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Progress and Prospects in Atmospheric Reanalysis for Determining Climate Variability

Introduction

Analyses of global atmospheric observations in real time for numerical weather prediction (NWP) lack continuity over time because 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 multi-decadal changes. Moreover, although several reanalyses from NOAA's National Centers for Environmental Prediction (NCEP), NASA Goddard, the European Centre for Medium Range Weather Forecasts (ECMWF) and the Japanese Meteorological Agency (JMA) now exist, the task is far from done as 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 longterm variations. Many climate data sets are inhomogeneous: the record length is either too short to provide decadal-scale information or the record is inconsistent owing to operational changes in instruments, their siting, and data transmission and processing, and absence of adequate meta-data. 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.

The global setting and advances to date

The World Climate Research Programme (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 enable the optimal use of global Earth observations in a number of the domains, such as the atmosphere, ocean, and terrestrial, 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 underway.

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, analyse 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 archival; modelers, and data assimilation experts. Also, sponsors of reanalysis already have been well-rewarded, as basic assimilation and prediction systems improve as deficiencies are identified and corrected, by applying improvements to both reanalysis and routine weather and climate prediction. The products of 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, oceanographers, land surface, polar, and coupled Earth system experts are increasingly active.

Within the atmosphere, new developments are occurring as recognition occurs that 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 time scales (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 are 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, NASA Goddard, 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 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 when it was proposed twenty 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.

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Author Information

Kevin E. Trenberth, NCAR, Boulder, Colo; E-Mail trenbert@ucar.edu; Toshio Koike, University of Tokyo, Tokyo, Japan; and Kazutoshi Onogi, Japan Meteorological Agency, Tokyo, Japan