Ongoing Analysis of the Climate System: A Workshop Report

Boulder, Colorado
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WORKSHOP ON ONGOING ANALYSIS OF THE CLIMATE SYSTEM
EXECUTIVE SUMMARY

The world's weather and climate vary continuously on all time scales, and the observation and prediction of these variations is vital to many aspects of human society. One essential aspect of a comprehensive climate observing system is the capability to synthesize observations into a coherent, internally consistent depiction, or analysis, of the evolution and present state of global climate. To further the planning that will ensure such a National capacity, a Workshop on Ongoing Analysis of the Climate System, sponsored by NOAA, NASA and NSF, was held in Boulder, Colorado, from August 18-20, 2003.Approximately 65 scientists and managers from several Federal agencies, the academic community and overseas reanalysis groups participated. The workshop had two principal objectives: to provide guidance on the steps needed to ensure that ongoing developmental ocean, atmosphere and land surface data assimilation/reanalysis efforts remain complementary, and to identify near-term, high priority actions required for future atmospheric reanalyses that will:

- Deal more effectively with the changing climate observing system and with uncertainties in analyzed fields;
- Improve the description of atmospheric interactions with the land, ocean and cryosphere; and
- Improve the description of the hydrological cycle.

This report summarizes the results of the Workshop. Additional information can be found on the Workshop web page at http://www.joss.ucar.edu/joss_psg/meetings/climatesystem/.

The Workshop began with a discussion of the benefits of climate analyses and reanalyses, together with a description of the drawbacks of available datasets. While prior efforts have made it possible to describe and begin to understand the long term mean state of the atmosphere and much of its variability, there remains scope for significant improvement. Not all trends and long time scale variability are well represented, budgets of basic quantities such as heat, momentum and moisture do not fully balance, some fundamental modes of variability such as the diurnal cycle are incorrect, and efforts to date have utilized systems optimized for weather prediction rather than climate analysis. Furthermore, there is no comprehensive description of uncertainty in analyzed fields. Clearly further efforts are required to achieve the necessary integrated perspective on the climate system.

Descriptions of the several pioneering efforts conducted so far and the lessons learned during those projects were presented next. The U.S. National Centers for Environmental Prediction (NCEP), in collaboration with the National Center for Atmospheric Research (NCAR), completed a reanalysis of the period beginning in 1948 that continues to be updated. The European Centre for Medium Range Weather Forecasts (ECMWF) has just completed a reanalysis of the period from September 1957 to August 2002 using a relatively high resolution and modern system. The U.S. Global Modeling and

Assimilation Office (GMAO – formerly the Data Assimilation Office) of the National Aeronautics and Space Administration (NASA) has conducted several reanalyses for specific purposes, including one of the period from 1980 to 1995, and has plans for more efforts. The Climate Prediction Division of the Japan Meteorological Agency (JMA), in partnership with other organizations in Japan, has begun a reanalysis of the period from 1979 to 2004.

It is clear that an ongoing program of climate analyses and reanalyses is required for the U.S. to accomplish its climate monitoring and prediction mission. A proposed program consisting of three threads, covering the post-satellite era (R1979), the era of upper air observations (R1950), and the era of quantitative surface observations (R1850), was presented. The possibility of including a higher resolution regional reanalysis, such as the pioneering Regional Reanalysis conducted by NCEP, was discussed, and the many complex infrastructure and institutional issues involved were described.

The Workshop concluded that the U.S. must establish a U.S. National Program for Ongoing Analysis of the Climate System to provide a retrospective and ongoing physically consistent synthesis of earth observations in order to achieve its climate monitoring, assessment and prediction goals. The program would comprise a substantial data development activity, a research element including a grants program to improve methods and products, and an on-going operational production component with periodic reanalyses of the historical record and ongoing data distribution. The development strategy will be tailored to different time scales, and the entire program will have an infrastructure that facilitates participation by the entire community and an interagency approach that capitalizes on the strengths and expertise of various organizations. Reports from five Working Groups: Hydrological Cycle, Surface Coupling, New Scientific Developments in Assimilation and Analysis, Data and Observing System Issues, and Implementation and Infrastructures Issues, provided detailed findings and recommendations.

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WORKSHOP ON ONGOING ANALYSIS OF THE CLIMATE SYSTEM

1. Introduction/Background

The world's weather and climate vary continuously on all time scales. The observation and prediction of these variations is vital to many aspects of human society. Extreme weather events can cause significant loss of life and damage to property. Seasonal to interannual changes associated with the El Niño/Southern Oscillation (ENSO) phenomenon have enormous impacts on society. Determining the nature and predictability of potential global climate changes (caused by increases in carbon dioxide and other radiatively active atmospheric constituents) is crucial to our future welfare. An extensive weather observing system has been put in place over the past century, and the U.S. is now developing a comprehensive climate observing system that can provide detailed information on the past and present state of the global climate system. Billions of dollars have been invested in obtaining observations of the ocean, land, cryosphere and atmosphere from satellite and surface-based systems, and plans to enhance and improve this system are being developed. In this report, we will focus on the essential integrating and synthesizing capability that must be created as part of our national effort to observe and understand our changing climate.

One essential aspect of a comprehensive climate observing system is the capability to synthesize observations into a coherent, internally consistent depiction, or analysis, of the evolution and present state of global climate. Climate analysis differs fundamentally from weather analysis in that observations throughout this evolution can be synthesized, rather than only those prior to a certain analysis time. It provides information to allow attribution of the origins of recent climate anomalies (e.g., in temperature, precipitation and atmospheric circulation) in terms of forcings wherever possible. The forcings include forcings external to the climates system (from the sun, volcanic eruptions, and human influences) and internal to the climate system (the influences of anomalous sea surface temperatures and the ocean, land surface properties, the biosphere and land and sea ice). It provides decision-makers with consistent and accurate information about current climate events and their relation to past events, and would be a key part of ongoing assessments. It provides the datasets that enable climate modelers and forecasters to improve their models and predictions. Such an analysis can provide the feedback necessary to identify redundancies and gaps in the observing system, which, when corrected, would allow the system to operate more cost-effectively. By directly linking products to observations, such an analysis helps to optimize the design and efficiency of the observing system and improve the products the system produces, thus justifying its investment.

The need for a comprehensive, consistent analysis of the climate system has been recognized for more than twenty years. Initial efforts focused on the atmosphere and were based on the products of numerical weather predictions. Such atmospheric analyses were instrumental in shaping our understanding of climate variations on relatively short time scales, but the frequent changes in the procedures used introduced many spurious variations in the perceived climate. In the mid 1990s, projects that used fixed modern analysis systems and long time series of observations produced more consistent atmospheric climate analyses, known as reanalyses. Their products have proven to be among the most valuable and widely used in the history of climate science, as indicated both by the number of scholarly publications that rely upon them and by their widespread use in current climate services. However, they are still affected by changes in the observing systems, such as the major introduction of satellite data in 1979, and other newer remote sensing instruments.

In spite of the tremendous achievements of past efforts, the current situation is unsatisfactory for several reasons. First, reanalyses to date have focused principally on the atmosphere with systems optimized for operational weather prediction. Climate analyses can make use of observations both before and after the analysis time. Climate analyses should analyze the other components of the Earth System (such as the ocean, land, cryosphere, hydrology and biosphere) and such efforts are underway, but so far no project has even attempted to bring the entire system together into a comprehensive whole. Second, severe scientific and technological challenges must be overcome. These include the wide variations in the types of observations available that change over time, the disparate quality of models of the components of the system (in part related to the types of observations currently available), and the continuing need to take advantage of improvements in observing, modeling, computing and data storage and communication technology. Finally, the institutional arrangements required to ensure that such an analysis system could be built and operated successfully are not in place in the U.S. No agency in the U.S. government has established a sustained programmatic commitment to the establishment and continued support and operation of such a system. Without a clear and systematic institutional commitment, our future efforts will be limited to the same sorts of ad-hoc, underfunded and inadequate projects as before, and are unlikely to result in high-quality sustained or cost-effective products.

In recognition of this situation, several U.S. agencies are supporting activities related to the development of a comprehensive plan for ongoing analyses of the climate system. Under this program, global and regional analyses of the atmosphere, oceans, land surface, hydrology and the cryosphere will be conducted using four-dimensional data assimilation procedures that process the multivariate data in a physically consistent framework. These analyses would provide essential feedback to the designers and operators of the climate observing system and would enable predictive models of the climate system to handle changes in the observing system without yielding artificial variations in the inferred and predicted climate. While the analyses of the various systems will initially be conducted independently, a concerted effort to converge to a comprehensive coupled analysis will be a vital component of the activity.

