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Abstract

The long observational record is critical to our understanding of the Earth's climate, but most observing systems were not developed with a climate objective in mind. As a result, tremendous efforts have gone into assessing and reprocessing the data records to improve their usefulness in climate studies. The purpose of this paper is to both review recent progress in reprocessing and reanalyzing observations, and summarize the challenges that must be overcome in order to improve our understanding of climate and variability. Reprocessing improves data quality through more scrutiny and improved retrieval techniques for individual observing systems, while reanalysis merges many disparate observations with models through data assimilation, yet both aim to provide a climatology of Earth processes. Many challenges remain, such as tracking the improvement of processing algorithms and limited spatial coverage. Reanalyses have fostered significant research, yet reliable global trends in many physical fields are not yet attainable, despite significant advances in data assimilation and numerical modeling. Oceanic reanalyses have made significant advances in recent years, but will only be discussed here in terms of progress toward integrated Earth system analyses. Climate data sets are generally adequate for process studies and large-scale climate variability. Communication of the strengths, limitations and uncertainties of reprocessed observations and reanalysis data, not only among the community of developers, but also with the extended research community, including the new generations of researchers and the decision makers is crucial for further advancement of the observational data records. It must be emphasized that careful investigation of the data and processing methods are required to use the observations appropriately.

Keywords (separated by "-")

Essential climate variables - Climate data records - Data rescue - Data provenance - Reanalysis - Uncertainty - Bias correction

On the Reprocessing and Reanalysis of Observations for Climate

[AU1] **Michael G. Bosilovich, John Kennedy, Dick Dee, Rob Allan, and Alan O'Neill**

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1 Reprocessing Observations

A major difficulty in understanding past climate change is that, with very few exceptions, the systems used to make the observations that climate scientists now rely on were not designed with their needs in mind. Early measurements were often made out of simple scientific curiosity or needs other than for understanding climate or forecasting it; latterly, many systems have been driven by other needs such as operational weather forecasting, or by accelerating improvements in technology. This has two major consequences.

The first consequence is that although large numbers of observations are available in digital archives, many more still exist only as paper records, or on obsolete electronic media and are therefore not available for analysis. Measurements made by early satellites, whaling ships, missions of exploration, colonial administrators, and commercial concerns (to name only a few) are found in archives scattered around the world. Finding, photographing and digitizing observations from paper records and locating machines capable of reading old data tapes, punch cards, strip charts or magnetic tapes are each time-consuming and costly, but they are vital to improving our understanding of the climate. Furthermore, there is a growing need for longer, higher quality data bases of synoptic timescale phenomena in order to address questions and concerns about changing climate and weather extremes, risks and impacts under both natural climatic variability and anthropogenic climate change. Such demands are leading to a greater emphasis on the recovery, imaging, digitization, quality control and archiving of, plus ready access to, daily to sub-daily historical weather observations. These new data will ultimately improve the quality of the various reanalyses that rely on them. There is also a sense of urgency as many observations are recorded on perishable media such as paper and magnetic tapes which degrade over time. Without intervention, our ability to understand and reconstruct the past is disintegrating in a disturbingly literal sense.

The second major consequence is that current observation system requirements for climate monitoring and model validation such as those specified by GCOS (http://www.wmo.int/pages/prog/gcos/index.php?name=ClimateMonitoringPrinciples) – typically emphasizing continuity and stability over resolution and timeliness – are met by few historical observing systems. Changes in instrumentation, reporting times and station locations introduce non-climatic artifacts in the data necessitating consistent reprocessing to recover homogeneous climate records. Nevertheless, reliable assessments of changes in the global climate have been made such as the IPCC's statement that "warming of the climate system is unequivocal". This assessment relies on the many multi-decadal climate series which now exist.

Reprocessing of observations aims to improve the quality of the data through better algorithms and to understand and communicate the errors and consequent uncertainties in the raw and processed observations. Reanalyses differ from reprocessed observational data sets in that sophisticated data assimilation techniques are used in combination with global forecast models to produce global estimates of continuous data fields based on multiple observational sources (to be discussed in the following section).

1.1 Data Recovery and Archiving

A vital first step for the understanding of historical data and hence past climate is to digitize and make freely available the vast numbers of measurements, other observations and related metadata that currently exist only in hard copy archives or on inaccessible (or obsolete) electronic media. Some estimates suggest that the number of undigitized observations prior to the Second World War is larger than the number of observations currently represented in the largest digital archives.

Digitizing large numbers of observations that are printed or hand-written in a variety of languages is labor intensive: imaging fragile paper records is time consuming and optical character recognition (OCR) technology is not yet capable of dealing with handwritten log book or terrestrial registers entries, so they must be keyed by hand. Scientific projects such as CLIWOC (García-Herrera et al. 2005), RECLAIM (Wilkinson et al. 2011) and the international ACRE initiative (Atmospheric Circulation Reconstructions over the Earth, Allan et al. 2011) have worked to recover and make available these observations. More recently they have been supplemented by citizen science projects such as oldweather.org (http://www.oldweather.org) and Data.Rescue@Home (http://www.data-rescue-at-home.org/) which have reliably and rapidly digitized large numbers of meteorological observations online at the same time as increasing public engagement with science via lively e-communities. Such projects are not only of climatological interest but can also be of wider historical interest (Allan et al. 2012).

