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THE VALUE OF WIND OBSERVATIONS FOR WEATHER FORECASTING AND CLIMATE STUDIES

by

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THE VALUE OF WIND OBSERVATIONS FOR WEATHER FORECASTING AND CLIMATE STUDIES

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1 INTRODUCTION

It is now feasible to design satellite systems capable of giving us wind observations in the remote parts of the world, using doppler wind lidar. However they are technically difficult, and hence expensive. In order to be able to demonstrate that they are value for money, it is necessary to estimate the value of the wind observations which they might give. In section 2 we review some theoretical ideas on the value of observations, before going on in sections 3 and 4 to some more practical results for weather forecasting, and climate studies. Section 5 summarizes conclusions.

2 THEORETICAL APPROACHES TO THE VALUE OF OBSERVATIONS

The value of a piece of information must be assessed with respect to two things: what we already know, and what we need to know. One measure of information content is based on Shannon's concept of information entropy. If the parameters we want to know are represented in a multidimensional vector \mathbf{x} , then our state of knowledge about the parameters can be represented by a probability distribution function (p.d.f.). If our prior knowledge was $p(\mathbf{x})$, and we receive observations \mathbf{y} , then our posterior knowledge $p(\mathbf{x}|\mathbf{y})$ is given by Bayes' theorem:

$$p(\mathbf{x}|\mathbf{y}) = p(\mathbf{x}|\mathbf{y})p(\mathbf{x})/p(\mathbf{y}).$$

Then the information content of our posterior knowledge, relative to the prior, is:

$$\mathcal{I} = \int p(\mathbf{x}|\mathbf{y}) \log \left(\frac{p(\mathbf{x}|\mathbf{y})}{p(\mathbf{x})} \right) d\mathbf{x}.$$

This does not however measure the useful information content. The specification of the usefulness of information depends (obviously) on the use to which it will be put. This has already been taken into account by defining \mathbf{x} to the parameters that we want to know, but no allowance has been made for the relative importance of different parameters.

More importantly, \mathcal{I} measures the information content of a p.d.f., while usually we want a single "best estimate" of the parameters. A posterior p.d.f. which restricts likely values for \mathbf{x} to a small but widely spread set of values, will have a large \mathcal{I} , but the set will not be very useful for initializing a single Numerical Weather Prediction (NWP) forecast. To avoid this, observations should have a simple error structure, with no unresolvable ambiguities, or difficult to detect gross errors. In this sense, additional prior information may increase the usefulness of an observation, while reducing \mathcal{I} . (Lorenc *et al.* (1992) showed that gross errors in a wind lidar could be dealt with.)

Some useful insight into the relative value of wind and mass field information may be gained from geostrophic adjustment theory. For the linearized "shallow water" equations on a cyclic f-plane, the fields can be represented as a sum of two-dimensional Fourier components. Then any initial state can be represented by a stationary height and rotational wind field, in geostrophically balance, and oscillatory inertia-gravity waves. Making the assumption that the latter disperse, or are damped, while the balanced modes are not, we can calculate the height and streamfunction of the final state from

$$gh_s/f = \psi_s = \alpha\psi_i + (1-\alpha) gh_i/f,$$

where ψ and h are fourier coefficients for a mode $\exp(i(kx+ly))$, subscript s indicates the final (stationary) value, and i the initial value. α , which determines how much of the final state comes from the initial rotational wind field, and how much from the initial height field, is given by

$$\alpha = \frac{gD(k^2+l^2)}{gD(k^2+l^2) + f}$$

The equivalent depth D , acceleration due to gravity, and coriolis parameter f define a critical wavelength:

$$\lambda_c = 2\pi \sqrt{gD/f}.$$

We can also define an effective wavelength for the mode by:

$$\lambda_{xy} = 2\pi (k^2+l^2)^{-1/2}.$$

Then we get

$$\alpha = 1 / (1 + (\lambda_{xy}/\lambda_c)^2).$$

Thus if $\lambda_{xy} \ll \lambda_c$ (small scale waves), the stationary mass and wind fields depend on the initial wind field, while if $\lambda_{xy} \gg \lambda_c$ (large scale waves), they depend on the initial mass field.

