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ASSIMILATION OF SATELLITE DATA IN MODELS FOR ENERGY AND WATER CYCLE RESEARCH

by

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July 1992

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ABSTRACT

Numerical models provide a detailed, self-consistent, fairly accurate picture of atmospheric processes. If there are sufficient data, assimilation techniques can keep the model's representation in line with the actual evolving atmospheric state, enabling detailed diagnosis and understanding of atmospheric phenomena. Satellite data from temperature sounders, and planned doppler wind lidars, are most useful through model assimilation.

Moisture in the models is controlled by the parametrisations of sub-grid-scale processes. The model reaches an equilibrium between evaporation and condensation, whose latent heating is an important driver of the dynamical circulations. Assimilation can force the model away from this equilibrium state, damaging the model's representation of atmospheric processes. Examples are given where incorrectly processed data have done this. Even with accurate data, assimilation is not the way to correct systematic deficiencies in the model. Rather, we learn about the model, and should be able to improve it and our understanding.

DATA ASSIMILATION

Definition

There are insufficient conventional observations to determine the state of the atmosphere in the detail required to represent processes essential to the understanding of the energy and water cycles. Even with the vast growth in satellite observations, (perhaps reaching 10^{10} bits per second during the next decade) this will remain true - satellite observations are necessarily indirect; it is not possible to observed all important aspects. Therefore we need additional information. This underdeterminacy can be resolved using prior knowledge of the structure and behavior of the atmosphere. Our knowledge can be conveniently encapsulated in a physically based numerical model. In particular, knowledge of the laws governing evolution with time is embodied in the models used for Numerical Weather Prediction. This enables us to use data distributed in time. The models also provide consistent means of representing the atmosphere, and deriving fluxes and other diagnostic quantities. *Data assimilation is the process of finding the model representation which is most consistent with the observations.*

Given observations distributed in time and space, and a forecast model, we can perform a four-dimensional data assimilation. This is normally done by integrating the model forward in time, adding observations. The model state summarizes in an organized way the information from earlier observations. It is modified to incorporated new observations, by combining old and new information, in a statistically optimal way.

Characteristics and Uses

Data assimilation provides a convenient comprehensive representation of the atmosphere. By combining information from a wide variety of observations with our prior understanding, it can provide a high space- and time-resolution. These attributes make assimilation the best approach for:

- providing a detailed best estimate of the atmospheric state, for example to initialize a forecast,
- studies of atmospheric mechanisms,
- determining higher-order moments, such as the horizontal water flux, as demonstrated below,
- providing auxiliary data for processing indirect observations from remote sensing, for instance the derivation of temperature soundings from satellite observed radiances has been demonstrated to be best performed in an assimilation context.

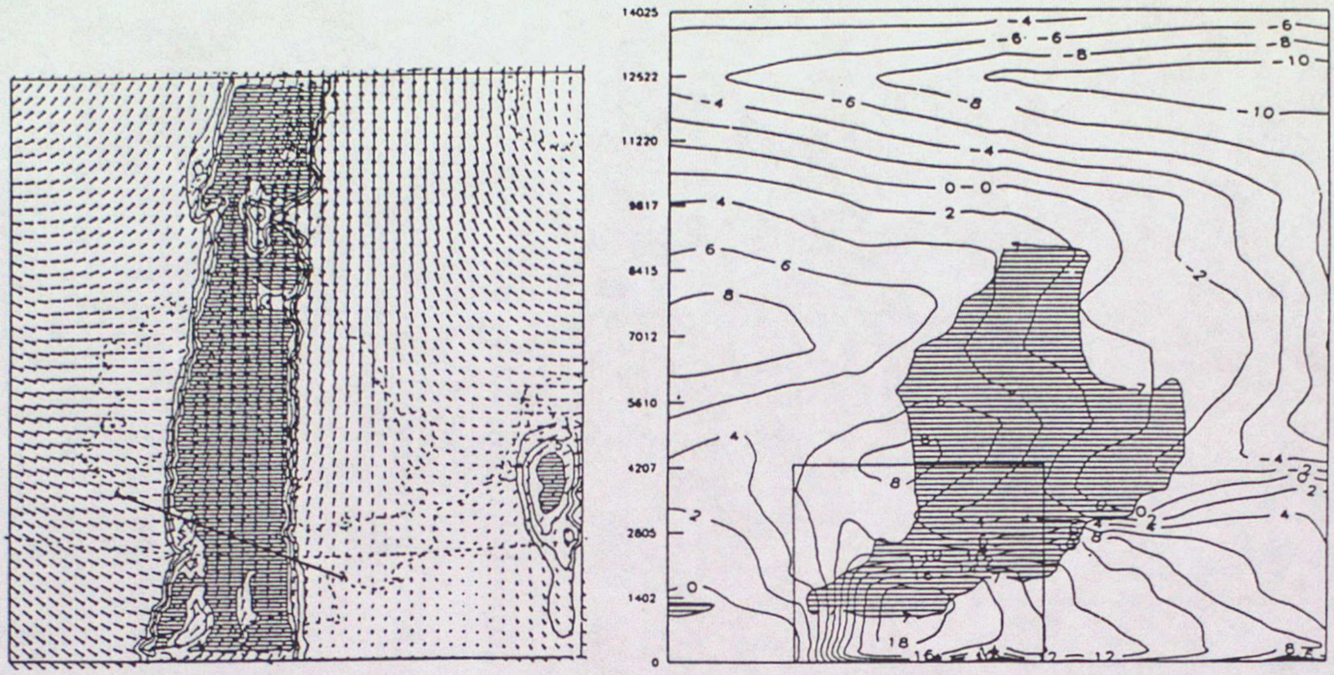
However, the mix of sources of information varies in space and time, so any bias will have a variable effect which is hard to quantify. This bias might be in the observations, or in the model. Moreover, because of the position of the model at the heart of the assimilation process, only aspects of the atmosphere well represented by the model can be assimilated. Assimilation is therefore not the best approach for:

- climate change detection in simple quantities like the mean temperature,
- providing assimilated datasets for improving our understanding in areas where the model is weak.

By contrast, the detailed information, obtained while trying to fit model to data in the assimilation process, can be very useful in diagnosing areas where the model is weak.

HORIZONTAL MOISTURE FLUXES

Part of the aim of the GEWEX experiment is an improved understanding of global and regional moisture transport. Deployment of a satellite Doppler lidar instrument is generally considered necessary to obtain the high resolution wind data necessary to achieve this goal. The results shown in this section are taken from a preparatory study of such an instrument /1/. Low-level wind systems giving rise to significant moisture transport are frequently located beneath clouds - and therefore will not be observed by the lidar. High resolution models represent such features well, so the fluxes are best studied using of model assimilated datasets.



(a) (b)

Figure 1. Mesoscale model 12hr forecast, valid 12GMT 23rd Nov 1991. (a) 1·5km wind and cloud cover at 4km. (b) cross section along the line marked on (a) of the wind component perpendicular to the cross-section. Cloud cover greater than 7/8 is shaded.

Figure 1 shows a 12hr mesoscale model forecast of a marked front approximately north-south across the British Isles. Figure 1b shows vertical cross section, of wind speed along the front, - regions where cloud cover is 7/8 or more are shown shaded. A well defined maximum in the low-level flow, reaching $18ms^{-1}$, may be seen ahead of the front at a height of ~1.5km. It is clear that the wind maximum will be completely obscured to observation from above by the accompanying frontal cloud. The meridional moisture flux (not shown) has a pronounced narrow maximum just below the cloud band shown in figure 1a. To verify that the main features of the model simulation are reasonable representations of the observed structure, look at figure 2. An area of continuous rainfall associated with the front has been delineated and clearly corresponds well with the cloud band in the forecast (figure 1a) The inset to figure 2 shows a time series, generated from radiosonde data at Cambourne (marked X), of the vertical profile of the wind component parallel to the front; the area of the cross-section corresponds to the enclosed part of the cross section in figure 1a. The model has a good representation of a well defined low-level jet. Such low-level jet structures ahead of cold fronts are well documented and are known as "warm conveyor belts" /2/.