The international ACRE initiative (Allan et al. 2011) both undertakes data rescue and facilitates data recovery projects around the world and their integration with existing data archives. A number of these data archives exist. The International Comprehensive Ocean Atmosphere Data Set (ICOADS Woodruff et al. 2010) holds marine meteorological reports covering a wide range of surface variables.

The World Ocean Database (WOD, Showstack 2009) has large holdings of oceanographic measurements. The Integrated Surface Database (ISD, Lott et al. 2008) holds high-temporal resolution data for land stations. The International Surface Pressure Databank (ISPD, Yin et al. 2008) contains measurements of surface pressure from ICOADS and land stations, supplemented by information about tropical cyclones from the International Best Track Archive for Climate Stewardship (IBTrACS, Knapp et al. 2010). The Global Precipitation Climatology Centre (GPCC) has gathered precipitation observations from many different sources. The International Surface Temperature Initiative (ISTI, Thorne et al. 2011a, b) is [AU3] bringing together temperature measurements from many different sources to provide a single, freely available databank of temperature measurements combined with metadata concerning the provenance of the data. Nevertheless, these various activities are very fragile, and often only exist as a result of ‘grassroots’ actions by the climate science community (Allan et al. 2011, 2012). These projects and initiatives urgently need to be imbedded in an overarching, sustainable, fully funded and staffed international infrastructure that oversees data rescue activities, and compliments the various implementation and strategy plans and documents on data through international coordinating bodies, such as GCOS, GEO, WMO and WCRP.

The consolidation of meteorological, hydrological and oceanographic reports and observations into large archives facilitates the creation of a range of ‘summary’ data sets which are widely used in climate science and can also act as a focus for an international community of researchers. However, further consolidation could bring greater benefits. A land equivalent of the ICOADS, for example, would bring together many of the elements needed to fully describe the meteorological situation and potentially reduce the efforts that are currently expended to maintain and grow a large number of different datasets. In fact, both the terrestrial and marine data efforts need to be integrated and better linked up under an international framework that supports their activities in a fully sustainable manner.

1.2 Data Set Creation and Evaluation

The difficulties of converting raw observations into data sets which are of use to climate researchers are well documented (e.g. Lyman et al. 2010; Thorne et al. 2011a; Kent et al. 2010; Lawrimore et al. 2011; Hossain and Huffman 2008). Systematic errors and inhomogeneities in data series caused by changes in instrumentation, time of observation and in the environment of the sensor are often as large, or larger than, the signals we hope to detect. Without reliable traceability back to international measurement standards, the problem of detecting and accounting for these errors is not easy. Before the satellite era, observations were often sparsely distributed. Various methods have been devised to impute the values of climatological variables at locations and times when no such observations were made. The problems are further compounded by the necessity of making approximations, using uncertain inputs (such as climatologies), the use of different data archives and having sometimes limited statistics with which to estimate important parameters. Three examples will help to illustrate some of these difficulties and the way that they have been tackled.

One long running example is seen in the different reprocessings of the data from the satellite-based Microwave Sounding Units (MSU) which can be used to derive vertical temperature profiles through the free atmosphere (Thorne et al. 2011a). The earliest processing by Spencer and Christy (1990) suggested a monthly precision of 0.01° C in the global average lower troposphere temperatures but the lack of a trend in the satellite data was not physically consistent with contemporary surface temperature estimates. However, when other teams (Prabhakara et al. 2000; Vinnikov and Grody 2003; Mears et al. 2003) processed the data they found quite different long term behavior. Successive iterations of the datasets have considered an increasingly broad range of confounding factors including orbital decay, hot target temperature and diurnal drift. Twenty years of analysis and reprocessing have undoubtedly improved the overall understanding of the MSU instruments (Christy et al. 2003; Mears and Wentz 2009a, b), the quality of the data sets and estimates of atmospheric temperature trends, but despite these improvements temperature trends from the different products still do not agree. This implies either the existence of unknown systematic effects, or significant sensitivity to data processing choices. Mears et al. (2011) used a monte-carlo approach to assess the uncertainty arising from data processing choices, but this did not fully bridge the gap between their analysis and others.

In the past decade, the view of ocean heat content has changed considerably. Early estimates of global ocean heat content (Levitus et al. 2000) showed marked decadal variability. Gouretski and Koltermann (2007) identified a time-varying bias in measurements made by eXpendable BathyThermographs (XBT). An XBT is a probe that is launched from the deck of a ship and falls down through the ocean trailing behind it a fine wire that relays water temperature measurements to the operator. The depths of the measurements are estimated from an equation that relates time-since-launch to depth. Gouretski and Koltermann (2007) found that there were time-varying differences between the actual and estimated depths. Since 2007, various groups (Wijffels et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009; Gouretski and Reseghetti 2010; Good 2011) have proposed adjustments for the XBT data based on a number of factors including, the make and model of the XBT, water temperature (which is related to viscosity) as well as a pure thermal bias of unknown origin. By running the different correction methods on a defined set of data, it has been possible to begin to assess the uncertainty arising from the different parts of the reprocessing e.g. bias adjustment, choice of climatology etc. (Lyman et al. 2010).