It is not correct however to deduce from this that we definitely require wind observations for small scales, and mass observations for large scales. If the assumptions are correct, then we can calculate the stationary state to fit either wind or mass initial field. Geostrophic adjustment theory only applies if data are simply inserted into the model; it does not necessarily apply to the multivariate analysis methods used in practice (e.g. Lorenc 1981), which combine mass and wind data using the geostrophic relationship. These statistical method combine data weighted by the inverse of their estimated error variance. Because of the differential relationship between streamfunction and wind, the wind data will be weighted proportionally to λ_{xy}^{-2} when analysing the mass field coefficients, so, other things being equal, large scale wind observations are less useful than small scale ones.

Note that this conclusion may not hold for modes not properly described by geostrophic theory, especially real divergent flows.

3 NUMERICAL WEATHER PREDICTION

In assessing value for NWP, we must take into account what we already know: a forecast from previous data, and observations from other observing systems. Table 1 shows typical numbers of observations received in six hours for the Bracknell global forecast system, and some estimates for future systems. The number of data available automatically from aircraft is currently undergoing a sharp increase; many aircraft are already making good quality wind observations automatically in their avionics systems; only communications are needed to make the data available for NWP. Over N America the ARINC system gives a very good coverage. Globally, fewer aircraft relay their data by satellite (ASDAR). Potentially, in the FANS system, most commercial aircraft could give soundings made during take-off and descent, and regular observations made during cruise. It will be difficult for any extra wind observing system to add information in areas where these data are abundant.

Table 1. Observations per 6hour period for Operational Global NWP

Radiosondes 00/12Z	850
Pilots 06/18Z	250
Surface land	4500
Ships	700
Drifting buoys	400
Aircraft reports	1100
Cloud motion winds	1700
Sat. soundings (2 satellite, ~120km spacing)	37000
ERS-1 scatterometer	70000
ASDAR (aircraft)	500
ACARS (aircraft)	4000
PROBABLE FUTURE	
Future air navigation system (FANS)	25000
wind profiler (~100 instruments)	600
POSSIBLE FUTURE	
LAWS (~100km spacing)	36000

We have learnt, mainly from experience using aircraft winds, that the wind analysis near a baroclinically active jet stream can be crucial in determining the forecast accuracy for important weather systems. Examples are given in Hollingsworth *et al.* (1985), and in figure 1. The wind observations plotted in figure 1 were too late for the operational forecast, which was dramatically incorrect. When the winds were used in a revised analysis, a much better forecast resulted (Lorenc *et al.* 1988). Although single level wind observations can sometimes be very valuable at jet stream levels, it is not always clear how the information should be spread in the vertical (Barwell and Lorenc 1985). Vertical profiles would avoid this.

Large quantities of wind observations are also now available from scatterometers. Figure 2 shows an example swath from ERS-1. When calibration and de-aliasing problems are overcome, these should provide much information, particularly on smaller scale features. Probably our assimilation systems do not at present make best use of this information; the impact of scatterometer data in NWP experiments has not usually been large.

Table 1 does not indicate any increase in the number of cloud motion winds. Improved instruments and image processing methods will increase the number and accuracy of these data. The current data have a positive impact on global NWP (Eyre, personal communication). Improving the data has a positive impact on hurricane forecasts (Velden *et al.* 1992).

3 CLIMATE STUDIES

It is not easy to put a value on what we need to know for research. Some would say that knowledge and understanding are intrinsically valuable. I will however pick three examples from projects of generally accepted direct value.

Ocean currents are largely driven by the surface wind stresses. Better understanding and modelling of the ocean circulation are needed for seasonal predictions of important coupled ocean atmosphere events, such as el Niño. There are differences between the wind stresses derived from different operational NWP assimilation systems (Burridge and Gilchrist, 1989). Using these to drive an ocean general circulation model, Carrington (1991) found that the variability due to different analyses was of the same magnitude as the inter annual variability. Better knowledge of the wind fields is needed. The curl of the wind is important, a derived quantity requiring good resolution of smaller scales. We have seen in figure 2 that scatterometers can give this. The time integrated stress is important, making lack of bias important (for weather forecasting, instantaneous accuracy is more important).

