Reanalysis Efforts in the United States: NASA and National Reanalysis Program

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1. Introduction

Reanalysis is the assimilation of long time series of observations with an unvarying assimilation system to produce data sets for a variety of applications; for example, climate, chemistry-transport, and process studies. The provision of reanalyses was advocated by Bengtsson and Shukla (1988) and Trenberth and Olson (1988) in order to provide homogeneous data sets for climate applications and to encourage research in the use of satellite observations without the operational constraints of numerical weather prediction. Kalnay and Jenne (1991) proposed that a reanalysis be performed as a partnership between the National Meteorological Center (NMC, now part of the National Centers of Environmental Prediction, NCEP) and the National Center for Atmosphere Research (NCAR). This project required the preparation of the input data sets, the definition of the analysis system, and a data distribution plan. The analysis system was a version of the operational system used for weather prediction, but at lower resolution.

Three organizations performed a first generation of reanalyses in the spirit of Bengtsson and Shukla (1988) and Kalnay and Jenne (1991). Aside from the NCEP-NCAR reanalysis (Kalnay et al., 1996), the European Centre for Medium-range Weather Forecasts (ECMWF) executed the ERA-15 project (Gibson et al., 1997) and the Data Assimilation Office (DAO) at NASA's Goddard Space Flight Center provided a 17-year reanalysis (Schubert et al., 1993). These three reanalyses have been cited in many studies, which document successes as well as identify a series of shortcomings that need to be addressed.

The quality of the first-generation reanalyses has been documented in the proceedings from two workshops (WCRP, 1998; 2000; see also, Newson, 1998). Kistler et al. (2001) give an excellent overview of the NCEP/NCAR reanalysis project, and the discussions in that paper are generally relevant to all of the projects. Broadly, quantities that are directly impacted by the observations, *i.e.* temperature, geopotential, the rotational component of the wind, are generally consistent across the three reanalyses. At the other extreme, quantities that are only weakly constrained by the observations and are dependent upon the physical parameterizations of the assimilating models differ greatly. Further, these derived quantities have significant errors, as revealed either by independent validation or through applications in scientific studies.

The lessons learned from the first-generation reanalyses provide the foundation for a second generation of reanalyses. These lessons can be summarized as general success in defining the major modes of variability on synoptic and planetary scales, as well as credible representation of the variability associated with longer-term, large-scale phenomena: *e.g.* monsoons, El Nino – La Nina, and the Madden-Julian oscillation. The deficiencies include fundamental problems in the hydrological cycle and artifacts in the reanalysis data sets that are directly related to changes in the observational network. The reanalyses are inappropriate for trend studies, largely because of this sensitivity to the observing system. An important product from the first-generation reanalyses is the quality-controlled input data record.

Current reanalysis activities at NASA are targeted on relatively short-term time periods. These time periods are chosen to support research activities that are expected to benefit from the inclusion of specific data sets or from specific improvements of the components of the assimilation system. Longer-term reanalysis data sets will be performed in concert with other activities in the United States (U.S.), perhaps under the umbrella of a proposed National Reanalysis Program. The NASA reanalysis plans and some of the issues facing a National Reanalysis Program will be discussed in this paper.

2. Reanalyses at NASA

The current strategy for reanalysis at NASA's Data Assimilation Office (DAO) is to focus on particular periods associated with major satellite missions. The decision to perform a reanalysis is based on the expectation that the addition of a particular observation type will have an important impact or that a particular development in the analysis system will have an impact on an important customer application. Based on these criteria there are two planned reanalyses. The first is the TRMM reanalysis, using precipitation observations from the Tropical Rainfall Measurement Mission (TRMM). The second is the Reanalysis for Stratospheric Trace Gas Studies (ReSTS). ReSTS is planned to overlap, minimally, the first four years of the Upper Atmospheric Research Satellite (UARS). In addition the DAO plans to perform a consistent reanalysis using conventional operational observations from the time of the Terra Launch (December 18, 1999).

2.1. TRMM Reanalysis

The Tropical Rainfall Measurement Mission (TRMM) was launched in November 1997. The TRMM reanalysis consists of a multi-year assimilation of tropical precipitation and total precipitable water (TPW) observations from microwave sensors including the TRMM Microwave Imager (TMI) and available Special Sensor Microwave/Imager's (SSM/I). The data are assimilated with a variational continuous assimilation scheme similar to that proposed by Derber (1989). These new data sources are to be used in addition to operational observations including online TIROS Operational Vertical Sounder (TOVS) temperature and humidity retrievals, European Remote-sensing Satellite (ERS) and QuikSCAT surface winds, and SSM/I surface wind speed. The primary point of contact for the TRMM reanalysis is Arthur Hou (Arthur.Y.Hou.1@gsfc.nasa.gov).

