NOAA OAR Technical Report CPO-4

Report from the NOAA Climate Reanalysis Task Force Technical Workshop

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1. Background

The goal of retrospective data assimilation or "reanalysis" is to combine disparate observations into physically consistent estimates of the past state of the Earth system and its components – e.g., ocean, atmosphere, waves, land, cryosphere, and ionosphere – with quantified uncertainties. Reanalyses spanning the limits of the instrumental record of each component serve as a key tool for climate monitoring and analysis, and for providing initial and boundary conditions and verification for retrospective forecasts. The reanalysis research enterprise, begun nearly 40 years ago, has led to a cycle of improvement of models, data assimilation systems, and historical observational databases required for improved reanalysis datasets. Together, these improvements have led to dramatic advances in understanding and predicting weather and climate variability, from extreme events to centennial trends. The National Oceanic and Atmospheric Administration (NOAA), which has a need to provide prediction capabilities at lead times from minutes to decades, continues to be an important contributor in the progress towards the goal of improved Earth system reanalysis.

Recent research activities across NOAA, in partnership with other Federal agencies, international agencies, and universities, are accelerating improvements to achieve this goal. The NOAA Climate Reanalysis Task Force (NCRTF[1]) is charged with coordinating those activities funded by the NOAA Climate Program Office Modeling, Analysis, Predictions and Projections (MAPP) Program. It is focused on advancing reanalysis towards monitoring and understanding of climate variability as well as the use of reanalysis in retrospective forecasts and their verification.

The NCRTF workshop consisted of a series of presentations and vigorous discussion of NCRTF activities, related developments in the NOAA National Centers for Environmental Prediction (NCEP) and other U.S. weather and climate forecasting centers, and related international efforts. The workshop goals were to 1) highlight advances in these areas across NOAA and at other Federal agencies, international agencies, and universities; 2) identify gaps; 3) improve coordination of future activities to meet the requirements of the diverse array of users of reanalyses; and 4) to strengthen NOAA's and partner organizations' development and utilization of new reanalysis and related datasets.

Specific workshop objectives were to:

(1) Report on NCRTF progress,
(2) Exchange reanalysis approaches, algorithms, and techniques currently in use and under development,
(3) Discuss techniques for addressing outstanding issues in the reanalysis efforts,
(4) Identify the various requirements for reanalysis products, and
(5) Determine strategies and overlaps for national and international reanalysis efforts based on scientific drivers for climate and weather research.

The NCRTF Workshop was held May 4–5, 2015 at the NOAA Center for Weather and Climate Prediction in College Park, Maryland. The workshop was attended by participants representing the national and international reanalysis community (see Appendix 1). Agencies represented included NOAA, the National Aeronautics and Space Administration (NASA), the National Center for Atmospheric Research (NCAR), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Chinese Meteorological Agency (CMA).

After welcoming remarks, the workshop began with an introduction to the NCRTF and the workshop, as well as background on the purpose of reanalysis. This was

1 http://cpo.noaa.gov/ClimatePrograms/ModelingAnalysisPredictionsandProjections/MAPPTaskForces/ClimateReanalysisTaskForce.aspx

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followed by five sessions, each to address a specific objective or objectives, as described below:

- *National and International Reanalysis Efforts (Day 1)*

  Objective: Determine strategies and overlaps for national and international reanalysis efforts based on scientific drivers for climate and weather research
- *Developments in the Stratosphere (Day 1)*

  Objective: Discuss techniques for addressing outstanding issues in the reanalysis efforts
- *Assimilation Development and Experiments: Atmosphere (Day 1)*

  Objective: Exchange reanalysis approaches, algorithms, and techniques currently in use and under development. Discuss techniques for addressing outstanding issues in the reanalysis efforts
- *Assimilation Development and Experiments: Ocean and Sea Ice (Day 2)*

  Objective: Exchange reanalysis approaches, algorithms, and techniques currently in use and under development. Discuss techniques for addressing outstanding issues in the reanalysis efforts
- *Reanalysis Evaluation and Intercomparison (Day 2)*

  Objective: Identify the various requirements for reanalysis products. Discuss the use of independent observations to evaluate the long-term fidelity of reanalysis products and the associated applications of reanalysis products for climate studies

Each session contained between four and eight 20-minute presentations, and was capped by a 20–30-minute discussion period led by a moderator furnished in advance with questions from attendees related to the session topic and objective. A rapporteur was assigned to each session. At the conclusion of the last session on Day 2, the rapporteurs provided 5-minute summaries of their session to spur a final round of discussion to close the workshop. The full workshop agenda is provided in Appendix 2.

In the remainder of the report, the key workshop outcomes and recommendations are described (sections 2 and 3, respectively). Next steps and opportunities are discussed (section 4), along with information about how to obtain further information on the workshop and NOAA reanalysis (section 5).

2. Summary of Key Workshop Outcomes

a. Improved coordination of NCRTF with ongoing reanalysis efforts at NCEP.

b. Enhanced awareness of complementary reanalysis efforts among national and international agencies.

c. Identification of challenges and possible solutions to the competing uses of reanalysis dataset, including needs for instantaneous accuracy and long-term consistency.

d. Recommendation that reanalysis centers disseminate datasets about the analysis process, such as observation feedback information.

3. Session Summaries

After a welcome by Arun Kumar and an introduction to the NCRTF and the workshop goals by Gil Compo, Huug van den Dool presented the keynote question of the workshop, “What is Reanalysis for?” With more than 20,000 citations to the main papers describing reanalysis datasets, there are many answers to this question, but a few overarching answers were articulated. One important reason for reanalysis is to provide initial conditions for retrospective forecasts (reforecasts). Another is to provide the framework to demonstrate improvements in a forecasting and analysis system by comparison to the reanalysis state estimates. A third key reason is to provide the fields needed to obtain a description of the general circulation, its statistics, and its variability in a reasonably consistent manner for as long a time period as the observational record permits. Challenges to meeting these goals include the temporal and spatial variations in the observing system coverage, which impose unphysical inhomogeneities ("jumps") on the reanalysis representation of those statistics. Interannual to decadal variability and trends can be of the same magnitude as these unphysical jumps. The observing system inhomogeneities make it difficult to simultaneously address other goals of reanalysis: generating the best short-term and best long-term climate diagnostics and monitoring, making maximal use of all observations ever taken, making use of observations never analyzed before, and studying and understanding historically important events (which are often extremes). It remains an open question of whether accuracy and homogeneity can be balanced in a single reanalysis dataset.