GEWEX aims to gain a quantitative understanding of the global water cycle. Wind observations are required to measure the horizontal

atmospheric transport. It is not accurate to do this directly from the currently available observations; sampling of the boundary layer and diurnal cycle is inadequate (Rasmusson 1967). Lorenc *et al.* (1992) showed that sampling by a satellite doppler wind lidar would also be inadequate, because of cloud obscuration. Much of mid-latitude transport occurs in narrow low-level jets, obscured by frontal cloud (figure 3). Such features are represented in high-resolution models; model assimilated datasets are the best means of quantifying the mean fluxes. Special high-density observational studies may be used to validate the models, but there is no hope of a continuous global coverage of sufficiently high density observations to avoid using models. The current model assimilated datasets are not sufficiently accurate for the required budget studies. This was shown by Lorenc and Swinbank (1984) for analyses for 1979. A knowledge of the water budget is essential when studying the effect of Amazonian deforestation on S America. Current operational analyses are not sufficiently accurate to provide this; figure 4 shows moisture budgets from ECMWF and NMC analyses; they differ significantly. The model assimilated datasets need to be improved by better observational coverage, and/or better assimilation models. We need to understand the mechanisms causing variations in such budgets. For this we need improved observations over several years, assimilated into a model which does not alter during the assimilation. As operational models are continuously being developed and improved, this requires a special research analysis effort.

Climate change prediction for the enhanced greenhouse effect is not an initial value problem, except perhaps for the deep ocean circulation. No atmospheric data is needed to initialize the climate models. However data is needed to validate and develop many aspects of the models. As well as the topics mentioned under GEWEX above, we need wind observations for the strength of the Hadley circulation, the life-cycle and energetics of depressions and storm tracks, and the vertical fluxes of momentum in the atmosphere. Unlike much of the research mentioned above, this model validation research cannot simply use model assimilated datasets, which are affected by the model deficiencies we wish to diagnose. For instance the strength of the Hadley circulation can be significantly altered by the assimilation scheme, as shown in Lorenc and Swinbank (1984), or by changes to the radiation scheme (Clive Wilson, personal communication). However detailed diagnostics of the differences between observations and model in the assimilation process can be very informative. For this the observations need to be accurate, with small biases.

5 CONCLUSIONS

From simple theoretical ideas in section 2 we deduce that:

- ▶ Information must be valued with regard to what we already know, and need to know.
- ▶ Observation error structure should be simple to use.
- ▶ Observations and prior information together should give unambiguous information.
- ▶ Winds are usually more useful for small scales.

Experience with NWP, in section 3, says:

- ▶ Aircraft and scatterometers can give wind observations along air routes, and at the sea-surface. Extra observations will be useful away from these areas.
- ▶ Mid-latitude, synoptic scale, NWP is very sensitive to wind errors near the jet streams.
- ▶ Single level observations are less easy to use for NWP.

For climate studies, in section 4, we conclude:

- ▶ Current observations are insufficient for many important research areas, such as ocean modelling (sea-surface winds) and moisture budgets.
- ▶ For moisture budget studies, there is little hope for observations which give a sufficient continuous global coverage; model assimilated datasets must be used.
- ▶ Current model assimilated datasets are not sufficiently accurate, for regional moisture budget studies. Better observations and models are both probably needed.
- ▶ Better models are also needed for climate change prediction. Model validation and development can be helped by studying the fit of model to observations during assimilation. Accurate unbiased observations are needed.

