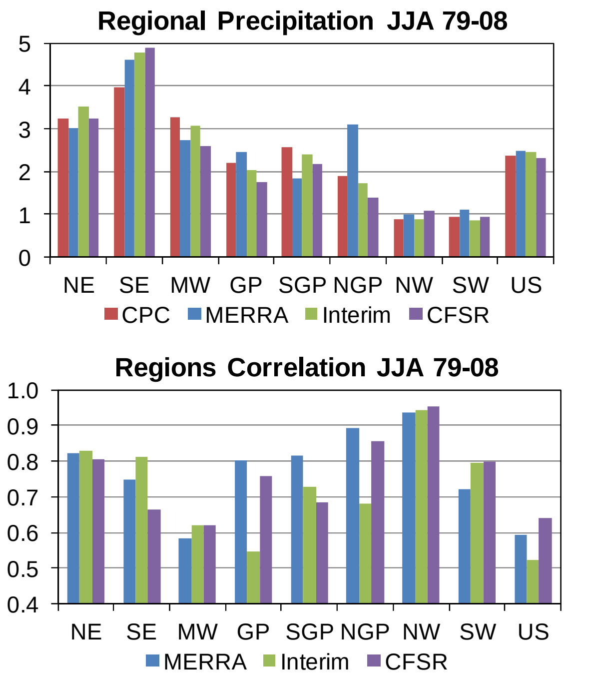


Figure 2. A comparison of regional precipitation (mm day^{-1}) from CPC gauge observations with reanalyses. Time and area averages for each region and June, July, August (JJA) (top). Correlation of the 30 (years) JJA seasonal area average precipitation anomalies of the reanalyses to observations (bottom).

2.3 National Climate Assessment Regions

Some of the assessment here implements the regional segments defined by the National Climate Assessment (NCA) in order to facilitate the use of MERRA data in NCA activities and sectors. The regions defined by NCA are included in Fig. 1, with the exception that their Great Plains (GP) region has been split into a Northern Great Plains (NGP) and Southern Great Plains (SGP) regions. Substantial latitudinal variations across the NCA GP region would alias smaller regional signals in the data analysis. There are also regional features, such as the SGP low-level jet (LLJ), that need to be isolated, requiring a limited spatial extent. With an understanding of MERRA's fidelity in these regions we can decide how best to use its capability in understanding the seasonal and decadal variations for the US.

3 SUMMER PRECIPITATION ASSESSMENT

Figure 2a shows the time and area averaged precipitation for CPC gauge observations and reanalyses for the continental United States regions. All considered reanalyses have high summer biases in the Southeastern US. MERRA's overestimate over the Northern Great Plains is the largest bias. Though, the summer dry bias in the Midwestern region is likely significant as well.

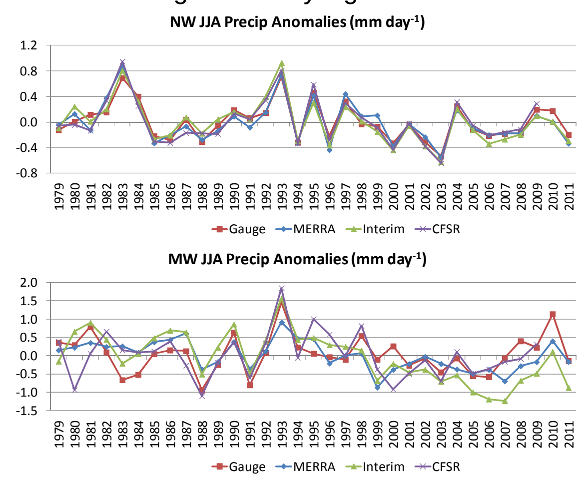


Figure 3 Contrasting time series of the JJA precipitation anomalies in the Northwest (NW) and Midwest (MW) regions of Figure 1.

Despite the high NGP precipitation bias, MERRA shows quite high correlation with the observed seasonal anomalies, while ERA-Interim shows a markedly lower correlation (Figure 2b). While ERA-Interim's regional biases tend to be small, it has a decreasing trend that may be adversely affecting the time series correlation (trends discussed later).