The motivation for this reanalysis comes from the successes that have been obtained in experimental versions of the Goddard Earth Observing System (GEOS) data assimilation system (Version 3.3). The incorporation of the precipitation observations has positive impact on both climate parameters and forecast skill, as discussed in Hou et al. (2001). Figure 1 shows the difference between the longwave cloud forcing from the assimilation and verification data from the Clouds and Earth's Radiant Energy System (CERES) instrument also aboard the TRMM satellite (Wielicki et al. 1996). Results are from two assimilation experiments with and without TRMM and SSM/I rain rates and TPW estimates. Rainfall and TPW assimilation reduces the monthly-mean spatial bias in longwave cloud forcing by 95% and the error standard deviation by 54%. Similar reductions in errors are found in outgoing longwave radiation, which, like the cloud forcing, is a derived quantity. Errors in rain rates and total precipitable water, parameters that are assimilated, are also reduced.

The positive impact of the TRMM data is also measurable in the humidity field as well as both the horizontal and vertical wind fields. This is consistent with improvement of the divergent portion of the wind field, a parameter that was fundamentally deficient in the first-generation reanalyses. These improvements manifest themselves in improved skill scores for tropical weather forecasts and hurricane forecasts. High-resolution experiments show that the rain bands in the hurricanes can be represented when the TRMM data are assimilated.

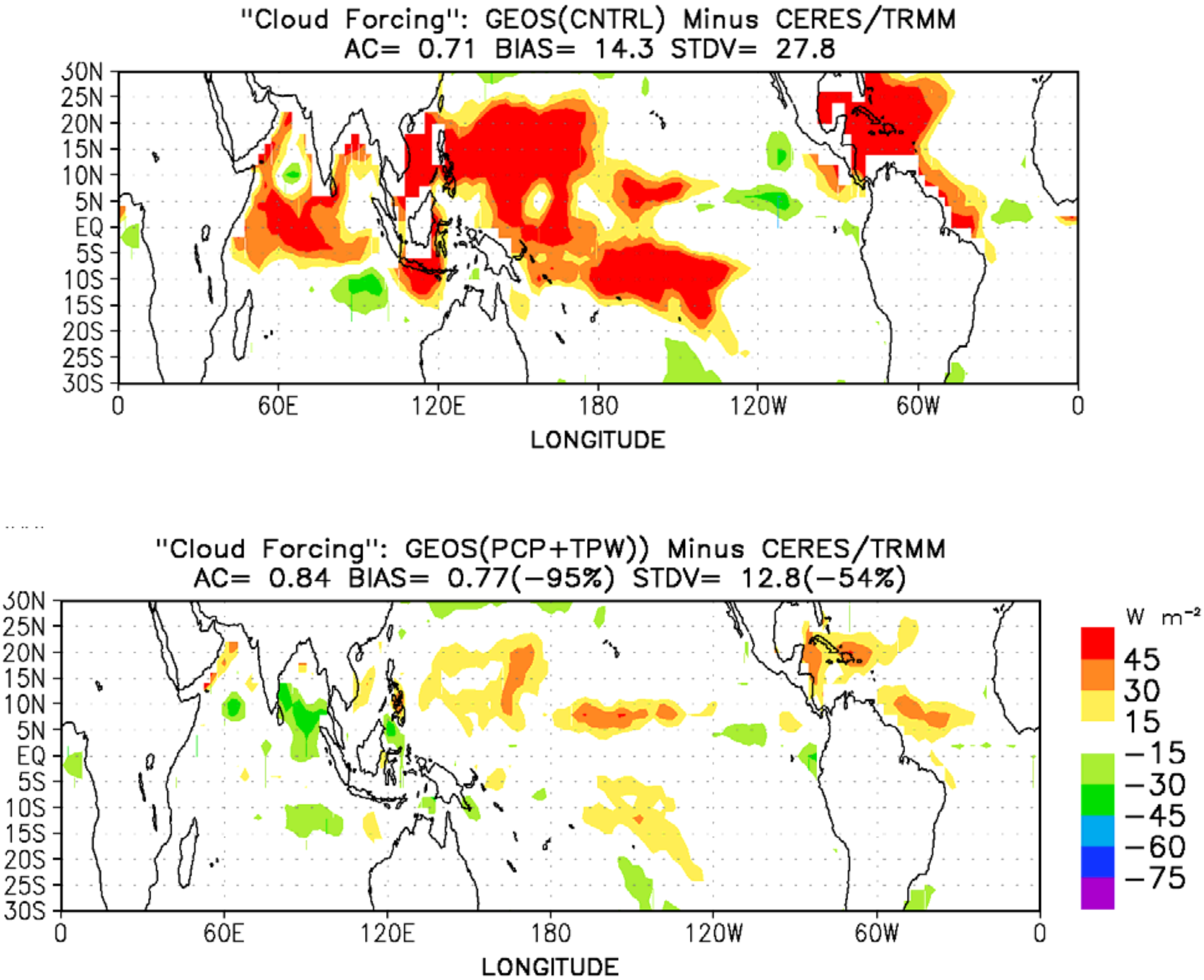

Figure 1: Difference between longwave cloud forcing from assimilation and from CERES observations. Top: Control assimilation without precipitation observations. Bottom: Assimilation with TMI and SSM/I precipitation and SSM/I total precipitable water.