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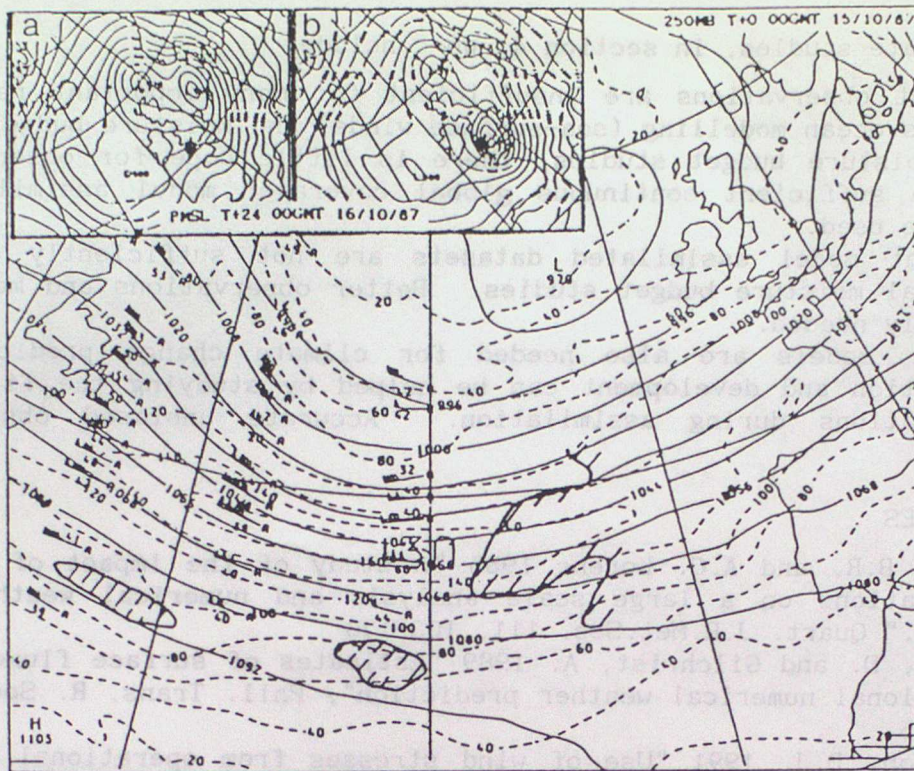


Figure 1. Analysis at 00GMT 15/10/87. Continuous lines show 250mb height, dashed lines show isotachs in knots. The plotted data are from aircraft which were not used in the analysis for the forecast shown in inset a, but were used for the forecast shown in inset b. The actual position of the low at the valid time of the forecasts is marked • in the insets. Areas of extensive cloud have been indicated; the important jet stream was not obscured.