The third example provides contrasting depth to the problems at hand. A number of sea-surface temperature data sets extend back to the start of the twentieth century (and before). Because observations become fewer the further back in time one goes, statistical methods are used to estimate SSTs in data gaps. However, as before, the data sets differ. Trends in SSTs in the tropical Pacific show different behavior depending on the data set used. Some data sets show an El Niño-like pattern, others a La Niña-like pattern (Deser et al. 2010) indicating that uncertainty in long-term trends can arise from sources other than systematic instrumental error.

Because of the obvious difficulties with observationally-based data sets, it is dangerous to consider them as unproblematic data points which one can use to build and challenge theories and hypotheses regarding the climate. The reality is not so simple. The data sets are themselves based on assumptions and hypotheses concerning the means by which the observed quantity is physically related to the climatological variable of interest. In the first example given above, the MSUs are sensitive to microwave emissions from oxygen molecules in the atmosphere. To convert the measured radiances to atmospheric temperature requires knowledge of atmospheric structure, the physical state of the satellite, quantum mechanics and orbital geometry.

In the first two examples above, the earliest attempts to create homogeneous data series underestimated the uncertainties because they did not consider a wide enough range of systematic effects. The physical understanding of the system under study was incomplete. Such problems are not unique to the study of climate data; see for example, Kirshner (2004) on the difficulties of estimating the Hubble constant. The uncertainty highlighted by the differences between independently processed data sets is often referred to as *structural* uncertainty. It arises from the many different choices made in the processing chain from raw observations to finished product. Part of this difference will arise from the different systematic effects considered – implicitly and explicitly – by the groups, but part will also arise from the different ways independent groups tackle the same problems. In most cases there are a wide variety of ways in which a particular problem can be approached and no single method can be proved definitively to be correct. The uncertainty associated with small changes in method (for example, using a 99 % significance cutoff as opposed to 95 % for identifying station breaks) can be assessed using monte-carlo techniques (see e.g. Mears et al. 2011; Kennedy et al 2011; Williams et al. 2012) and is referred to as *parametric* uncertainty to differentiate it from the deeper – and often larger – uncertainties associated with more significant structural chances that can only be assessed by taking independent approaches.

This slow evolution underlies what drives improvements in the understanding of the data. It also highlights the fact that no reprocessing is likely to be final and definitive. These considerations show the ongoing importance of making multiple, independent data sets of the same variable and many analyses that rely on climate data sets use multiple data sets to show that their results are not sensitive to structural uncertainty.

Comparisons between different methods have been used to assess the relative strengths and weaknesses of different approaches. Side by side comparisons of existing data sets have been made (Yasunaka and Hanawa 2011) but the use of carefully designed tests datasets can be far more illuminating. Real observations can be used (e.g. Lyman et al. 2010), but in this case the 'true' value is unknown. By using synthetic data sets, where the truth is known, much more can be learned (e.g. Venema et al. 2012; Williams et al. 2012). The use of carefully designed test data sets has been used in metrology to understand uncertainties associated with software in the measurement chain. However, the National Physics Laboratory (NPL) best practice guide on validation of software in measurement systems (NPL report DEM-ES 014) excludes measurement systems where the physics is still being researched which is arguably the case for many climate data sets. The International Surface Temperature Initiative (ISTI Thorne et al. 2011b) is developing a sophisticated process for developing test data sets based on synthetic 'pseudo-observations' that have been constructed to contain errors and inhomogeneities thought to be representative of real world cases. By running the algorithms designed to homogenize station data on these analogues of the real world as well as on the real data, it will be possible to directly compare the performance of different methods. Tests like these have been used to study the effectiveness of paleo-reconstruction techniques (Mann and Rutherford 2002) and have long formed the basis of Observing System Simulation Experiments (OSSE's). Ideally, such processes need to be ongoing for two reasons. Firstly, benchmark tests become less useful over time because there is a danger that the methods will become tuned to their peculiarities. Secondly, because the benchmarks might not address novel uses of the data or reflect new understanding of the error structures present in real world data.

Such methods are less effective for assessing homogenization procedures where they are based on empirical studies (Brunet et al. 2011), or on physical reasoning (Folland and Parker 1995). However, they could be used to cross-check results if statistically-based alternatives can be developed. A more empirical approach to the problem of assessing data biases is to run observational experiments (Brunet et al. 2011) whereby different sensors, including historical sensors, are compared side by side over a period of years. Such comparisons can be used to estimate the biases and associated uncertainties that can be used to cross check other methods, and in periods with fewer observations they may be the only means of assessing the data uncertainties.

Greater emphasis is now being given to the importance of uncertainty in observationally-based data sets, but it is not always clear how a user of the data should implement or interpret published uncertainty estimates. The traditional approach of providing an error bar on a derived value is often unsatisfactory because it provides information only on the magnitude of the uncertainty, but not how uncertainties co-vary. For example in the schematic in Fig. 1, each of the red lines is consistent with the median and 95 % uncertainty range indicated by the black line and blue area. By providing only the black line and 'error bar', information concerning (in this case) the temporal covariance structure of the errors is lost. This has implications when the data are further processed, because the covariance is needed to correctly propagate the uncertainties.

Recent approaches have drawn representative samples (roughly equivalent to the red lines shown in Fig. 1) from the posterior distributions of statistically reconstructed fields (Karspeck et al. 2011; Chappell et al. 2012) or representative samples from a particular error model (Mears et al. 2011; Kennedy et al. 2011). Each sample, or realization, can then be run through an analysis to generate an ensemble of results that show the sensitivity of the analysis to observational uncertainty.