The Workshop on Ongoing Analysis of the Climate System was sponsored by NOAA, NASA and NSF, and was held at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, from August 18-20, 2003. Approximately 65 scientists and managers from several Federal agencies, the academic community, and overseas reanalysis groups participated. The goal of the workshop was to advance plans to establish an ongoing capability to integrate and synthesize the wide variety of observations of the physical climate system that have been and will become available. The workshop had two principal objectives: to provide guidance on the steps needed to ensure that ongoing developmental ocean, atmosphere and land surface data assimilation/reanalysis efforts remain complementary, and to identify near-term, high priority actions required for future atmospheric reanalyses that will:

- Deal more effectively with the changing climate observing system and with uncertainties in analyzed fields;
- Improve the description of atmospheric interactions with the land, ocean and cryosphere; and
- Improve the description of the hydrological cycle.

This report summarizes the results of the Workshop. Additional information can be found on the Workshop web page at http://www.joss.ucar.edu/joss_psg/meetings/climatesystem/.

2. The Need for Climate Analyses

The Earth Observation Summit, an intergovernmental meeting held in Washington DC on July 31, 2003, agreed on the need for a comprehensive Earth Information System that will provide timely, high quality, long-term, global information as a basis for sound decision making. To this end, the Summit participants established a Group on Earth Observations and charged it with the development of a global observing strategy. The analysis and reanalysis of observations is a critical aspect of such a strategy. This Workshop on Ongoing Analysis of the Climate System is an important component of the planning for such analyses. Dr. Kevin Trenberth provided a summary of past reanalyses, advances and accomplishments and outstanding issues, as outlined below.

Trenberth et al. (*Bulletin of the American Meteorological Society,* November 2002, **83**, 1593-1602) describe the comprehensive nature of the observing system necessary to document the behavior of the global climate system. Critical components of such an observing system are:

- A climate observations analysis capability that produces global and regional analyses of products for the atmosphere, oceans, land surface and hydrology, and the cryosphere; and
- Four dimensional data assimilation capabilities that process the multivariate data in a physically consistent framework to enable production of the analyses for the components of the climate system.

Many observations are made that are useful for climate. However, they may not be usable for specific climate purposes without an evaluation of their quality and their ability to detect climate-relevant signals. As the time horizon of interest increases from weeks to decades and centuries, the range of processes that must be accurately observed and analyzed increases as well. **Given the continuing improvement in our understanding of climate observations and the need for long time series, reprocessing is and will always be a hallmark of every climate observing system (NOAA Climate and Global Change Advisory Panel, 2002).**

Prior to the first reanalyses, the analyzed climate record was beset with major discontinuities from changes in the data assimilation systems. It was difficult, if not impossible, to reliably infer anomalies and to analyze climate variability. The several reanalyses that have been conducted (see section 3) have used a stable data assimilation system and have produced fairly reliable atmospheric climate records that have enabled:

- climatologies to be established;
- anomalies to be reliably calculated;
- empirical and quantitative diagnostic studies to be conducted;
- the exploration and improved understanding of climate system processes; and
- model initialization and validation to be performed.

These reanalyses have provided a vitally needed test bed for model improvement on all time scales, especially for seasonal-to-interannual forecasts, as well as greatly improved basic observations and data bases.

We have learned a great deal from the reanalyses that have been completed so far. Extensive changes to the observing system strongly affect the variability that is inferred from reanalyses. In particular, inferred trends and low frequency variability are of limited reliability, a result exacerbated by model bias. Budgets of momentum, heat and moisture calculated from reanalyses do not balance, reducing the confidence in diagnostic studies based on the products. The hydrological cycle suffers from sensitivity to approximations in the model physics, such as the handling of atmospheric convection on scales finer than the model grid. The diurnal cycle of cloudiness and precipitation over continents during warm seasons is poorly represented. The reanalyzed fluxes between the atmosphere and the surface exhibit unrealistic behavior, limiting both their utility for applications such as forcing models of ocean circulation and the ability to perform coupled assimilations of the atmosphere and ocean or land surface.

A number of issues must be addressed for future climate analyses. The primary goal of reanalysis conducted so far has been to produce the best analysis, given available data. This inevitably makes the set of reanalyses inhomogeneous, reducing confidence on trends and long-term variability. Existing reanalyses have been creating using four dimensional data assimilation, a process developed for numerical weather prediction, where the goal is to produce the best forecast, not the best analysis. Such constraints may sometimes limit the capability of analysis systems to utilize the full historical observation database. Furthermore, while true four-dimensional data assimilation capabilities have been developed, operation numerical weather prediction realities (the need to have an analysis and a forecast ready for use promptly) mean that actual analysis procedures do not use data after the time of the analysis in the same manner as data prior to that time. This constraint is not very relevant for climate analyses, and modified techniques may be needed. Finally, all climate analyses and reanalyses make use of the same input database and produce valuable output statistics related to the quality control of observations. A concerted effort is needed to keep track of such results so that newly recovered data can be used while the benefits from prior reanalyses are maintained.

3. Lessons Learned from Pioneering Efforts

A number of climate reanalyses have been conducted already. The NASA Data Assimilation Office completed a version, in the early 1990s. Its successor, the Global Modeling and Assimilation Office (GMAO) continues to be active in using reanalyses. The US National Centers for Environmental Prediction (NCEP), together with the National Center for Atmospheric Research (NCAR), conducted a reanalysis for the period from 1948 – 1996. The European Centre for Medium Range Weather Forecasts (ECMWF) has just finished its second reanalysis, this one covering the period since 1957. At present, the Japan Meteorological Agency is working on a reanalysis that they call JRA-25. Brief reports describing the results of these efforts and the lessons learned were presented at the workshop and are summarized below.

Dr. Louis Uccellini, Director of NCEP, described the NCEP/NCAR efforts. He began by describing NCEP's role in NOAA's mission to produce weather, water and climate observations and forecasts, and to continually improve their services through integrated research and development. Weather and climate forecasts are part of the "seamless suite of products and forecasts" of the National Weather Service (NWS). Reanalysis has a number of important applications for the NWS, including weather, water and climate. The original NCEP/NCAR reanalysis is being extended operationally as the Climate Data Assimilation System, and has proven invaluable for both operational climate monitoring and for a wide variety of research studies. Well over 1000 scientific papers using the dataset have been published. Dr. Uccellini described an investigation of intense snowstorms in the US Northeast, comparing results from the earlier, relatively low resolution reanalysis with those of a newer version. The results showed that finer spatial resolution was critical in accurately depicting the significant features of such events. Since extreme events such as these storms are a significant contributor to climate variability, and since their accurate analysis is vital to skillful prediction on short time scales, it is clear that their accurate analysis and reanalysis is important for the NWS mission. He also described the relevance of reanalyses for NCEP's climate monitoring, assessment and forecasting efforts.

Dr. Adrian Simmons of the ECMWF presented the status of the most recent reanalysis performed at the centre, ERA-40, and their future plans. The ERA-40 covers the period from September 1957 to August 2002, with a spatial resolution of approximately 125 km. Support in various forms was provided by a number of partner organizations, both in the European Community and elsewhere. Access to some of the output is available through a public server, and all of the data will be available to the U.S. community through NCAR. He summarized their experience in the processing of in situ observations and the direct assimilation of satellite radiances, and discussed areas where further effort is necessary. The quality of the ERA-40 analyses is best in most recent years, and for the Northern Hemisphere troposphere and lower and middle stratosphere. The analysis of the

Southern Hemisphere was greatly improved by the availability of satellite observations beginning in the 1970s. Global temperature trends appear to be captured quite well, but regional trends must be interpreted with caution and considering model and observation biases, observation coverage, and the characteristics of the analysis system. The hydrological cycle appears to be better represented in the extratropics than in the tropics. While the stratospheric Quasi Biennial Oscillation is well depicted, other aspects of the stratosphere are problematic. The Centre continues to document the ERA-40, engage in diagnostic studies, the production of atlases, and related model studies, and is beginning the development of an updated reanalysis system.