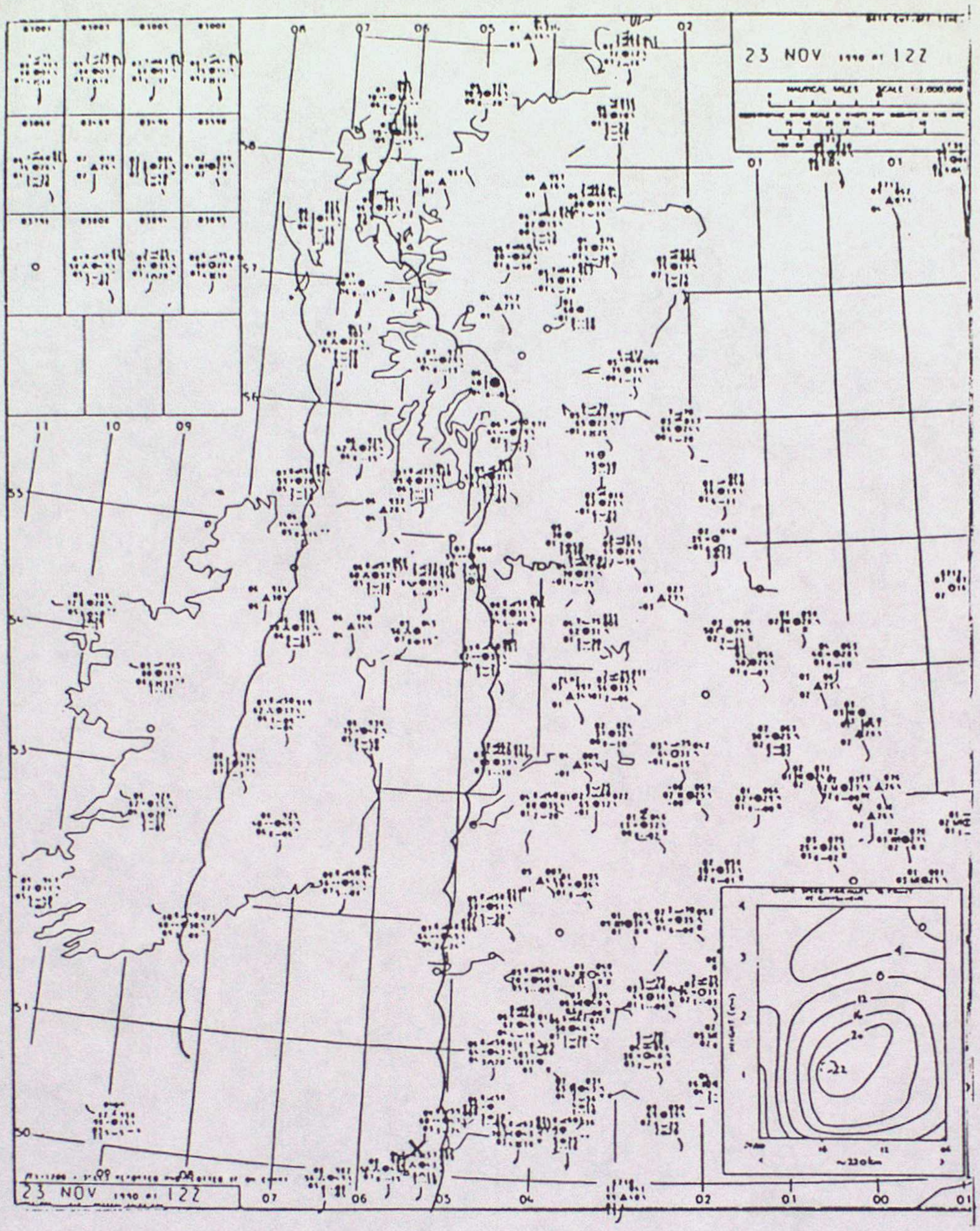


Figure 2. Synoptic observations at 12GMT 23rd Nov 1991. The band of of continuous rainfall associated with the front has been delineated. The inset shows a vertical cross section of the wind speed parallel to the front derived from radiosonde data from Cambourne (X).

Because of the concentration of moisture at low levels, horizontal fluxes will be dominated by strong low-level flows. In mid-latitude systems, such as that studied above, such flows are usually associated with fronts and hence clouds. At other latitudes, other types of system (e.g. boundary currents such as the Somali Jet, and sea-breeze circulations) may dominate. Nevertheless, the biased sampling induced by clouds remains important. We demonstrate this using a global assimilation. Model analysis fields for 12GMT 20 June 1991 (from the UK Met. Office unified model) were used to compute the moisture flux across selected latitude circles. Since the greater part of the moisture flux occurs at low-levels, only the flux at 850mb is shown. First, the total 850mb meridional moisture flux across each model grid length was found. Second, to obtain the part of the flux occurring under clear skies, the flux across each grid length was multiplied by the fraction of clear sky, above 850mb, assigned to the grid square by the model's parametrisation scheme. Results are shown in table 1. At all latitudes, the flux calculated using observations biased towards clear sky cases will grossly misrepresent that given by an assimilation.