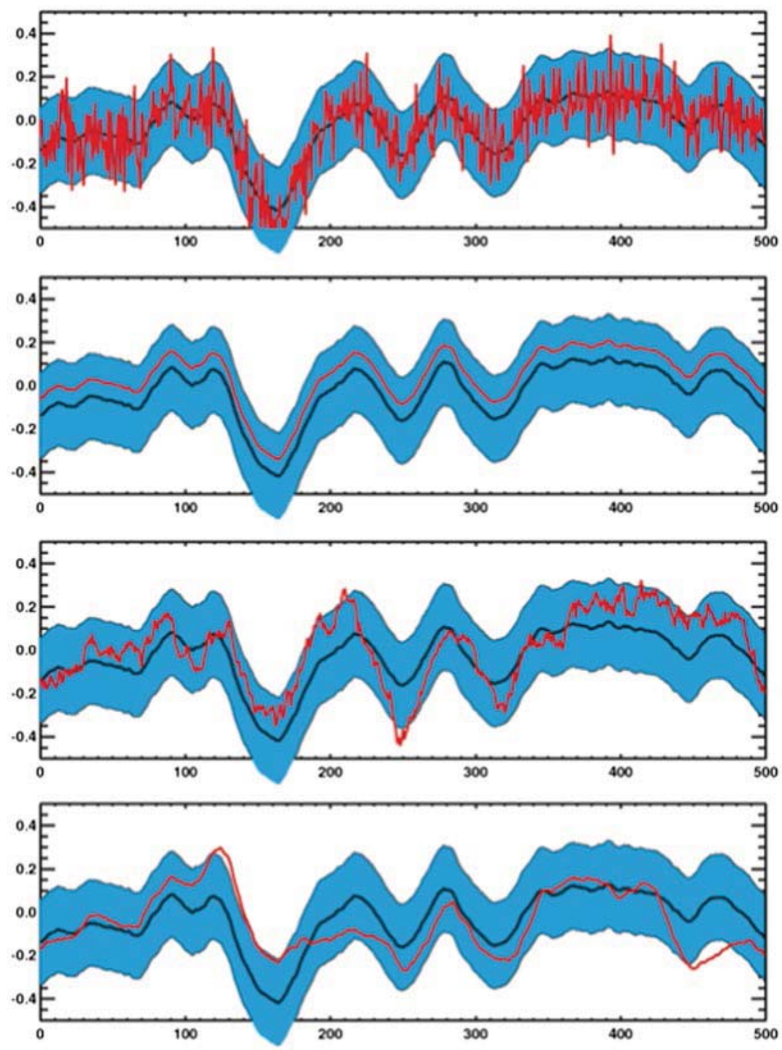

Fig. 1 Four examples showing that very different behaviors are consistent with the same 'error bars'. (*Top*) uncertainty range indicates that high-frequency variability is missing. (*second* from *top*) uncertainty range indicates a systematic offset. (*bottom* and *second* from *bottom*) uncertainty range indicates red-noise error variance

While these issues have been important for assessing large scale long term climate change, the challenges become even more formidable when data sets are used to assess climate change at higher resolution in time and in space. It is the extremes of weather that most often have the highest societal impacts and detecting and attributing changes in the statistics of these events is hampered by sparse data and poorly characterized uncertainties (see the OSC Community Paper on Extremes by Alexander et al.). The analysis of extremes demands more careful quality control – which in turn necessitates greater understanding of the underlying processes – because unusual events can sometimes resemble data errors and vice versa. In order to provide the data sets demanded by climate services the problems detailed above need to be resolved for a new generation of high resolution data set; from the discovery imaging and digitizing of paper records and metadata, through the management of appropriate archives, the generation of multiple independent data sets and their intercomparison to the wide dissemination and documentation of the final products.

Addressing the above concerns is vital for the creation of Climate Data Records (CDR http://www.ncdc.noaa.gov/cdr/guidelines.html), defined by the National Research Council (NRC) as “a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change”. At the moment, the concept of a CDR has been associated with satellite processing, but a similar approach would be illuminating for in situ measurements of other geophysical variables. Of particular interest, from this point of view are the importance accorded to transparency of data and methods. Openness and transparency have many advantages over their opposites. They lay bare the assumptions made in the analysis: although methods sections in papers can adequately describe an algorithm, there is always the danger of ambiguity, or unstated assumptions. Where computer codes are provided, they unambiguously describe the methods used. In addition, the discovery and correction of errors in data and analysis are greatly facilitated, as is the reuse of methods in later analyses (Barnes 2010). The Climate Code Foundation (http://climatecode.org/) has been set up to help improve the visibility, availability and quality of code used in climate assessments and has recoded the NASA Goddard Institute of Space Studies global temperature data set, which has been developed over a number of years, in a single consistent package.

Assessing the quality of anything is a difficult task (Pirsig 1974) and CDRs are no exception. Indices attempting to measure the quality, or maturity of CDRs have been proposed (www1.ncdc.noaa.gov/pub/data/sds/cdrp-mtx-0008-v4.0-maturity-matrix.pdf). These include considerations of criteria such as scientific maturity, preservation maturity and metadata completeness as well as highlighting the importance of independent cross-checks and the provision of validated uncertainty estimates. A concept such as “maturity” is dangerous when applied to a single dataset: longevity and quality are not equivalent. As shown above, scientific maturity has typically developed by means of making *multiple independent* data sets. Even when considering the understanding of a variable across a range of data sets, difficulties arise because systematic errors in the data can go undetected for many years. “Immaturity” has only ever been obvious in hindsight.