Figure 3 contrasts the precipitation anomalies in the NW with those in the MW, the former with highest temporal correlation, the latter with the lowest. In NW, all reanalyses track the observed JJA precipitation anomalies remarkably well. The mean flow of JJA moisture is predominantly eastward from the Pacific Ocean. In the MW region during summer, recycling ratios increase (Bosilovich and Schubert, 2001), thereby increasing the dependence of precipitation on both the land model (through its representation of evaporation) and the past rainfall and snowmelt. In addition, MW reanalysis precipitation calculations depend more heavily on the convection parameterization of the model. In the MW region, moisture transport has played an important role in extreme anomalies. Here, we see that MERRA underestimates both the anomalies from the 1988 drought and the 1993 flooding. This is generally true of the NGP region as well (not shown). The other reanalyses also struggle in this region, with either false extremes or underrepresentation of extreme events.

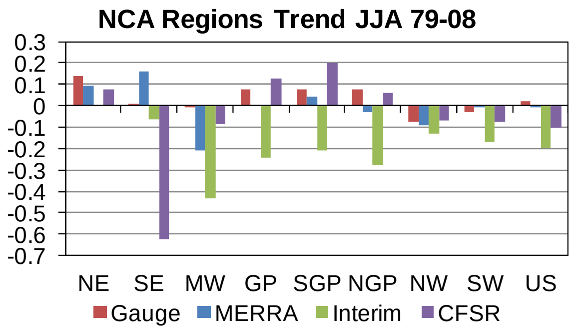


Figure 4 As in Figure 2, except for the precipitation trend over each region (mm day^{-1} per decade).

While the mean and correlation of the seasonal anomalies are reasonable in some regions, the reanalyses display some trends that are unrealistic compared to observations. CFSR's SE region experiences a dramatic downward shift in precipitation in 1997-1998, which leads to a large negative trend (Figure 4). In the MW region, MERRA and Interim both experience systematic decreasing trends in precipitation over the period to varying degrees. However, Interim's decreasing trends extend across the continent at magnitudes much greater than observed. The NW region's precipitation trends in all the reanalyses are comparable to observations.

4 ENSO RELATIONSHIP

While summer teleconnections are not as strong over the United States as those in the winter, Barlow et al. (2001) found that the North American hydroclimate responds to several modes of variability in the Pacific Ocean, including El Niño Southern Oscillation (ENSO), in that the north western United States receives increasing precipitation during El Niño conditions. In this section, we evaluate the ability of reanalyses to reproduce this low frequency variability for the United States.

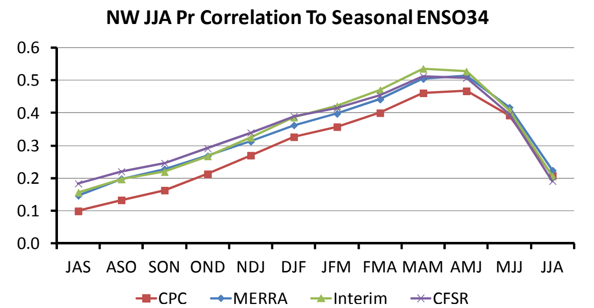


Figure 5 Time correlation of summer seasonal precipitation (as in Figure 3) with ENSO34 seasonal values.

Reanalyses are expected to implicitly include ENSO variability because of their extensive use of observational data. On the other hand, the physical processes are only guided by the observations and rely also on model parameterizations, especially in summertime.