latitude	Poleward flux (Kgs^{-1})			Equatorward flux (Kgs^{-1})			Net flux (Poleward)	
	total	clear sky	ratio	total	clear sky	ratio	total	clear sky
50N	389	148	0.38	330	267	0.81	+ 59	-119
30N	611	355	0.58	507	420	0.83	+104	- 65
10N	785	501	0.64	393	329	0.84	+392	+172

Table 1: Total and "clear sky" moisture flux at 850mb across latitudes 50, 30 and 10N. Note that the net poleward moisture flux under clear sky is considerably smaller than the total flux, and is of opposite sign at 50N and 30N, illustrating the difficulties of estimating global moisture transports from flux observations based on Doppler lidar winds.

ASSIMILATION OF MOISTURE DATA

In the previous section we showed that assimilation into a model is essential if we are to get an adequate representation of the horizontal fluxes which help determine the water cycle. Indeed, by assimilation of wind, pressure, and temperature data alone, the assimilation model can get a reasonable picture of the moisture distribution /3/. The physical parametrisations of moist processes within the assimilation models provide sources and sinks of moisture in the atmosphere, which get advected into realistic looking patterns, closely matching those seen in satellite images.

Spin-up

Because many of the methods used to insert the observational information into the model can cause excessive imbalance (i.e. unrealistic oscillations), many assimilation schemes include an explicit balancing step; usually nonlinear normal-mode initialisation (NNMI). NNMI enforces a dynamical balance, however it does not properly take into account diabatic effects such as latent heating. This is a major cause of a phenomenon known as *spin-up*: the rainfall rates, on average, tend to alter as the forecast progresses. Efforts have been made in several NWP centres to alleviate this by including consideration of physical processes in the balance; in particular the spin-up of tropical convection can be improved /4/. The Meteorological Office's "Analysis Correction" data assimilation method /5/, by avoiding excessive imbalance in the insertion of data, and hence the need for NNMI, does not exhibit a large spin-up phenomenon. This is shown in figure 3 (top); globally averaged precipitation and evaporation rates are in balance, and do not change much during the forecast.