Climate research encompasses a large range of studies, from process studies, overlapping more traditional research, that focus on large space-time scale interactions and coupling (i.e, feedbacks) to global, long-term monitoring (change detection) and attribution (change explanation). Planning for the needs of all of these uses is difficult. The need for greater transparency and traceability of raw data characteristics, analysis methods and data product uncertainties also have to help users judge whether a particular product is useful for a particular study. Given the large range of data products currently available—both raw and analyses—it is sometimes difficult for users to identify, locate and obtain what they need unless there is an organized set of information available. A number of approaches can help users find the data they need.

First, users need information about the various data sets. Journal papers and technical reports describing data set construction are often less useful as user guides, with technical details hidden behind journal paywalls or spread across a series of publications. Initiatives such as the Climate Data Guide project aims to provide expert and concise reviews of data and quality (http://climatedataguide.ucar.edu/). By comparing data sets side by side in a common setting, it should be easier for users to understand the relative strengths and weaknesses of different data sets.

Second, the users need to be able to find the data. This is easiest to do if there exists a common method for data discovery. At the basic level of individual meteorological reports, there exist a large number of archives (as mentioned before). At a higher level, there is no single repository for gridded and otherwise processed observational data sets that is analogous to the CMIP archive of model data (Meehl et al. 2000). Generating such an archive would have the dual effect of giving users easy access to the data in a standard format while allowing data producers to get their work more widely recognized. Presenting different data sets side by side will also serve to highlight the uncertainties in the observations themselves. A problem common to all data sets is that of accurate citation. Where data sets are regularly updated, a citation to a journal paper might not be sufficient to allow full reproducibility. Data archives could allow systematic version control of data set through a common mechanism allowing future users to extract a particular data set downloaded at any time. There is a growing concern about archiving and ready access to all of these data under a viable system that can easily handle the storage and access to an ever expanding volume of data. By combining such an archive with detailed provenance information, as anticipated by ISTI, would allow users to use data of a kind that is appropriate for their particular analysis. In gathering together observational data, thought must also be given to archiving and systematizing metadata and documentation. Such things as, quality flags, stations histories, calibration records, reanalysis innovations and feedback records, observer instructions, and so on, provide valuable information for analysts. Ideally, archives of metadata should coexist with the archives of data to which they refer.

Third, the information and data sets need to be integrated. There is not as yet a systematic way to gather value that has been added by a community that works with the data. The Climate Data Guide points to the data, but the data exist in a variety of formats. Collections of data sets exist, but they are sometimes divorced from the expert guidance necessary to understand them. A number of initiatives are addressing these problems. The ICOADS does incorporate some information concerning quality control, or bias identification and adjustment, but the IVAD (ICOADS Value-Added Data http://icoads.noaa.gov/ivad/) data base plans to add a layer which will give users access to a range of value-added data. The ISTI (International Surface Temperature Initiative) plans to create an archive of air temperature data and go further by planning to include other variables, as well as full provenance information for each observation in the archive allowing users to drill down from fully analyzed products to the original handwritten note made by the observer. Other projects, such as Group for High Resolution Sea Surface Temperature (GHRSST, www.ghrsst.org; Donlon et al. 2007), have produced alternative models for their own user communities that give access to greater detail allowing them to make their own evaluations of uncertainty.

1.3 Recommendations

1. Projects and initiatives concerning data digitization and archiving of basic observations urgently need to be imbedded in an overarching, sustainable, fully funded and staffed international infrastructure that oversees data rescue activities, and compliments the various implementation and strategy plans and documents on data coming out of GCOS, GEO, WMO, WCRP and the like.
2. Terrestrial and marine data efforts need to be integrated and better linked up under an international framework that supports their activities in a fully sustainable manner.
3. An archive of observational data sets analogous to the CMIP archive of model data, should be set up and integrated with user-oriented information such as the Climate Data Guide.

2 Reanalysis of Observations

Reanalyses differ from reprocessed observational data sets in that sophisticated data assimilation techniques are used in combination with global forecast models to produce global estimates of continuous data fields based on multiple observational sources. One advantage of this approach is that reanalysis data products are available at all points in space and time, and that many ancillary variables, not easily or routinely observed, are generated by the forecast model subject to the constraints provided by the observations. An important disadvantage of the reanalysis technique, however, is that the effect of model biases on the reanalyzed fields depends on the strength of the observational constraint, which varies both in space and time. This needs to be taken into account when reanalysis data are used for weather and climate research (e.g. Kalnay et al. 1996). Nevertheless, recent developments in data assimilation techniques, combined with improvements in models and observations (e.g. due to reprocessing of satellite data) have led to increasing use of modern reanalyses for monitoring of the global climate (Dee and Uppala 2009; Dee et al. 2011b; Blunden et al. 2011).

