PART I: SCIENCE AND OBSERVATIONS

N94-21640

1. Monitoring Issues from a Modeling Perspective[1]

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Introduction

Recognition that earth's climate and biogeophysical conditions are likely changing due to human activities has led to a heightened awareness of the need for improved long-term global monitoring. The present long-term measurement efforts tend to be spotty in space, inadequately calibrated in time, and internally inconsistent with respect to other instruments and measured quantities. In some cases, such as most of the biosphere, most chemicals, and much of the ocean, even a minimal monitoring program is not available.

Recently, it has become painfully evident that emerging global change issues demand information and insights that the present global monitoring system simply cannot supply. This is because a monitoring system must provide much more than a statement of change at a given level of statistical confidence. It must describe changes in diverse parts of the entire earth system on regional to global scales. It must be able to provide enough input to allow an integrated physical characterization of the changes that have occurred. Finally, it must allow a separation of the observed changes into their natural and anthropogenic parts. The enormous policy significance of global change virtually guarantees an unprecedented level of scrutiny of the changes in the earth system and why they are happening.

These pressures create a number of emerging challenges and opportunities. For example, they will require a growing *partnership* between the observational programs and the theory/modeling community. Without this partnership, the scientific community will likely fall short in the monitoring effort.

The monitoring challenge before us is not to solve the problem now, but rather to set appropriate actions in motion so as to create the required framework for solution. Each individual piece needs to establish its role in the large problem and how the required interactions are to take place. Below, we emphasize some of the needs and opportunities that could and should be addressed through participation by the theoreticians and modelers in the global change monitoring effort.

Requirements for Theory/Modeling Support for Monitoring

Context. All observing systems are incomplete in the sense that they will never be able to measure everything, everywhere, all of the time with perfect accuracy and sustained calibrations. Moreover, even if this impossible goal could be achieved, the changes recorded by the "perfect" measurements would still need to be interpreted in the context of previous predictions and to be explained scientifically. Thus, the challenge before us is to seek the mechanisms by which models can be used in cooperation with observational systems to yield the maximum information and to produce the required synthesis.

Information content of observational networks. One of the most straightforward ways to utilize models in a monitoring context is in the evaluation of existing or hypothetical networks. For the atmosphere, successful studies conducted at GFDL have included evaluations of the global radiosonde

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[1] Much of this essay has been taken from Mahlman, J.D., 1992: Modeling Perspectives on Global Monitoring Requirements. Proceedings of the NOAA Workshop on "Assuring the Quality and Continuity of NOAA's Environmental Data," Silver Spring, MD (in press).

network, the Dobson total ozone network, global surface temperature measurements, and satellite temperature soundings. In such approaches, time-dependent, three-dimensional model output statistics are sampled in ways identical or similar to that of a given network. The advantage of using the model is that the "right" answers in this context are readily available for comparison against the answers inferred from the network subsample. Such research has revealed a number of significant deficiencies in the existing networks.

A frequent objection to using models for research in this context is that the models can be seriously incomplete depictions of reality. True enough. However, models have the virtue of constituting a *self-consistent* global dataset. Moreover, a typical model problem is that they produce only a restricted version of the much richer spatial and temporal structure found in nature. Thus, model diagnoses of network information tend to err on the conservative side; problems identified in networks through use of models are likely to be even worse in the real world.

Evaluation of models from sparse observational data. The other side of the coin is that even the current monitoring networks can be very powerful tools for evaluating strengths and weaknesses of models. Surprisingly, this is still true even for seriously undersampled quantities such as tropospheric ozone or oceanic salinity. It is a common misconception that 3-D global models can only be tested through use of complete 3-D global datasets. Just the opposite is true. Even *individual* local time series can (and often do) demonstrate that a global model is deficient in certain respects. This is because a global 3-D model attempts to capture both regional and global structures. Thus, if a global model exhibits local structure and temporal variations quite unlike the real world, the model has already been determined to be deficient. Thus, observed data properly taken at local sites can provide a powerful tool for model evaluation. In turn, improved models can provide a means for filling in the inevitable gaps in monitoring systems. We shall return to this theme below.

Design of observational networks. A particularly attractive possibility is to use models to design optimum networks at the outset. This concept is almost irresistible because of the prodigious expense of constructing and maintaining dense sampling networks. In principle, models can provide perspective and predictions on the value of data at various accuracies and sampling densities. In practice, this approach will be somewhat limited by the accuracy and credibility of the model employed. Models themselves undersample the environment because their data density is also limited by costs, in this case computational.

It is becoming increasingly common to hear that a new proposed monitoring network can be designed in advance using model-based insights. In principle, this is true; in practice, serious barriers remain. The most serious barrier seems to be the lack of properly focussed human talent. Each potential network design problem represents a serious and major research problem that typically requires several years of concentrated research to provide targeted, useful answers. Currently, there is a major deficiency of properly trained and focussed talent, backed by serious *commitment*, both personal and institutional, to solve such problems. The design of observational networks has the potential to become a significant new priority area in the context of global change monitoring and assessment.

