Inaugural Lecture

The Essence of Data Assimilation, or Why Combine Data with Models?

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1. Introduction

At its beginnings, numerical weather prediction was confronted with having to solve an initial-value problem without the right initial data. As soon as they wished to carry out numerical forecasts — first experimental, and then operational — dynamic meteorologists were faced with the lack of synchronous (also called synoptic) observations on a sufficiently dense grid (Panofsky, 1949). To overcome this obstacle, they developed a methodology which we now call *sequential estimation* (Bengtsson *et al.,* 1981). This methodology uses data at various places and times, in combination with the forecast model, to provide an essentially time-continuous "movie" of the atmosphere in motion (Daley, 1991).

Oceanography lived for a long time without sufficiently many data to even bother combining them with models. Remote-sensing instruments changed this state of affairs (Munk and Wunsch, 1982), but no customers for ocean prediction were there to confuse the researchers. Hence, *inverse methods* were carried over from solid-earth geophysics to estimate, at first, the state of an idealized steady-state ocean (Wunsch, 1996).

We now understand the relationships between inverse methods, *variational methods* (Sasaki, 1958), and sequential estimation much better (Ghil and Malanotte-Rizzoli, 1991). All of them are used, more or less successfully, to provide movies of the ocean (Bennett, 1992; Malanotte-Rizzoli, 1996) and the ocean-atmosphere system (Ji and Leetmaa, 1997), as well as the atmosphere, on time scales from hours to months and years. Ocean prediction on the time scale of days-to-weeks (Robinson *et al*., 1989) and coupled-system prediction on the time scale of seasons-to-years (Latif *et al*., 1998) are finding their place alongside weather prediction on the time scale of hours-to-weeks, with data assimilation an inseparable component of the forecast cycle (Panel, 1991).

Data assimilation has become a major tool of research throughout the Geosciences, extending to planetary atmospheres (Banfield *et al*., 1995; Lewis and Read, 1995), space weather (Angelopoulos and Panetta, 1998), and beyond. The present WMO Symposium represents yet another milestone in the history of the field, and this Inaugural Lecture outlines the theoretical basis for the developments sketched above.

2. Basic Ideas

The solid Earth — with its layered structure of core, mantle and crust — stays put on the time scale on which humans have been observing it. Earth's fluid envelope, the atmosphere and oceans, however, move on a time scale comparable with that on which we observe them: weather changes over the few hours between radiosonde launches or while a meteorological satellite circles the Earth; the ocean certainly does so between hydrographic sections being carried out by research vessels or while an oceanographic satellite covers the ocean basins with its footprints.

There are thus two main types of information concerning these fluid motions: (i) direct observations, unevenly distributed in space and time, and (ii) the partial differential equations that govern these motions and carry forward in time the information provided by past observations. Both of these types of observations, direct and indirect, contain errors, which have to be properly weighted in combining the two to yield the best possible estimate of the atmosphere or ocean in motion.

The latter is the goal of data assimilation. There are essentially two main methodologies used to achieve this goal: the *control-theoretical* and the *estimation-theoretical* methodology. The latter relies on the state-vector approach of Kalman (1960) to sequential estimation and was formally introduced into geophysical flow problems by Ghil *et al*. (1981). The former relies on the work of the French (Lions, 1971) and Russian (Marchuk, 1975) mathematical schools; the full power of this approach was introduced into meteorological problems by Lewis and Derber (1985) and Le Dimet and Talagrand (1986).

The two types of methods, sequential and variational, are essentially equivalent for simple linear systems (Gelb, 1974; Ghil and Malanotte-Rizzoli, 1991). They differ in accuracy and computational efficiency when applied to large nonlinear systems. To help in the comparison of their performance, Ide *et al*. (1997) introduced unified notation for both methodologies, as well as for operational methods in use at the time of the 2nd WMO Symposium, held in Tokyo in 1995 (Ghil *et al*., 1997).

The two main issues involved in data assimilation for the atmosphere, oceans and the coupled system, are (a) the spatio-temporal propagation of information through the system via advection by winds or currents and wave propagation, and (b) the trade-off between variables that can be directly observed and those that cannot. In principle, it is useful to measure any variable that appears in the equations governing the geophysical flow of interest; moreover, observing any physical quantity that can be derived from these variables, such as spatial averages or other diagnostic quantities, is also useful. The relative efficacy of a given observation at a given epoch and location, however, depends on the flow pattern and various properties of the governing equations.

Estimating the flow fields' present state from past data is called *filtering*, its past from data up to the present is called *smoothing*, and estimating its future is *prediction* (Wiener, 1949). Beyond the best-possible filtering, smoothing and prediction of the evolving flow fields, data assimilation methodologies are being brought to bear on a few additional topics of current interest, such as parameter estimation and observing-system design. Systematic *parameter estimation* can be carried out at the same time as state estimation and can supplant the trial-and-error methods that still dominate both meteorological and oceanographic modeling (Ghil, 1997; Navon, 1997).

The location and timing of observations have grown at the beginning out of practical considerations — to coincide with population concentrations or airport locations in meteorology and with shipping lanes in oceanography — and more recently out of technological innovation such as remote-sensing instruments being placed on polar-orbiting and geostationary satellites. A number of results on observability (Gelb, 1974; Cohn and Dee, 1986) and observing-system design (Ghil, 1997) should eventually permit the fully rational design of observing systems used in one-time field experiments, as well as in long-term monitoring programs.

3. Concluding remarks

Each field of geophysical fluid dynamics seems to move through a number of phases with respect to its uses of data assimilation (DA). In the *pre-DA* phase, few data and poor models lead to an antagonism between the theoretician — "science is truth, don't bother me with the facts" — and the observer or experimentalist: "don't ruin my beautiful, hard-won data with your lousy model." In the *early-DA* phase, the data and models both improve somewhat, and the first attempts are made at combining the two by direct insertion of the data into the models or "nudging."

During the *mature-DA* phase, the data are more numerous and the models more skillful. Spline interpolation (Wahba and Wendelberger, 1980) and statistical regression, or "optimal interpolation" (Daley, 1991) methods become widespread. The present WMO Symposium illustrates the *advanced-DA* phase in meteorology and oceanography. Plentiful data sets and truly fine models motivate the use of high-performance DA methods, such as the extended Kalman filter and four-dimensional variational methods. It gives me hope that at the next symposium, the fourth and the first one in the next century, we shall see the beginnings of *post-modern* DA, with satellite images being directly converted into weather forecasts and climate movies.

Acknowledgements. It is a pleasure to thank the International Program Committee for the invitation to deliver this Inaugural Lecture and the participants for watching patiently while I was trying to be funny. The continuing support of NASA grant NAG5-731 over the quarter Century that I kept learning about data assimilation is greatly appreciated.. F. Fleuriau helped with the Word processing of the Lecture's extended abstract, as well as the transparencies.

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