Reanalysis at NCEP: Past, Present and Future

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Introduction to Reanalysis

It was 1990. Ron McPherson was the Director of the National Meteorological Center (NMC now NCEP, see the Appendix for an explanation of acronyms), Eugenia Kalnay was the Chief of the Development Division (now the Environmental Modeling Center, EMC) , David Rodenhuis, the Chief of the Climate Analysis Center (CAC now CPC) , and Masao Kanamitsu was the Development Division Modeling Branch Chief. The National Atmospheric and Oceanic Administration (NOAA) had just replaced two Cyber 205's with a Cray YMP-8 in record time due to the insolvency of the Cyber's parent company. Along with the Cray came its UNIX like UNICOS operating system which eventually would permeate every NCEP computer system.

In the fall of 1990 Eugenia asked me to prepare a set of specifications for a major research project that Rodenhuis and the staff of CAC saw as the solution to the problem of trying to extract climate signals from the NMC Global Data Assimilation System (GDAS). An example of a problematic time series, originally from Kalnay *et al.,* 1996, is shown in Figure 1. CPC staff was proposing a separate, frozen system to be known as the Climate Data Assimilation System (CDAS). However, they realized that CDAS would need to be extended backward as far as sufficient observations were available, and, more importantly, would need to be created in a timely manner. My initial reaction, which I kept to myself, was "You can't be serious!" I soon confirmed with tests on the newly acquired Cray YMP8 that the computational requirements dictated the acquisition of another YMP8, which seemed absolutely unobtainable. Assuming we were able to obtain the unobtainable, my two decades of experience were fraught with non-robust numerical systems, error prone observations, manual storage systems and a funding environment where development projects were the first to be cut when the inevitable budget crisis arose. All that was about to change.

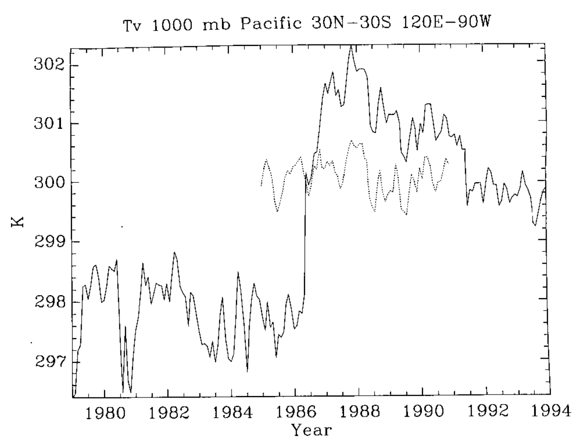

FIG. 1. Trace of the 1000-hPa virtual temperature averaged for the tropical Pacific ocean in the NCEP operational Global Data Assimilation System (solid line), showing the impact of changes in the model and in the reanalysis (dotted line).

An analysis of NCEP's strengths and weaknesses revealed a need for partners to obtain quality controlled historical observations and to distribute the multiple decades of output. Further inquiries revealed that NCAR could service both functions. A formal partnership was arranged in which Eugenia and Roy Jenne, NCAR, served as the principle investigators. A workshop was held at NMC April 25-26, 1991 (Kalnay and Jenne, 1991) to announce the project and get feedback regarding the initial planning. The issue of system robustness had been addressed by the advent of a 3D-VAR type analysis at NMC (Derber, Parrish and Lord, 1991). Stable funding was to be supplied by NOAA's Office of Global Programs (OGP) and overseen by Mike Coughlin. The storage issues were addressed by the acquisition of a robotic silo and Cray's tape management system. A pilot test, Mo *et al*., 1995, showed that we had assembled a viable system. A plan, NMC Office Note 401, was in place. We began in April 1994, started CDAS in 1995, and completed 50 years of reanalysis in mid-1997.

