ASSIMILATION OF DATA FROM SATELLITE SYSTEMS IN THE 1990s

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1. INTRODUCTION

The new instruments to be flown in this decade pose new challenges to our assimilation techniques, if we are to exploit the data to the full. Section 2 discusses the information content of data for NWP. Section 3 discusses two approaches to the use of satellite data. Section 4 describes the new satellite instruments likely to become available, and discuss the problems of assimilating each of the data types.

2. INFORMATION CONTENT OF DATA IN NWP

Most assimilation systems lead to analysis error estimates of the form

$$\boldsymbol{A}^{-1} = \boldsymbol{P}^{-1} + \boldsymbol{D}^{-1} \tag{1}$$

where $\boldsymbol{P}$, $\boldsymbol{D}$, $\boldsymbol{A}$ are the error covariances of our prior knowledge, of the data, and of the analysis.

Information content is a relative concept. If we speak of the determinant of $\boldsymbol{P}$, the error covariance matrix of our knowledge of a physical system using all earlier information, but before we use a new data source as the *a-priori* uncertainty, and if we speak of the determinant of $\boldsymbol{A}$, the error covariance matrix of our knowledge of the physical system after we have used the new data source as the *a-posteriori* uncertainty, then the information content of a data source is proportional to $\log\,[\det(P)/DET(A)]$, i.e. the log of the ratio of the volumes of the *a-priori* and *a-posteriori* uncertainty ellipsoids. Thus, the more accurate the new data, the higher its information content, while the better the *a-priori* information, the lower the information content of new data.

To judge the information content of a new data source, we need to know the error characteristics of the data and the error characteristics of the prior information. For many purposes in data assimilation, the best prior information is provided by the NWP model variables, or by inferences from the model state. The accuracy of the prior information from the model changes with the variable in question: winds and temperatures will be much more reliable than clouds and precipitation.

3. APPROACHES TO USING REMOTELY-SENSED DATA

Any effort to use remotely-sensed radiance measurements in a quantitative way must interpret the radiance measurements in terms of geophysical quantities. To proceed from the remote measurements to the unknown geophysical quantities, one must somehow invert the radiative transfer equation. The equation can be highly non-linear in the transmission properties and in the boundary conditions, both of which may be unknowns; the set of measurements is finite, so the problem is usually underspecified, and the physical effect of the variable of interest on the radiation may not be well understood. Extraction of information from remotely sensed measurements is a non-trivial problem.

3.1 The satellite to model (retrieval) approach

The most common approach to the problem of using satellite data has been the 'satellite-to-model' approach, where one transforms the radiance measurements into estimates of model variables, through a retrieval procedure which precedes the assimilation. This approach requires additional information, in the form of recent climatology, and assumptions about the permissible types of atmospheric variations.

The satellite to model (retrieval) approach is useful when the most accurate *a-priori* information is statistical or climatological. In the NWP context, the retrieval approach is useful when one requires *a-priori* information on fields which are not forecast by the model, or which are badly forecast by the model. The retrieval approach to TOVS data certainly works well in the southern hemisphere.

Recent NWP experience with temperature retrievals in the northern hemisphere has been that the retrieved temperature profiles have flow-dependent errors, which are much larger than the errors of the short-range forecasts. The errors arise because the source of the required additional information - recent climatology - gives a much less accurate estimate of the state of the atmosphere than a short range forecast. Thus the information content of present-day retrieved soundings relative to present-day forecasts is low. As a result of these problems, there is considerable activity in an alternative approach to the use of satellite data, the model to satellite approach.

3.2 The variational 'model to satellite' approach

In the model to satellite approach to using satellite data, one compares the radiances $K(x_b)$ calculated from the model background field x_b with the observed radiances r. A variational method is used to find the most likely model state x, by minimising a functional of the form

$$J(x) = (x - x_b)^T B^{-1} (x - x_b) + (K(x) - r)^T (E + F)^{-1}(K(x) - r) \tag{2}$$

where $\boldsymbol{B}$, $\boldsymbol{E}$, $\boldsymbol{F}$ are the error covariances of the background field, of the measurements, and of the forward calculation $\boldsymbol{K}$. When $\boldsymbol{K}$ is non-linear, minimisation of the functional $\boldsymbol{J}$ requires an iterative descent process, where information on the descent is provided by the adjoint of the linearised version of the operator $\boldsymbol{K}$. This 3-dimensional approach, and its generalisation to 4-dimensions, utilises the accuracy of the forecast model very directly, and should produce better results. The method has still to be tested in real-size problems.