With multiple reanalyses now available for weather and climate research, investigators must consider the strengths and weaknesses of each reanalysis. Estimates of the basic dynamic fields in modern reanalyses are increasingly similar, especially in the vicinity of abundant observations (Rienecker et al. 2011). The physics fields (e.g. precipitation and longwave radiation) are more uncertain due to shortcomings in the assimilating model and its parameterizations. Understanding the effect of model errors is important both for users and developers of reanalyses, and ultimately needed to further improve the representation of climate signals in reanalysis. Observations provide the essential information content of reanalysis products; their quality and availability ultimately determines the accuracy that can be achieved. The types of observations assimilated span the breadth of remotely sensed and instrumental in-situ observations. Dealing with the complexities and uncertainties in the observing system, including data selection, quality control and bias correction, can have a crucial effect on the quality of the resulting reanalysis data.

Given the importance of reanalysis for weather and climate research and applications, successive generations of advanced reanalysis products can be anticipated. In the near future, coupling ocean, land and atmosphere will allow an integrated aspect of the reanalysis of historical observations, but may also increase the presence of model uncertainty. However, with the complexity of all the components of the Earth system, realizing the true potential of such advancements will require coordination, not only among developers of future reanalyses but also with the research community.

2.1 Current Status

The most used and cited reanalysis is the NCEP/NCAR reanalysis, which includes data going back to 1948 (Kalnay et al. 1996). The 45 year ECMWF reanalysis (ERA-40, Uppala et al. 2005), which stops in August 2002, has also been extensively used in weather and climate studies. Both of these reanalyses span the transition from a predominantly conventional observing system (broadly referring to in situ observations and retrieved observations that are assimilated) to the modern period with abundant satellite observations, marked by the introduction of TOVS radiance measurements in 1979. Many spurious variations in the climate signal have been identified in these early-generation reanalyses (Bengtsson et al. 2004; Andersson et al. 2005; Chen et al. 2008a, b), mainly resulting from inadequate bias corrections of the satellite data and modulated effects of model biases related with changes in the observing system. There now exist several atmospheric reanalyses covering the post-1979 period that are being continued forward in near-real time. The Japanese 25-year Reanalysis (JRA-25), released for use in March 2006 (Onogi et al. 2007) is the first effort by the JMA, and their second, JRA-55 is underway (Ebita et al. 2011). The National Centers for Environmental Prediction (NCEP) second reanalysis (NCEP-DOE, Kanamitsu et al. 2002) improved upon the NCEP/NCAR reanalysis data. More recently, ECMWF has produced the ERA-Interim reanalysis based on a 2006 version of their data assimilation system (Dee et al. 2011a), in preparation for a new climate reanalysis to be produced starting in 2014. NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA) was developed as a tool to better understand NASA's remote sensing data in a climate context (Rienecker et al. 2011). The NCEP Climate Forecast System Reanalysis (Saha et al. 2010) became available in early 2010, produced with a data assimilation system that includes precipitation assimilation over land, and a semi-coupled ocean/land/atmosphere model and intended for seasonal prediction initialization. This is a brief description of the latest atmospheric reanalyses. The basic information about the data can be found at http://reanalyses.org/atmosphere/comparison-table, along with similar information for the latest oceanic reanalyses.

While the fundamental strength in resolving dynamical processes remains, recent reanalyses have improved on many aspects of the earlier-generation systems. Direct assimilation of the remotely-sensed satellite radiances, rather than assimilation of retrieved state estimates, has become the norm. Variational bias correction of the satellite radiances effectively anchors these data to high-quality observations from radiosondes and other sources (Dee and Uppala 2009; used in ERA-Interim, MERRA, and CFSR as well as the forthcoming JRA-55). The recently completed CFSR is the first reanalysis to use a weakly-coupled ocean/atmosphere model, and also assimilates precipitation data over land. In addition to the technical and scientific improvements of the reanalysis systems, increased computational resources allow the use of higher-resolution models that better resolve the observations. These advances combined have lead to improved representations of many physical parameters and processes in reanalyses, for example improved skill of the large-scale global and tropical precipitation (Bosilovich et al. 2008, 2011). In addition, the need for reanalyses to contribute to climate change studies has prompted significant innovations. For example, the twentieth century Reanalysis (20CR) project carried out by NOAA in collaboration with CIRES uses the available global surface pressure observations and sea surface temperature record reconstructed through the 1870s in an ensemble-based global analysis method. The resulting analysis is able to produce weather patterns with the quality of a modern 3-day numerical forecast (Compo et al. 2011).

Even with substantial improvements, assessment of the uncertainties in reanalysis output, especially in the physical processes needed to study climate variations and change, remains a significant concern. For a more complete picture of the climate system, as represented by reanalyses, the impact of the observations on the resulting data should be captured in the analysis of the physical processes (as in Roads et al. 2002). Even the most recent reanalyses demonstrate, to varying degrees, shifts in the time series that can be related to changes in the observing systems being assimilated (Dee et al. 2011a, b; Saha et al. 2010; Bosilovich et al. 2011). These shifts, which may be due to changing biases in the observations, systematic errors in the assimilating model, or both, interfere with the ability to detect reliable climate trends from the reanalyses. While there are some post-processing techniques that may address these spurious features (Robertson et al. 2011), dealing with biases in models and observations remains the most difficult challenge for the reanalysis and data assimilation community in developing future generations of climate reanalyses.

The number of global reanalyses has increased greatly in recent years, as computing improves, and various entities have need for specific missions to support.