3a. National and International Reanalysis Efforts

Suru Saha presented that reanalysis priorities at NCEP's Environmental Modeling Center (EMC) are focused on coupled data assimilation and forecasting. EMC priorities are predictions at the subseasonal range and at the seasonal to the 6-month range. An outstanding issue is how improve upon the previous computing and storage systems, perhaps by utilizing cloud computing and storage. Plans for EMC's next reanalysis include an upgrade in data assimilation to a hybrid ensemble-variational (4D-EnVar) algorithm and inclusion of aerosols, sea ice, land, waves, and ocean components. High priorities in terms of development in the "physics" are scale-aware probability density function-based subgrid scale turbulence and cloudiness schemes, aerosols with consistent microphysics, improved convection-cloudiness-radiation interactions, non-orographic gravity wave drag, use of the hybrid gain 3D-Var/Local Ensemble Transform Kalman Filter in the Global Ocean Data Assimilation (GODAS), and use of Near Sea Surface Temperature (NSST) in a mixed layer assimilation.

Arun Kumar described how NCEP's issues and requirements for climate reanalysis address two major areas: forecasting and monitoring. Reanalyses for monitoring are needed both for attribution and for many societal applications. In terms of forecasts, reanalyses are needed to initialize, provide base climatologies for bias correction, and to verify and re-calibrate models. A key challenge is dealing with discontinuities in reanalysis datasets arising from interactions between model bias and observational platform changes. Another challenge is balancing requirements for reforecasts versus climate monitoring, climate studies, and attribution. One way to meet this challenge is with multiple reanalysis datasets using a common assimilation framework and model, such as in the developing NOAA next generation climate reanalysis system. This will use a hierarchical approach with systems of increasing complexity from models driven only by sea surface temperature (SST) (i.e., an Atmospheric Model Intercomparison Project simulation), to assimilation of only surface observations (e.g., 20th Century Reanalysis; 20CR), to assimilation of only conventional upper-air observations, to assimilation of the modern observing system including satellite radiances, radars, and GPS signals.

Dick Dee described work at ECMWF on ERA5, a reanalysis which will succeed the ERA-Interim and will be available for 1979–present). ERA5 will have a spectral resolution of wave number T639 (~34 km horizontal resolution) with 137 levels in the vertical. It will use a 10-member ensemble of 4D-Var data assimilation integrated at ~63 km horizontal resolution. A novel feature is that it will assimilate all-sky radiances, instead of only cloud-cleared. It will include a variational bias correction (varBC) for many input data sources. The European Reanalysis of Global Climate Observations (ERA-CLIM) project to generate reanalyses spanning the 20th century will transition to ERA-CLIM2, which will develop coupled land-atmosphere-ocean-sea ice-biogeochemical components and extend back to 1900. The project includes considerable data rescue, both of conventional observations and historical satellite observations from the 1960s and 1970s. Additionally, he reported that another project, the new Copernicus climate change services, will include operational support for reanalysis.

Zhiquan Liu presented Chinese Meteorological Agency reanalysis plans for a satellite era (1979–present), near-real-time 30-km resolution, atmospheric reanalysis and a concurrent land-surface reanalysis. It will be created from a previous version of IFS (T639), using the gridded statistical interpolation (GSI) 3D-EnVar. The ensemble will be run at a spectral resolution of total wavenumber (T213). The Data Assimilation Research Testbed (DART) will be used for land surface data assimilation.

Ron Gelaro introduced NASA's new Modern Era Reanalysis for Research and Applications, Version 2 (MERRA-2), designed to address limitations of MERRA and provide a development milestone for a future integrated Earth system reanalysis. MERRA-2 uses a recent version of GEOS-5 with a nominal horizontal resolution of 50 km and 72 levels in the vertical, and a similar 3D-Var data assimilation system as MERRA. MERRA-2, which was made publically available in September 2015, uses new satellite observation types, reduces spurious trends and imbalances in water and energy cycles, and tests new coupling methodologies, including a fully interactive aerosol analysis. MERRA-2 spans 1980–present and will continue to be updated in real time with 2–3 week latency. Hourly surface and two-dimensional fields are provided; 20% of the total dataset is related to aerosols. MERRA-2-driven analyses of the ocean and land are planned for the near future, as is a full atmospheric chemistry simulation. The next GMAO reanalyses will target increased coupling between the atmosphere, ocean, sea ice, and land components. The system configuration is still in the planning phase but will likely include a 25-km atmospheric model with 4D Ensemble-Variational (4D-EnVar) assimilation, and Ensemble Kalman Filter (EnKF) approaches for land, aerosol and chemistry assimilation.

General Discussion:
The discussion from this session centered on how technology and/or resources could be shared among various groups for a common benefit. The workshop participants first discussed whether a centralized database is useful for reanalysis observations and observation feedback. There was more than one opinion about the optimal format of such a database. It was pointed out that a decentralized approach using conversion software is more practical, at least for the time being. The latter is, in fact, what has developed over the three decades of collaborative reanalysis activities internationally. It is likely in the future that databases of common and open scientific interest will feature multi-lingual access and storage of information without a need for concern about common formats.

The question was raised of whether it is possible to scale the observational database as new satellite instruments are introduced. It was suggested that the most important issue is adopting unified standards for metadata in order to bridge the gap between hindcasts and monitoring.

The question was raised (here and in other venues) as to whether some unification of the reanalysis systems for hindcasts and climate monitoring is possible or worthwhile. It was noted that the NCEP/NCAR Reanalysis 1 (R1) is still widely used for monitoring because of its near real-time aspect, and because it is relatively stable for a long term time series. The point was made that a family of reanalysis systems and products, using shared technology, is the most appropriate way to resolve conflicting requirements for different reanalysis purposes, without having necessarily separate project boundaries.