Dr. Michele Rienecker, Director of the GMAO, described the mission and activities of this new organization. The GMAO is a new focus activity for NASA's global modeling and data assimilation efforts. It will be a core resource for NASA's Earth Science Enterprise in the development and use of satellite observations, whose main thrust will be to maximize the impact of satellite observations in climate and weather prediction using comprehensive global models and data assimilation. Among its principal priorities will be the production of research-quality assimilated datasets – focused on trace gases, aerosols and climate products, with the aim of maximizing the return of NASA's investment in Earth observations. Reanalyses have been an important tool for the GMAO's predecessor organizations, and will continue to be used extensively by GMAO. An extended reanalysis of the satellite era (1980 – 1995) was the original effort, and was succeeded by a number of special purpose, shorter time period, reanalyses devoted to specific missions or datasets. At present, the GMAO is preparing for a Modern Era Reanalysis for Research and Applications (MERRA), a funded effort to reprocess the era of satellite observations. MERRA will cover the period 1979-2009, using a spatial resolution of 1^{o} x 1.25^{o}. It will include assimilation of precipitation and coupled skin temperature, and will focus on the water and energy cycles.

Dr. Masato Sugi of the Climate Prediction Division (CPD) of the Japan Meteorological Agency (JMA) described the JRA-25 project. This project is a collaboration among CPD, the Climate Research Division of the Meteorological Research Institute of JMA, and the Central Research Institute of Electric Power Industry. Its objectives are to produce a comprehensive analysis data set from the JMA data assimilation system for the period 1979-2004 a number of purposes, including advanced operational climate, monitoring services of JMA, dynamical seasonal prediction, and for various activities in climate system and global warming studies. JMA plans to continue this analysis effort as JMA-CDAS (JCDAS) after the completion of JRA-25. JRA-25 has both an Advisory Committee and a Working Group composed of Japanese scientists, and an Evaluation Group, to which scientists from other countries are welcome, has been established. Dr. Sugi presented the planned schedule for JRA-25, and described the assimilation system and input data to be used. Dr. Sugi concluded by presenting his personal view of potential future reanalysis activities for JMA, including a JRA-30 to cover the satellite data period from 1979 – 2009, and JRA-50, which would cover the period from 1958 – 2009 and would use only conventional observations.

4. A Proposed National Program

It has been clear for some time that further reanalyses for climate were necessary. Dr. Siegfried Schubert summarized recent discussions and presented a proposed future program. The National Research Council, in a 1991 report, stated that "A coordinated national program should be implemented and funded to develop consistent, long-term assimilated data sets for the study of climate and global change". A Workshop on Global Reanalysis that took place on June 5 and 6, 2000 at the University of Maryland in College Park, MD noted a number of critical needs:

- all relevant components of the climate system, not solely the atmosphere, needed to be included;
- research and development on high priority climate analysis problems, such as the inhomogeneities in the observing network and the adequate representation of analysis uncertainties, must be supported;
- somehow, critical expertise on climate analysis problems has to be fostered and encouraged; and
- the necessary infrastructure to accomplish periodic reanalyses as warranted by improved observations and analysis systems must be ensured.

A proposal for a US National Program including an ongoing program of research and development with periodic data generation and distribution, an infrastructure that facilitates broad participation, an interagency approach that capitalizes on the strengths and expertise of various organizations, and a development strategy tailored to different time scales has been developed. The program includes a core group of scientists and support personnel dedicated to work on high priority research and development issues, open opportunities for community research and development focused on critical climate analysis problems, and partnerships with selected organizations to help with production and to facilitate validation and data distribution.

The proposed development strategy breaks the task into three analysis components: the satellite era (R1979), roughly 1979 to the present, the era of upper air observations (R1950), roughly 1950 to the present, the period with a substantial but changing upper air network, and the historical era (about 1850 to the present – R1850), the period defined by the availability of a minimal set of surface observations. This formulation recognizes the differing needs of the broad user community, and development issues, quality and scope of the data products are strongly tied to the availability of observations. The proposed product data sets would be continued into the future, thus providing a consistent basis for short and long-term climate change evaluations.

R1979 would be focused on obtaining the best comprehensive, consistent, high-resolution global dataset, with emphasis on improving the representation of the hydrological cycle and related physical processes. It would utilize latest state-of-the-art data assimilation system, and would emphasize the link between four-dimensional data assimilation and model development with efforts that utilize data assimilation output to assess and improve the model performance with a focus on hydrological cycle. R1979 would extend the use of new assimilation techniques, such as those using precipitation and cloudiness, to earlier periods. This thread would support efforts to apply a global land data assimilation system to reanalysis, to improve the depiction of ocean surface fluxes, and to develop data assimilation techniques that handle observations of atmospheric moisture more realistically. Improved stratospheric analyses, the assimilation of atmospheric constituents and aerosols, and improved satellite radiance datasets would be among the foci of R1979. Research to assess the impact of model and analysis resolution and observing system impact studies would be important elements.

R1950 would strive for improved global estimates of interannual to decadal variability by improving the consistency of the global observational dataset over the last one-half century in the face of major changes to the observing system. While four-dimensional data assimilation will be an important tool, its implementation may differ from that in operational systems. R1950 will emphasize continuity of the product datasets and the estimation of low frequency signals. This goal will require improved methods of bias estimation and correction, better understanding of the impact of changes to the observing system based on model and data sensitivity studies, and links to model experiments that explore the role of boundary forcing. R1950 will require the development of analysis techniques that best incorporate data prior to and after analysis time to optimize the fidelity of the analyzed low frequency signal and the improved use of surface observations. Close coordination with sea surface temperature dataset development, the production of optimal consistent observational datasets, and the recovery of historical observations will be critical to the success of this thread.

R1850 will focus on obtaining the best and longest possible consistent record of a limited number of surface, near surface, and upper air fields for the study of global climate variability and climate change on time scales from about a day to a century and a half. This thread is the most challenging, in terms of conventional four-dimensional data assimilation, and may have to utilize very different methodologies. Methods that obtain maximum information suitable for estimating low frequency and trend information from very sparse observations and innovative techniques for using surface observations will have to be explored. Improved methods of bias estimation and correction, extended recovery of historical observations, and the development of optimal consistent observational datasets will be required.

All three components will cover the entire globe. The possibility of a fourth thread, one that focuses on a limited spatial domain but with much finer spatial resolution, needs to be explored as well. Many applications for climate datasets, including the statistical correction of weather forecasts on fine scales and the investigation of the application of climate information to fields such as hydrology, agriculture and health, require extremely high spatial resolution, as fine as 1 km. Such a high resolution analysis can be created using a combination of data from a global reanalysis and a high resolution data assimilation system. A prototype regional reanalysis has recently been completed by NCEP using a 32 km version of the eta model; details about the process and the output datasets can be found on their web page (http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/).

A number of infrastructure issues and requirements must be addressed. It will be critical to ensure that the various threads and their components all feed into the development of the new climate analysis system and the production of new climate data sets in a coordinated manner. The relative roles of the various major centers involved, including at least NCEP, GMAO and NCAR, must be clearly defined. How will production activities be coordinated and carried out, what will be the relationship of this program to in-house and agency priorities, how will the necessary development tasks be coordinated, and how can community participants obtain access to the appropriate datasets and computer systems? The roles and responsibilities of various organizations regarding data distribution, validation, and other shared tasks must be defined. It is critical that resources for stewardship and dissemination of results from the Program be identified. Perhaps most vitally, the question of how the interested community external to the major centers can contribute in a meaningful and timely fashion must be answered.