The visionary decision to seek a broad distribution via CD-ROM's, first published along with the two NCEP/NCAR Reanalysis BAMS articles (Kalnay *et al.*, 1996 and Kistler *et al.,* 2001), and thereafter by NCAR, was affirmed in 2003. Eugenia received an email from the ISI Web of Science noting that the 1996 paper was the most cited paper in Geosciences in the last decade, and that the 2001 paper was among leading paper in the previous year. According to Chi Fan of NCAR, by 2004 868 orders had been received from 54 countries and 11508 CD-ROMS had been delivered.

In 2001, the every-fifth-day frequency of 16.5 day 0000 GMT forecasts was increased to 1xdaily, and the sequence of daily forecasts was extended back to 1996. This enabled month-by-month assessments of the performance of the operational GFS compared to the CDAS forecasts. Figure 2a compares yearly NH and SH scores since the inception of GFS scoring in the mid -1980's, and Figure 2c plots the improvement of the GFS by plotting GFS minus CDAS along with the trend lines for each hemisphere.

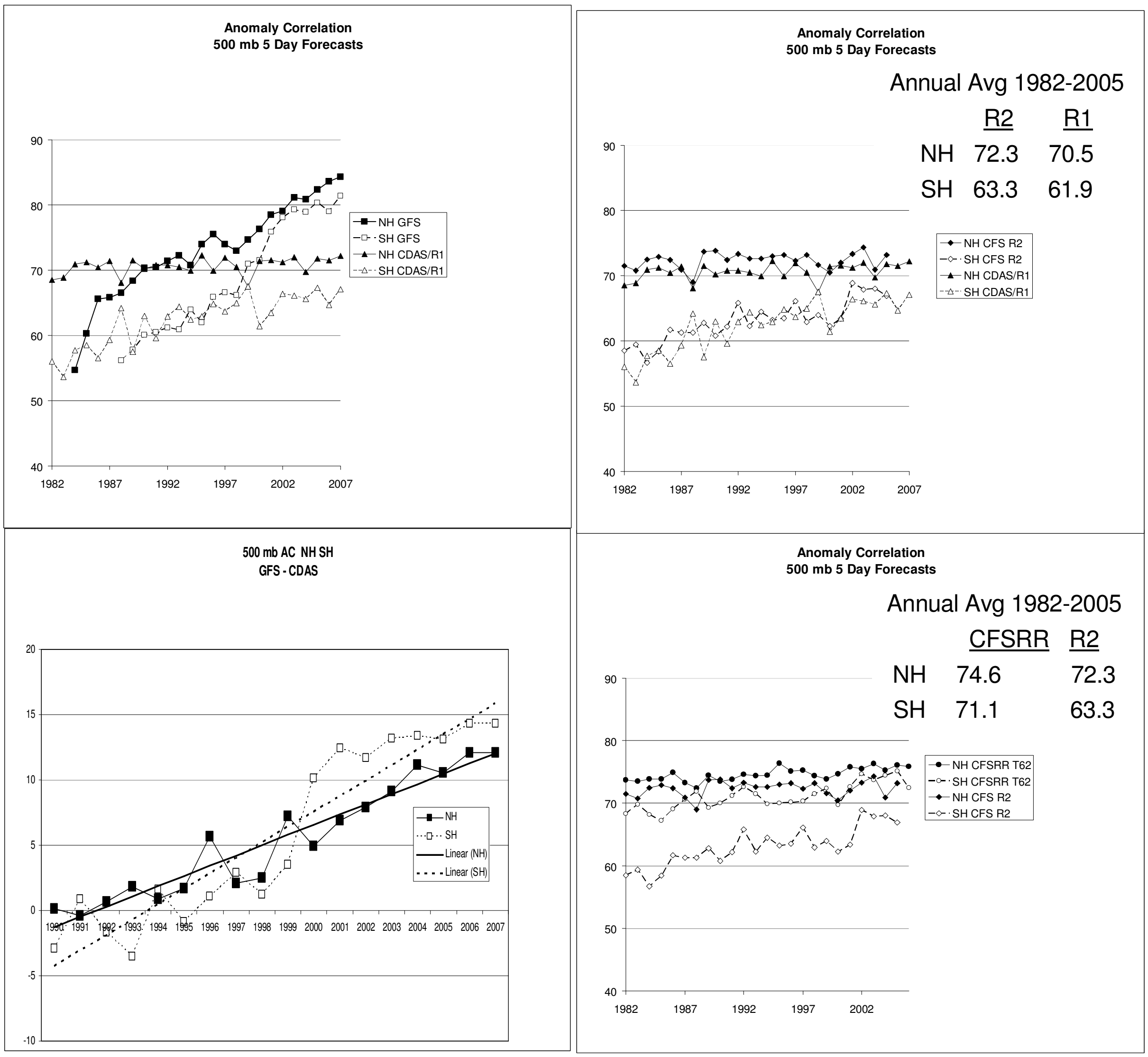

Figure 2. Northern Hemisphere (NH) and Southern Hemisphere (SH) yearly averaged anomaly correlation scores (x100) at day 5 between 1992 and 2007; a) top left, GFS vs. GR1; b)top right, CFS R2 vs. GR1; c) bottom left (GFS minus GR1) and trend lines; d) CFSRR vs. CFS GR2

NCEP/DOE Global Reanalysis 2 (GR2)

The inevitable problems that arose from GR1's being a pioneering endeavor motivated a follow-up effort with a start in 1979, the NCEP/DOE Reanalysis, GR2 (Kanamitsu *et al.*, 2002). By securing time on the DOE computers at Lawrence Livermore, GR2 could begin to repeat the problematic GR1 years. A summary of GR1 vs. GR2 is found in Table1. Two of the items should be highlighted since they would carry forward into the future. First, the errors in the GR1 observational database were corrected, creating a quality controlled set of observations. In hindsight, the most significant modeling innovation of GR2 was the replacement of soil moisture relaxation to climatology with rainfall from CMAP pentads, the first of a continuing effort in what has come to be known as Land Data Assimilation (LDAS).