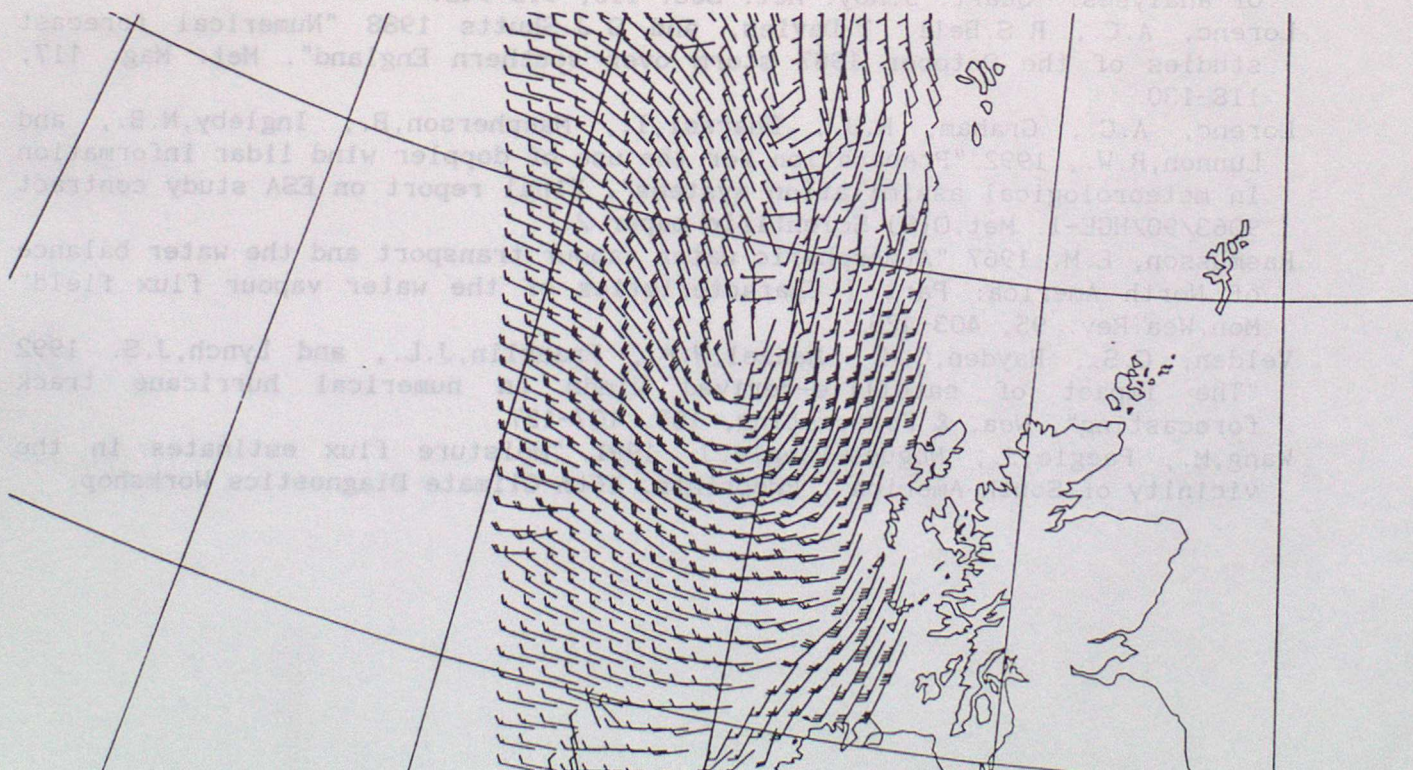


Figure 2. ERS-1 winds processed at the Met. Office, for 26/11/1991. They clearly indicate a mesoscale polar low which was not analysed by an NWP assimilation not using the data.

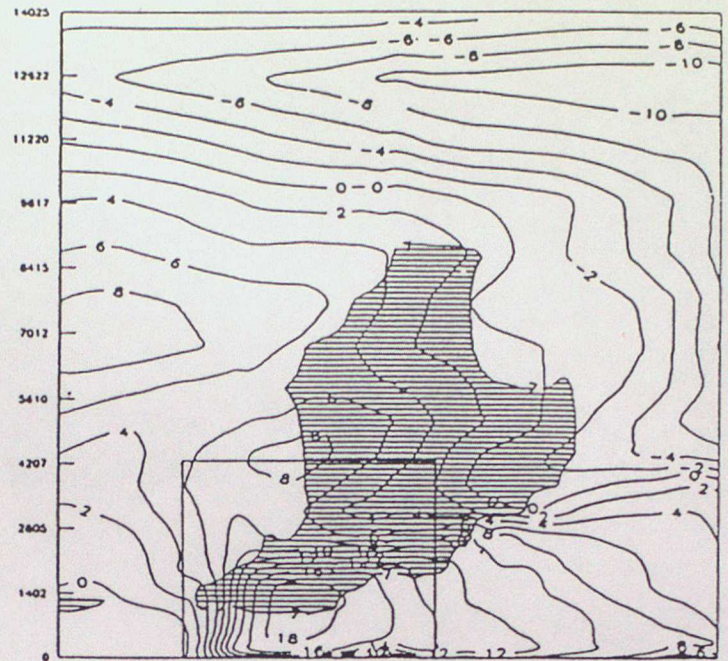
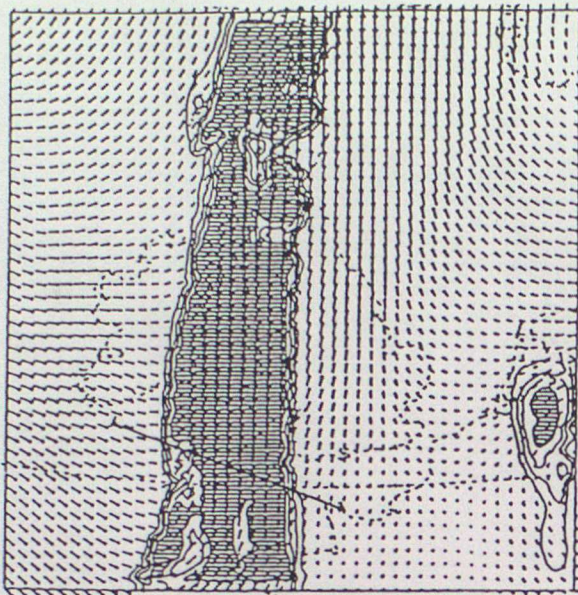