3.3 DISCUSSION

Provided the relevant geophysical variables are known, the satellite to model approach can be implemented through statistical relations between the radiances and the geophysical quantities. This approach by-passes the need to understand the detailed physics of the matter/ radiation interaction. The statistical relations can be updated as new collocations of field data and satellite data become available. The statistical methods can compensate for stable errors in calibrations of the satellite instruments. Through the use of climatological information, the retrieval approach may impose a climatological constraint on the evolution of the assimilation.

If the relation between the geophysical quantities of interest and the radiative fields is explicitly known with useful accuracy (i.e. if we have a good forward model $\boldsymbol{K}$), and if the NWP model has useful predictive skill (i.e. skill better than climatology) for the variables needed in calculating $\boldsymbol{K}(\boldsymbol{x})$, then the preferred approach is the model to satellite approach. The model to satellite approach will give more accurate and more satisfactory results because the radiances calculated from the analysis will match the measurements to within acceptable tolerances.

The successful use of the model to satellite approach places fairly stringent requirements on the assimilation system

- We need a forecast model which can forecast the variables of interest with useful accuracy.
- The forward calculation (and its offshoots, the linearised forward calculation and its adjoint) must be accurate and affordable.
- The measurements be well calibrated.

There is some concern about the stability of the model-to-satellite approach in long assimilations. A longterm climate drift in the model may bias the interpretation of the data. The climatological information in current retrievals may serve to stabilise an assimilation in otherwise data-void areas. Experimentation is needed to see if this is a real problem.

4. ASSIMILATION OF DATA FROM NEW INSTRUMENTS

We consider the major instruments which will give extensive coverage, at resolutions typical of global or regional models (10km or coarser) during the 1990s. We do not discuss instruments with resolution in the range 10m-10km, even though such instruments are invaluable in problems such as cloud detection. The existing satellite data systems -TOVS soundings from polar orbiters, and cloud motion vectors from geostationary satellites, will play an important role throughout most of the decade and so we also discuss likely new developments in the treatment of these data.

Examples of new types of satellite data becoming available in the first half of the decade include:

- surface wind speed, integrated water vapour, or integrated liquid water content, or rain rate, from microwave imagers such as SSM/I.

- surface wind data from ERS-1 (1991) and from the NASA scatterometer NSCAT on the Japanese satellite ADEOS (1994/95);

- improved microwave temperature and humidity soundings from AMSU (1994).

All of the above instruments exist or are being built, and the time-frame for their launch is known to within a year or two. In the second half of the decade we move into the era of the polar platforms. The major new possibilities in this time frame are

- higher resolution temperature and humidity soundings from spectrometer instruments such as AIRS (100 - 4000 channels), or from interferometers such as HIS or ISAS, each with up to 4000 channels.

- global wind coverage with 1-2km resolution in the vertical from LAWS/ALADIN/BEST

In this time-frame, many projects are the subject of phase-A (project definition stage) or pre-phase-A studies. Consequently the funding and the time scales for deployment are rather uncertain, particularly for very ambitious projects such as LAWS. Limitations of space preclude discussion of other possibilities such as wind speed from altimeters, estimates of cloud-top height, and PBL height, from scanning differential absorption lidars, or broadband earth radiation measurements from CERES, all of which could perhaps be used operationally.

4.1 Developments in the use of current data

We discuss the problems of assimilating data from each of the instruments mentioned above with particular attention to the skill of the forecast model in forecasting relevant geophysical parameters, the accuracy and cost of the full and linearised forward model and its adjoint, and the problems associated with maintaining calibration.

a) TOVS DATA

Up to now the satellite to model approach of using retrievals for assimilation has been widespread. Recent results in the northern hemisphere demonstrate serious shortcomings of the retrieval approach in cases of marked temperature advection over ocean. As the assimilation systems have become more accurate, the effects of the climatological data used in the satellite to model approach, and the limited vertical resolution of the instrument, have become increasingly damaging. To overcome these limitations, extensive research is underway on the alternative model to satellite approach.

