

Progress and Prospects for Reanalysis for Weather and Climate

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Analyses of global atmospheric observations in real time for numerical weather prediction (NWP) lack continuity over time as the operational system evolves. Reanalysis of the observations—with more complete data, improved quality control, and a constant state-of-the-art assimilating model and analysis system—greatly improves the homogeneity of the record and makes it useful for examining climate variations. This whole endeavor is now referred to as “reanalysis.”

However, even as atmospheric reanalysis of past observations has greatly improved our ability to determine climate variability, challenges still exist in depicting multidecadal changes. Moreover, although several reanalyses—from the U.S. National Oceanic and Atmospheric Administration’s National Centers for Environmental Prediction (NCEP), NASA Goddard Space Flight Center (GSFC), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Japan Meteorological Agency (JMA)—now exist, the task is far from done. Further improvements to reanalysis—including expansion to encompass key trace constituents and the ocean, land, and sea ice domains—hold promise for extending their use in climate change studies, research, and practical applications (such as how extremes of climate and their impacts on agriculture have changed).

Global gridded analyses of observations taken for many purposes—such as weather forecasting in the atmosphere or core oceanographic research—become part of the climate record but often display biases that mask long-term variations. Many climate data sets are inhomogeneous: The record length either is too short to provide decadal-scale information or is inconsistent owing to operational changes in instruments, their siting, and data transmission and processing and to the absence of adequate metadata. Hence, major efforts have been required to homogenize the observed data for them to be useful for climate purposes. Reanalysis of atmospheric observations using a constant state-of-the-art assimilation model has helped enormously in making the historical record more homogeneous and useful for many studies. Indeed, in the 20 years since reanalysis was first proposed by *Trenberth and Olson* [1988] and *Bengtsson and Shukla* [1988], there have been great advances in our ability to generate high-quality temporally homogeneous estimates of the past climate.

Global Setting and Advances to Date

The World Climate Research Program (WCRP) and the Global Climate Observing System (GCOS) have provided continuing leadership in promoting the underpinning

research and observational needs for reanalysis. Global analyses are an essential tool to enabling the optimal use of global Earth observations in the atmosphere, ocean, and terrestrial domains covered by the Group on Earth Observations (GEO); indeed, the GEO work plan identifies as a specific task the reanalyses for climate along with the improvement of corresponding observation data sets. Further, the GCOS Implementation Plan (GIP; *GCOS* [2004] and its supplement on space observations, *GCOS* [2006]), which describes the required actions to improve the future climate data, strongly supports reanalysis of the past record using state-of-the-art analysis systems. While progress in implementing the GIP has been modest, numerous valuable efforts under WCRP, GCOS, and GEO are under way.

Global reanalysis of the climate system requires substantial infrastructure and intellectual resources to establish and enhance the basic database of observations, carry out the computations, analyze the output to ensure the quality of the products, and archive and distribute the products. However, reanalysis can often draw on much of the infrastructure and other resources established for global NWP. Scientists involved in reanalysis include observationalists; experts in data processing, management, and access and archiving; modelers; and data assimilation experts. Also, sponsors of reanalysis already have been well rewarded, with basic assimilation and prediction systems improving as deficiencies are identified and corrected, by applying improvements to both reanalysis and routine weather and climate prediction.

The products of global reanalysis have provided the basis for advances in many areas, including the essential foundation for an accurate assessment of current climate (“climate nowcasts”); diagnostic studies of features and phenomena such as weather systems, monsoons, El Niño–Southern Oscillation, and other natural climate variations; seasonal prediction; and climate predictability.

Global reanalysis is also the foundation for regional reanalysis projects and downscaling where detailed climatologies can be prepared to support studies of local climate and climate impacts. There has also been some progress in the use of reanalysis to investigate the difficult problem of the detection and attribution of long-term climate trends and variability. Reanalysis of the ocean and atmosphere has helped to identify and correct deficiencies in the observational record, including the recovery of additional observations.

Prospects for Advances

The potential for major advances in reanalysis is apparent. While the origins of

reanalysis have been in atmospheric climate and weather, and although atmospheric scientists currently make up the majority of scientists involved in reanalysis, oceanographers and land surface, polar, and coupled Earth system experts are increasingly active.

Trace constituents of the atmosphere influence the thermodynamics and dynamics of climate through both short-lived constituents such as aerosols (tiny particulates) and ozone, and longer-lived gases such as carbon dioxide and methane. As assimilation techniques for observations related to these constituents are refined and extended, reanalysis could eventually provide the means to develop consistent climatologies for the chemical components of the atmosphere, including the carbon cycle. This would help address key uncertainties in the radiative forcing of climate, as identified, for example, in the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

There have been significant studies of reanalysis (or synthesis) of ocean data. Because of the limited size of historical ocean data sets, it has been necessary to develop novel techniques for increased homogeneity of ocean reanalysis. Other promising developments are occurring in sea ice, Arctic, and land surface reanalysis. There has also been initial development of coupled atmosphere-ocean data assimilation, which is laying the foundation for future coupled reanalysis studies that may lead to more consistent representations of the energy and water cycles. With the ongoing development of analysis and reanalysis in the ocean, land, and sea ice domains, there is huge potential for further progress and improved knowledge of the past climate record.