The TRMM reanalysis is currently being produced at 1^o x 1^o horizontal resolution. The first two years (November 1997 – October 1999) will be completed in late 2002. The primary components of the data assimilation system are the same as the DAO's operational mission support system and are described at http://dao.gsfc.nasa.gov/. Details of the rainfall assimilation method will be described in Hou et al. (2002). (More information about the system can be found at http://polar.gsfc.nasa.gov/sci_research/atbd.php)

2.2. Reanalysis for Stratospheric Trace Gas Studies (ReSTS)

The Reanalysis for Stratospheric Trace Gas Studies builds on the successes of the use of DAO products in chemistry-transport applications for both the troposphere and the stratosphere. The project includes using transport applications as a rigorous test of the assimilation's general circulation and a variety of sensitivity experiments to investigate the relationship of the assimilation quality to the comprehensiveness of the assimilation system and input data. The ReSTS project is anchored by the UARS mission, which was launched on September 12, 1991. The baseline period for the reanalysis is May 1991 through April 1995. This corresponds to the part of the UARS mission that has the highest data density. The baseline assimilation will be extended to the present. The time period also includes the Pinatubo eruption, and the ability of the assimilation to provide quantitative information about the climatic impact of the eruption will be a priority. The primary point of contact for the ReSTS reanalysis is Steven Pawson (Steven.Pawson.1@gsfc.nasa.gov).

ReSTS will use the DAO's next-generation data assimilation system, which introduces the finite-volume general circulation model (Yeh et al., 2002 and references therein). The finite-volume model includes the dynamical core proposed by Lin and Rood (1997), a Lagrangian vertical coordinate, and the suite of physics parameterizations from the Community Climate Model (Version 3, see Kiehl et al., 1996). All previous stratospheric analyses have suffered from difficulties in representing transport processes on time scales longer than those associated with planetary scales. Two recent studies (Douglass et al., 2002; Schoeberl et al., 2002) investigate these transport problems in assimilated data products and the free-running finite-volume general circulation model. The finite-volume model has superior transport characteristics over previous models and a goal of ReSTS will be to preserve these improvements in the presence of data insertion.

One aspect of the improved representation of transport is the reduction of noise, which is illustrated in Figure 2. This figure shows Ertel's potential vorticity on the 840 K potential temperature surface. The left panel shows potential vorticity from the assimilation using the finite volume model; the right panel shows that from the operational TRMM assimilation system. The reduction of spurious small-scale structure is clearly seen. The assimilation using the finite volume model has features that are more homogeneous and represent organized structure consistent with transport theory. For instance, in the left hemisphere there is an intrusion of low potential vorticity from low to high latitudes. In the TRMM assimilation, using the old finite-difference model with sigma coordinate, the connection between high and low latitudes is not clear. In fact, where the finite-volume model suggests continuous sharp gradients, the finite-difference model suggests a fragmented field. A number of the larger features are analyzed in both fields. This reduction of noise has

