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Reanalysis for TOGA (Tropical Oceans Global Atmosphere), 1–3 February 1989, Center for Ocean-Land-Atmosphere Interactions

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1. Introduction

The international TOGA Scientific Steering Group (SSG) and the U.S. TOGA Panel have decided to use the concept of reanalysis as an organizing theme for TOGA data collection, archiving, and management. This decision is based on the recognition that physically comprehensive, time dependent, dynamic models of the atmosphere and oceans provide the best methodology for space-time interpolation of asynchronous global observations. In this context, "reanalysis" is the process whereby all available past observations of the atmosphere (and ocean) are assimilated using a single, highly accurate data assimilation system to produce an internally consistent, homogeneous multivariate description of the global atmosphere and world ocean. It has also been recognized that the existing model-based global datasets have serious deficiencies due to inadequacies and frequent changes in the models and the data assimilation systems during the past ten years. It has therefore been suggested that an internally consistent, homogeneous, multivariate description of the global atmosphere and the oceans could be obtained by reanalyzing all the available past observations using a single, more accurate model and data assimilation system.

In this context, the international TOGA-SSG and U.S. TOGA Panel sponsored a meeting to develop a plan for the reanalysis of atmospheric datasets for the pre-TOGA period and the TOGA period (1985–95), to identify suitable pilot periods for reanalysis and to evaluate the resource requirement for TOGA reanalysis. The first meeting of the *ad hoc* Panel on Reanalysis for TOGA was convened at the Center for Ocean-Land-Atmosphere Interactions (COLA), Department of Meteorology, University of Maryland, College Park, Maryland, 1–3 February 1989. The panel included A. Hollingsworth (European Centre for Medium-Range Weather Forecasts [ECMWF]); P. Julian (U.S. National Meteorological Center [NMC]); J. L. Kinter III (COLA); K. Miyakoda (Geophysical Fluid Dynamics Laboratory [GFDL]); and J. Shukla (COLA). Presentations were made by Shukla, Miyakoda, Hollingsworth, Julian, and W. Baker (NMC); M. Kanamitsu (NMC); J. Susskind (NASA Goddard Laboratory for Atmospheres [GLA]); Kinter, D. Paolino, (COLA); R. Jenne (National Center for Atmospheric Research [NCAR]); J. Carton (COLA) and A. Leetmaa (NMC). Also present to participate in the discussions were R. Bates (GLA); K. C. Mo (NMC); J. Pfaendtner (GLA); and J. Young (University of Wisconsin).

Because a reanalyzed dataset is deemed to have high value, and because such a dataset could be used for a wide range of studies including climate variability, atmospheric and oceanic model validation, and global climate change detection, selected parts of the report of the *ad hoc* Panel, which was communicated to the SSG and U.S. TOGA Panel, are published here. The following are the Panel's summarized recommendations and details of the major issues facing the community.

2. Discussion of issues

While the discussion was far-ranging, and a number of topics were raised and debated, the issues involved in reanalysis for TOGA may be broken down as follows:

a. *Are operational analyses sufficient to provide an ample number of initial and boundary conditions needed for TOGA numerical experimentation?*

There was a general consensus that the ECMWF operational analyses are not adequate for TOGA studies before 1985 and that NMC operational analyses have only recently become suitable. The question of whether or not the operational analyses are sufficient

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can only be answered in the context of what the analyses will be used for. Since there have only been a small number of numerical experiments for the TOGA program, no definitive answer is available except in one circumstance. That is, if operational wind analyses are used to compute surface wind stress time series, and these stresses are used to force a tropical ocean model, the consensus is that the resulting ocean circulation is not sufficiently close to the observed to be considered adequate for the purposes of TOGA.

Since a large number of El Niño-Southern Oscillation (ENSO) cases is desirable, the operational analyses for the 1985–95 period may not be sufficient for TOGA purposes. Based on statistics from the historical record, one expects that during the TOGA period (1985–95) there will be two or at most three ENSO events. The database could be expanded by one-third to one-half by the inclusion of the 1982–83 event. Insofar as the 1982–83 operational analyses are deficient for TOGA use, then, the reanalysis of the 1982–83 period would be invaluable for the study of the ENSO phenomenon.

b. Is there any basis for comparison of operational analyses and reanalyzed data? If so, how do they compare?