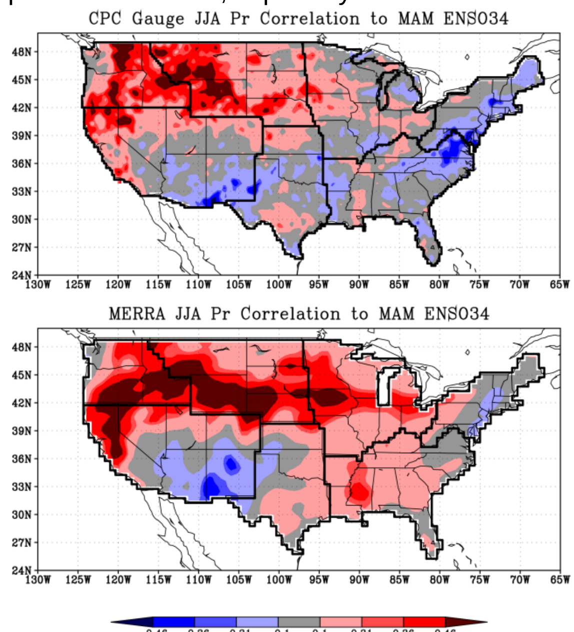


Figure 6 Spatial distribution of the correlation between summertime precipitation and spring ENSO34. The colors indicate level of significance of the correlation (0.31~90%, 0.36~95% and 0.46~99%). CFSR and Interim show similar patters to MERRA

Following Barlow et al (2001) in looking at the northwestern U.S., we find the NW region summer precipitation positively correlated with ENSO34[1] index (Figure 5). We find this correlation is strongest with the antecedent springtime (MAM) values of the index. The reanalyses follow the observed pattern, with the exception that their correlations are somewhat stronger than the observations, and all the reanalyses are closer to each other than the observations. In order to bring

[1] SST anomalies in 5°N-5°S, 120°-170°W, also called Niño34.

out teleconnections, the subsequent comparisons will focus on the relationship of summertime precipitation and springtime ENSO34 index.

Figure 6 shows the spatial distributions of the correlation of summer precipitation with spring ENSO34 in both CPC gauge observations and MERRA. The gauge correlations are highest in the NW and NGP regions, with little significant correlation elsewhere, in agreement with the results from Barlow et al. (2001). MERRA tracks the observed pattern well, with positive and significant correlations in the NW and NGP regions. As shown in Figure 6 for the NW, the areas of positive correlations have generally larger values compared with observations.

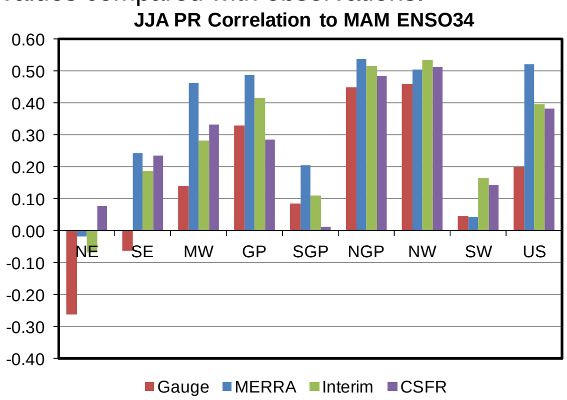
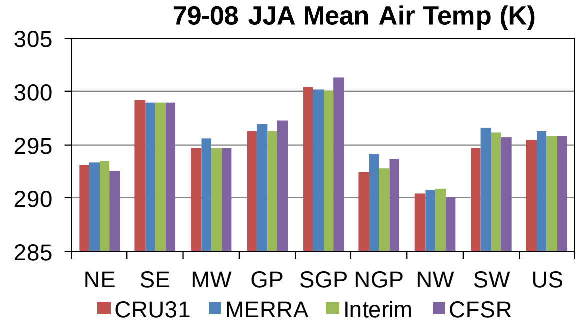


Figure 7 Correlation between summertime precipitation and springtime ENSO34 for each of the reanalyses and gauge observations, in each region and the whole of the U.S.

The stronger correlation in MERRA, compared with the gauge observations, is also found in other reanalyses, and generally spans all the sub-regions considered here (Figure 7). In particular, when looking at the whole US, the large scale correlation is apparent. The broad result is that summertime precipitation and attendant physical processes are too closely related to ENSO compared to observations. If the correlation is derived from the coarse scale of resolved circulations and the inability to explicitly simulate fine scales of convection, it would effectively act as a filter. Possibly, incorrect land-atmospheric interactions have some affect. More analysis is needed to determine if there is a tendency for the reanalysis systems to draw energy away from longer modes of variability, such as the North Pacific Decadal Oscillation (Higgins et al., 2007).