Another question raised was what advances toward closer atmosphere-ocean coupling are appropriate now, and as the oceans become more tightly coupled, how to best 'spin up' the ocean component of a coupled system. It was noted that using multiple 'streams' to speed up the production of multi-decade reanalyses is problematic for ocean reanalysis. It was reported that ECMWF is looking at the sensitivity of the deep oceans as the ocean spins up, and that it is only possible to constrain the first few hundred meters of the ocean, not the deep oceans. On the other hand, those layers of the upper and intermediate ocean which are ventilated on decadal and shorter time scales can be tracked to some extent using the observational network of the last 30 years.

Finally, the question was raised as to how, if a reanalysis dataset is not uniformly better in each new iteration, this should be communicated, or justified to the user community. Of course, the definition of uniformly better is an important factor in considering this question.

3b. Developments in the Stratosphere

The status of NCEP's improvements of the stratosphere in their reanalysis was presented by Craig Long. Problems were noted with the representation of the quasi-biennial oscillation (QBO) in the Climate Forecast System Reanalysis (CFSR) and with capturing the transition of the QBO in most other reanalyses. Difficulties with necessary satellite bias corrections were discussed and associated with issues in the stratospheric mean state of CFSR, such as a warm bias in the upper stratosphere. Observation transitions between satellite observing systems have led to jumps. Multiple observing system experiments with the atmospheric model from CFSR have been performed and compared, in which the Stratospheric Sounding Unit (SSU) Ch3 and Advanced Microwave Sounding Unit (AMSU) Ch14 were either included or withheld and either bias-adjusted or left unadjusted. One conclusion is that the vertical structure of the analysis depends sensitively on how the SSU and AMSU data are included. Another conclusion was that the seasonal cycle of ozone in the upper-stratosphere is a result of the prognostic ozone parameterization as implemented in the atmospheric model, and not an effect of errors in the assimilated observations. Overall, while there is an understanding of why problems exist in the representation of the stratosphere, it is not known how to solve them.

John McCormack from the Naval Research Laboratory (NRL) discussed water vapor in the stratosphere, photochemical production and loss, and its latitudinal, altitudinal, and seasonal dependence. These dependencies are an important aspect to include in any parameterization of stratospheric water vapor photochemistry. Analysis of specific humidity was presented with and without photochemistry. Some of the large differences in the analyses at upper levels that were shown are potentially due to the inclusion of erroneous observational data. It was noted that accurate prognostic humidity in the upper-troposphere and lower-stratosphere region can reduce model bias. The quality of the available upper-level data, both historically and currently, was discussed.

Sarah Lu gave an overview of aerosol modeling and described the need for including aerosols in climate reanalysis. She noted that aerosols are critical for capturing cloud-radiation interactions, to improve data assimilation, and to assess air quality. Including aerosols affects operational model performance, with operational benefits seen for medium-range forecasting. Operational climate models also benefit from capturing aerosol-chemistry-climate interactions. It is also desirable to have prognostic aerosol capabilities, and to do trajectory analysis related to volcanic eruptions.

Arlindo DaSilva presented the NASA Goddard aerosol reanalysis (MERRAero), which is underway. It was noted that aerosols are underdetermined in general. Observing systems include Lidar, a ground-based network (aeronet), and satellite retrievals. MERRAero, which spans 2002–present, was described. It was found to compare well with aeronet and was also evaluated with OMI. The radiative effects of different species and the regional climatology of Particulate Matter with a diameter of less than 2.5 micrometers (PM2.5) over the continental U.S. was discussed, with particular focus on differences in PM2.5 in winter months in the U.S. Northwest and Southwest, and uncertainties in observing PM2.5. A new model will resolve mass and number concentration. MERRA-2 was noted as the first to integrate aerosols into reanalysis.

General Discussion:

Several important details from the talks were discussed, as well as some well-known issues that hamper progress in stratospheric reanalysis. On the detail side, the topic of the advantages of having a model top at 0.01 hPa, compared to 0.2 hPa was raised. The higher top moves the issue of a so-called "sponge-layer" that absorbs planetary waves further away from the altitude where the waves are often reflected, possibly increasing the realism of the model. The differences in the winter month climatology of PM2.5 in the U.S. Northwest compared to the Southwest were also discussed. This results from a weak nitrate signal due to the drop-off of agriculture and biomass burning in the winter. More generally, the issue of whether better modeling or more observations of the stratosphere is needed. The general consensus is that progress is needed in both. It is difficult to utilize the observations without improvements in the model.

3c. Assimilation Development and Experiments: Atmosphere

Developments of 20CR using the Ensemble Kalman filter were presented by Jeff Whitaker. It was shown that 20CR surface pressure-only analysis is a useful testbed for new ideas. For a reanalysis like this without many observations quality control (QC) is very important. Assuming a non-Gaussian distribution for errors in the QC system and using varying localization length scales are novel aspects of the new development. It is believed that the QC technique, together with a higher resolution model, should produce an analysis that is ~25% better than 20CRv2. It was noted that the QC technique is similar to Fuqing Zhang's adaptive covariance relaxation method but that it adds perturbation to the ensemble. The technique retains the rotation of the structure but changes the amplitude. Jack Woollen presented a comparison of two ensemble based reanalysis systems. The first is the NCEP dual resolution T254/126 hybrid 3D-Var/EnKF, and the second is the ESRL single-resolution pure EnKF excluding satellite observations (EN NOSAT). The comparison was made for parallel assimilation experiments spanning three 1-year periods. Both were compared to the ERA-40, ERA-Interim, and NCEP R1 reanalyses. It was concluded that the EN NOSAT system shows good potential to rerun NCEP R1) very efficiently. The EN NOSAT results are good in the Northern Hemisphere even without satellite observations, but direct radiance assimilation is nominally necessary for a full NCEP R1 replacement. The EN NOSAT could be used for reanalyzing 1948–1975 in any case. In the subsequent discussion, the general issue of whether the ensemble mean from the "pure" Ensemble Kalman Filter system is meaningful, even though it is not balanced. It was suggested that if there is any imbalance, it should be visible in the precipitation field. For any initial assessment, the ensemble mean is the natural first field to examine. The discussion also suggested additional directions to the study such as examining the anomaly correlation and fit to observation metrics, as well as precipitation metrics. The general issue of whether the replacement for NCEP R1 should even use satellite data was raised. A specific question of whether Southern Hemisphere examples had been generated to show the need of the observations, and the surprising response was that the 1975 ensemble, even without satellite radiances, is an improvement over R1.