While a number of studies in which such a comparison could be inferred were presented at the meeting, it is only the first GARP (Global Atmospheric Research Program) global experiment (FGGE) main and final analyses of ECMWF which represent a suitable database upon which to base conclusions. When the FGGE reanalysis is completed by Geophysical Fluid Dynamics Laboratory (GFDL), it will be another dataset where comparisons may be made with some rigor. The implication of the presentations by Hollingsworth and Miyakoda was that the reanalyzed data are substantially superior to the operational analyses in the sense that they more faithfully represent the observational data which were used in the analyses.

c. How sensitive is a given assimilation system to the inhomogeneity of the observational data?

There are considerable spatial and temporal inhomogeneities in the observational data. A considerable effort is needed to provide better quality input data in the current observational network and in the historical data. Major changes in the observing systems (i.e., addition or subtraction of a satellite system) have taken place and will occur again. Inhomogeneities of this kind will affect the accuracy of the reanalyzed fields. Such effects are unavoidable unless one discards observation types whose availability varies greatly over the period of study; however, this is not a realistic approach.

d. What improvements in the observational database, quality control, and data assimilation system may be expected?

The trade-off between development and data availability was considered under the assumption that analyses made today are distinctly better in some quantifiable sense than those made in the contemporary period; i.e., if it is stipulated that current analyses are a substantial improvement over the operational analyses made between 1979 and 1985, can we expect to see a similar magnitude improvement in the ensuing three to five years? The question was considered in three parts, namely, the observational database, the data assimilation system and the first-guess model. The database enhancement project was considered to be essential and it was concluded that a substantial benefit would accrue from recovering the non-GTS data.

For data assimilation system development, the case is not as clear, but there are a number of promising techniques such as the utilization of quality control statistics, the inclusion of previously unused types of observational data (OLR, scatterometer winds, etc.) and the development of the adjoint method for full three- and four-dimensional data assimilation. It was the consensus that, while there are no studies in which these ideas have been tested in an operational system, the studies in simpler systems show considerable promise.

There is already active research into the problems involved in the quality of observational data. The ECMWF has been archiving the statistics from the quality control procedures in the data assimilation system since 1983. We are not aware of any other operational center which is archiving these statistics. A procedure for making use of quality control information was discussed in which either a backward or a backward/forward looking data assimilation system could benefit. It was suggested that all forecasting centers be urged to begin saving the operational quality control statistics as soon as possible. Julian and Baker indicated that the NMC plans to begin saving quality control statistics as soon as the current database management enhancements are installed.

The conclusion for the first-guess model is even less clear, but it was noted that improved parameterizations of physical processes such as the fluxes of energy and momentum through the Planetary Boundary Layer (PBL) and condensational heating of the atmosphere can have a measurable and significant impact on the forecast at short and medium range, so it may be presumed that these changes can also

improve the analysis.

e. Timing for the reanalysis effort

Current assimilation systems based on optimal interpolation are reaching a level of maturity and can assimilate data much more faithfully than the systems which were in use during the 1979–85 period. New techniques (including four-dimensional variational methods) hold promise and will be tested over the next three to five years. Substantial gains can be made in the availability of observations (e.g., Comprehensive Ocean and Atmosphere Dataset (COADS) data) which were made but which never entered the GTS system.

If a reanalysis is delayed until the newest techniques are mature enough to produce high-quality analyses from an enhanced level II-b database, the reanalyzed fields will be produced too late to be of use to the TOGA modeling program. As such, there is a trade-off between assimilation system development and the availability of reanalyzed fields. If reanalysis is done using current mature optimal interpolation systems and an enhanced Level II-b dataset, the product will be a considerable improvement over what was produced operationally in the early 1980s. Mature variational data assimilation systems will be available in the mid-1990s. If we wait for that improvement we will not have reliable reanalyzed fields for TOGA experimentation until the TOGA project is over. The consensus was that there should be a near-term reanalysis for a pilot period with an optimal interpolation system and an enhanced Level II-b dataset. In the longer term, current developments will produce mature variational assimilation systems by the mid-1990s and one can envisage a more extended reanalysis effort at that time.

f. What are the measures of improvement which should be applied to reanalyzed data?