5. Conclusions and Recommendations

The Workshop received reports (Appendix C) from five Working Groups: Hydrological Cycle, Surface Coupling, New Scientific Developments in Assimilation and Analysis, Data and Observing System Issues, and Implementation and Infrastructures Issues. **The Workshop concluded that the U.S. must establish a National Program for Ongoing Analysis of the Climate System to provide a retrospective and ongoing physically consistent synthesis of earth observations in order to:**

- **Provide long time series of global and regional climatic analyses for use in design, evaluation, and modification of observing systems.**
- **Produce and sustain the growing climate record.**
- **Reconcile disparate climate observations and characterize analysis uncertainty.**
- **Establish initial conditions for climate prediction.**
- **Validate prediction and projection models.**
- **Provide long time series of global and regional climatic analyses for all types of prediction and projection verification.**

This Program must plan to:

- **Continue to improve upon the existing analyses and reanalyses of atmospheric, oceanic, and land surface observations.**
- **Assimilate all remotely sensed and in-situ data into a coupled, comprehensive earth system model in the longer term.**
- **Produce high resolution gridded fields of all required/relevant parameters, e.g., temperature, circulation/wind, precipitation, carbon dioxide, phytoplankton biomass, etc.**

The program would comprise a substantial data development activity, a research element including a grants program to improve methods and products, and an on-going operational production component with periodic reanalyses of the historical record and ongoing data distribution. The development strategy should be tailored to different time scales, and the entire program will have an infrastructure that facilitates participation by the entire community and an interagency approach that

capitalizes on the strengths and expertise of various organizations. The operational component of the program should utilize routine Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) to assess ongoing observing system changes and help design and optimize the system. One possible configuration for such a program, and an initial attempt at estimating the costs thereof, is as follows:

- **Data set development ($1M/year).**
- **Research and development, peer reviewed proposals ($5M/year).**
- **Operational arms of NOAA/NASA to: ($3M/year).**
  - **Update reanalyses (enhanced CDAS activity).**
  - **Continually pursue OSEs and OSSEs to document impact of continuing observing system changes.**
  - **Actively participate in observing system development.**
- **Production phases: ($1.5M/year enhancement).**
  - **Post 1979 reanalysis with goal of continuous climate record.**
  - **Post 1950 reanalysis with same goal.**
  - **Post 1850 surface NH oriented.**
  - **Continental-scale regional reanalysis at very high spatial resolution.**
  - **Stewardship and dissemination.**

The critical recommendations from the Working Groups are presented here; their full reports are contained in Appendix C.

Panel 1: The Hydrological Cycle

More accurate information on water and energy cycles than can be obtained from current analysis and assimilation methods is needed. We are at present unable to adequately diagnose, simulate, and predict variations in water and energy cycles on subseasonal to decadal time scales. To improve the present state of affairs, we recommend the following actions:

Observations:

- Obtain improved observations of precipitation, snow, soil moisture, upper atmosphere humidity, evaporation, and other components of the water and energy cycles.
- Incorporate such observations into model-independent global estimates of various hydrological processes.
- Encourage efforts within the remote sensing community to assess capabilities and uncertainties of water and energy budget estimates from current research and operational satellites.

Budgets:

- In addition to work on individual processes, community efforts to close the water and energy cycles over both the land and ocean from observations in order to provide benchmarks for model based analysis and prediction methodologies should be established.

Water and Energy Processes in Analysis/Assimilation Activities:

- Increased attention should be paid to physical assimilation of precipitation, cloudiness, vegetation, and other measurable components of the water and energy cycles.
- Observing System Simulation/Sensitivity Experiments should be performed to evaluate the consistency between model physics and observations.
- More realistic water and energy processes, especially those associated with convection, and boundary layer processes, should be a focus of development efforts.
- Water and energy processes in different climate analyses need to be compared and contrasted to better understand current uncertainties in depicting the hydrological cycle, with particular attention paid to spinup and spindown, comparison to observations, and the behavior and role of analysis increments.
- In addition to better characterizing mean water and energy processes, we also need to improve the description of the processes contributing to hydrological extremes such as droughts and floods.
- Since current individual analyses do not adequately represent all critical aspects of water and energy cycles, we need to understand the hydrological capabilities of a broader spectrum of climate models when placed in an assimilation environment (e.g. ESMF).
- Increased efforts should be placed on the development of coupled atmosphere-land data assimilation systems in order to achieve internally consistent, accurate and unbiased estimates of the hydrological cycle. The long-term goal is for the development of a fully coupled data assimilation system that will ensure consistency between all the sub-components of the Earth System.

Panel 2: Surface Coupling

Improved analyses of fluxes between the atmosphere and the surface, both land and ocean, are critical to improving our understanding of and ability to forecast the future of the global climate system. Accordingly, we recommend the following actions:

- Atmosphere, ocean, land surface, and sea-ice analyses, and the associated interfacial fluxes, should be “synchronized”, i.e., coordinated programmatically.
- Atmospheric reanalyses for climate purposes should be kept current as is presently done with the NCEP Climate Data Assimilation System, and as is planned by ECMWF and JMA.
- Analysis should be the best estimate of the state variables, since those are what we measure.
- The fractional coverage of ocean, land, and sea-ice must be represented as accurately as possible within the atmospheric model grid-box.
- Surface analyses should encompass:
    - surface components (including spectral fluxes) and all the elements required for their calculation (10m wind components, wind speed, surface air

temperature, air surface specific humidity, SST, atmospheric stability, cloud properties, sea level pressure, sea state);
    - stand-alone surface-only analyses that are adequate for forcing ocean general circulation models (OGCMs) and land surface models (LSMs), and for validating the surface fluxes from full atmospheric analyses and from coupled models;
    - surface analyses consistent with atmospheric analyses, assimilating available surface observations, and
    - realistic variability in the modern era with spatial resolution of 1°x1° globally, resolving the diurnal cycle, and including regional resolution as high as feasible.
- Priorities:
    - keep climate analysis current;
    - ensure accurate fractional coverage of ocean, land, and sea-ice within each atmospheric model grid-box and produce fluxes for multiple surface types;
    - improve assimilation methods so that use of surface observations is optimized;
    - assimilate cloud and precipitation observations;
    - include uncertainty in SST;
    - identify a pilot two year period with good buoy/ship coverage and land coverage for continual testing of enhancements to models, parameterizations, and assimilation methods, using withheld data for validation; and
    - gauge progress towards improved analyses by comparisons with in independent observations such as those from the SURFA project;
    - Pursue international collaboration on continual enhancement of observations, including error corrections and data archeology.
- R&D priorities:
    - Improve cloud and planetary boundary layer representations over both atmosphere and ocean so that analyses can produce realistic fluxes;
    - Transition results from research efforts, including process studies and the new U.S. CLIVAR Climate Process Modeling Teams;
    - Develop assimilation for coupled systems;
    - Improve assimilation methods so as to use surface observations more effectively; and
    - Improve assimilation methods to use satellite observations (clouds, precipitation, radiation, moisture, etc) more effectively.

Panel 3: New Scientific Developments in Assimilation and Analysis

Certain recommendations, together with the relevant science issues, for the climate analysis effort that we envision are presented below.

- **Ensemble Kalman Filter**: This is a promising, recent development by the research community. One major advantage is that it provides information about the uncertainty. It also can be extended to include assimilation at the right time, the major advantage of 4D-Var. So far it has been shown to be superior to 3D-Var only for data sparse situations. It should be pursued energetically because of its potential. An investment in 4D-Var would require many years, and may not be better, so that comparisons with ECMWF 4D-Var should be carried out.

- **Surface data reanalysis:** For the third stream (1850+) reanalysis described above, Ensemble Kalman Filtering has already shown promise. Other statistical methods, using simplified models or without models of any sort, are also promising and should be pursued.
- **Model deficiencies:** These are a very important problem, although this group does not deal with model development. One symptom of model deficiencies and biases is spurious trends when the composition of the observing system changes. Another is the lack of balance in the budgets. There should be an effort to improve the balance within the assimilation framework. There are several new promising approaches, including the Chi- approach, the use of a smoother, and statistical model corrections.
- **Assimilation of new variables:** We support the new MERRA reanalysis project of NASA with assimilation of precipitation. In addition, we recommend taking advantage of the LDAS technology and assimilating other non-prognostic variables (such as surface fluxes) at high resolution.
- **Anthropogenic changes:** Incorporate trends of greenhouse gases, and observations of land-use and land-use changes, including urbanization.
- **Additional prognostic variables:** Ozone, using both historic data and satellite-derived data, and aerosols should be assimilated. Incorporate volcanic aerosol information and atmospheric chemistry as possible.
- **Ocean Reanalysis:** They are an important component of this project, and should be carried out and current ocean reanalyses should be compared.
- **Stratospheric Reanalysis:** A large community has already begun to investigate means of improving both current and historical analyses of stratospheric circulation and temperature, and the proposed National Program should seek to take advantage of their efforts. Additionally, the use of a hybrid vertical coordinate (sigma at lower levels with pressure used above the tropopause) should be investigated.
- **Important additional variables:** Opacity, ocean color (related to upwelling, attenuation), mixed layer and thermocline depth, T/S relationship, and water masses should be investigated for potential utility.
- **Coupled reanalysis:** This is the ultimate goal, and the only one that will provide accurate fluxes. One first step approach is to incorporate ocean mixed layers.