Daryl Kleist presented progress on the 4D hybrid Ensemble Variational (4D-EnVar) data assimilation and other developments for the NCEP Global Forecast

System (GFS). Experiments were performed with real observations using hybrid 3D-Var and hybrid 4D-Var, bias correction for radiance and conventional observations, and assimilation of cloud and precipitation observations. It was suggested in the presentation that a suite of future work to be conducted at NCEP and the University of Maryland includes scale-dependent weighting, synergy between EnVar and ENKF in initialization, issues with the static (time-invariant) error covariance, etc. In discussion, the issue was raised of whether hybrid 4D-EnVar works as well as 4D-Var in head-to-head comparisons. It was found that with the right configuration, experiments show that the hybrid 4D-EnVar does not precisely match 4D-Var, but it is close.

Eugenia Kalnay showed new applications of data assimilation to reanalysis: algorithms for correcting model bias and reanalysis jumps. Estimation and correcting model bias was done by focusing on the analysis increments. As part of this, model errors in the diurnal cycle were identified using Empirical Orthogonal Functions (EOFs) from reanalysis. It was shown that the state dependent errors could be found using the patterns from a coupled Singular Value Decomposition (SVD). A correction scheme was proposed based on new and old analysis increments to correct potential bias introduced by new observations. The discussion centered on the issue of the importance of bias in the diurnal cycle, which she proposes to correct inline through small nudges to the model equations. The correction procedure will also find and remove jumps in model bias.

Gil Compo presented a reanalysis effort for Tambora 1815 in which it was shown that 20CR surface pressure-only system can represent the 1815 event with good skill. It was shown that the atmospheric circulation change may be driven by volcanic aerosols based on the better forecast skill from a set of assimilations including the volcanic aerosols and a set excluding the aerosols. Of note was that the climate variability in the reanalysis seems to be larger than the signals derived from tree rings. In the discussion, the use of additional observations, such as rainfall was suggested. The counter-argument however is that limiting the observation set to surface pressure ensures the most homogeneous observation set. The presentation concluded that there are small improvements of forecast skill when volcanic aerosols were included in the first guess. Given the large number of observations in the full year of evaluation, it was suggested that the differences were statistically significant.

General Discussion:
New research is required to understand reasons for the characteristics of jumps in climate reanalysis as new observational platforms are introduced. It was asked how it can be known where the jumps come from, where the model bias is, and how it can be diagnosed. It was noted that there are model drifts in addition to jumps. Jumps can be corrected once identified, while drifts are usually not easily identifiable and thus not easily corrected. Drifts may be a confluence of model biases and jumps, with no automatic ways to identify them. To address this issue of drift, feedback data are needed, as well as gridded versions of intercomparisons.

3d. Assimilation Development and Experiments: Ocean and Sea Ice

The session began with a presentation by Guilliame Vernieres of NASA/GMAO describing some of the activities being carried out by the GMAO oceans group, the integrated Ocean Data Assimilation System (iODAS). The iODAS project does have a 0.083° eddy resolving effort led by Christiane Keppenne, but the main effort is directed towards the current 0.5° version of the Modular Ocean Model version 4p1 (MOM4p1) ocean, which is likely transitioning to a 0.25° resolution MOM5 in the coming months (the final decision has not been made). The analysis period mirrors the analysis period for the GMAO atmospheric reanalysis product MERRA-2 (1980–present). The current assimilation methodology is an ensemble method drawing from EOFs of static covariances known as Ensemble OI (ENOI). The data being assimilated include historical hydrographic data, SST (currently a gridded product), sea surface salinity (SSS) from the Aquarius satellite, and altimeter sea level. Much effort has been expended to develop a skin-SST model to allow coupling to the GEOS atmosphere. The system also includes a wave model, while work is underway to include ocean color information.

The second and third presentations in this session, by Yan Xue and Steve Penny, introduced the corresponding NCEP ocean analysis system Global Ocean Data Assimilation System (GODAS). The presentation by Xue compared a number of variables such as ocean heat content from various operational centers, highlighting some of the strengths and weaknesses of the current GODAS and results of some data sensitivity experiments. This presentation was followed up by Penny's presentation on new developments in GODAS. A highlight was his presentation of tests of the new hybrid-GODAS, which builds on the current 3D-Var with the local ensemble transform Kalman Filter (LETKF). The control experiment uses the current GODAS for the period 1991–2011. The second experiment uses the hybrid-GODAS with 56 ensemble members. Surface forcing perturbations are provided by 20CR fields recentered about NCEP R2. In brief, the new analysis represents considerable improvement over the current system. For example, it was shown that the root mean square error and the mean of observation minus forecast differences of variables such as temperature and salinity are significantly reduced. Finally, he pointed to the use of his system at ECMWF in a series of comparison studies.

A closely related data assimilation activity is being carried out at University of Maryland and was described by James Carton. In this activity a significant upgrade of the Simple Ocean Data Assimilation system was described. Changes include an upgrade to the 0.25° MOM5 ocean model, similar to that being examined at GMAO and also similar to one likely to be adopted at NCEP. Interactive sea ice (SIS) is also included, constrained by microwave emissivity for sea ice data assimilation. The system is still in development, with several improvements possible, such as improving the sea ice analysis and Arctic salinity, and improving the representation of continental discharge.