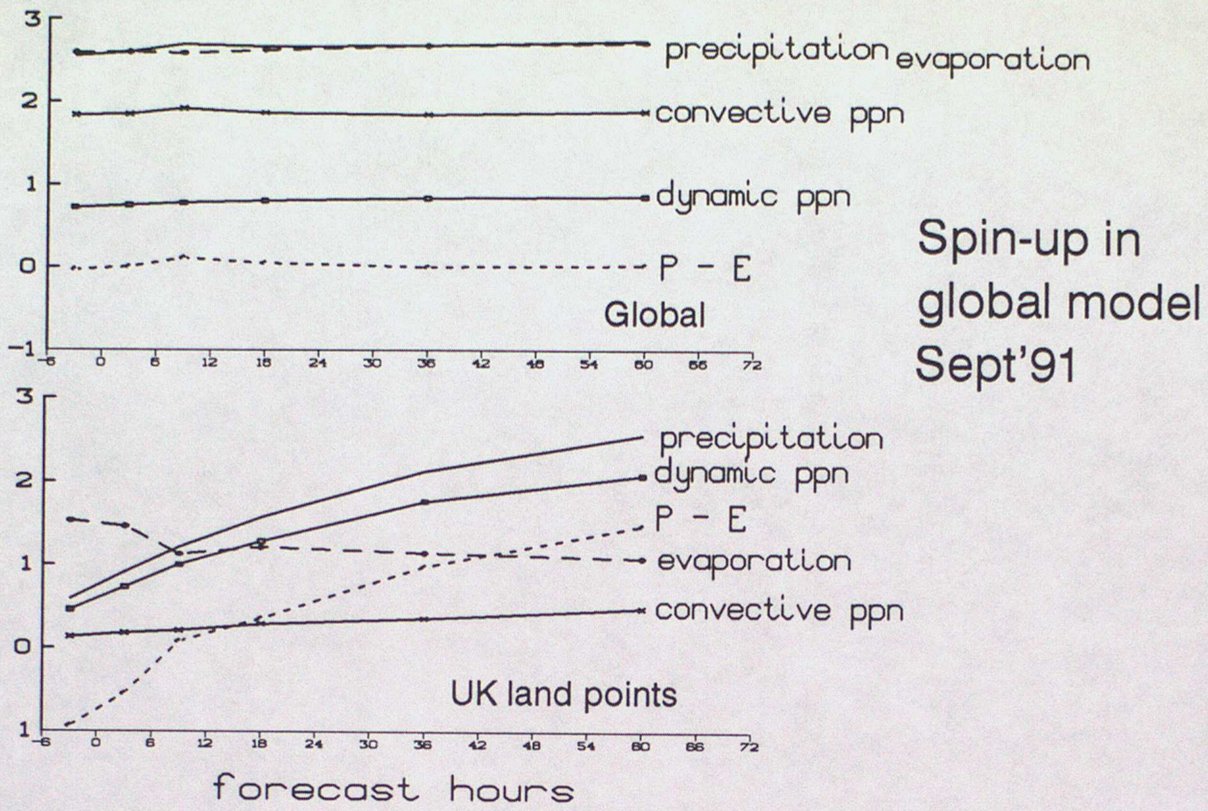


Figure 3. Precipitation rates (kg $m^{-2}day^{-1}$) for the operational Meteorological Office global model, for September 1991. The assimilation values are shown as -6-0 hours, forecast periods shown are 0-6, 6-12, 12-24, 24-48, 48-72 hours. *Top:* global averages. *Bottom:* averages for UK land points.

Water vapour

Because of inaccuracies in the parametrisations, the model's humidity fields are often slightly biased. For instance, Meteorological Office Unified Model (so called because it is used both for NWP and climate research) has an explicit cloud water variable, and generates cloud amount and water content by assuming a distribution about the grid-box mean thermodynamic and water content variables /6/. A further parametrisation give the rate of conversion of cloud to precipitation. To a first, simplistic approximation, the humidity and cloud water adjust to values giving a rainfall rate which balances the humidity sources. These values may be biased, in which case assimilation of humidity data can in degrade the rainfall simulation in the model. This is the cause of the large spin-up shown in figure 3 (bottom). Unfortunately for us, the UK area exhibits one of the largest spin-up problems in the world. This is mainly due to it being well provided with humidity data, with a dense network of stations many giving four radiosonde observations per day. These give lower humidity values than required by the parametrisation schemes described above. Assimilating them removes cloud from the model and reduces the rainfall. By the end of the period shown, the model has recovered to give a fairly good estimate of the rainfall, as shown in figure 4.

It is not only models which have biases. Because of their indirect nature, satellite observations of moisture, cloud and rainfall are also biased, and can have deleterious effects on the assimilation. For instance, a preliminary vertically integrated precipitable water content product from SSM/I (which gave values that were probably too high), when assimilated into the NMC global model, increased the available latent heat energy and unrealistically strengthened the model's Hadley Circulation (D Parrish, personal communication). It is difficult to design assimilation methods which can cope with, and get useful information from, data with biases which need more than a simple recalibration. This is why, despite many years of efforts, it was not found possible to get much useful information from satellite temperature soundings in the northern hemisphere, where other data make the assimilation rather good without them. The derived temperatures have situation dependent biases. Only by using the observed radiances more directly in the assimilation, have positive results been obtained.

Precipitation

In the tropics, there is a fairly strong relationship between Outgoing Long-wave Radiation (OLR), high (cold) cloud, convective systems, rain, and latent heating /7/. This has been used in a variety of techniques to reduce the spin-up, by forcing the model to have convection in regions where the OLR criterion is passed (see /4/ for a review). Microwave instruments such as SSM/I give rather more direct data on precipitation over the sea, which can also be used in this way. The TRMM satellite will have both of these types of data, as well as a precipitation radar. It should be possible to assimilate this.