Furthermore, spanning the various Earth system disciplines shows that uncoupled ocean and land reanalyses are being performed as regularly as those for the atmosphere (Guo et al. 2007; Xue et al. 2011; an evolving list of reanalyses is maintained at *reanalysis.org*). Regional reanalyses attempt to improve upon the local representation of climate and processes that must be handled more generally in global systems (Mesinger et al. 2006; Verver and Klein Tank 2012). While this increase in new reanalyses can cause additional work for the research community in understanding the various strengths and weaknesses, it does provide opportunity to more quantitatively investigate the uncertainties of the reanalysis data. For example, in studying the global water and energy budgets Trenberth et al. (2011) characterized the range of values for each term. In addition, collections of analyses have been used to derive a super ensemble mean and variance for the ocean (Xue et al. 2011), land (Guo et al. 2007) and atmosphere (Bosilovich et al. 2009). While the ensembles can expose biases in the character of various reanalyses, there is some evidence that the ensemble itself can also provide reasonable data from weather to monthly timescales. Despite the difficulties in dealing with a large amount of data, a researcher will find more advantage to have multiple data sets available for study. Just as several coupled model integrations are required for present day and future climate projections, multiple reanalyses will better contribute to the characterization of present day climate. Reanalyses may well benefit from common data standards that facilitate evaluation and analysis of the IPCC climate change experiments.

2.2 Integrating Earth System Analyses

Observations are the critical resource for a reanalysis, which needs as many as possible to characterize the state of the Earth system. As decadal predictions begin to play a role in understanding near-term climate variations, the Earth system ocean/land/atmosphere needs to be initialized in a balanced state. Newer measurements, such as aerosols, sea ice and ocean salinity contribute to the need for reanalyses that encompass the broad Earth system. Therefore, Integrated Earth Systems Analysis (IESA) encompasses the connections of these disparate observations, and have become an important challenge for data assimilation development.

NCEP CFSR provides a reanalysis produced with a semi-coupled ocean/land/atmosphere model, along with an analysis of land precipitation gauge measurements (Saha et al. 2010). Development of the next reanalysis from NASA includes aerosols, ocean (temperature and salinity), land (soil water) and ocean color (biology) analysis. While there are significant difficulties in both the modeling and assimilation of the integrated Earth system, extending these more complex reanalyses to historic periods, when little or none of the diversity in observations is available will require even more effort on addressing the impact of changes in the observing systems. Likewise, maintaining and expanding many of the Earth observations forward in time is also a critical issue (Trenberth et al. OSC position paper on observing system), and reference networks can provide stable benchmarks for reanalyses and their data assimilation. Consistency and overlap of newer systems will help maintain the consistency in the integrated reanalyses.

2.3 *Reanalysis Input Observations*

Essentially, reanalyses without input observations revert to model products, hence the importance of the observing system emphasized here. As discussed previously, there are numerous value added advantages from reanalysis, but they cannot replace observed data. It is very important, especially for new reanalysis users, to understand that reanalyses are *not* observations, but rather, an observation-based data product. Since reanalyses combine many types of observations, their relative comparison should be valuable in assessing the quality of the observation as well. However, it is not always easy to determine which observations are included in the reanalysis at specific spatio-temporal coordinates. Any given observation will be weighted with other nearby observations and the model forecast in the assimilation process. It may be accepted or rejected, and if accepted will contribute to the overall analysis including other accepted observations. The degree to which an observation influences an analysis can be determined from the output background model forecast error and the analysis error (as discussed in Rienecker et al. 2011).

Such output data have been available from reanalysis and data assimilation products for some time, but generally only used by developers or those closely familiar with the data assimilation methodology. However, these assimilated observations represent a key component in the output of the reanalyses, and can show which observations are used and how. For example, Haimberger (2007) used feedback information from ERA40 to better characterize inhomogeneities in the radiosonde time series, and this information was, in turn, used to improve the input observations to both ERA-Interim and MERRA. To facilitate broader access, assimilated observations need to be provided in a format easily accessible to the reanalysis users, so that users can more appropriately identify the agreement between observed features (including all sources of a given state variable) and reanalysis features at any specific point in space and time. Even just the capability of easily determining the presence (or lack thereof) of assimilated observations during a given event would be useful in many research studies. Typically, the data is produced in "observation-space", in that, it is an ascii record including space and time coordinates. To facilitate comparisons with the gridded reanalysis output, the GMAO has processed MERRA's assimilated observations to its native grid (Rienecker et al. 2011) called the MERRA Gridded Innovations and Observations (GIO). It includes each observation, its forecast error and analysis error (as well as the count of observations and variance within the grid box). Similarly, recent efforts at ECMWF aim to make assimilated observations and the "feedback" files available through a WWW interface. With these data, researchers can quickly identify the observation assimilated at each of the reanalysis grid points.

Of course, reanalyses rely on the broad and open availability of increasing numbers of observing systems and variables. Regarding in situ (or sometimes referred to as conventional) observing networks, reanalysis projects have been able to coordinate and update data holdings to reflect the latest quality assessments and reprocessing of the data. For the remote sensing data, however, there remains much less organization of the data and how it is used in reanalyses. As part of preparations for a new comprehensive climate reanalysis, an inventory of satellite radiances potentially available for reanalysis is currently being compiled at ECMWF. Some remotely sensed data is still assimilated as retrieved state fields, instead of radiances, and is therefore a function of the algorithm or radiative transfer model and its version, as well as the version of the input radiance.