Panel 4: Data and Observing System Issues

A principal goal of this working group was to offer recommendations to improve and develop input data for climate analyses and to address strategies for improving continuity of reanalyses. A series of recommendations on aspects of these topics are presented below.

Producing the most consistent time series rather than the best analysis at any particular time:

- Retain fairly consistent observational datasets, for example, by excluding unique observations and data from short field campaigns
- Use Observing System Experiments (OSEs) to determine the effects of changes remaining in observing system
- Focus on bias-corrected observations
- Assess uncertainties in trends and estimates of variability.

Improving datasets and the processing of data in reanalyses:

- A baseline set of observations should be created and made widely available. Closest to such a baseline dataset, but still unsatisfactory, is the Global Climate Observing System (GCOS) Upper Air Network (GUAN) of designated radiosonde stations.
- A comprehensive database of global conventional and satellite data suitable for reanalysis should be created and made available.
- A subset of the feedback files should be extracted from each available analysis for all radiosonde stations, with an emphasis on the GUAN stations, and made available.
- Efforts should be made to validate ERA-40 and improve the quality of the GUAN.
- The feedback files should be used to adjust radiosonde observations and fill in missing data, with appropriate flags, to generate an improved radiosonde record. Similar steps should be taken for other in situ observations. These steps will allow the basic data then to be used independently, for instance, for climate change detection.

Trends and Low Frequency Variability:

- Document reliability of trends and communicate them and the results of the studies to users**.**

Observing System Experiments:

- Carry out an ensemble of model simulations using defined boundary forcings to establish the model climate and its natural variability.
- Carry out selected OSEs with and without major new observing components such as VTPR (1973), TOVS (1979), SSM/I (1987)

Periodic Production Phases of Reanalyses

- Carry out a series of OSEs for different seasons to assess overall gradual changes in the global observing system by utilizing results from recent years (1998-2003) and degrading the observing system to match that of:
    - Late 1950s (include simulated weather ship observations)
    - Mid 1970s (include simulated VTPR from HIRS)
    - Mid 1980s (representing the TOVS era)
- Establish a core (base) ongoing activity to carry out OSEs and Observing System Simulation Experiments (OSSEs) to:
    - Better establish the true climate record by determining impacts of changing observing systems and interpreting reality of trends.
    - Help optimize and design observing system for climate
    - Routinely assess subtle changes in the observing system

Panel 5: Implementation and Infrastructure Issues

An Ongoing Analysis of the Climate System must be created to serve as an enduring national component of a comprehensive Environmental Earth Observing System. We recommend the following actions:

- Pursue support for the OACS as a required component of "Environmental Observations" under Section 5 (Environment and Energy) of the FY 2005 Interagency R&D Priorities.
- NOAA/NCDC and NCAR coordinate the "data activity" described above in partnership and collaboration with other agencies (see Linkages below).
- NOAA coordinates the "central activity" described above in partnership and collaboration with other agencies (see Linkages below).

- NASA, NSF, and NOAA… lead the "research activity" described above in partnership and collaboration with other agencies (see Linkages below).
- Linkages – implementation of the OACS will require extensive partnerships and collaborations, including:
    - An Interagency Working Group with members from NASA, NOAA, NSF, DOE and other agencies as appropriate.
    - Integration with the NOAA-NASA Joint Center for Satellite Data Assimilation.
    - A commitment to formal national interaction and planning with partners in labs and centers in NOAA, NASA, NSF, NCAR, DOE, LLNL, universities, and elsewhere as appropriate.
    - A commitment to international interaction and planning with international, multinational and other partners, including the European Center for Medium-Range Weather Forecasts, the Japan Meteorological Agency, the World Meteorological Organization, the World Climate Research Programme, the Global Climate Observing System, and others as appropriate.

Appendix A: Workshop Agenda

Workshop on Ongoing Analysis of the Climate System

18-20 August 2003
Boulder, Colorado

August 18 (Monday)

0900 - 0920: Goals/Objectives - Phil Arkin
0920 - 0930: Logistics, etc.
0930 - 1015: The need for climate analysis - benefits, pitfalls, etc. - Kevin Trenberth
1015 - 1030: Discussion
1030 - 1100: Break
1100 - 1145: Description of proposed program - Siegfried Schubert
1145 - 1230: Discussion
1230 - 1330: Lunch
1330 - 1400: Lessons learned/recommendations for future efforts – NCEP - Louis Uccellini
1400 - 1430: ECMWF - ERA40 - Adrian Simmons
1430 - 1500: GMAO activities - Michele Rienecker
1500 - 1530: Break
1530 - 1600: JMA - JRA-25 - Masato Sugi
1600 - 1645: Panel 1 - Hydrological Cycle
    John Roads – Scripps (Chair)
    Pete Robertson - NASA
    Chet Ropelewski - IRI/Lamont Doherty Earth Observatory
    Stan Benjamin - NOAA
1645 - 1715: Discussion

August 19 (Tuesday)

0815 - 0900: Panel 2 - Surface Coupling, and how to produce better fluxes
    Michele Rienecker – GMAO (Chair)
    Bob Weller - Woods Hole
    Bill Large - NCAR
    Tim Liu - JPL
    Huug Van den Dool – CPC/NCEP
0900 - 0930: Discussion
0930 - 1015: Panel 3 New Science Issues and Possibilities in Assimilation/Analysis -
    Eugenia Kalnay – Univ. of Maryland (Chair)
    Jeff Anderson - NOAA/GFDL
    Huug Van den Dool – CPC/NCEP
    Jeff Whitaker - NOAA

Masao Kanamitsu - Scripps
James Carton - Univ. of Maryland
Ichiro Fukimori - Jet Propulsion Lab

1015 - 1045: Break
1045 - 1115: Panel 3 - Discussion
1115 - 1200: Panel 4 - Data and Observing System Issues including changes in observing system
Kevin Trenberth - NCAR (Chair)
David Easterling - NOAA
Sakari Uppala - ECMWF
Bob Atlas - NASA/Goddard
Roy Jenne - NCAR

1200 - 1230: Discussion

1230 - 1330: Lunch
1330 - 1415: Panel 5 - Implementation and Infrastructure Issues
Jim Laver – CPC/NCEP (Chair)
Suru Saha - NCEP
Tony Busalacchi - ESSIC
Cecelia Deluca - NCAR
Ed Sarachik - JISAO
Wesley Ebisuzaki - NCEP

1415 - 1445: Discussion
1445 - 1515: Break
1515 - 1615: General discussion and formation of working groups oriented around the panels - Chair Phil Arkin

August 20 (Wednesday)

0910 - 0930: Panel 1 Report - Hydrological Cycle - Chair John Roads
0930 - 0950: Panel 2 Report - Surface Coupling, and how to produce better fluxes - Chair Michele Rienecker
0950 - 1010: Panel 3 Report - New Science Issues and Possibilities in Assimilation/Analysis - Chair Eugenia Kalnay
1010 - 1040: Break
1040 - 1100: Panel 4 Report - Data and Observing System Issues including changes in observing system - Chair Kevin Trenberth
1100 - 1120: Panel 5 Report - Implementation and Infrastructure Issues - Chair Jim Laver
1120 - 1200: General Discussion
1200 - 1215: Wrap-Up

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Appendix C: Working Group Reports

Panel 1: The Hydrological Cycle

John Roads, Chair
Pete Robertson, Chet Ropelewski, Siegfried Schubert, Phil Arkin

1. Background

The hydrological cycle links all components of the physical and biological Earth System. Accurate simulation and prediction of the hydrological cycle continues as a major research challenge. One of the objectives of this workshop is to identify near-term, high priority actions required for future atmospheric reanalyses that will improve the description of the global hydrological cycle.

Many national and international observational and research programs have an intense focus on the global water and energy cycles, with the goal of advancing our capability to diagnose, simulate, and predict water and energy budgets on a variety of time and space scales associated with natural variability. In the U.S., the Global Water Cycle is one of the Research Elements of the Climate Change Science Program (CCSP). Internationally, many components of the World Climate Research Programme (WCRP), including Climate Variability and Predictability (CLIVAR), the Global Energy and Water Cycle Experiment (GEWEX), and the Coordinated Enhanced Observing Period (CEOP), maintain a strong focus on the behavior of water in the climate system. IGOS, the Integrated Global Observing Strategy, is developing a Water Cycle Theme.