Model identification of global change "Fingerprints". Questions regarding what the monitoring networks are capable of measuring are strongly influenced by the presence of an evolving theoretical/modeling perspective on what the expected changes *should* look like. Unfortunately, the issue is clouded by the presence of significant uncertainty in the model predictions. Even though they are uncertain, the model predictions still can provide major guidance to the kinds of signals that a network needs to be able to detect.

As examples, can the network detect a global warming signal in the ocean? Change in cloud-radiation feedbacks? How about CO_2 uptake changes? How will the warming signal differ from the expected low frequency variability operating on time scales similar to the expected anthropogenic climate signal? Can the signals be separated and understood independently?

An instructive example of the role of modeling in interpreting climate change can be seen in Figs. 1.1a-c taken from a 200 year integration of the low-resolution coupled ocean-atmosphere GFDL climate model. This is an integration which is in near perfect long-term statistical equilibrium and which incorporates no trends in climate forcing. Figure 1.1a for the Northern Hemisphere annual-mean surface air temperature shows trough-to-peak swings of nearly 0.5°C over time intervals of 40-60 years. These changes are of comparable magnitude to the observed changes in this century. Natural variability can either amplify or damp anthropogenically induced climate warming signals. Figures 1.1b and 1.1c show the same quantities but for the contiguous U.S. and for the "Washington, DC" gridbox (roughly 500 km on a side). These model results show how the natural variability increases dramatically as the region size decreases. An intelligent monitoring system must take such variability under careful consideration, particularly on time scales less than a decade or so.

Clearly, there are many questions that we cannot answer about climate change at this time. However, it is a very safe prediction that we will have to deal with them in the context of a global monitoring system. At the very minimum we must design our systems so that we at least deal with the difficult interpretative questions that are already before us. We must take on the natural variability question head on as a concomitant part of global change. We also must address the global sampling and long-term calibration question with sufficient skill to address adequately the proper monitoring identification of the regional climate change signals that are *already predicted for the climate/chemical system*. In many cases, the models are already predicting significant regional structures in the expected changes.

Model assimilation of data in the context of climate change. One of the inevitable aspects of expanded global monitoring systems is that they will be composed of data from heterogeneous sources. The data will be heterogenous in terms of types of instruments and the nature of the data obtained. The sampling will frequently be spotty in space and sporadic in time. The systems will be dynamically incomplete; temperature may be available, but winds and tropospheric ozone amounts may not be. Much of the data will be in the form of extended time series that contain gaps, errors, and calibration problems.

All of these data inconsistencies create the need for a unified approach for combining and synthesizing the data. Fortunately, over the past decade or so, viable approaches for accomplishing this have been developed for both the atmosphere and the ocean. This is the so-called four-dimensional data assimilation method (4DDA).

The 4DDA approach uses comprehensive numerical models to provide a physically consistent synthesis and global analysis. In effect 4DDA uses a global general circulation model to accept input data in a dynamically consistent manner. The model serves as a "traffic cop" determining which data in which forms are acceptable for inclusion. The data are incorporated in such a way as to "nudge" the model closest to a self consistent analysis of the data. In this context, the model serves also as a non-linear interpolator to fill in missing spatial and temporal information as well as missing variables (such as winds or trace constituents).

A great strength of this approach is the production of a self-consistent final analysis. A great weakness is that the quality of analysis can be quite sensitive to the quality of the model used. This is a particular concern for regions where the data coverage is extremely coarse and model quality remains relatively low. However, the insightful use of 4DDA techniques hold great promise to help improve the models as well as the data analyses.

(a) Northern Hemisphere

Mean = 264.94
Stdev = 0.13
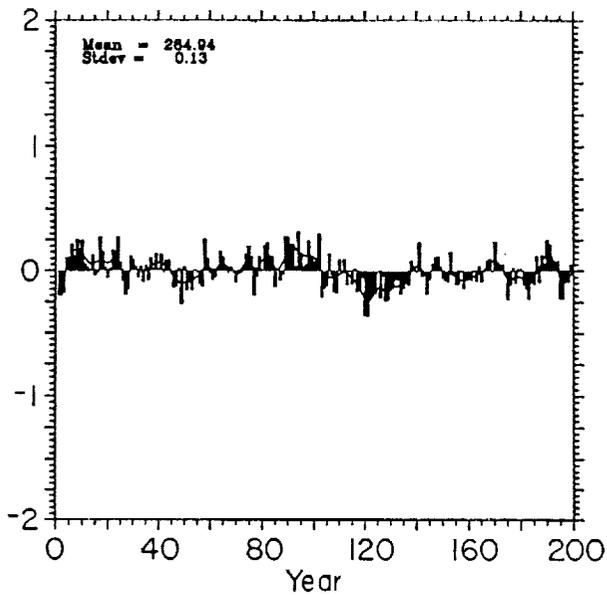
Fig. 1.1. Annual-average surface air temperature
(°C) from a 200-year integration of the low
resolution (≈ 500 km grid spacing) coupled ocean-
atmosphere GFDL climate model. This is a model
in statistical equilibrium in which no trends in
climate forcing are applied. (Courtesy S. Manabe
and T. Delworth). Part (a) is for the Northern
Hemisphere; (b) is for the contiguous U.S.; (c) is
for the grid box encompassing Washington, DC.