There is significant work progressing on the radiances themselves that should affect their use in reanalyses. For example, intercalibrated MSU (channels 2–4) (Zou et al. 2006) were newly available and assimilated from the start of MERRA production, but this was not an option for reanalyses beginning prior to it. The satellite data input is generally handled by the reanalysis center, which must maintain contacts with the data community to be informed on all the latest information and updates. Presently, each center documents its own data usage, but there is no central information about this for research users to access and intercompare among reanalyses. As discussed earlier, observations are the key resource for reanalysis, reanalysis are sensitive to the assimilated observations and so, it is vitally important for reanalysis projects to have the latest information and reprocessing of the input data type, and also convey that information to the research community. The series of international reanalyses conferences have provided a focal point for discussions on the accomplishments, challenges and future directions of reanalyses (e.g. jra.kishou.go.jp/3rac_en.html and icr4.org). Additionally, a grass roots effort to open communication among reanalysis developers and the research community leveraging internet communication technology has begun and is gaining momentum (reanalysis.org).

2.4 Recommendations

1. The research community and reanalysis developers benefit from the availability of multiple international reanalysis products. Researchers should be encouraged to use as many as possible to better define the uncertainty of reanalyses. Data management practices and utilities should be developed to facilitate intercomparison among reanalyses.
2. Given the criticality of observations and their quality in reanalyses, efficient and open communications among the reanalyses developers and observation developers/stewards needs to be enhanced. Likewise, information on how the observations are used in the reanalysis can be used by the observation developers and research community. Reanalysis developers should be encouraged to provide the assimilated observations and innovations alongside the characteristic reanalysis data.
3. Interdisciplinary coupled modeling and assimilation across the atmosphere (including aerosols and the stratosphere), ocean, land and cryosphere needs significant advancement and communications to accomplish the long-term goals of integrated reanalyses.

3 Future Directions

Global data products and their further refinement will continue to be a critical resource for understanding the Earth's climate, variability and change. Not only is reduction of uncertainty for any individual product important, through improved algorithms and processing, but also, global data must be physically integrated and consistent in their use of ancillary information and consistency in assumptions. These considerations are leading to more formal assessments of global data products, such as those put forward by the GEWEX Data and Assessment Panel (e.g. Gruber and Levizzani 2008).

A substantial amount of observations are not regularly analyzed in present day research projects because it has yet to be digitized. Projects and initiatives concerning data digitization and archiving of basic observations urgently need to be imbedded in an overarching, sustainable, fully funded and staffed international infrastructure that oversees data rescue activities, and compliments the various implementation and strategy plans and documents on data coming out of international coordinating agencies. Terrestrial and marine data efforts need to be integrated and better linked up under an international framework that supports their activities. An archive of observational data sets analogous to the CMIP archive of model data, should be established and integrated with user-oriented information such as the Climate Data Guide.

The reanalysis developer and user community has increased substantially over the last decade, mostly due to the broad utility of the data. This paper has addressed some of the most pressing challenges facing the international reprocessing and reanalysis communities. WCRP has been an integral partner in the development of reprocessing and reanalyses, fostering communications within the community through workshops, conferences and its scientific panels. Recently, reanalyses data have been discussed and considered in the derivation of Essential Climate Variables (ECVs), as well as using the data for climate monitoring and information services (Dee et al. 2011b). Assessment of global data products is also a major issue for ECVs.

As can be easily seen in the overview summary of reanalyses, the reanalysis systems are evolving and growing. There will be newer, more advanced and comprehensive reanalysis data products available in coming years. Regarding the most recent reanalysis data products, there are many questions on their relative performance for the many uses and regions covered. It is not feasible for any one institution to be able to fully address the exact quality among all the reanalyses, simply because there are too many applications of reanalyses. While this does put the burden of intercomparison on the individual researcher, in quite a few instances, communication and sharing of knowledge between users and developers will have become critically important. In a grass roots effort to address the communications issues, an effort to utilize the internet and live documents has begun, to provide a forum that facilitates communication within the reanalysis community. It is considered a pilot project, and is called *reanalyses.org*. At this site, developers can contribute to a central knowledge-base regarding all issues of reanalyses.

In addition, reanalyses.org provides a function to allow users to compare reanalyses. In the long run, users are encouraged to summarize their results with pointers to detailed information and ultimately publications on the ongoing efforts. While this should not be the sole effort to facilitate communications, it does provide an outlet and focal point for anyone in the community. The Climate Data Guide (climate-dataguide.ucar.edu) provides concentrated information and expert analysis of many reprocessed data set, data sources for reanalysis and the reanalyses themselves. Another platform, the Earth System Grid (ESG) is under development and will allow users to easily compare the existing reanalyses with observations and also CMIP present day simulations. While significant challenges remain, the active communities of users and developers have numerous avenues of information and interaction to pursue the solutions.

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Author Queries

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Queries	Details Required	Author's Response
AU1	Please confirm the corresponding author and also affiliation of all authors.	
AU2	Citations García-Herrera (2005a), Thorne et al. (2010), Prabhakara (2000), Good (2010), Yasunaka et al. (2011) have been changed to García-Herrera et al. (2005), Thorne et al. (2011), Prabhakara et al. (2000), Good (2011), Yasunaka and Hanawa (2011) as per the reference list. Please check.	
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