In the model to satellite approach, the forward calculation needs temperature (T) and humidity (q) fields and clouds. The NWP models predict the T and q fields rather well, but do not predict the cloud fields nearly so well. Cloud detection and cloud correction is therefore an important step. Improvements in cloud prediction are desirable. The fast forward models currently in use show significant biases which vary with airmass and season. The reasons for these biases need to be better understood. Until we have a better understanding of the cause of these biases, empirical corrections will have to be applied to the results of the forward calculation. Cross-comparison of the same TOVS channels on different NOAA satellites show biases arising from differences in the instruments themselves. However these biases are easy to identify, they seem to be fairly stable over time, and so can be corrected for.

b) Cloud track vectors

For the foreseeable future, the satellite to model approach will be used to process this data. Distinct improvements in the quality of METEOSAT winds have been obtained from improved calibrations of the instruments and from the use of *a-priori* estimates of the wind from a forecast model. More recently, improved GOES winds have been obtained through the experimental use of the CO_2 channels on VAS. It is to be hoped that these improvements will be implemented in operations at an early date. The problems with INSAT data are well known. It is unclear if the problems are inherent in the stabilisation of the space craft, or originate in the ground processing. It is devoutly to be hoped that the 3-axis stabilisation on GOES-NEXT works well. If not we shall be bereft of good winds in a large sector of the tropics for most of this decade.

4.2 New operational instruments in the 1990-95 period

a) SSM/I

The first of this series of instruments was launched in 1987, but the data is not yet generally available. The scanning microwave imager operates on four microwave frequencies (19, 22, 37, 85 GHz, and two polarizations). The radiances are sensitive to many aspects of the atmosphere and of the land, sea-ice, and ocean surfaces. The surface wind over the ocean affects the surface emissivity. There is sensitivity to water vapour, to emission from water droplets, (and so to cloud and rain-rate), and to scattering from ice-particles (from cirrus, and deep convection) at high frequencies .

Most of the atmospheric water properties inferred so far from SSM/I data using the satellite to model approach have been vertical integrals. Depth-averaged quantities of this kind are difficult to use, and so the model to satellite approach may provide a better approach. It is not clear that the interaction of matter and radiation is fully understood at these frequencies, and there is a need for further studies in this area. Even without this difficulty, the forward problem involves many variables and is quite complex. Use of the model to satellite approach will require that forecast models be able to supply useful estimates of surface wind, integrated water vapour, cloud depth (and mean drop size) and quantitative estimates of precipitation and the depth of the precipitating layer.

There are encouraging reports about the wind speed estimates derived from the SSM/I data, once the effects of rain contamination have been removed. Since wind speed is a non-linear function of the model's wind variables (u,v), and since an assimilating model can give a useful indication of the location of rain areas, the variational (model to satellite) approach is probably the best way to use the data in a quantitative way. There are obvious spin-off benefits for model validation from the approach.

Recent work suggests that at least for the lower frequency channels, the calibration can be monitored on an almost daily basis, using global data assimilation fields. Normally of course, it can take months to get enough matches with single point measurements to establish a calibration. The situation for the higher frequencies is much more complicated.

b) ERS-1 scatterometer wind data

The scatterometers on ERS-1 and later satellites (ADEOS, EOS-A) will measure the Bragg scattering from gravity capillary waves in the 1-10cm range. It is expected that the wind data will be particularly useful in delineating small-scale structures, such as hurricanes, polar lows, and fronts.

The physics of the interaction of the radar beam with a rough sea-surface is poorly understood. Many effects - wave-breaking (white-capping) - modulation by long waves - the effects of rain on the sea-surface and on the transmission function -the effect of static stability on the surface stress - make the problem complicated. For the moment the forward calculation of the normalised radar scattering cross-section (sigma-nought) must be based on statistical relations between sigma-nought and wind. From the three radar beams it is possible, in the absence of noise, to produce a good (maximum-likelihood) estimate of the wind. This is a non-trivial problem in the presence of noise.

Several approaches to the de-aliasing (ambiguity-removal) problem have been developed. If there are no instrumental problems, so that the noise level is low, then simple methods should work well. If however there are instrumental problems (e.g. thermal problems, pointing errors, antenna bias) then more sophisticated variational methods may be necessary. All the methods currently planned for operational use will need forecast information; some methods will use only very large scale aspects of the forecasts, others will use detailed forecast information. In general we would expect that the variational (model to satellite) approach will prove the most reliable.

Experience with SeaSat has shown that combination of the data from the scatterometer and from the SMMR (the precursor of SSM/I) was very useful in establishing the location of fronts. A similar synergy between the SSM/I microwave imager and the ERS-1 scatterometer will only be possible through the use of assimilation methods, because the two satellites are in different orbits.

c) AMSU

This 20-channel microwave instrument offers the prospect of sounding capability in clouds, similar to current TOVS sounding capability in clear skies. The temperature sounding capability comes from channels in the oxygen band at 55GHz, with a footprint of about 45km (cf. 150km on the current MSU). The water vapour sounding capability comes from channels in the 183GHz water vapour band, with a footprint of 15km. Additional channels will permit estimates of *(inter alia)* surface T, q and emissivity, total ozone and total cloud liquid water.