This suite of activities provides a "natural experiment" for testing the capability of current analysis systems to diagnose and simulate subseasonal to decadal variations in hydrologic processes, which should eventually help us to develop models capable of predicting even longer-term variations in the hydrological cycle.

2. Goal

The production and evaluation of analyses of the climate system are necessary steps in the development of accurate and useful coupled land, ocean and atmosphere data assimilation and prediction systems for the global hydrological cycle. The scales resolved by the analyses must include diurnal to centennial time scales, and individual catchment basins to global spatial scales. The full spectrum of water and energy processes in the system must be covered, including cold and warm season, high and middle latitude, subtropical, and tropical regions, and atmosphere, land and ocean from the subsurface to the top of the stratosphere. To enable application to water resources, streamflow, soil moisture, evaporation and precipitation must be realistically represented.

3. Findings

At present the many national and international programs utilize separate, inconsistent and imperfect atmosphere, ocean and land data assimilations. These assimilation systems do not currently maximize information extraction from a growing suite of remote sensing measurements that now make up a major component of the global observing system. Water and energy cycles are not adequately described by current atmospheric analysis systems. In fact, water and energy budgets are not a focus of the output. Many of the water and energy terms must be derived from 4 times daily instantaneous output. Analysis increments (disagreements between the model first guess and observations) still result in important non-physical contributions to the water and energy budgets. Analysis errors are often the sum of large compensating errors in individual processes. The tendency of atmospheric models to undergo a rapid monotonic drift in certain aspects of water and energy budgets, including precipitation, and surface and atmospheric fluxes, in the early hours of a forecast (referred to as spinup and spindown) remains noticeable in the most recent reanalyses. The diurnal cycle in water and energy cycle parameters is inadequately represented in present analyses, and analysis runoff needs to be improved and better related to streamflow measurements.

While we need to develop coupled assimilations in order to eventually improve coupled predictions, at present, separate land data assimilation methodologies (it should probably be clarified that most current LDAS efforts don't actually assimilate any observations) may be better for describing surface water and energy cycles than current atmospheric based analyses. The reason for this is that land data assimilations are now using observed precipitation and solar radiation as forcings (not true assimilation yet), and thus reducing errors resulting from atmospheric model shortcomings. Uncoupled land data assimilation is presently more relevant to water resources research and applications because it clearly produces better streamflow, and it may provide better evaporation and a better depiction of the soil and snow water storage. In the future, fully coupled atmosphere-land data assimilation systems should produce the best and most physically consistent estimates of the hydrological cycle including such parameters as precipitation, evaporation, snow, soil moisture, and streamflow. To achieve this goal we will need improved models, and better observations of precipitation, snow, soil moisture, upper atmosphere humidity, and evaporation, as well as improved methods for assimilation of such observations.

4. Recommendations

There are a wide variety of scientific and practical applications that require more accurate information on water and energy cycles than can be obtained from current analysis and assimilation methods. Such critical questions as: Is the hydrological cycle intensifying? cannot be answered at present. We are at present unable to adequately diagnose, simulate, and predict variations in water and energy cycles on subseasonal to decadal time scales. To improve the present state of affairs, we recommend the following actions:

Observations:

- Obtain improved observations of precipitation, snow, soil moisture, upper atmosphere humidity, evaporation, and other components of the water and energy cycles.
- Incorporate such observations into model-independent global estimates of various hydrological processes.
- Encourage efforts within the remote sensing community to assess capabilities and uncertainties of water and energy budget estimates from current research and operational satellites.

Budgets:

- In addition to work on individual processes, community efforts to close the water and energy cycles over both the land and ocean from observations in order to provide benchmarks for model based analysis and prediction methodologies should be established.

Water and Energy Processes in Analysis/Assimilation Activities

- Increased attention should be paid to physical assimilation of precipitation, cloudiness, vegetation, and other measurable components of the water and energy cycles.
- Observing System Simulation/Sensitivity Experiments should be performed to evaluate the consistency between model physics and observations.
- More realistic water and energy processes, especially those associated with convection, and boundary layer processes, should be a focus of development efforts.
- Water and energy processes in different climate analyses need to be compared and contrasted to better understand current uncertainties in depicting the hydrological cycle, with particular attention paid to spinup and spindown, comparison to observations, and the behavior and role of analysis increments.
- In addition to better characterizing mean water and energy processes, we also need to improve the description of the processes contributing to hydrological extremes such as droughts and floods.
- Since current individual analyses do not adequately represent all critical aspects of water and energy cycles, we need to understand the hydrological capabilities of a broader spectrum of climate models when placed in an assimilation environment (e.g. ESMF).
- Increased efforts should be placed on the development of coupled atmosphere-land data assimilation systems in order to achieve internally consistent, accurate and unbiased estimates of the hydrological cycle. The long-term goal is for the development of a fully coupled data assimilation system that will ensure consistency between all the sub-components of the Earth System.

Panel 2: Surface Coupling

Michele Rienecker, Chair
Bill Large, Bob Weller, Tim Liu, Huug Van den Dool, Glenn White, Yochanan Kushnir, John Young, Ben Giese, Tsengdar Lee, David Legler

1. Background

Fluxes through the interface between the atmosphere and the ocean, and land surface, including sea-ice, represent the exchanges between the fast component and those components that represent the memory in the climate system. Although critical for understanding climate variability and change, global surface flux products have large errors and are a major source of error and uncertainty for ocean and land surface products. Biases in products and analyses derived from numerical weather prediction efforts often have a deleterious effect on ocean and land simulations, leading a number of groups to generate their own products, correcting the fields input to flux computations. In addition to better products, such efforts need information on error statistics as input to ocean and land surface data assimilation. Climate observation programs and process studies, such as those of the CLIVAR program of the WCRP, are helping to address the need for more accurate measurements of fluxes. These include reference stations, ship-based observations, process studies, and the characterization of the means and uncertainties in spatial and temporal variability of fields. Our understanding of the behavior of surfaces fluxes is highly dependent on the manner in which surface boundary layer and mixing processes are parameterized in models. Ocean observations can provide a constraint on surface flux estimation yet such constraint also relies on the imperfect representation of surface and interior mixing processes.

2. Findings

Current Reanalysis surface flux products are not adequate for climate analyses (not accurate, budgets don’t close) or to force ocean and land surface models (not accurate). It is well known that there are significant flux biases in many locations. While it is often assumed that problems with variability are not as severe as those related to biases, this is not necessarily justified - errors in bias and variability could be due to the same mechanism. Of particular note are significant biases in precipitation and radiation in current analyses. Accurate precipitation is crucial for inferring land surface fluxes because of the positive feedback common to land surface models when coupled to the atmosphere. Errors in shortwave and longwave radiation at the surface are usually compensating, so it is important to use these from a common source (or address the bias in separate components).

Oceanographers and land surface hydrologists often prefer to calculate their own surface fluxes, and thus prefer accurate analyses of surface fields rather than accurate fluxes from other analyses. They commonly replace reanalysis fields with corrected fields or other observational analyses (such as satellite-based surface radiation) when needed to improve their own flux calculations. Surface data are not currently used in analyses in an optimal fashion: large differences between the state of the model and in-situ observations often lead to the exclusion of the data rather than to corrections to the analysis. Corrections for humidity are particularly problematic.

Different atmospheric analyses, such as the NCEP/NCAR and ECMWF reanalyses, are converging, but often not to agreement with observations. Progress towards improved analyses should be gauged by comparisons with independent observed data. Of course, most observation-only products (e.g., precipitation, cloudiness, surface radiation) also have large uncertainties, making such evaluation challenging. Since current analyses use prescribed sea surface temperature (SST), the use of surface heat flux observations has not been a priority. In addition, errors in SST have not been taken into account in the analysis process. The distribution of sea-ice, particularly sea-ice fractional coverage within an atmospheric model grid box, is crucial to accurate surface fluxes, since ice-ocean flux is much smaller than air-sea flux.