Global atmospheric reanalysis results in high-quality and consistent estimates of the short-term or synoptic-scale variations of the atmosphere, but variability on longer timescales (especially decadal) is not so well captured by current reanalyses. The primary causes of this deficiency are the quality and homogeneity of the fundamental data sets that make up the climate record and the quality of the data assimilation systems used to produce reanalyses. However, research into bias corrections and advanced reanalysis techniques is showing promise, and further reanalysis efforts are needed. A challenge is to improve estimates of uncertainty in the reanalysis products.

Improvements in reanalysis depend upon continuing support for the underpinning strategic research, for the development of comprehensive Earth system models required to expand the scope of reanalysis, and for the infrastructure for data handling and processing. The magnitude of the resources required for global reanalysis is such that only a small number of centers of expertise (such as those at NCEP, GSFC, ECMWF, and JMA) are expected to be able to support the whole process. Reanalysis centers and

sponsors should continue to be responsive to user needs. Moreover, there needs to be continued close cooperation among these centers, as well as among the broader community involved in aspects of global reanalysis, to ensure that the global benefits are maximized and that each new reanalysis learns from the knowledge gained from previous efforts. In particular, a number of future plans—including those at NCEP, GSFC, ECMWF, and JMA—exist for further reanalyses of both the atmosphere and ocean. Future global reanalyses should be coordinated and, if possible, staggered so that the basic observational data record is improved before each reanalysis, and so that there is time to analyze and hence learn from the output of past efforts.

Reanalysis has proved to be as valuable for monitoring climate, climate research, and applications as was believed it would be when it was proposed 20 years ago. However, as the scope of global reanalysis grows, the research effort needed to optimize the

benefits is so large that international cooperation is essential. Further challenges remain, and we urge sponsors to continue their support for further reanalysis efforts in all domains spanning the instrumental record, and for the climate system as a whole.

Acknowledgments

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—KEVIN E. TRENBERTH, National Center for Atmospheric Research, Boulder, Colo.; E-mail: trenbert@ucar.edu; TOSHIO KOIKE, University of Tokyo, Tokyo, Japan; and KAZUTOSHI ONOGI, Japan Meteorological Agency, Tokyo, Japan

NASA Stardust mission principal investigator and University of Washington astronomer Donald Brownlee, AGU member, after learning the International Mineralogical Association had named a new mineral in his honor. Brownleeite, a combination of manganese and silicon, is the first mineral discovered in a particle from a comet. The mineral was found inside a particle collected by a high-altitude NASA aircraft from a dust stream that entered Earth's atmosphere in 2003. A team led by NASA scientist Keiko Nakamura-Messenger found the particle and had requested that it be named for Brownlee.

—RANDY SHOWSTACK, Staff Writer

NEWS

In Brief

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Gulf of Mexico hypoxia plan On 16 June, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force released an action plan to reduce, mitigate, and control hypoxia in the northern Gulf of Mexico. The plan builds upon a 2001 plan by including more accountability through an annual operating plan, better tracking of progress, and state and federal

nutrient reduction strategies. “Our improved plan unites governments and citizens across the country to take action upstream and along the coast to reduce river nutrient pollution and increase Gulf of Mexico health,” said U.S. Environmental Protection Agency assistant administrator for water Benjamin Grumbles. For more information, visit <http://www.epa.gov/msbasin/>.

Astronomer honored with a mineral “I have always been very intrigued by minerals, so it is great to be one,” commented

FORUM

Controlling Hypoxia on the U.S. Louisiana Shelf: Beyond the Nutrient-Centric View

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As the Earth's population continues to increase, the projected effects of contaminant loading and human encroachment on biodiversity remain unclear. One area of intense interest is coastal eutrophication and associated hypoxia events (with hypoxia defined as oxygen < 2 milligrams per liter = 1.4 milliliters per liter = ~63 micromoles per cubic decimeter). On average, the Mississippi River discharges to the northern Gulf of Mexico (GOM) 550 cubic kilometers of freshwater and approximately $60\text{--}70 \times 10^9$ moles of dissolved inorganic nitrogen per year [Dagg *et al.*, 2004], which contains

anthropogenic nitrogen derived primarily from agricultural fertilizer as well as effluent from animal feedlots.

During most summers, since the time the widespread occurrence of hypoxia was first observed, in the mid-1980s, resultant organic matter production has led to extensive bottom-water hypoxia (through microbial respiration), mainly on the Louisiana inner shelf. The hypoxic zone there typically has covered more than 15,000 square kilometers annually since 1993 [Rabalais *et al.*, 2002]. The general consensus is that hypoxia in the northern Gulf of Mexico is controlled primarily by algal production, stimulated by excess nitrogen delivered from the

Mississippi-Atchafalaya river basin, and by seasonal vertical stratification of incoming streamflow and Gulf waters, restricting replenishment of oxygen from the atmosphere.

Here we review controversial aspects of the largely nutrient-centric view of the hypoxic region, and we introduce the full suite of sources driving the hypoxic potential, including the role of nonriverine organic matter inputs as other oxygen-consuming mechanisms. We also discuss nonnutrient, physically controlled processes that affect water column stability: the stratification envelope, as an alternative mechanism for controlling, in part, the seasonality and extent of hypoxia.

In 2000, the *Mississippi River/Gulf of Mexico Watershed Nutrient Task Force* [2001] suggested as an environmental goal that by 2015 there be a 5-year running average hypoxic zone of 5000 square kilometers, based upon a 30% reduction in total riverine nitrate flux. Last year, the U.S. Environmental Protection Agency's Science Advisory Board (SAB) produced a more rigorous and comprehensive plan for hypoxia in the