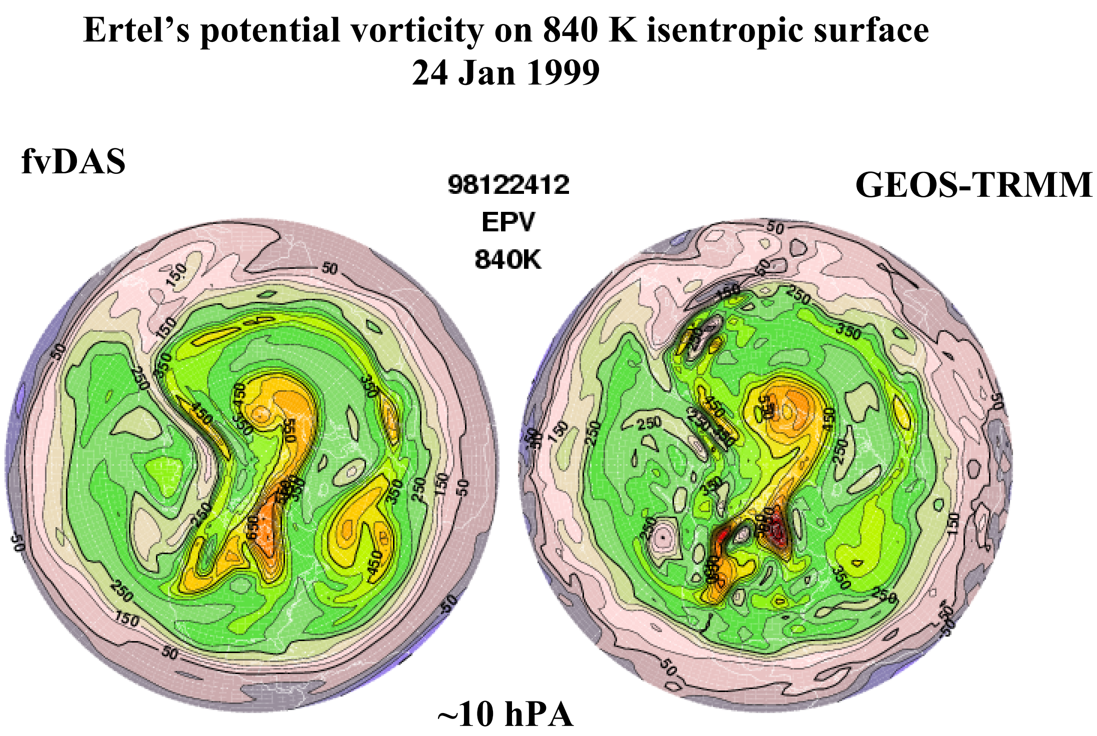

Figure 2: Ertel's potential vorticity on 840 K isentropic surface. Left: Next-generation data assimilation system using finite-volume general circulation model. Right: Operational data assimilation system used to support the TRMM mission. Note the difference in the small-scale structure between the two assimilations.

broad implications, none more significant that in the representation of the divergent component of the wind. Tracer experiments with the finite-volume model indicate a more physically robust representation of vertical transport.

Besides the focus on transport experiments with the baseline assimilation, there will be a number of other experiments performed for comparison with the baseline. These experiments will include the impact of using specified versus interactive ozone and the use of temperature, water vapor, and ozone observations from UARS to determine their impact on the assimilated data products relative to the operational products.

ReSTS is currently in production and the baseline period will be completed in 2002. The horizontal resolution is 2.5 degrees longitude by 2.0 degrees latitude. The operational data are drawn from the same input data archive used in the ERA-40 project. With the use of this data set by the DAO, all of the ongoing reanalysis projects will be sharing the same quality controlled input observations, leading to better controlled experimentation to understand model physics and their interaction with the assimilation method. Another important change to the assimilation system is the use of the DAO's treatment of the TOVS radiances.

(More information about the system can be found at http://userpages.umbc.edu/~pawson/rests.html and http://polar.gsfc.nasa.gov/sci_research/atbd.php)

2.3. National Reanalysis Program

A National Reanalysis Program for the United States is discussed elsewhere in this volume by Kanamitsu. A proposal entitled "National Program for Analysis of the Climate System (NPACS)" has been submitted to both NASA and NOAA to develop both a science and an implementation plan. Phillip Arkin of the University of Maryland is the Principal Investigator of proposal. The point of contact for NASA is Siegfried Schubert (Siegfried.D.Schubert.1@gsfc.nasa.gov). The discussion presented here is derived from discussions at this workshop by M. Fiorino, R. Jenne, R. Rood, and J. Woollen.

The National Reanalysis Program calls for a commitment to sustained research and the production of consistent multi-year assimilated data sets. Long-term data sets extending back into the pre-satellite era would be generated on the time scale of 4-5 years. The decision to generate such a data set would follow scientific investigation that suggests a new reanalysis might have significantly improved quality relative to previous products. Collaboration and partnering with non-U.S. activities is desired, possibly with the staggering of the generation of data sets. The proposed U.S. program also calls for the generation of shorter length data sets to investigate specific geophysical events and investigation of the impact of specific observing systems. Within the U.S., the activity is expected to be multi-agency as the different agencies hold key resources that can contribute to the success of the program. The project is expected to include a core team and a set of validation teams with commitments to timely validation of the reanalysis data sets.

The first-generation reanalyses identified key issues with the internal physical consistency of assimilated data products and sensitivity to the input observations. These problems are fundamental, and a goal of the program would be sustained investigation to address these key issues. Current results suggest that tremendous challenges will need to be overcome to assure consistency between the pre- and post-satellite era. Possible projects would include the definition of minimal observing systems, with a hierarchy of experiments including more complete observing systems.

Continued activity in data archeology should be important for improving the quality of the reanalysis, especially in the pre-satellite era. This might allow pushing to earlier times the starting point for the reanalyses. Continual improvement of a quality controlled observational data set will be an important product of the program. It is anticipated that this will build from the current collaborations between ECMWF and the U.S. agencies. Other activities will include the investigation of assimilation methodology for climate assimilation and whether or not this is sensitive to the comprehensiveness of the observing system.

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