(b) United States

Mean = 280.78
Stdev = 0.49

(c) Washington, DC

Mean = 283.21
Stdev = 0.86
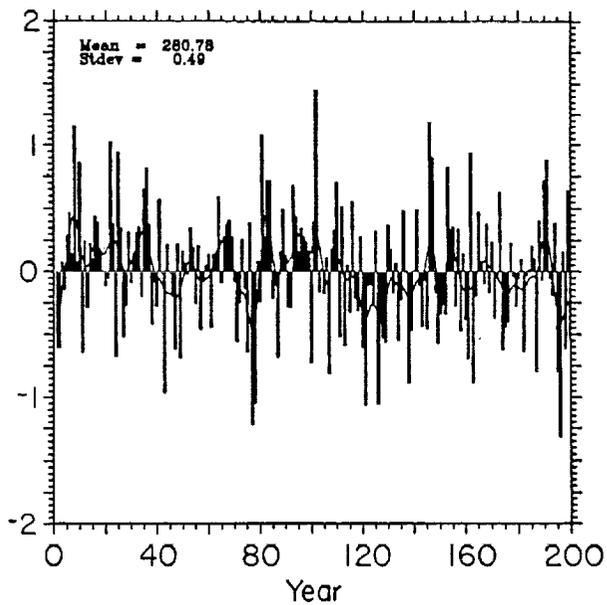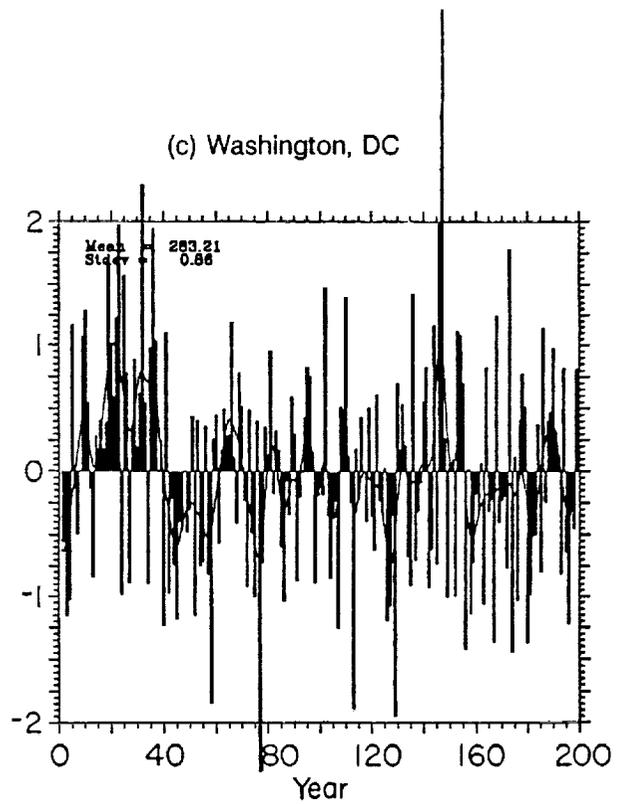
In the monitoring context, perhaps the most promising use of 4DDA is in the retrospective analysis of historical datasets, such as is now in preparation at NOAA's National Meteorological Center. This approach may be able to yield analyses over decades that are appropriately time calibrated for monitoring use and evaluation. An unsolved problem with this approach is the limited ability of today's data checking procedures to filter out small apparent "trends" due to calibration drift or instrument changes. For a given analysis, this is a small effect; for climate change analysis, it can be as large as the signal itself. However, the advantage of the reanalysis procedure is that it can be redone as many times as necessary to glean the maximum information from the dataset. A major hurdle in reanalysis (and re-reanalysis) is that it is computationally and labor intensive. Obviously, there will be tradeoffs between the quality of the analyses and resources available, just as in the monitoring networks themselves.

Final Comments

It is clear that success in the monitoring problem will require a growing partnership between theory/modeling and the observational data system. It is equally clear that the task will be extraordinarily difficult. It will take a long time, perhaps decades, and will require a new generation of scientific talent, institutional resolve, and financial resources.

Finally, some will counter argue that the problem is too difficult and too unglamorous to command the sustained resources and commitment required. When such counter arguments are advanced, it will be important to remember the challenge facing us all:

We are faced with nothing less than the need to identify how the earth system is changing over the next century, explain why the changes are occurring, separate natural from anthropogenic change, and learn if our predictions were correct or incorrect.

If we in the scientific community cannot step up to this challenge, it is a safe prediction that all of us will be held accountable.