5 SUMMER SURFACE TEMPERATURE ASSESSMENT

Near surface atmospheric temperature is another essential climate variable, and is important for analysis of summertime extremes such as drought and heat waves. In reanalyses and global models, this quantity is still closely related to the model parameterizations, situated between the state variables of temperature at the surface and at the lowest atmospheric model level. As such, model uncertainty will play a role in the representation of climate variability in reanalyses.



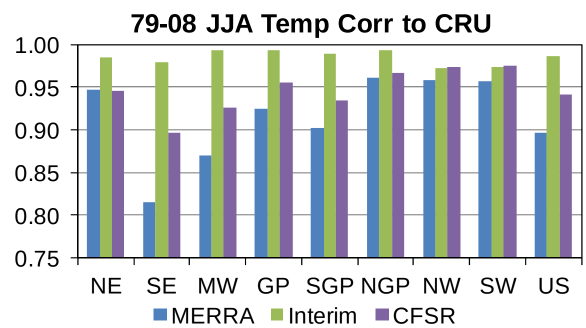


Figure 8 Regional temperature (K) comparison between CRU v3.1 station observations and reanalyses. (top) Temporal and areal averages for each region for June, July, August (JJA). (bottom) Correlation of the 30 (years) JJA seasonal area-average precipitation anomalies of the reanalyses to observations.

However, representation of temperature in reanalyses generally appears more robust than precipitation, likely because atmospheric temperature is assimilated from both radiosonde and satellite sources regularly. For an observed baseline we use the Climate Research Unit (CRU, 2008; Mitchell and Jones, 2005) atmospheric temperature, version 3.1. Figure 8 shows the mean temperature for each of the US regions. Many summertime biases are less than 1K, and none more than 2K. The correlation between reanalyses and observed time series are also quite high relative to those of precipitation (note the difference in scales for Figure 2 and 8).

One noticeable feature in the reanalyses representation of temperature is that across all the regions, the ERA-Interim air temperature correlates with CRU observed analysis in the high nineties. This is a direct result of their use of both near surface atmospheric temperature and water vapor to constrain soil moisture (Dee et al. 2011). CFSR also uses precipitation observations over land to better constrain their soil moisture. While coupling land data assimilation to the atmospheric reanalysis is in the GMAO's development plan, MERRA has no direct land data assimilation and so relies greatly on the model physics for the representation of near surface atmospheric temperature. To illustrate the interannual variability of mean temperature anomalies, the time series of SE and NW temperature are presented in Figure 9. In the SE, where MERRA has the lowest regional correlation, many of the interannual extremes are still represented well. Further investigation of certain years, such as 2000, may point to correctable problems in the system.

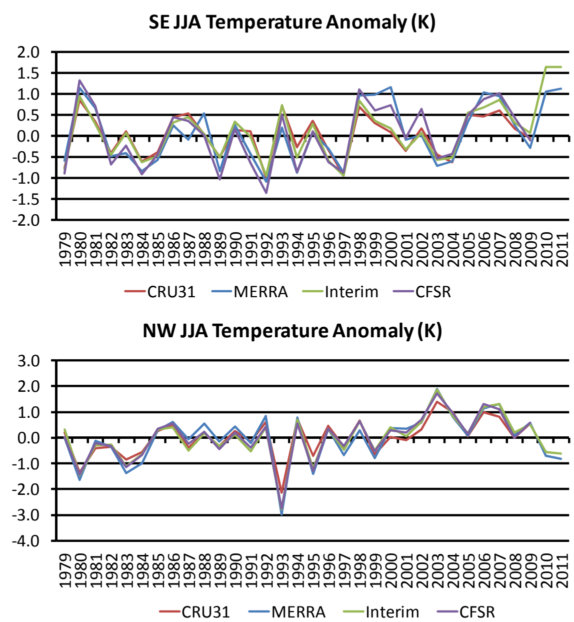


Figure 9 Time series of regional temperature anomalies (K) determined from the CRU observations and reanalyses

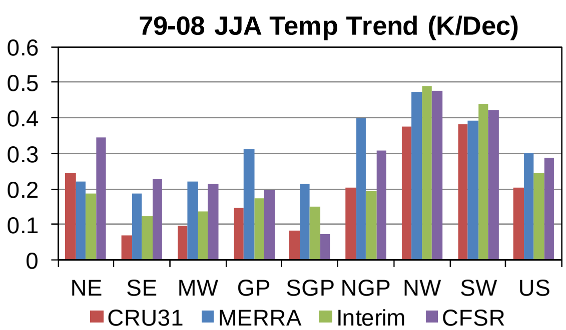


Figure 10 Trends (K per decade) for the area-average JJA seasonal temperature anomalies in the CRU observation and reanalyses.