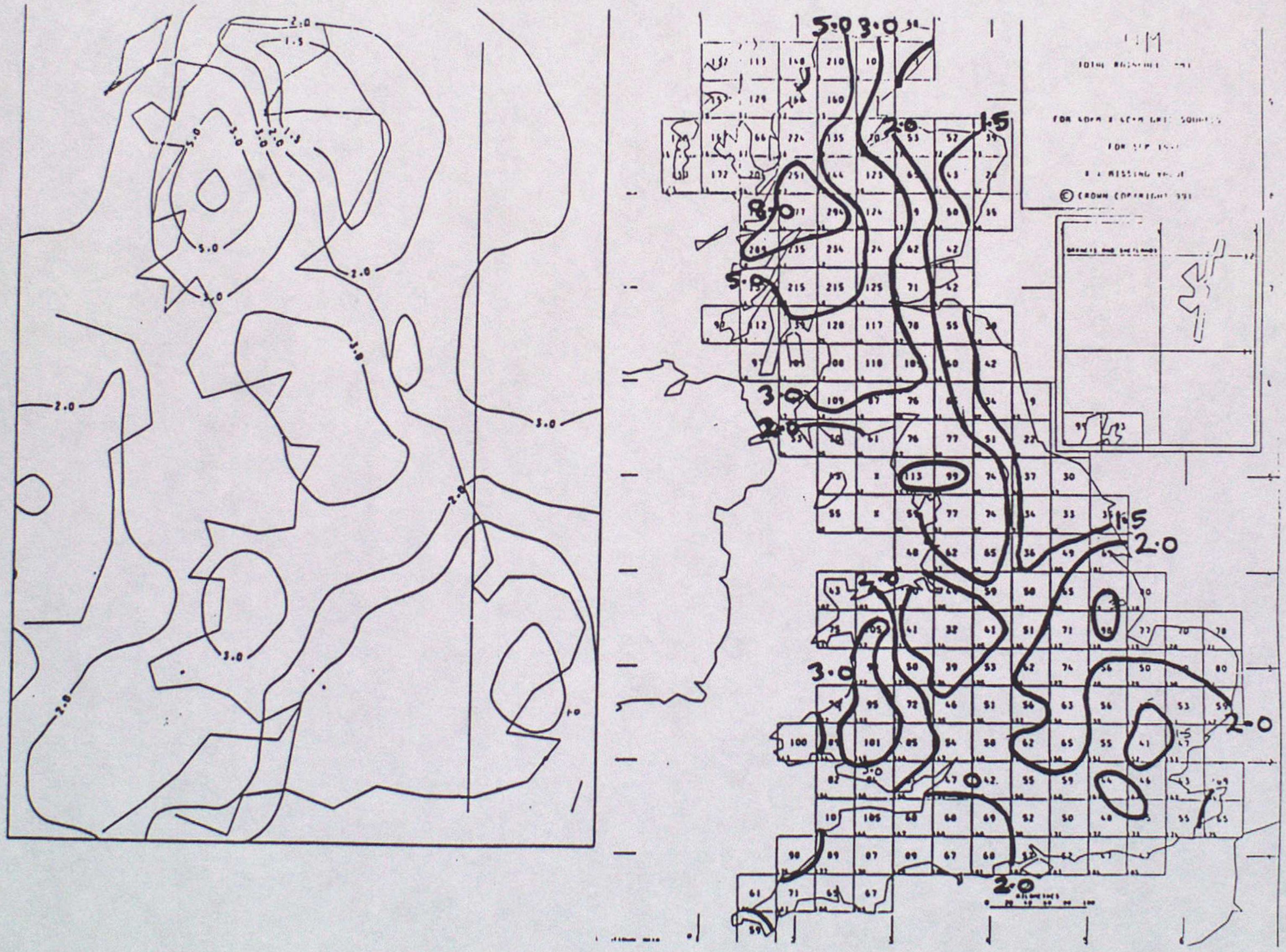


Figure 4. Precipitation for September 1991. *Left:* average of 48-72 hour forecasts (corresponding to the last point in figure 3). *Right:* observed values, processed by the Met Office Rainfall and Evaporation Calculation System (numbers shown are monthly totals). The 1.0 1.5 2.0 3.0 5.0 and 8.0 kg $m^{-2}day^{-1}$ contours are plotted on both.

The main goal of the mission is to use the three instruments together to get a better monthly averaged rainfall; the radar data are more direct, but have a narrow swath, so combination with the wider swath visible, IR and microwave imagers will improve sampling. Model data can also make a contribution to this. Figure 4 shows a model produced rainfall field which is probably better than any which could be obtained by currently planned remote sensing. In particular the model (to the extent permitted by its 90km grid) obtains the orographic enhancement to rainfall which occurs in low layers of the atmosphere, and is hard to observe from space. For the tropical rainfall which is the objective of TRMM, convective rainfall dominates. The associated diabatically driven irrotational circulations are less well handled by current assimilation systems /8/. Work is needed to evaluate and characterize the errors in model tropical rainfall estimates.