As will be noted in following sections, GR2 has served as the foundation of several subsequent NCEP developments. Forecasts from GR2 were not made until the development of the CFS (Saha *et al*., 2006). Figure 2b compares scores from the T62L28 GR1 with the T62L64 CFS model initialized from GR2 for the period 1982-2005; the latter system makes a slight improvement in the SH, and a larger one in the NH, which may be attributed to the improved parameterizations, higher vertical resolution, and more realistic soil moisture working over the continental areas.

Table 1. Comparison of GR1 and GR2

NCEP/NCAR
R1 vs R2

Similarities…

1) same spatial and temporal resolution as R-1—
T62L28, 6 hour cycle
2) similar raw observational data
(some additional data after 1993);
3) Special Sensor Microwave Imager (SSM/I) data not used
4) same NESDIS temperature retrievals;
5) similar output variables and file formats
(GRIB and BUFR).

New system components:

1) simple rainfall assimilation over land
2) smoothed orography
3) treatment of snow.

Model physics improvements:

1) implementation of planetary boundary layer that utilizes nonlocal diffusion
2) new shortwave radiation
3) minor tuning of convective parameterization;
4) more realistic cloud-top cooling
5) updated cloud-tuning coefficients for stratus clouds
6) radiation on full Gaussian grid
7) radiation run hourly vs 3h in R-1.

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)
6) fixed snowmelt term (entire period).

Fixed field improvements:

1) improved desert albedo
2) sea-ice and SST fields (AMIP-II, provided by PCMDI)
3) new ozone climatology
4) Northern Hemisphere snow cover analysis (interpolated from
weekly to daily values)
5) CO2 set to 350 ppmv (AMIP-II specified constant).