Methods suggested to measure the worth of the reanalyzed datasets ranged from simple strategies, such as the archival of differences between observations and first guess, to the relatively expensive measure of medium- and long-range forecast skill for forecasts initialized from operational analyses and reanalyzed data. Other measures discussed included the spatial coherence of differences between observations and analyses, the results of forcing an ocean circulation model with reanalyzed surface wind stress and surface energy flux, and the results of forcing an ocean wave model. It was pointed out that oceanographers who have used NMC and ECMWF surface wind products have reported that the products have improved considerably in recent years.

g. What strategies can be devised to address the problem that some of the variables of interest to TOGA are the most difficult to measure and verify?

Some of the main variables of interest to TOGA atmospheric experiments are the surface energy fluxes and the diabatic heating in the atmosphere. Oceanic TOGA experiments will require the surface energy flux and the surface wind stress. These quantities are difficult to measure and, therefore, difficult to provide analyses for. Several strategies for improving these analyses and issues which need to be addressed were discussed including: the use of outgoing longwave radiation and cloud-top histograms to infer the diabatic heating rate; improvement of the parameterization of the PBL; and improvement in the parameterization of convection: While it is clear that the diabatic heating rate is sensitive to the choice of convection scheme, how closely coupled to the surface and PBL treatment should the convection be?

h. What model resolution is desirable or required in the first-guess model used in the assimilation system?

There is a trade-off involved in the reanalysis of historical data. Since the target period may be up to ten years long, it will be essential to have the capability to perform several days of reanalysis per day of the project. At least five days of reanalysis per day would be required to complete a single reanalysis in three years, assuming that about one-third of the project would be consumed in the logistics of starting up and reaching the production level of operation, as well as computer malfunctions and unavailability. Therefore, it will not be possible to perform the reanalysis using the highest resolution model and data assimilation system available. On the other hand, comparison studies at several centers have indicated that there is a minimum resolution below which the first-guess fields can have a negative impact on the analysis. Based on the current experience, it was deemed that a minimum resolution of wavenumber 63 (triangular truncation; 42 for rhomboidal; 1.8° mesh for a grid point model) would be required with at least as many vertical levels as are currently used in operational numerical weather prediction models. There was a discussion of the need to assimilate hurricane central pressures or to produce analyses on the spatial scale of individual hurricanes. The consensus was that such resolution is desirable but not feasible. It was noted that the hurricane scale forcing can be significant to drive tropical ocean circulation transients.

Table 1 gives the estimated computer time required for reanalysis using models of various resolutions with assumptions based on results of actual data as-

Table 1. Estimated computer time required for reanalysis.

	(a) *Assumptions*	
Model Type	Resolution	Computer
T40	1–2 h/day	Cray 1
T63	3 h/day	Cray 1
T106	3 h/day	X-MP
	(b) *Estimates*	
	Model Type	
Computer	T106	T63
Cray 1A (1977)	1 yr/yr	3 yr/yr
X-MP 48 (1985)	5 yr/yr	15 yr/yr
Y-MP (1989)	15 yr/yr	45 yr/yr
C90 (1992)	45 yr/yr	135 yr/yr

similation systems based on Cray computers.

i. Which institution(s) could be involved in reanalysis?

Representatives from several laboratories expressed the position of those institutions on the problem of reanalysis. Hollingsworth said that ECMWF would be willing to consider performing the reanalysis if sufficient resources were provided. He expressed a personal opinion that the required resources would not be made available by the European community alone. As regards the possibility of performing reanalysis at NMC, Julian expressed the opinion that NMC should not be involved and Baker indicated that NMC would consider taking responsibility for reanalysis given sufficient resources. Pfaendtner noted that GLA has no plans beyond the interactive satellite re-retrieval already begun by Susskind. The possibility of a university performing the reanalysis was also discussed along with the possibility that UCAR could establish a center for reanalysis.

At NCAR, Jenne plans to help improve the data inputs for the reanalyses. Projects to merge ship data (COADS) will be accomplished and the results made available. Other projects (better aircraft data, raobs at isolated locations, etc.) have been on hold since 1986, awaiting resources. Jenne noted that any reanalysis project should be built on a database assimilation experience. Reanalyses could be run at NCAR by some other group (such as a university group) and Jenne would help to make it easy to input the datasets. He pointed out that computer time is now very tight at NCAR. However, new computer hardware could be scaled to include a reanalysis project.