Cloud

Outside of the tropics there is not a strong relationship between cloud and precipitation. Observations of layer cloud can be used to infer humidity; insertion of these data can have a beneficial effect particularly where the dynamical forcing is not strong /8/.

These uses of cloud observations are based on empirical relationships, and require tuning and experimentation. They are helpful in maintaining the assimilation model state, its flow and weather systems, in line with reality. But they are less help in the quantitative understanding of cloud. Now that models are explicitly representing cloud /6/, work has started on using quantitative data on cloud water. At present, there is still some gross tuning of the parametrisations to be done. For example figure 5 shows the zonal, monthly mean vertically integrated cloud liquid water from a run of a climate model. The output algorithm of the model only crudely differentiates ice and liquid water: cloud with temperatures below $0^{\circ}C$ is assumed frozen. Nor does the model include convective cloud. Because of these limitations, a precise comparison with the SSM/I liquid water values shown is not possible. However it is clear that there are biases. Some of these come from the model (including its output algorithms); plausible different parameters in the parametrisation can change the model values significantly. Some also come from the data, for instance the SMMR data quoted in /7/ have significantly lower values.

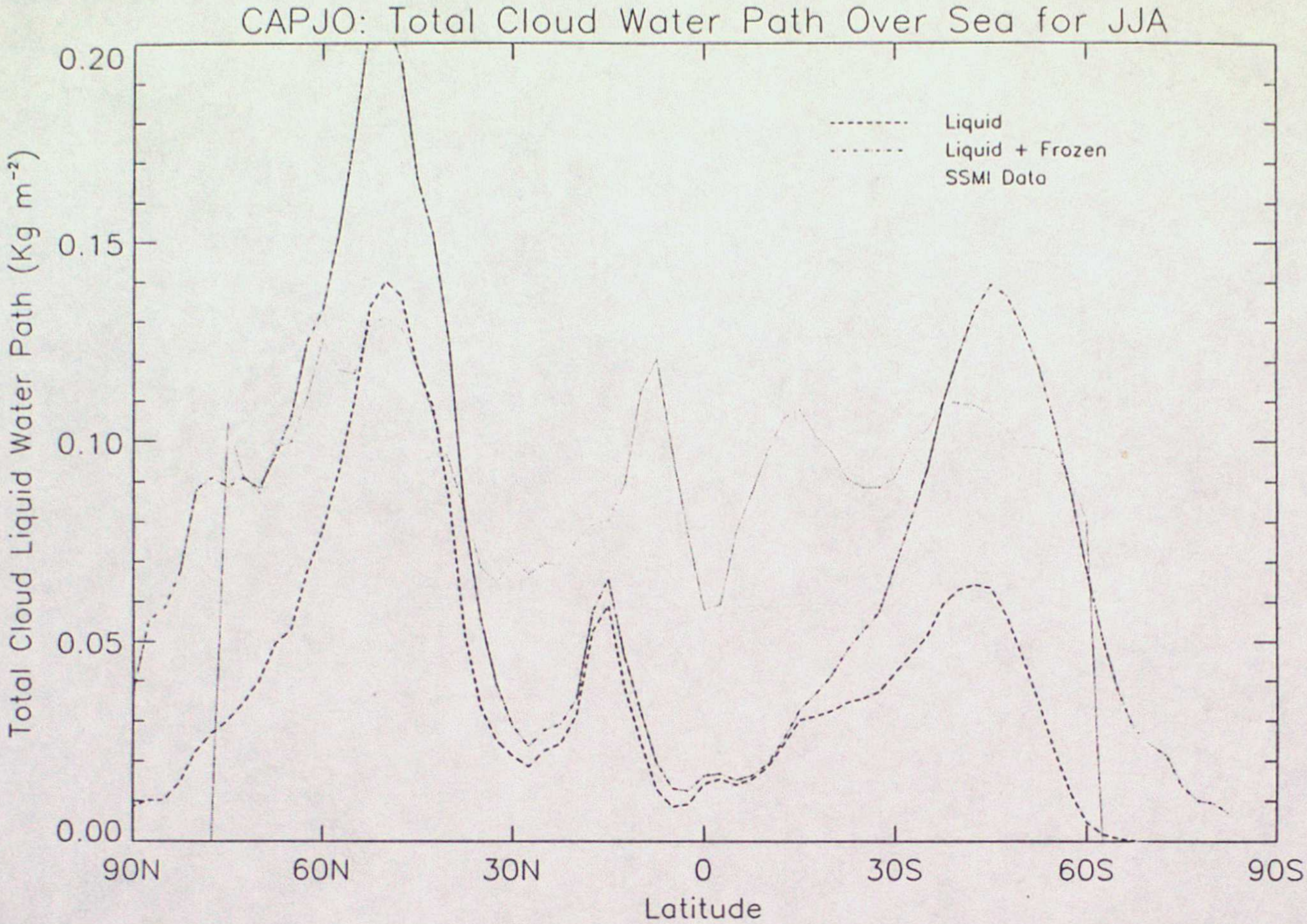


Figure 5. Zonal average of vertically integrated cloud water over sea points, from a Meteorological Office GCM simulation of June July and August. **Liquid + frozen** curve shows all large scale cloud, **liquid** curve shows large scale cloud above 0°C (convective cloud are excluded), **SSM/I** curve shows estimates of total liquid water. (J Mitchell, personal communication).

DISCUSSION

We have presented three ways in which assimilation can be used to help Global Energy and Water-cycle EXperiment (GEWEX) related research:

Model assimilated datasets are provided as the best available, and most convenient, representation of the atmosphere. These are particularly useful for studies requiring higher resolution in space and time, and complete coverage, for instance evaluating horizontal moisture fluxes.

Diagnostics on the fit of assimilation to observations are very useful in research aimed at improving the models. This is the classical scientific method: models are developed based on past data, and tested against new data, in a continuing process of improvement. We saw in the discussion of cloud, that studies of bias are an essential prerequisite to effective assimilation of the data; only when the model and data biases are understood can useful information be assimilated. However the assimilation process, of trying to fit model to data, is an excellent means of diagnosing these biases, especially the more subtle, situation dependent ones. Some operational assimilation systems now routinely archive, along with each observation used, the prior model estimate (background), and the assimilation's fitted value (analysis). These archives can be classified and averaged as desired to give information on o-b and o-a biases. If there are several different observing systems, intercomparison can indicate whether it is the observations or the models which are biased /10,11/.