Improvement to the diagnostics:

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

North American Regional Reanalysis (NARR)

The period from 1997, the end of GR1, to 2003, the next NCEP reanalysis, NARR, was a period of rapid transformations. Several crises (Cray fire, asbestos in FOB 4, and the terrorist attacks) prompted a rapid transition from Cray to IBM massive parallel machines, a stable contract for future upgrades, and reliable mirrored machine configurations at commercially maintained sites. The marked improvement and convergence of NH and SH GFS scores in this period in Fig 2a are attributed to the 1) direct assimilation of radiances and other 3D-VAR advances, 2) replacement of RTOVS with ATOVS instruments, and 3) increased model resolution and improved physical parameterizations. As originally envisioned by Dave Rodenhuis in 1990, Wesley Ebisuzaki of CPC became the caretaker of both GR1 and GR2 running in CDAS mode.

While resources were readily available, they were limited, so it was decided to focus global climate modeling on the development of the coupled CFS, and devote the next reanalysis to a regional effort using the NCEP ETA model at 32 km and 45 levels. By focusing over the data rich North American area, it would be possible to exploit the newly introduced Noah land surface model, and directly assimilate observed precipitation as noted in Mesinger *et al*., 2004. Lastly, the 3dVAR analysis which covered a significant portion of the Atlantic and Pacific would use the newly developed direct assimilation of radiances.

One question posed by NARR was the ability to access historical NESDIS radiances. Jack Woollen began a working relation with NESDIS and its Class archive to offload historical radiances in bulk, which NARR was the first beneficiary. NARR also benefited from the first IBM upgrade, using a robust "just replaced" system to run 4 consecutive streams and complete the 1979-2003 period in just 3 months. The NARR took advantage of the GR2 quality controlled observational database as well as the GR2 analyses to drive the boundaries of the limited area ETA model. NARR output had two notable upgrades. Its BAMS article was accompanied by a DVD, and users could access archive files via the internet from NCDC's NOMAD servers.

Historical Northeast US Snowstorms

In 2002, the director of NCEP, Dr. Louis Uccellini, visited ECMWF and saw ERA 40 depictions of Northeast U.S. snowstorms, which had far greater detail than the analyses produced by the lower resolution GR1. Independently, EMC was rerunning past storm cases with the newly upgraded T254L64 GFS/GDAS systems. Feb 2003 was the 25th anniversary of the Boston Blizzard of 1978 (Brown and Olson, 1979), and I reran the case based on the success we had in GR1 with the Appalachian storm of Nov, 1950. When Dr Uccellini saw the resulting maps, he proposed the reanalysis of the historical 73 cases for the period 1947 - 2003 that comprise the contents of the two volume monograph (Kocin and Uccellini, 2004) using the current global system.

Additional motivations for revisiting the historical cases were provided by the Jan 2004 symposiums for Fred Sanders and Norm Phillips at the annual AMS meeting in Seattle, WA. In tribute to each, we targeted 2 storms to reanalyze and reforecast: the December 1947 NYC record storm, when Fred Sanders was a forecaster at LaGuardia Airport, and the November 1950 Great Appalachian Storm, when the early numerical forecasts of Norm and Jules Charney are attributed to the advent of operational NWP in the United States.

The AMS website (http://ams.confex.com/ams/84Annual/techprogram/meeting_84Annual.htm) contains the presentations. In addition, the Sanders presentation has been expanded and included in an AMS Monograph (Uccellini *et al.,* 2008)

Climate Forecast System Reanalysis and Reforecasts (CFSRR)

As noted previously, NCEP climate modeling efforts earlier this decade concentrated on building a coupled ocean-atmosphere prediction system for monthly and seasonal forecasts. This effort came to fruition in 2004 when the Climate Forecast System (CFS) became operational in August (Saha *et al.,* 2006), and as noted in that paper, "The CFS