3. Recommendations

Improved analyses of fluxes between the atmosphere and the surface, both land and ocean, are critical to improving our understanding of and ability to forecast the future of the global climate system. Accordingly, we recommend the following actions:

- Atmosphere, ocean, land surface, and sea-ice analyses, and the associated interfacial fluxes, should be "synchronized", i.e., coordinated programmatically.
- Atmospheric reanalyses for climate purposes should be kept current as is presently done with the NCEP Climate Data Assimilation System, and as is planned by ECMWF and JMA.
- Analysis should be the best estimate of the state variables, since those are what we measure.
- We should ensure that the fractional coverage of ocean, land, and sea-ice is represented accurately within the atmospheric model grid-box. Satellite estimates of sea-ice fraction are available for the modern era and should be used.
- Surface analyses should encompass:
  - surface components (including spectral fluxes) and all the elements required for their calculation(10m wind components, wind speed, surface air temperature, air surface specific humidity, SST, atmospheric stability, cloud properties, sea level pressure, sea state);
  - stand-alone surface-only analyses that are adequate for forcing ocean general circulation models (OGCMs) and land surface models (LSMs), and for validating the surface fluxes from full atmospheric analyses and from coupled models;
  - surface analyses consistent with atmospheric analyses, assimilating available surface observations, but not feeding back to the atmosphere; and
  - realistic variability in the modern era with spatial resolution of 1°x1° globally, resolving the diurnal cycle, and including regional resolution as high as feasible.
- Priorities:
  - keep climate analysis current;
  - ensure accurate fractional coverage of ocean, land, and sea-ice within each atmospheric model grid-box and produce fluxes for multiple surface types;
  - improve assimilation methods so that use of surface observations is optimized;

- assimilate cloud and precipitation observations;
- include uncertainty in SST;
- identify a pilot 2 year period with good buoy/ship coverage and land coverage for continual testing of enhancements to models, parameterizations, and assimilation methods, using withheld data for validation; and
- gauge progress towards improved analyses by comparisons with in independent observations such as those from the SURFA project;
- Pursue international collaboration on continual enhancement of observations, including error corrections and data archeology.

- R&D priorities:
  - Improve cloud and planetary boundary layer representations over both atmosphere and ocean so that analyses can produce realistic fluxes;
  - Transition results from research efforts, including process studies and the new U.S. CLIVAR Climate Process Modeling Teams;
  - Develop assimilation for coupled systems;
  - Improve assimilation methods so as to use surface observations more effectively; and
  - Improve assimilation methods to use satellite observations (clouds, precipitation, radiation, moisture, etc) more effectively.

Panel 3: New Scientific Developments in Assimilation and Analysis

Eugenia Kalnay, Chair
Jeff Anderson, Joaquim Ballabrera, Jim Carton, Gil Compo, Ichiro Fukumori, Masao Kanamitsu, Alexey Kaplan, Prashant Sardeshmukh, Masato Sugi, Adrian Simmons

1. Background

We envision an ongoing research effort into retrospective analysis of climate variability spanning the atmosphere, ocean, land, and cryosphere. This effort will be led by the large government laboratories, but should exploit grass roots efforts as well. One possible way of allowing the two communities to interact is through the formation of a central data assimilation center (NCDAC). Such a facility would relieve the current laboratory staffs from extensive additional workload while providing a way for external scientists to become more directly involved in assimilation research.

A major goal of this program is to determine the current state of the climate as accurately as possible and to determine whether any observed longer-term trends are due to the inhomogeneous observational input data, the result of real climate changes, or a mixture of both. We must isolate the real climate changes from those arising artificially.

The goal of our research is to explore ideas that can be exploited in this expanded analysis system on a relatively short 2-4 year timescale with a lower priority for investigation of ideas such as coupled a/o assimilation that are unlikely to be included in the next analysis cycle. The goal of the analysis is that it should be as accurate and consistent as possible. Changes in the observing systems, accuracy and consistency will likely require multiple separate reanalyses.

2. Science Issues and Recommendations

We have summarized the present state of several aspects of the relevant science and provided certain recommendations for the climate analysis effort that we envision. These are presented below.

- **Ensemble Kalman Filter**: This is a promising, recent development by the research community. One major advantage is that it provides information about the uncertainty. It also can be extended to include assimilation at the right time, the major advantage of 4D-Var. So far it has been shown to be superior to 3D-Var only for data sparse situations. It should be pursued energetically because of its potential. An investment in 4D-Var would require many years, and may not be better, so that comparisons with ECMWF 4D-Var should be carried out.
- **Surface data reanalysis:** For the third stream (1850+) reanalysis described in the white paper, Ensemble Kalman Filtering has already shown promise. Other statistical methods, using simplified models or without models of any sort, are also promising and should be pursued, since they are not as affected by model bias.
- **Model deficiencies:** These are a very important problem, although this group does not deal with model development. One symptom of model deficiencies and biases is spurious trends when the composition of the observing system changes. Another is the lack of balance in the budgets.

There should be an effort to improve the balance within the assimilation framework and there are several new promising approaches, including the Chi- approach, the use of a smoother, and statistical model corrections.

- **Assimilation of new variables:** We support the new MERRA reanalysis project of NASA with assimilation of precipitation. In addition, we recommend taking advantage of the LDAS technology and assimilating other non-prognostic variables (such as surface fluxes) at high resolution.
- **Anthropogenic changes:** Incorporate trends of greenhouse gases, and observations of land-use and land-use changes, including urbanization.
- **Additional prognostic variables:** Ozone, using both historic data and satellite-derived data, and aerosols should be assimilated. Incorporate volcanic aerosol information and atmospheric chemistry as possible.
- **Ocean Reanalysis:** They are an important component of this project, and should be carried out and current ocean reanalyses should be compared.
- **Important additional variables:** Opacity, ocean color (related to upwelling, attenuation), mixed layer and thermocline depth, T/S relationship, and water masses should be investigated for potential utility.
- **Coupled reanalysis:** This is the ultimate goal, and the only one that will provide accurate fluxes. One first step approach is to incorporate ocean mixed layers.

Panel 4: Data and Observing System Issues

Kevin Trenberth, Chair
Steve Worley, Dave Easterling, Saki Uppala, Bob Kistler, Bob Atlas, Mike Fiorino, Chris Miller, Chidong Zhang

1. Background, Goals and Key Questions

A principal goal of this working group was to offer recommendations to improve and develop input data for climate analyses and to address strategies for improving continuity of reanalyses.

For monitoring low frequency variability, we need long-term stable homogeneous climate data records of known quality. Implicit in this goal is the need to improve global estimates of interannual to decadal variability and their uncertainty, and to improve the consistency of the climate record in the face of major changes to the observing system. One consequence of this goal is that one or more reanalysis must be aimed at producing the most consistent time series rather than the best analysis at any particular time. Candidate time periods for such an analysis include post 1950 and post 1979. Among the implications of such an effort are the needs to:

- Retain fairly consistent observational datasets, for example, by excluding unique observations and data from short field campaigns
- Use OSEs to determine the effects of changes remaining in observing system
- Focus on bias-corrected observations
- Assess uncertainties in trends and estimates of variability.

A number of crucial questions must be answered in order to accomplish these goals.

- How can the availability of data be tracked and improved?
- How do we deal with changing data bases, such as the type and availability of radiosondes and satellite observations?
- What is the utility of OSEs? Should they be done routinely every time a new observation suite is introduced?
- How much emphasis should be placed on improving model biases?
- Should the climate relax to a recent known climate rather than model climate (e.g. for ozone in pre-satellite periods)
- Do we need a better baseline network of observations that have guaranteed and known accuracy?

2. Improving Datasets and the Processing of Data in Analyses

A number of issues must be borne in mind when obtaining and preparing datasets for climate system studies. Climate analysis and reanalysis are "data cleansing" processes. It is crucial that metadata be gathered, developed, and made available. Basic observations must be enhanced by assigning or even, on occasion, applying biases. It is important to be aware that an observation may have been deliberately omitted from an analysis (blacklisted) due to an analysis problem, such as the failure to resolve a tropical cyclone, rather than any actual defect in the observation. Finally, all of the data cleansing activities should be part of a continual process that provides feedback to the operators of the observing system.

There are a number of other issues of which one must remain aware when dealing with observational archives. Observational databases must continually be upgraded through the rescue of old observations and the improvement of international exchanges. Careful data stewardship is required, included the application and documentation of basic quality control, the improvement of station libraries, and the verification of station locations and elevations, which can be the source of biases. It is crucial to maintain irreplaceable data in perpetuity through archiving data in a form suitable for use and ensuring convenient access.

The reanalysis "feedback file" is potentially immensely valuable for improving the basic input data by exploiting the use made of the data, its biases relative to the first guess and final analysis, and any quality control (QC) flags. There is a critical need to provide full tracing of datasets and to ensure that newly issued versions, with improved coverage or QC, are documented and made available to future analysis efforts. There is also a need to provide easy access to the feedback files from current and past efforts, as well as to the basic observations.