The presentation by Xu Li introduced NOAA's effort in developing a skin-SST algorithm (NSST). The need for a skin-SST algorithm had previously been discussed in Verniere's talk. It arises partly because passive remote sensing of SST uses either infrared/visible frequencies or at microwave frequencies. While the former provides an accurate measurement with uncertainties less than 0.5°C, they reflect the temperature of the upper microns of the water column, well within the near surface laminar sublayer. The latter, while less accurate are insensitive to cloud cover, and may reflect the temperature of the upper few mm of the water column. The distinction is important because solar stratification and evaporative cooling can leave a subtropical ocean under low wind conditions with a complex temperature structure that may vary by as much as 3°C in the upper 3 m of the water column. The final observational data set to be included are the in situ observations reflecting temperature one or more meters below the surface. Many of these are ship intake measurements. Others are from fixed buoys and surface drifters. Of these, the latter are the most accurate, with an individual uncertainty of perhaps 0.5°C. Li reviewed this complex problem and presented the result of this effort to parameterize the effects of these unresolved processes. The results showed a positive impact of NSST on weather prediction. The parameterization will be incorporated into the NCEP CFS, with improvements expected for both weather and climate prediction.

The sixth presentation by Ben Giese examined a reduced version of the Simple Ocean Data Assimilation

(SODA) system in a series of experiments with the Compo/Whitaker 20CR effort in which the ocean is forced by 20CRv2 fluxes, then the modified SSTs resulting from the ocean reanalysis are reintroduced into the atmospheric reanalysis system, etc. This "sparse observational input" SODA system (SODAsi) only assimilates sea surface temperature observations during each update cycle. The system starts with surface forcing from 20CRv2. The SSTs from SODAsi.2 are then used as boundary conditions by 20CRv2c. These resulting winds and near-surface fields are then used by SODAsi.3. The presentation illustrated two large ENSO warm events: the 1918/19 El Nino, when observations were sparse, and the 1997–98 El Nino with dense observations. It was found that prescribing monthly-mean SST to the atmosphere may artificially reduce uncertainties in surface forcings and reduce ensemble spread. Overall the iteration appears to be improving the reanalysis.

The final two talks addressed two other key systems: the land surface and sea ice. The land surface assimilation system was presented by Michael Ek and Jesse Meng. For the Global Land Data Assimilation (GLDAS), there is an upgraded Noah Land model with new land data, an improved land data assimilation scheme, CPC daily precipitation, streamflow, and a GLDAS-2 single stream replay compared to CFSR. The land surface spin up is more critical in dry land. The talk by Xingren Wu discussed some of the ongoing sea ice prediction activities within NOAA EMC. These include a very simple empirical sea ice prediction system and some preliminary planning for a full sea ice prediction system within the upcoming CFSv3.

General Discussion:

This session prompted considerable discussion about the details of the ocean analysis systems (GODAS, iODAS, SODA, SODAsi) and the one coupled system (CFS). Among the topics discussed was the source of the data, for example, for sea ice cover, the constraints on the temperature and salinity of water in the deep ocean, and the impact of observations from the TOGA/TAO array. The lack of sea ice thickness information was discussed. In a related discussion, it was pointed out that there is a need to resolve diurnal processes within the oceanic mixed layer (a component of NSST) as a necessary component to improving the assimilation of satellite data.

Another topic discussed was the appearance of "jumps" in the reanalyses due to the introduction of new observations and whether or not this is a result of an observing system bias or a model bias. The jumps illustrate issues in the use of reanalyses. Climate reforecasts require continuous climate reanalysis fields without artificial jumps for calibrating model climatology and model hindcast skill. It was noted that changes in observations also lead to changes in surface fluxes, leading to changes in background covariance and jumps in ocean reanalysis. Indeed, concern about those jumps led to efforts such as 20CR which deliberately excludes satellite and upper air data. The alternative view was put forward that perhaps jumps in variability due to changes in the observing system are an inherent aspect of the inconsistent historical sampling and that we should not try to lessen their impact but allow users to see the variations.

Another topic which came up in this session was the need to carry out the production of a reanalysis in a set of overlapping streams for wall-clock efficiency. The question then arises, how much overlap is needed in order to stitch together the individual streams (an issue that arose in the CFSR)? In terms of data assimilation streams, when one is including the ocean, land, and stratosphere, it was suggested that there was a need for a spin-up overlap of 2–5 years. It was suggested that running a low resolution version of the coupled data assimilation system could provide initial conditions from which different streams can be initialized. The session also included recommendations regarding the types of reanalysis performance statistics that should be kept for each system. Among those considered vital are the forecast minus observation and forecast minus analysis statistics. The issue of how much horizontal resolution is needed for the ocean was raised in this session but remained unresolved.

3e. Reanalysis Evaluation

Ricardo Todling described a recent work on the dry mass and water conservation in the NASA GMAO MERRA system, the former following on from work by Trenberth and Smith. Modifications were made to the model, analysis, and application of the increments in the incremental analysis update (IAU) system to improve conservation. Issues were raised as to why changing integrated dry mass to be constant makes precipitation better and what is the effect of bias in the mass and water conservation scheme. Because the dynamics conserve mass, the only thing that should change or control the water is the physics, but if you allow the assimilation to adjust it then water can get out of balance. Todling also pointed out that with these changes, the model becomes less biased than before.

Lisan Yu presented an evaluation of ocean surface energy and freshwater budgets in early and recent atmospheric reanalyses, satellite-based products, and an ocean state estimation. Independent buoy time series measurements and satellite salinity observations were used to identify and understand the source of uncertainty. She showed that most uncertainties are concentrated in the tropical oceans, and that the spread in the ocean energy budget uncertainty is due primarily to the shortwave components and the spread in the freshwater budget is due to uncertainty in the precipitation associated with the Intertropical Convergence Zone and the South Pacific Convergence Zone. The large uncertainties present a major challenge for using reanalysis records for detection and attribution of long-term climate trends and variability. In discussion, the question was raised on the use of buoy measurements. Specifically, the concern was raised that buoy measurements of shortwave radiation are made at different heights for different heights. Yu responded that the more serious problem for shortwave measurements made by buoys at sea is the changing incident angle due to surface wave rocking of the buoys and not to the change of height. A question was raised that focused on the CFSR data processing. The concern was that CFSR has hourly output, each hour is a cumulative measure up to the forecast hour, and hourly output should not be averaged to get daily data. Yu responded that the data processing followed the instructions specified in the CFSR technical documentations and the identified uncertainty in the CFSR clouds is not due to data processing but a “real” problem in the model.