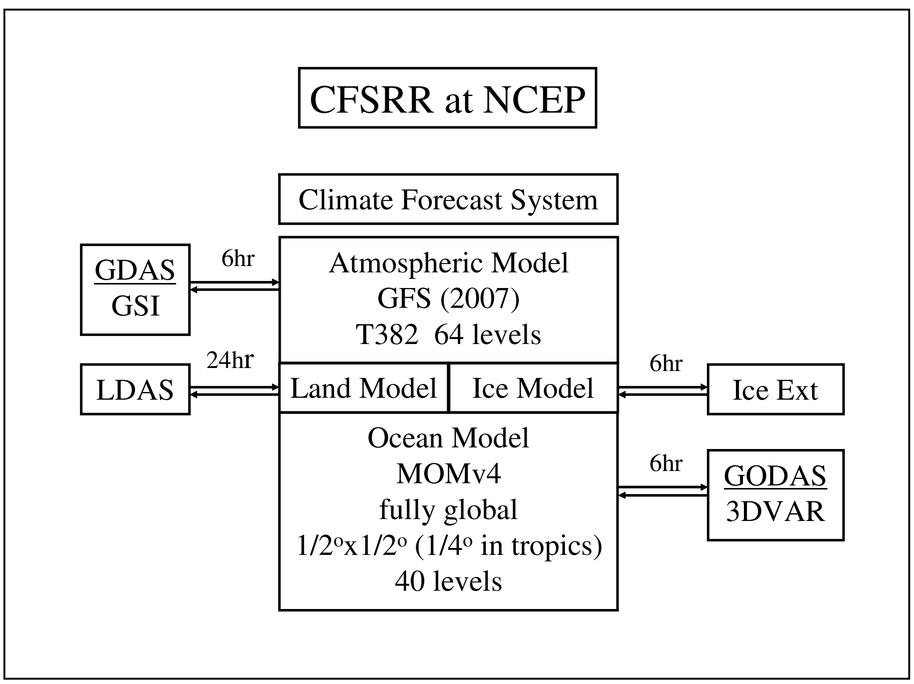

Figure 3. Climate Forecast System Reanalysis and Reforecasts (CFSRR)

includes a comprehensive set of retrospective runs that are used to calibrate and evaluate the skill of its forecasts. Each run is a full 9-month integration. The retrospective period covers all 12 calendar months in the 24 years from 1981 to 2004. Runs are initiated from 15 initial conditions that span each month, amounting to a total of 4320 runs. Since each run is a 9-month integration, the CFS was run for an equivalent of 3240 yr!"

Those retrospective runs were possible because of the existence of a set of consistent initial conditions provided by GR2. In order to upgrade the CFS in 2010, it will be necessary to replace the GR2 initial conditions with a new reanalysis from 1979-2009 and rerun the reforecasts for 1981-2009. The atmospheric and land assimilation of CFSRR reanalysis will be based on the NCEP GDAS to be implemented into operations in 2008, and will be coupled with the GODAS reanalysis. Reforecasts will be run with a coupled land-ocean-ice-atmosphere system.

A more complete report on the CFSRR system and plans is given in this volume under the title "the New Reanalysis and Reforecast of the NCEP Climate Forecast System (CFSRR) by S. Saha *et al.*" (G5-513). A schematic of the CFRSS coupled system is shown in Figure 3. One preliminary result is available from a "Practice System" test which ran 29 streams (1 per year) through the entire period 1979-2007 using a reduced resolution version of the GDAS, T62L64, without the ocean component, and a preliminary version of the SST analyses. Figure 2d compares the yearly averaged hemispheric 5 day forecasts scores with the comparable CFS forecasts using R2 as the initial condition. While the scores for the CFSRR are better in both hemispheres, the improvement in the SH make the scores relatively closer to those for the NH, as is seen in the last several years of the GFS as noted earlier in Figure 2a. Since the CFSRR system is comparable in resolution to the GFS system of 2007, we expect the skill of the initial conditions of the CFSRR to be comparable to the present GFS for the 1999-2007 ATOVS period, but to be somewhat lower during the1979-1998 RTOVS period.

Future Reanalyses

A fundamental change in the allocation of computer resources for future NCEP reanalyses and reforecasts is included in the EMC plans for the future, as early as the next upgrade cycle (see Figure 4). With the CFS operational since 2004, and its continued improvement depending upon a set upgraded reanalyses and reforecasts, future NCEP production job suites will have dedicated time and computational nodes devoted to the running of reanalyses and reforecasts. In addition, upgrades to the NARR will alternate with the global system.