As in the case of SSM/I, there are unresolved questions about radiative transfer in the presence of cloud at the relevant frequencies. The uncertainties in these areas need to be resolved soon, so that sound preparations can be made for the production of retrievals using both HIRS and AMSU.

Developments in the assimilation of AMSU data using the model to satellite approach will follow closely the pattern for the use of HIRS data, with the added complexity of a surface emissivity specification. The emissivity specification over ocean is relatively simple compared to the specification over land.

4.3 New operational instruments after 1995

a) High resolution I-R spectrometers and interferometers

Towards the end of the decade high resolution I-R instruments with up to 4000 channels will be flown. The main benefit from these instruments will be significant increases in the vertical resolution of clear-sky temperature and humidity soundings, resulting from narrower weighting functions. Results from aircraft flights of the Wisconsin interferometer HIS have been very encouraging. The data rates from these instruments will be two orders of magnitude larger than from current instruments such as TOVS. For many users the retrieval approach may be the only feasible approach to using the data, with retrievals being made at central sites.

For those centres following the model to satellite approach, there will be corresponding increases in the cost of the forward calculation and associated calculations. This will be probably be tolerable for three dimensional variational calculations using the satellite to model approach. Given the uncertainties of where we will be at the end of the decade in terms of the resolution of operational models, the efficiency of descent algorithms and the power of computers, one can only speculate on the possibilities of using these data in a four-dimensional assimilation using the model to satellite approach. If economies are needed one can always integrate over wave-length to degrade the resolution of the instrument to any desired degree.

b) Laser atmospheric wind sounders

Observation of the global three dimensional wind field is a Holy Grail for NWP and climate studies. Several instrument designs have been proposed to measure the three dimensional wind field using the Doppler shift of laser light back-scattered from aerosol. Such data will be available down to cloud top with a resolution of about 1km.

The US proposal is the subject of phase-A (project definition) studies by industry at present. The main technological problems are the number of shots one can get in the lifetime of the laser, and the difficulty of building a satisfactory scanning device. An alternative French design proposes the use of fixed telescopes, but may have problems with the weight of the telescopes.

It is not clear if the first instruments will be in sun-synchronous polar orbit at about 800km, providing global coverage once or twice a day, or in a low altitude (300km) low inclination (30deg) orbit, which would provide tropical coverage several times per day. The latter orbit probably makes more achievable demands on the technology.

From the point of view of users, there is lively debate about the type of data to be used in an assimilation. The lowest level of data considered for use is the spectrum of the return signal which will show a clear signature at the frequency corresponding to the line-of-sight velocity. In a noisy system there may be several such signatures of nearly the same amplitude, and it may not be possible to pick the right one without some *a-priori* information from a forecast model. Depending on the noise of the system, one could make the case for providing the full spectrum to the users (current plans are to limit the velocities analysed to a range of a few m/s around the clearest signature).

If the system is not too noisy, the next issue will be whether it is better to use line of sight velocities for assimilation, or whether the data producers should manage the shot pattern so that shots from different angles coincide, enabling one to derive (u,v) components at selected points. Most of the sophisticated data users would probably prefer the line of sight velocities, as they would have a less heavily processed product, on which they could then perform their own preferred filtering and interpretation. All of these considerations will affect decisions on how to manage the pattern of shots.

5. DISCUSSION

The coming decade offers many new and exciting developments in our capability to observe the atmosphere. To exploit these capabilities to the full we need

- new developments in radiative transfer in cloudy and rainy atmospheres, in both the IR and the microwave region of the spectrum.
- Developments in the accuracy and efficiency of variational assimilation.
- improved modelling capability for geophysical quantities affecting the emitted radiation (e.g. rain, cloud, surface properties, skin temperature).
- increases in telecommunications power to handle the increased data flow
- increases in computer power to develop four dimensional assimilation systems capable of dealing effectively with the many new types of data.

The development in observational capability will stimulate the development of improved modelling capability for the geophysical variables affecting the emitted radiation. Improved modelling capability in turn will refine the accuracy of our interpretations and syntheses of the observations.
Our main concern is that it will take so long to get the new instruments into orbit.

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