Caihong Wen presented the difference in oceanic response to two different surface forcings: NCEP Reanalysis 2 (R2) and CFSR surface fluxes, using ocean simulations with a model based on GFDL MOM4 numerics. The experiments examined both variations in the depth of the thermocline as represented by the depth of the 20C isotherm (mainly reflecting surface winds), SST (generally controlled by net surface heat flux except in upwelling regions), and SSS (generally controlled by net surface freshwater flux). The work aimed to explore the ways in which surface flux uncertainties impact the ocean uncertainty in ocean properties.

Erica Dolinar presented an evaluation and intercomparison of clouds, precipitation, and radiation budgets between 5 different recent reanalysis datasets, satellite and surface observations. She evaluated cloud fraction, precipitation rate, top-of-atmosphere and surface radiation budgets for March 2000–February 2012. Compared to the annual averaged cloud fraction of 56.7 % from CERES MODIS, four of the five reanalyses underpredicted cloud fractions by 1.7−4.6%, while 20CR overpredicted cloud fraction by 7.4 %. Precipitation from the Tropical Rainfall Measurement Mission (TRMM) is 3.0 mm/day and the reanalyzed

Precipitations agree with TRMM within 0.1−0.6 mm/day. The shortwave and longwave top of the atmosphere cloud radiative effects (CREtoa) calculated by CERES EBAF are −48.1 and 27.3 W/m2, respectively, indicating a net cooling effect of −20.8 W/m2. Of the available reanalyses for comparison, the CFSR and MERRA calculated net CREtoa values agree with CERES EBAF within 1 W/m2, while the JRA-25 result is ~ 10 W/m2 more negative than the CE result, predominantly due to the underpredicted magnitude of the longwave warming in the JRA-25 reanalysis. Additionally, a regime metric is developed using the vertical motion field at 500 hPa over the oceans. Aptly named the “ascent” and “descent” regimes, these areas are distinguishable in their characteristic synoptic patterns and the predominant cloud-types: convective-type clouds and marine boundary layer (MBL) stratocumulus clouds. The dichotomy between the atmospheric ascent and descent regimes appears to be a good measure for determining which parameterization scheme requires more improvement (convective vs. MBL clouds) in these five reanalysis datasets.

Xiquan Dong compared extreme summer Arctic sea-ice extent anomalies in the summers of 2007, 1996, and 2012. They investigated the mechanisms for the formation of the extremes of 2007 and 1996, and quantitatively estimated the cloud-radiation-water vapor feedback to the sea-ice-concentration variation utilizing satellite-observed sea-ice products and the NASA MERRA reanalysis. The low sea-ice extent in 2007 was associated with a persistent anticyclone over the Beaufort Sea and simultaneous low pressure over Eurasia, which induced anomalous southerly winds. Ample warm and moist air from the North Pacific was transported to the study area and resulted in positive anomalies of cloud fraction, precipitable water vapor (PWV), surface longwave net (down minus up), total surface energy and temperature. In contrast, the high sea-ice extent event in 1996 was associated with a persistent low pressure over the central Arctic and simultaneous high pressure along the eastern Arctic coasts, which generated anomalous northerly winds and resulted in negative anomalies of the above mentioned atmospheric parameters. In addition to their immediate impacts on sea ice reduction, it was suggested that the interplay of cloud fraction, precipitable water vapor, and radiation can lead to a positive feedback loop , which plays a critical role in decreasing sea ice to the great low value in 2007, indicating that cloud fraction, precipitable water vapor and longwave radiation are indeed having significant impacts on the sea-ice extent variation. A new record low occurred in the summer of 2012 was mainly triggered by a strong cyclone over the central Arctic Ocean in early August that caused substantial mechanical ice deformation on top of the long-term thinning of an Arctic ice pack that had become more dominated by seasonal ice.

Richard Cullather provided an introduction to the results of recent atmospheric reanalyses of high latitude fluxes. His presentation included comparison between regional and global models for reanalysis over polar ice sheets. The results suggested that the reanalyses are still struggling to do better than climatology in these regions, but progress may be helped by examination of higher resolution regional model reanalysis studies such as the Greenland regional models MAR and RACM02.

General Discussion:

The main themes of this session included (i) evaluating and understanding the various dimensions of uncertainty in reanalyses, (ii) articulating and prioritizing critical uncertainties and their impacts on applications of the reanalysis products, and (iii) promoting focused research endeavors that improve the reanalysis models and reduce the uncertainties.

The leading issue in the presentations was the identification of the source, degree, and nature of uncertainty in reanalyses. Biases in surface fluxes in the open oceans and at high latitudes were highlighted in the session. The lack of sufficient in situ observations to identify and quantify the global biases in flux components was acknowledged. It was noted that some biases are the artifacts of the changes in observation platforms, such as the injection of the ATOVS data around 1998 that causes an abrupt change in precipitation and/or humidity time series, and some biases might be due to the parameterization schemes, such as for cloud, that remain a challenge for model development.

The polar talks raised more issues than could be resolved. Among these was a follow-up question about the relative roles of cloud-radiation feedback processes in the reanalyses and in nature. Several other questions addressed the uncertainties in comparison data sets. For example, Cullather pointed to the uncertainty in sea ice cover in summer based on passive microwave remote sensing because of the complex surface properties of the sea ice during that season. He pointed out that when you change sea ice cover you need to change the ocean to be compatible with this cover. Also, he pointed out that there is still considerable uncertainty in estimates of sea ice volume.

The session raised questions about the potential applicability of the reanalyses to studies of climate change detection and attribution. The time-varying biases in reanalysis products often raise concern about the statistical significance and meaningfulness of the decadal and longer-term variability exhibited in the reanalysis time series. It was noted that the global ocean-surface energy and freshwater budgets are not conserved in recent reanalyses, and reanalyses still have issues with the representation of processes in in the polar regions, such as from the parameterization of clouds, longwave radiation, and cloud-aerosol interaction..