Figure 3. (a) 1.5km flow and cloud cover at 4km associated with a front crossing the British Isles on 23/11/91. (b) Cross section along the line shown in (a), Contours show the flow perpendicular to the cross section, and shading indicates cloud. Most of the moisture flux is in a low-level jet ~100km across, obscured by cloud.

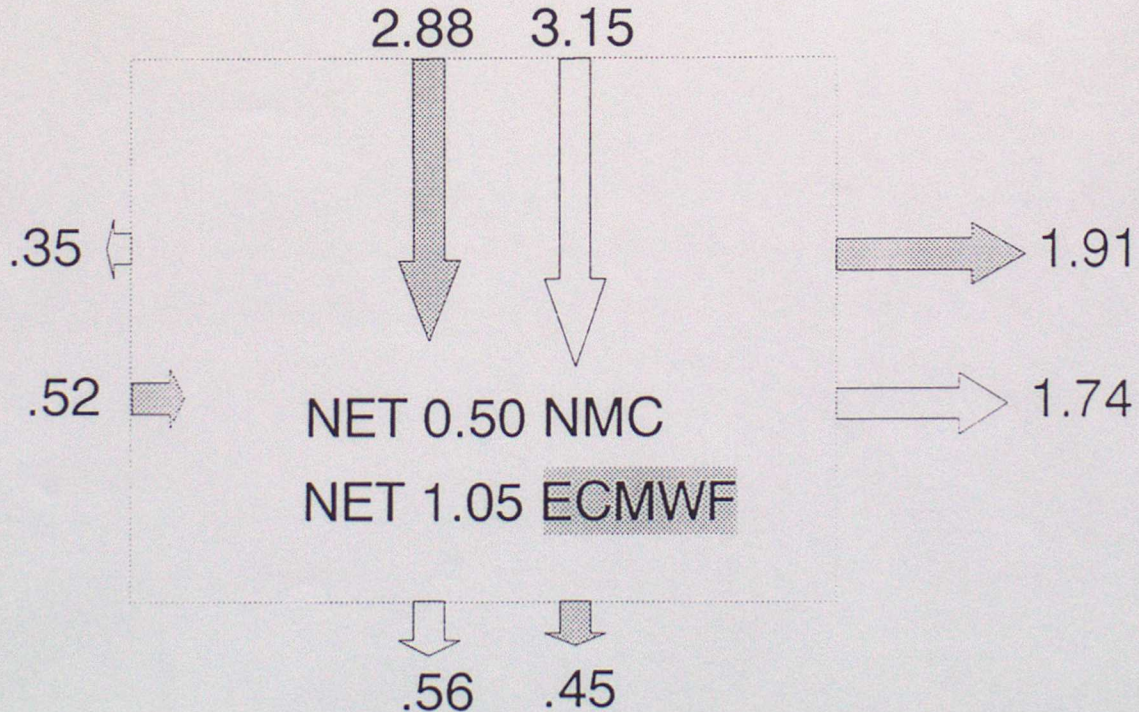


Figure 4. Moisture budget for the region 65-45W 40-20S, January 1989, calculated from NMC and ECMWF operational analyses. (Courtesy of Julia Nogues-Paegle, from Wang *et al.* 1991).