Temperature trends from the station observations are complicated due to variations at vast numbers of stations used and their uncertainties (Vose et al. 2012; Mitchell and Jones, 2005). While all the reanalyses and observations show increasing trends, some regions exhibit distinct differences from CRU31. ERA-Interim reproduces the observed trend in most regions (Figure 10), but despite the additional land assimilation, it does not fully reproduce the observed trends. The ERA-Interim analysis of the surface temperature prevents feedback of their persistent precipitation trend deficiency from degrading the reanalysis surface temperature (Figure 4), compensating for the model biases with analysis tendencies. For MERRA, the unrealistic precipitation trends in MW and SE are likely a major contribution to the degradation of the surface temperature representations. While the reanalyses generally overestimate the upward trend of temperature, there are some indications that updated quality adjustments to the station records will lead to increased upward trend estimates (Vose et al. 2012). Despite the apparent robustness in variability of near surface air temperature, trends from reanalyses need to be considered at least as carefully as the observational record, due to the modeling components of the system and its uncertainty. Additionally, the analysis of the observational record has distinct benefit for the ERA-Interim record of the near surface temperature, but presumably does not permit correct feedback from other components of the Earth system, for example land fluxes.

6 REANALYSES CONFIDENCE LEVELS

Quantifying the uncertainty of reanalyses has been a long outstanding research issue. Since the goal of most reanalyses is to assimilate as many observations as possible, the amount of independent data for validation is small. Of course, as in the example of continental precipitation, which is not typically analyzed directly in these reanalyses, extensive comparison and statistical evaluation is possible.

In assessing the uncertainty of reanalyses, there are several issues to consider. For example, despite extensive quality control, even the most recent versions of observation data may still contain yet undetermined errors, which can be propagated into the reanalysis by assimilation. This confounds uncertainty that may be independently determined in the background numerical model.

Several strategies can provide quantitative and qualitative estimates of the confidence in reanalyses. As presented here, jointly assessing multiple reanalyses against independent sources provides a straightforward methodology. Also, the uncertainty in quantities that are predominantly model-derived can be estimated with a modest sample of analyses (Bosilovich et al. 2009).

Historically, certain output from the data assimilation procedure has not been widely or conveniently available for research and applications. For example, analysis increments[2] represent an estimate of the error in the background, integrated across all assimilated observing systems. MERRA has archived the analysis increments in an effort to close the reanalysis system's budgets (Bosilovich et al., 2011). Ideally, the analysis increment should be small when averaged over long periods, and when and where it is not, can be an indicator of systematic model error.

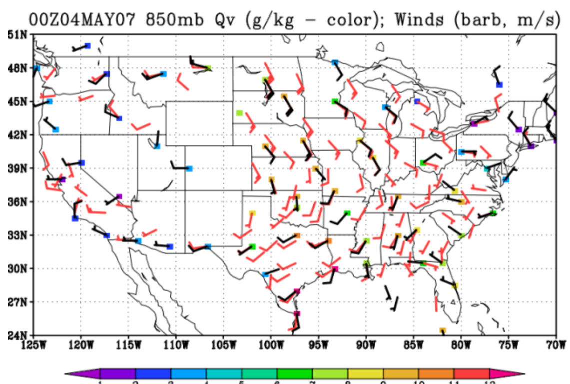


Figure 11 Example of MERRA Gridded Innovations and Observations (GIO) data, showing radiosonde water vapor measurements in the colored squares, radiosonde winds in the black barbs and LIDAR Profiler winds in the red barbs. GIO also includes the forecast and analysis error results from the data assimilation.