The entire reanalysis project need not be done at a single institution. A group of centers could cooperate to perform segments of the task. For example, the problem of database enhancement could be covered by a suitable expansion of the ongoing data recovery effort at NCAR with assistance from Naval Contract Distribution Center (NCDC) and others. The issue of quality control and means of making fruitful use of archives of quality control statistics could be addressed at ECMWF. Meanwhile, all the centers involved would carry on with their planned data assimilation developments, and criteria for evaluation of reanalyzed data could be developed in the universities. It was noted that such a plan would address the scope of the problem, but could lead to the long postponement of a date when reanalyzed data would be available to the TOGA scientific community.

j. Data assimilation for the tropical oceans

Although there were some presentations on ocean data assimilation, the main focus of the meeting was reanalysis of atmospheric datasets. However, the concept and the methodology of reanalysis is equally applicable to the oceans. In fact, a reanalyzed atmospheric dataset of surface wind stress and energy fluxes will be extremely useful for analysis and reanalysis of ocean observations for TOGA and World Ocean Circulation Experiment (WOCE).

3. Summary of recommendations

A list of recommendations to the SSG and the U.S. TOGA Panel was drawn and presented. Those recommendations were

a. Reanalysis is necessary to produce a multiyear, multivariate, homogeneous dataset for the global atmosphere and oceans

The usefulness of such a dataset over a 10-year period (1979–88) for the purposes of ocean modeling and atmospheric prediction, sensitivity experiments, and diagnostic studies is clear. In order to understand the physical mechanisms responsible for the generation of intraseasonal and interannual variability of the tropical diabatic heating field and the wind stress and surface energy flux fields, including the full spatial and temporal structure of these quantities, these data would be invaluable. This conclusion is based on controlled reanalysis experiments in which comparisons between old and new analyses and comparisons of reanalyzed fields with independently derived, observed fields confirm that the new analyses are both different from and superior to the information previously available. In fact, for a number of applications, the old analyses are unsuitable and should only be used with considerable care. The new analyses presented at the meeting were judged acceptable

under this standard. Reanalysis also represents a means for providing a focus on historical data and preventing the observations so painstakingly gathered from being lost. According to records from NCAR, there are substantial increases possible in the existing archive of data for the pre-TOGA period of 1979–85 and periods prior to that. In fact, there is some evidence that reanalysis could be performed to some advantage on datasets going back to 1972 with the inclusion of relatively reliable satellite data and up to 25 years into the past if only Northern Hemisphere analyses were required. Also, relatively good manual analyses were made of daily sea-level pressure (SLP) and 500-mb height in the Southern Hemisphere during the International Geophysical Year (IGY) 1957–58.

b. The national and international weather prediction centers should be approached to get their support and commitment to the TOGA reanalysis

It was recognized that current data assimilation systems in use at the prediction centers have reached a level of maturity which would ensure a dramatic improvement in analyses if reanalysis were carried out today. On the other hand, there are data assimilation and satellite data retrieval developments underway which may make it possible to substantially increase the quality and fidelity of analyses of atmospheric observations within the next three to four years. These include the objective use of archived quality control information, which allows both forward and backward looking (in time) quality control and data assimilation; the inclusion of outgoing longwave radiation observations; the more accurate rendering of the tropical boundary layer; the merging of satellite data retrieval with data assimilation; and variational methods of full four-dimensional analysis of observations.

There is also evidence that considerable enhancements to the existing Level II-a data archive are realizable in a timely manner which could substantially improve analyses if they were included in the reanalysis. *It was therefore recommended that TOGA scientific management implement enhancement of Level II-a data with other available data to produce a high quality Level II-b dataset as soon as possible.*

At a minimum, this should include the current Level II-a plus the COADS data being updated at NCAR, both for the period of 1979–88. The updating could also include additional aircraft data and a comprehensive set of upper air stations. In addition, satellite operators should be requested to archive operational cloud vector winds and the archives should be made available in delayed mode.

c. An orderly application of both current and soon to be developed schemes should be made to a pilot period of shorter duration