Future systems will also benefit from the collaboration that has begun between NCEP/EMC and the NASA/GMAO MEERA project. (See the extended abstract by Schubert, et. al. V1-104). Both systems share the NCEP GSI analysis program and common observation databases.

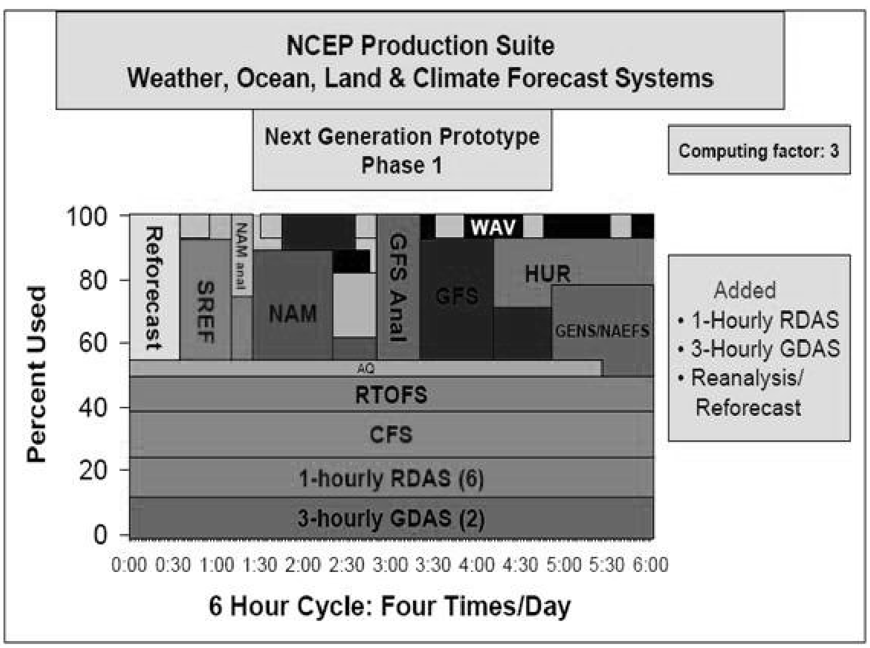

Figure 4. NCEP Production Suite including Reanalysis/Reforecasts in the next computer upgrade

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Appendix

Acronyms

AMIP Atmospheric Model Intercomparison Project
ATOVS Advanced TIROS Operational Vertical
BAMS Bulletin of the American Meteorological Society
BUFR Binary Universal Form for the Representation of meteorological data
CDAS Climate Data Assimilation System
CFS Climate Forecast System
CFSRR Climate Forecast System Reanalysis and Reforecasts
CDROM Compact Disc read-only memory
CMAP CPC Merged Analysis of Precipitation
CPC Climate Prediction Center
DVD Digital Versatile Disc
ECMWF European Center for Medium Range Weather Forecasts
EMC Environmental Modeling Center
FOB 4 Federal Office Build 4, Suitland MD
GR1 Global Reanalysis 1 (NCEP/NCAR Reanalysis)
GR2 Global Reanalysis 2 (NCEP-DOE Reanalysis)
GRIB GRIdded Binary
GDAS Global Data Assimilation System
GFS Global Forecast System
GMAO Global Modeling and Assimilation Office
GODAS Global Ocean Data Assimilation System
GFDL Geophysical Fluid Dynamics Laboratory
GSI Gridded Statistical Interpolation
LDAS Land Data Assimilation System
MEERA Modern Era Retrospective-Analysis for Research and Applications
MOM GFDL Modular Ocean Model
NARR North American Regional Reanalysis
NASA National Aeronautical 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
NMC National Meteorological Center
NOAA National Oceanic and Atmospheric Administration
NOMADS NOAA Operational Model Archive and Distribution System
PCMDI Program for Climate Model Diagnosis and Intercomparison
RTOVS Revised TIROS Operational Vertical Sounder
SST Sea Surface Temperature
TIROS Television and InfraRed Observation Satellite Sounder