Forecast and analysis errors are routinely output from reanalysis systems, usually at the observations location. To facilitate diagnostics, especially the use of the observations in the reanalysis, MERRA includes these data binned to its native grid. The MERRA Gridded Innovations and Observations (GIO) data can be used to identify the availability, or not, of observations in a region of interest (Figure 11). More advanced statistical analysis can be used to determine the degree to which the varying observing systems are driving the reanalysis. A capability with this simplicity is not presently available in any other reanalysis.

[2] Analysis Increments represent the total forecast error of the observational analysis. These are described in a budget sense by Bosilovich et al. (2011)

Quantifying the uncertainty exactly is challenging since, as seen here, it varies regionally. In addition, the results presented for precipitation are seasonally dependent. While we have assessed the most difficult season – summer – the results may differ for other seasons. Results also vary across reanalysis systems, and uncertainty may change depending on the observing system quality. It must be emphasized that any reanalysis may have strengths and weaknesses that must be individually tailored for any given research topic or application. Broad overviews, such as this, may lack the specificity needed for certain studies.

In the case of MERRA, the overall results for the US precipitation variability indicate that the confidence level is medium low, owing to the poor performance of trends in some regions. At present, there is little or no confidence in trends in any region, regardless of whether the calculations agree with observations.

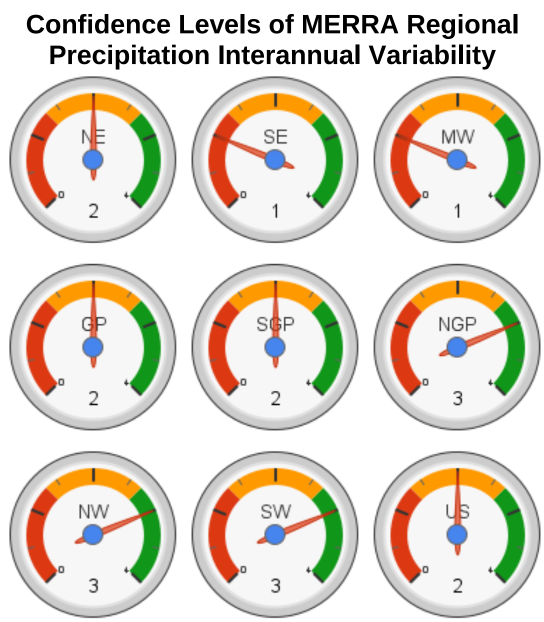


Figure 12 Schematic of the regional confidence levels of interannual variability of MERRA summertime precipitation based on the analysis here (1 low, 2 medium low, 3 medium high, 4 high).

Regionally, NW shows medium high confidence, owing to the close ties with antecedent ENSO conditions in the Tropical Pacific Ocean and attendant large scale circulation. The NGP region is also reasonably related to ENSO, but hampered by an overestimate (bias) in the mean precipitation. The SE and MW regions could be classified as medium-low confidence, owing to excessively high correlation to ENSO and significant bias. Since reanalyses tend to be internally correlated (Newman et al. 2000), we can expect these results to hold for related atmospheric properties, such as cloudiness, radiation and surface turbulent fluxes.

7 INTEGRATED EARTH SYSTEM ANALYSIS FOR THE NATIONAL CLIMATE ASSESSMENT

This section summarizes the recent GMAO reanalysis data development, processing and dissemination in support of NCA research and application activities.

7.1 MERRA and NCA Subsets

The MERRA data presented here represent a subset from the more expansive data collection disseminated from the GES DISC (http://disc.sci.gsfc.nasa.gov/mdisc/). Area averages were derived using the NCA region definitions from MERRA's one hourly intervals for the available 33 years of data, which lead to the seasonal data used for assessment here. Monthly data are presently available at the GMAO FTP site (ftp://gmaoftp.gsfc.nasa.gov/pub/data/mikeb/NCA/).