The session also engaged with the issue of improving the assimilation systems, and using diagnosed observation and forecast differences to improve the physical representation of the model. This kind of endeavor was deemed welcome and necessary.

Recommendations for this session included prioritizing the dissemination of critical uncertainties in reanalyses and the critical areas of improvement.

4. Next Steps and Future Coordination

The brief reports by the rapporteurs from the individual sessions were accompanied by a series of audience questions that highlighted some of the uncertainties and the need for follow-up projects. For session 2 one question asked what was needed to improve historical analysis of the properties of the stratosphere – more observations or better models? For session 3 there were several questions, leading to discussion, about how to initialize the ocean for coupled predictions. For example, most observations today only extend through the upper 2 km of the ocean, and the question was asked whether it could be possible to use CMIP-type models to initialize the lower 2 km of the ocean. There was also some discussion about the usefulness of eddy permitting (e.g. 0.25°) or eddy resolving (0.0833°) resolution for the ocean. Finally there was a brief statement by Dr. Saha regarding a key step being taken by NOAA EMC to develop CFSv3. It was recognized that this meeting was a bit premature to map out the details of CFSv3.

More broadly, several subjects were recurring issues throughout the meeting. The subject of coordination of activities was an important issue, and the continual involvement through the MAPP/CRTF was a helpful way to make this happen. There was a recognition of the need for more information from the reanalyses as part of the released products, such as the increments, and the quality control feedback on the used and rejected observations. The continual development of reanalyses of increasing resolution for the ocean, atmosphere, land, and cryosphere from sparse observations back to the 19th century to highly detailed reconstructions of the last 40 to 60 years using the most advanced satellite sensors suggests that a bevy of new, improved products for users will soon be available. The participants discussed several important reasons for continuing to develop new reanalyses: to provide initial conditions for reforecasts and to demonstrate improvements in a forecasting and analysis system by generating better forecasts with a new system compared to an older system using historical observations. Another key reason is to improve the description of the general circulation, its statistics, and its variability in a consistent manner for as long as possible. An additional reason of increasing interest is to assess and understand climate change. The new Copernicus Climate Change Service (C3S) highlights the important role that these reanalyses will play in delivering such climate information to stakeholders.

5. Further information

- Information on the NOAA Climate Reanalysis Task Force: cpo.noaa.gov/MAPP/CRTF
- NCRTF workshop website: cpo.noaa.gov/MAPP/CRTF_workshop
- Climate Reanalysis website: Reanalysis.org

Acknowledgements

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Appendix 1: Table of Registered Participants

Full Name	Affiliation
Alison Stevens	NOAA/CPO/MAPP
Annarita Mariotti	NOAA/CPO/MAPP
Arlindo da Silva	NASA/Goddard Space Flight Center
Arun Kumar*	NOAA/NWS/NCEP/CPC
Benjamin Giese	Texas A&M
Caihong Wen	NOAA/NCEP/CPC
Christian Keppenne	NASA GMAO
Craig Long	NOAA/NWS/NCEP/CPC
Daniel Barrie	NOAA/CPO/MAPP
Daryl Kleist	University of Maryland
Dick Dee	ECMWF
Erica Dolinar	University of North Dakota
Eugenia Kalnay	University of Maryland
Gilbert Compo*	U. of Colorado/CIRES & NOAA/ESRL Physical Sciences Division
Guillaume Vernieres	GMAO, NASA/SSAI
Heather Archambault	NOAA/CPO/MAPP
Huug van den Dool	NOAA/NWS/NCEP/CPC
James Carton**	University of Maryland
Jeffrey Anderson	NCAR
Jeffrey Whitaker	NOAA ESRL/Physical Sciences Division
Jesse Meng	NOAA/NWS/NCEP/EMC
John McCormack	Naval Research Lab
John Woollen	NOAA/NWS/NCEP/EMC
Jose-Henrique Alves	NOAA/NWS/NCEP/EMC
Jun Wang	NOAA/NWS/NCEP/EMC
Lisan Yu	Woods Hole Oceanographic Institution
Michael Bosilovich	NASA GMAO
Ricardo Todling	NASA GMAO
Richard Cullather	NASA GMAO
Ronald Gelaro	NASA/GMAO
Santha Akella	GMAO, NASA/SSAI
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Shrinivas Moorthi	NOAA
Stephen Penny	University of Maryland/ NOAA/NCEP

* NCRTF lead

** NCRTF co-lead

Appendix 1 Cont'd: Table of Registered Participants

Full Name	Affiliation
Suranjana Saha**	NOAA/NWS/NCEP/EMC
Wesley Ebisuzaki	NOAA/NWS/NCEP/CPC
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Xingren Wu	NOAA/NWS/NCEP/EMC
Xiquan Dong	University of North Dakota
Xu Li	NOAA/NWS/NCEP/EMC
Yan Xue	NOAA/NWS/NCEP/CPC
Yiyi Huang	University of North Dakota
Yury Vikhliaev	USRA/GMAO
Zhiquan Liu	NCAR

* NCRTF lead
** NCRTF co-lead

Appendix 2: Final Agenda

NOAA Climate Reanalysis Task Force Technical Workshop

NOAA Center for Weather and Climate Prediction
College Park, MD

Organizers: Jim Carton, Gilbert Compo, Arun Kumar, Suru Saha, Heather Archambault

Workshop Objectives:

- Report on NOAA Climate Reanalysis Task Force progress.
- Exchange reanalysis approaches, algorithms, and techniques currently in use and under development.
- Discuss techniques for addressing outstanding issues in the reanalysis efforts, e.g., presence of spurious discontinuities and trends, coupling of Earth System components, inclusion of new areas such as aerosols.
- Identify the various requirements for reanalysis products.
- Determine strategies and overlaps for national and international reanalysis efforts based on scientific drivers for climate and weather research.

Each presentation slot is 80% for oral presentation and 20% for questions.