Recommendations:

- A baseline set of observations should be created and made widely available. Closest to such a baseline dataset, but still unsatisfactory, is the Global Climate Observing System (GCOS) Upper Air Network (GUAN) of designated radiosonde stations.
- A subset of the feedback files should be extracted from each available analysis for all radiosonde stations, with an emphasis on the GUAN stations, and made available.
- Efforts should be made to validate ERA-40 and improve the quality of the GUAN.
- The feedback files should be used to adjust radiosonde observations and fill in missing data, with appropriate flags, to generate an improved radiosonde record. Similar steps should be taken for other in situ observations. These steps will allow the basic data then to be used independently, for instance, for climate change detection.

3. Issues Related to Trends and Low Frequency Variability

Quite likely the most important objective of a comprehensive environmental information system is to distinguish real trends in the climate system from natural variability and the many artifacts that arise in any effort to synthesize the available observations. While real trends, such as those that might arise from secular changes in radiatively active atmospheric constituents or SSTs, may be captured by the observing system or reflected in other quantities through the dynamics of the coupled system, in general the null hypothesis should be that indicated trends and low frequency variability are more likely to be spurious unless proven otherwise. For example, since models provide input to analyses, the tendency of model fields to approach their own climatology, which in general differs from that of the real world in unknown ways, in the absence of data, can lead to trends in analysis products.

Changes in observing systems are exceedingly common, and can easily lead to spurious trends in analyses. The methods and coverages of observing SSTs have changed dramatically over the years. Similarly, observations of upper air winds have been based on varying instruments, in changing locations, at different times of the day, and with varying coverage over the earth. Observations from instruments on earth orbiting satellites are exceedingly powerful and valuable to global analyses, but they have undergone enormous, revolutionary, change since they began to be available in the early 1970s. Satellites vary in number, have finite lifetimes and must be replaced every few years. They experience orbital decay, change in observing times, platform heating and instrument degradation. New and improved instruments are constantly being introduced. All of these changes introduce artificial variations that must be distinguished from real trends and require corrections. The increasing tendency of analysis systems to use satellite observed radiances rather than derived quantities introduces other requirements as well. Problem periods for specific channels have to be identified and recorded, detection and removal of the effects of clouds and aerosols is necessary, and overlapping observations from successive instruments becomes even more crucial.

There is a need to track and validate system performance viz a viz trends using independent measures and constraints such as the global mass of dry air, surface air temperature over land in selected regions, Dobson ozone measurements, SAGE observations of water vapor, ocean wave measurements, alpine summit station data, and field campaign data. Quantities derived without recourse to any of the analysis products or inputs, such as tropospheric and stratospheric temperature indices from MSU 2 and 4, cloud analyses from the International Satellite Cloud Climatology Project and other GEWEX and SPARC datasets and reports can serve as standards for comparison. Model and analysis diagnostic quantities, such as time series of forecast performance measures and analysis fits to observations, can indicate artifacts in analyses.

Recommendation:

- Document reliability of trends and communicate them and the results of the studies to users.

OSEs and OSSEs provide effective tools to aid in the interpretation of trends found in model reanalyses, as well as determining the optimal observing system configuration for both weather and climate analysis.

Recommendations:

- Carry out an ensemble of AMIP-type model simulations with the available forcings to establish the model climate and its natural variability.
- Carry out selected OSEs with and without major new observing components such as VTPR (1973), TOVS (1979), SSM/I (1987)
- Carry out a series of OSEs for different seasons to assess overall gradual changes in the global observing system by utilizing results from recent years (1998-2003) and degrading the observing system to match that of:
    - Late 1950s (include simulated weather ship observations)
    - Mid 1970s (include simulated VTPR from HIRS)
    - Mid 1980s (representing the TOVS era)
- Establish a core (base) ongoing activity to carry out OSEs and OSSEs to
    - Better establish the true climate record by determining impacts of changing observing systems and interpreting reality of trends.

    - Help optimize and design observing system for climate
    - Routinely assess subtle changes in the observing system

4. A Proposal for a US National Program

We suggest that a U.S. National Program for Ongoing Analysis of the Climate System is needed to satisfy the many requirements described in this report. Such a program should have an on-going development program with periodic data generation and distribution, a development strategy tailored to different time scales, an infrastructure that facilitates participation by the entire community, an interagency approach that capitalizes on the strengths and expertise of various organizations, and routine OSEs and OSSEs to assess ongoing observing system changes and help design and optimize the system. One possible configuration for such a program, and an initial attempt at estimating the costs thereof, is as follows:

- Data set development
- Research and development, peer reviewed proposals ($5M/year)
- Operational arm of NOAA/NASA to: ($3M/year)
    - Update reanalyses (CDAS-activity)
    - Continually pursue OSEs and OSSEs to document impact of continuing observing system changes.
    - Actively participate in observing system development.
- Production phases: ($1M/year enhancement)
    - Post 1979 reanalysis with goal of continuous climate record.
    - Post 1950 reanalysis with same goal.
    - Post 1900 surface NH oriented.

Panel 5: Implementation and Infrastructure Issues

Jim Laver, Chair

Tony Busalacchi, Wesley Ebisuzaki, Mel Gelman, Suru Saha, Ed Sarachik, Siegfried Schubert, Jiayu Zhou

1. Background

A comprehensive Environmental Earth Observing System (EEOS) is incomplete without an Ongoing Climate Analysis to integrate diverse global observing subsystems into an EEOS that successfully describes the Climate. An Ongoing Analysis of the Climate System (OACS) is the primary tool that will integrate and assimilate diverse environmental data from the bottom of the ocean to the top of the stratosphere. This OACS is the integrating link between EEOS data and earth system models. It will provide the products necessary to enable us to understand, monitor, and predict variability and change in the Earth's climate system for ultimate benefit to society.

2. Findings

At present the U.S. has no strategy for a comprehensive Ongoing Analysis of the Climate System (OACS). A comprehensive OACS is required to provide a physically consistent synthesis of earth observations in order to:

- Provide long time series of global and regional climatic analyses for use in design, evaluation, and modification of observing systems.
- Produce and sustain the growing climate record.
- Reconcile disparate climate observations.
- Establish initial conditions for climate prediction.
- Validate prediction and projection models.
- Provide long time series of global and regional climatic analyses for all types of prediction and projection verification.

A comprehensive OACS must plan to:

- Continue to improve the existing analyses and reanalyses of atmospheric, oceanic, and land surface observations.
- Assimilate all remotely sensed and in-situ data into a coupled, comprehensive earth system model.
- Produce high resolution gridded fields of all required/relevant parameters, e.g., temperature, circulation/wind, precipitation, carbon dioxide, phytoplankton biomass, etc.

The infrastructure required to provide a comprehensive OACS includes:

- A "data activity" to produce and improve quality controlled climate data records.
- A "central activity" that will execute earth system models and assimilation and develop methods to QC and ingest data from diverse observational subsystems.
- A "research activity" to continually develop, evaluate, and improve techniques for doing the above.

3. Recommendations

To create an Ongoing Analysis of the Climate System as an enduring national component of a comprehensive Environmental Earth Observing System, we recommend the following actions:

- Pursue support for the OACS as a required component of "Environmental Observations" under Section 5 (Environment and Energy) of the FY 2005 Interagency R&D Priorities.
- NOAA/NCDC and NCAR coordinate the "data activity" described above in partnership and collaboration with other agencies (see Linkages below).
- NOAA coordinates the "central activity" described above in partnership and collaboration with other agencies (see Linkages below).
- NASA, NSF, and NOAA… lead the "research activity" described above in partnership and collaboration with other agencies (see Linkages below).
- Linkages – implementation of the OACS will require extensive partnerships and collaborations, including:
    - An Interagency Working Group with members from NASA, NOAA, NSF, DOE and other agencies as appropriate.
    - Integration with the NOAA-NASA Joint Center for Satellite Data Assimilation.
    - A commitment to formal national interaction and planning with partners in labs and centers in NOAA, NASA, NSF, NCAR, DOE, LLNL, universities, and elsewhere as appropriate.
    - A commitment to international interaction and planning with international, multinational and other partners, including the European Center for Medium-Range Weather Forecasts, the Japan Meteorological Agency, the World Meteorological Organization, the World Climate Research Programme, the Global Climate Observing System, and others as appropriate.