7.2 MERRA-Land Reprocessing

In the years since MERRA became available to the broad science community, several issues with the data, especially related to the land parameterization, as well as the forcing biases described above, have been uncovered. Since a reanalysis necessarily must not change during its processing (one way to limit artificial variations in the time series), a land-only reprocessing constrained by MERRA forcing has been conducted to address improvements in the modeling system (Reichle et al., 2011). This reprocessed data, called MERRA-Land, will be disseminated in parallel with MERRA at the GES DISC (before the summer of 2012).

7.3 25 Km NCA Reprocessing

The development and production activities to support future NCAs relies on GMAO's current near-real-time 25-km analysis, which includes an aerosol analysis. An updated short-term reanalysis will bring together observations from EOS/Aqua (AIRS, AMSU-A, MODIS, AMSR-E) in addition to observations from EOS/Aura (MLS temperature and ozone retrievals, MLS stratospheric moisture, and OMI ozone retrievals) and from other observing systems (IASI and GPSRO) to make a consistent estimate of meteorology (winds, temperature, humidity, cloud properties), aerosols and ozone in both the troposphere and stratosphere. The 1/4° product will include substantial advances over presently available reanalyses in that various contributions to radiative forcing will be added.

This forthcoming reanalysis is a major step towards an Integrated Earth System Analysis focused on NASA observations and will provide the most thorough integrated view of the current climate available to date. The current plan is for the updated 25-km reanalysis to be conducted for the EOS/Aura period (2004 onwards), and represents GMAO's commitment to support ongoing NCA needs.

8 SUMMARY

Reanalyses offer many advantages to climate research, but how do those relate to the needs of regional climate assessment? In evaluating the United States regional summer climate from MERRA, we characterize the ability of reanalyses to represent precipitation and temperature variability throughout the modern satellite data era. While precipitation is one of the most difficult physical processes to model, we do find a certain amount of summertime variability represented realistically in the reanalyses. The NW and NGP regions seem best represented, owing to large-scale controls from springtime ENSO variations. In addition, all the reanalyses seem to overdo the correlation between ENSO and U.S. precipitation. Interannual correlations with observations of surface temperatures are more robust than for precipitation, owing to the assimilated air temperatures. Since ERA-Interim assimilates near surface temperatures, it is likewise able to reproduce the variability quite closely, even trends. However, trends have little fidelity with observations, generally speaking. ERA-Interim's broad decreasing precipitation trend across the US is a significant problem for determination of interannual precipitation variability.

Determining the uncertainty of one, or many, reanalyses is an outstanding research issue. The uncertainty of a reanalysis can be estimated with several key components. First, independent observations, with sufficient quality, are needed to provide a benchmark. Further, several independently derived reanalyses also provide a range of comparisons for the latest advancements. Lastly, reanalyses are derived from the direct confrontation of model prediction with high quality observations. Statistics and diagnostics from the data assimilation procedure, including analysis increments and background forecast error, can provide useful guides to the reanalysis quality. However, at this time, not all reanalyses provide these data alongside standard output.

Fundamental dependencies of reanalyses include the available observations and degree to which they can be assimilated. New observing types take effort to assimilate properly. Advances in computer technology allow better use of observations through higher resolution and improved models. The GMAO reanalysis development plan is directed at integrating crucial aspects of the Earth System for better representing the current weather, climate and interrelationships of the system processes. The United States regional climates present key challenges in producing a consistent analysis. Feedback from NCA researchers and participants can guide Earth system diagnostics, and provide metrics for regional and sectoral assessments.

9 DATA TRACEABILITY

It should be noted that each of the other reanalyses presented here, and the observational data sets are freely available through online resources supported by their developing centers. Data and documentation are available from the links provided here.

9.1 Observations

CPC Precipitation
ftp://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_CONUS/
Xie et al. (2007), Chen et al. (2008)

CRU Temperature
http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276
Mitchell and Jones (2005)

9.2 Reanalyses

MERRA
http://gmao.gsfc.nasa.gov/MERRA/
Rienecker et al. (2011)

ERA-Interim
http://www.ecmwf.int/products/data/archive/descriptions/ei/index.html
Dee et al. (2011)

NCEP CFSR
http://cfs.ncep.noaa.gov/cfsr/
Saha et al. (2010)

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