Monday 4 May

8:00-9:00 a.m.	Registration
9:00 a.m.	*Welcome* Arun Kumar, NCEP/CPC
9:05 a.m.	*Introduction to the Climate Reanalysis Task Force and Workshop* Gil Compo, U. of Colorado/CIRES & NOAA/ESRL/PSD
9:20 a.m.	*What is Reanalysis for?* Huug van den Dool, NCEP/CPC

1. National and International Reanalysis Efforts

Objective: Determine strategies and overlaps for national and international reanalysis efforts based on scientific drivers for climate and weather research.

Session Chair: Gil Compo, U. of Colorado/CIRES & NOAA/ESRL/PSD
Rapporteur: Jeff Whitaker, NOAA/ESRL/PSD

Appendix 2 Cont'd: Final Agenda

9:40 a.m.	*Plans for Reanalysis at NCEP's Environmental Modeling Center* Suru Saha, NCEP/EMC
10:00 a.m.	*Issues, Requirements, and Research towards NOAA's Next Generation of Climate Reanalysis* Arun Kumar, NCEP/CPC
10:20 a.m.	Coffee Break
10:40 a.m.	*Reanalysis at ECMWF* Dick Dee, ECMWF
11:00 a.m.	*CMA 40-year GSI based reanalysis: plans and progress* Zhiquan Liu, NCAR
11:20 a.m.	*MERRA-2, GMAO reanalysis efforts/plans* Ron Gelaro, NASA/GMAO
12:10 p.m.	Lunch

2. Developments in the Stratosphere

Objective: Discuss techniques for addressing outstanding issues in the reanalysis efforts

Session Chair: Ron Gelaro, NASA/GMAO
Rapporteur: Erica Dolinar, U. of North Dakota

1:30 p.m.	*Status at NCEP to improve the stratosphere in reanalysis* Craig Long, NCEP/CPC
1:50 p.m.	*Aerosol modeling* Sarah Lu, SUNY-Albany
2:10 p.m.	*Water vapor in the stratosphere* John McCormack, Naval Research Laboratory
2:30 p.m.	*Aerosol Reanalysis at NASA Goddard Space Flight Center* Moderator: Dan Barrie, NOAA/CPO
3:10 p.m.	Coffee Break

Appendix 2 Cont'd: Final Agenda

3. Assimilation Development and Experiments: Atmosphere

Objectives: Exchange reanalysis approaches, algorithms, and techniques currently in use and under development. Discuss techniques for addressing outstanding issues in the reanalysis efforts

Session Chair: Arun Kumar, NCEP/CPC
Rapporteur: Lisan Yu, WHOI

3:30 p.m.	*Developments in the Ensemble Kalman Filter* Jeff Whitaker, NOAA/ESRL/PSD
3:50 p.m.	*Forcast results and QBO response from NCEP conventional data only T254 EnKF only cycling semi-Lagrangian Reanalysis in 1970, 1981* Jack Woollen, IMSG & NCEP/EMC
4:10 p.m.	*Hybrid Data Assimilation at NCEP* Daryl Kleist, U. of Maryland
4:30 p.m.	*New applications of Data Assimilation to Reanalysis* Eugenia Kalnay, U. of Maryland
4:50 p.m.	*Reanalysis for Tambora 1815* Gil Compo, U. of Colorado/CIRES & NOAA/ESRL Physical Sciences Division
5:10 p.m.	Discussion Moderator: Gil Compo
5:30 p.m.	Close for day

Appendix 2 Cont'd: Final Agenda

Tuesday 5 May

4. Assimilation Development and Experiments: Ocean and Sea Ice

Objectives: Exchange reanalysis approaches, algorithms, and techniques currently in use and under development. Discuss techniques for addressing outstanding issues in the reanalysis efforts

Session Chair: Suru Saha, NCEP/EMC
Rapporteur: Yan Xue, NCEP/CPC

8:30 a.m.	*NASA ocean data assimilation* Guilliame Vernieres, NASA/GMAO SSAI
9:00 a.m.	*Impacts of ocean observations on NCEP GODAS analysis* Yan Xue, NCEP/CPC
9:15 a.m.	*Advancing Ocean Data Assimilation and Reanalysis* Steve Penny, U. of Maryland & NCEP
9:30 a.m.	*UMD SODA - problems and progress* Jim Carton, U. of Maryland
9:45 a.m.	*The development of NSST within the NCEP GFS/CFS* Xu Li, NCEP/EMC
10:00 a.m.	Coffee Break
10:30 a.m.	*ENSO in a large ensemble of historical reanalyses* Ben Giese, Texas A&M University
10:45 a.m.	*Land data assimilation at NCEP/EMC* Xingren Wu, NCEP/EMC
11:15 a.m.	Discussion Moderator: Jim Carton, U. of Maryland
12:10 p.m.	Lunch

5. Reanalysis Evaluation
Objective: Identify the various requirements for reanalysis products.

Session Chair: Jim Carton, U. of Maryland
Rapporteur: Steve Penny, U. of Maryland

1:30 p.m.	*Dry-mass conservation and water consistency in reanalysis* Ricardo Todling, NASA/GMAO
1:50 p.m.	*Air-sea heat and freshwater fluxes in Atmospheric Reanalyses* Lisan Yu, Woods Hold Oceanographic Institute
2:10 p.m.	*Impacts of NCEP Reanalysis R2 and CFSR fluxes on MOM4 simulations* Caihong Wen, NCEP/CPC
2:30 P.M.	*Evaluation and intercomparison of clouds, precipitation, and radiation budgets in recent reanalyses using satellite-surface observations* Erica Dolinar, U. of North Dakota
2:50 p.m.	Coffee Break
3:10 p.m.	*Investigation of two extreme summer Arctic sea-ice extent anomalies in 2007 and 1996* Xiquan Dong, U. of North Dakota
3:30 p.m.	*Reanalysis evaluation in polar regions* Richar Cullather, NASA/GMAO
3:50 p.m.	Rapporteurs give 5 minute summary of their session
4:15 p.m.	Discussion and writing assignments Moderator: Gil Compo
5:00 p.m.	Close of Workshop

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