FUNDAMENTALS OF ATMOSPHERIC DATA ASSIMILATION

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Introduction

Fifteen years ago, data assimilation was a minor and often neglected sub-discipline of numerical weather prediction. The situation is very different today. Data assimilation is now felt to be important for all climate/environmental monitoring and estimating the ocean state. There have been great advances in both modelling and instrumentation for a variety of atmospheric phenomena and variables, and data assimilation provides the bridge between them. It is now possible to imagine modelling, observing and assimilating many physical, chemical and biological state variables, in addition to the traditional meteorological variables.

Object

The object of atmospheric data assimilation is to produce a regular, physically consistent four dimensional representation of the state of the atmosphere from a heterogeneous array of in situ and remote instruments which sample imperfectly and irregularly in space and time. The regular, physically consistent aspects of the procedure come from the use of models, and thus data assimilation is a discipline which naturally integrates theory (via models) with sampled reality (via instruments). But data assimilation does more than simply optimally combine observations with model estimates; it also confronts models (theory) with reality, which can potentially lead to improvements in both models and instruments.

Filtering, interpolation and completeness

Data assimilation extracts the signal from noisy observations (filtering), interpolates in space and time (interpolation) and reconstructs state variables that are not sampled by the observation network (completeness). It is possible to regard any data assimilation system as an elaborate filter whose spectral properties are adjustable. Atmospheric data assimilation systems are inherently complex. In order to understand such systems, it is well to keep three things in mind.

Characteristics

(1) What is the purpose of the data assimilation - weather prediction, physical understanding, signal detection, environmental monitoring etc?

(2) What are the physical characteristics of the phenomenon of interest? In particular, what are its temporal and spatial characteristics and what relations exist between the state variables? What are the characteristics of other physical phenomena which might obscure the desired signal?

(3) What are the characteristics of the observing system? Is the observing system largely under the control of the scientist (as in a field experiment) or is it given (the World Weather Watch)? If it is possible to influence the design of the observing system, can data assimilation considerations be given any weight, or can data assimilation techniques (such as observation system experiments) be used in the observation system design?

The observing system

There are many types of instrument and they sample the atmosphere (and earth surface) in many different ways. In order to use the information from these instruments in an optimal fashion it is necessary to understand the characteristics of the instrument. Instruments can be roughly divided into three categories - in situ (point) instruments such as thermometers, remote instruments which are active (radars) or passive (radiometers) which measure volumes from a distance and Lagrangian measurements in which identifiable targets are tracked in order to determine the circulation. Some instruments, such as constant level balloons, have characteristics of both in situ and Lagrangian instruments.

Sampling patterns for instruments vary widely. Traditional instruments such as radiosondes sample the atmosphere at fixed times and from (essentially) fixed locations. Orbiting instruments sample more irregularly in both space and time. In general, the sampling patterns of instruments have been traditionally driven by external considerations rather than the needs of atmospheric science. Thus, most surface observations tend to be in densely populated areas and the sampling patterns of orbiting instruments are governed by orbital mechanics. However, as noted later in section 5, there is an increasing reliance on the forecast/analysis system itself in designing and deploying new instrument systems.

Some observation errors can be represented statistically - notably the instrument errors and the errors of representativeness. (Errors of representativeness are due to the discrete sampling of a continuous medium). These errors may be biased, spatially or temporally correlated or correlated with the signal. Other errors, human or electronic, may not be so amenable to a statistical treatment, but can sometimes be removed if recognized.

In atmospheric data assimilation, it is important to understand as much as possible about each instrument whose observations are to be assimilated. In particular, the observation error characteristics of the instrument should be as well-understood as possible.

Subjective and objective analysis

Atmospheric data assimilation has its roots in the subjective analysis procedures developed in the last century for producing hand-drawn weather maps. Such maps were a necessary preliminary step in the production of weather forecasts. In fact, such hand-drawn maps are still used today by forecasters as a preliminary step in manual forecast procedures.

In the mid-1950s, the development of electronic computers made it possible to imagine the production of weather forecasts using numerical models based on simplifications and discretizations of the atmospheric governing equations. While such numerical models were originally advocated by Richardson in the 1920's, practical implementation was delayed until the dawn of the computer age. Numerical weather prediction is an initial value problem and requires analyses of the initial conditions to begin a time marching process. Subjective analyses were too time-consuming for this purpose and so the first objective analyses were produced in 1949 by Panofsky. The early objective analyses were produced by ad hoc (but relatively inexpensive) techniques from the observations alone.

Improving analyses with forecast information

It was discovered quite early on (Bergthorsson and Doos, 1955 and Thompson, 1961) that analyses could be improved if they were not based solely on available observations, but also on forecasts made by a model from previous observations. In effect, the model integrated the effect of previous observations and updated them to the present. Of course, for this idea to be successful, the model had to have some skill and it was necessary to combine the observations and forecast in an optimal fashion.

Combining observed values with estimates obtained by a model of some kind is not a new idea. In fact, it goes back to Gauss and his attempt to determine the orbits of comets and planets from incomplete astronomical data. In addition to his astronomical observations, Gauss also had the laws of Newtonian mechanics (his model) and invented least-square techniques to optimally estimate the orbits. This work, described in Theoria Motus Corporum Coelestium (1809) is the beginning of what is known today as estimation theory. A paragraph from this work is still relevent for atmospheric data assimilation.

> "If the astronomical observations and other quantities on which the computations of orbits is based, were absolutely correct, the elements also, whether deduced from three or four observations, would be strictly accurate (so far indeed as the motion is supposed to take place exactly according to the laws of Kepler), and therefore, if other observations were used, they might be confirmed, but not corrected. But since our measurements and observations are nothing more than approximations to truth, the same must be true of all calculations resting upon them, and the highest aim of all computation made concerning concrete phenomena must be to approximate, as nearly as practicable to the truth. But this can be accomplished in no other way than by a suitable combination of more observations than the number absolutely requisite for the determination of the unknown quantities. This problem can be only

properly undertaken when an approximate knowledge of the orbit has been already obtained, which is afterward to be corrected, so as to satisfy all of the observations in the most accurate manner possible."

This paragraph contains a number of key ideas - (1) all models and observations are approximate, (2) the resulting analyses will also be approximate, (3) the observations must be combined in some optimal fashion, (4) it is better to have enough observations to overdetermine the problem, (5) the model is used to provide a preliminary estimate, and (6) the final estimate should fit the observations within their (presumed) observation error.

Development of the theory

In atmospheric data assimilation, estimation theory is applied to a complex physical system which is being sampled by a large suite of instruments. The fundamental theory is discussed in Daley (1991,1996), beginning with simple scalar systems and then proceeding to three and four dimensional analysis.

References

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