Since one of the main advantages of reanalyzing the pre-TOGA period is to expand the sample of El Niño and La Niña (or anti-El Niño) events available for study, the pilot period chosen is March 1982–September 1983—the period during which the strongest ENSO event ever observed took place. Therefore, this period should receive immediate attention for the assembly of the Level II-b dataset; while merging the data for the entire ten-year period represents a substantial effort, the 19-month pilot period dataset could be accomplished before 1990. Once the best available Level II-b data are assembled, the reanalysis should be performed using the data assimilation system operational at that time. During this reanalysis, the full set of quality control information should be saved for possible future correction of radiosonde, drifting buoy or satellite retrieval data. In addition, short-range (~48 h) forecasts for each day should also be saved to examine the spinup of the hydrological cycle. A one-month subset of the pilot period should be chosen for intensive study including possible reanalysis by several groups. When the 19-month reanalysis is complete, a rigorous evaluation of the new analyses and the quality control data is recommended in order to plan for the full 10-year reanalysis. Since this planning will be taking place during 1991, progress on development of new techniques may also be evaluated.

d. The model used in the anticipated reanalysis should be of sufficiently high, but not necessarily the highest, resolution and include a comprehensive physical parameterization scheme

In this context, the horizontal resolution should be a 1.8° grid point mesh, or for a spectral model, in the range of wave 63 (triangular truncation; wave 42 for rhomboidal truncation) although it may be possible to obtain acceptable results with wave-40 truncation. It would be desirable to have vertical resolution comparable to current operational systems with adequate PBL resolution. For T63 resolution, the best estimates of computational resources required for such a reanalysis indicate that between one and two hours of CPU time would be required per reanalyzed day on a Class VI supercomputer. The wall clock requirement would be approximately twice as large, depending on efficiency of the computer system used. The pilot period would therefore require between 200 and 350 hours of CPU time, and the full 10-yr reanalysis would require between 3500 and 7000 hours of CPU time or the dedication of half-time for

production on a current supercomputer for two yr.

e. *Further research and development for the validation of reanalyzed data and to produce objective criteria for the evaluation of these data should be initiated*

Among the techniques are the verification of reanalyses against observational data; the statistically derived spatial coherence of the fit of the reanalyzed fields to the observations; the short-range (3–6 hours) atmospheric forecast skill from reanalyzed initial conditions; the results of forcing ocean models of either the wave heights or the general circulation; the results of forcing atmospheric models with prescribed diabatic heating; the general circulation characteristics of the reanalyzed fields; and the global and local energetics. All these criteria should be used when trying to determine the relative quality of reanalyzed quantities. A second meeting of experts on analysis and diagnostic studies should address these questions and make further recommendations on evaluation procedure.

f. *Institutional plans and arrangements for reanalysis*

While there are plans for interactive satellite data retrievals over a multiyear period at NASA-GLA, plans to finish the FGGE reanalysis at GFDL, and development efforts underway at ECMWF (four-dimensional variational assimilation) and NMC (Climate Data Assimilation System), no center has firm plans of addressing the question of reanalysis. A willingness to consider the possibility, given sufficient incremental funding, was voiced by representatives of ECMWF. It was suggested that further discussions with ECMWF, NMC, GLA, and other prediction centers, such as those in Japan or India, and with research centers, such as NCAR and GFDL, be continued.

4. Conclusions

The international TOGA program is approaching its midway point and, as a result, a critical examination of the requirements for successful completion of the program is needed. An essential component of TOGA's success will be the quality, fidelity, and timeliness of available observational and modeling results. Hence, the problem of how to organize the collection, archival, and management of TOGA data must be solved, and reanalysis provides a theme for solution.

Given the length of the program and the observed frequency of ENSO events, it is essential to broaden the TOGA database by including at least the 1982–83 period. With current mature optimal interpolation data systems and an enhanced Level II-b dataset, it is possible to produce a high quality analysis for the 1982–83 ENSO event. However it will be the mid-1990s or later before the four-dimensional variational assimilation systems become sufficiently mature to provide such a product. In order to provide the modeling component of TOGA with reasonable datasets for validation and verification, it will be necessary to initiate a reanalysis pilot project with an optimal interpolation data assimilation system in the near future.

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