Supplementary data in geophysical retrieval, from the assimilation, can greatly enhance the accuracy and value of indirect data retrieved from satellite remote sensing /12/. This has been clearly demonstrated for satellite temperature soundings in operational NWP. The model can aid the quality control and interpretation of data, as shown by /1/ for doppler lidars winds and /10/ for scatterometer winds. It can provide contextual information, helping in algorithms to convert data into geophysical parameters. It can provide another source of information, inferred by the model's parametrisations from observations of other quantities, as we discussed above for rainfall.

Organisation of Assimilation

The above uses place different requirements on the assimilation; no one system can satisfy them all.

Re-analyses, with a frozen assimilation system, can provide a set of model assimilated datasets, free from changes due to development of the model. This is an advantage for longer term studies, for instance of inter-annual variations. However changes in the observing system will still be present, so great care must be taken before they are used for climate change detection. Multi-year re-analyses are expensive to perform, and hence those available may use models which are below the state-of-the-art in resolution or parametrisations, so some users of modern data may prefer datasets from a operational NWP assimilation system.

Experimental analyses, for special process study observational campaigns, benefit from the extra data both for assimilation, and for validation. Assimilation experiments with such data help increase our understanding, and improve the models. Often, several assimilation experiments are needed, as the model and assimilation techniques are improved.

Operational NWP analyses, are a valuable resource, which should be fully used. The requirements of NWP have driven nearly all the recent improvements in data assimilation techniques, and they still largely coincide with those of GEWEX in requiring better assimilation, modeling and forecasting of the water cycle, since it is responsible for most "weather". It is usual to spend 1-2 hours of the fastest available computer's time per day on NWP assimilation. As computers get more powerful, models get more complex and satellites give more observations, so this is unlikely to change. In order to make best use of this resource for GEWEX research, observations should be processed and made available within a few hours. This will encourage the development of assimilation techniques, and provide a quick look use of the data which experience has shown is invaluable in validating observing systems, as well as providing useful model assimilated datasets. Re-analyses, and experimental analyses can benefit from this foundation. For example the Japanese are planning a real-time processing of TRMM data; this is more useful than the slower (~48 hours) processing planned for the US EOSDIS.

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