THE RELATIVE IMPORTANCE OF MASS AND WIND DATA IN THE FGGE OBSERVING SYSTEM

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1. BACKGROUND

There are two theoretical arguments that have been used to discuss the relative importance of mass and wind data in numerical weather prediction (NWP). We will analyze these arguments in this section as clearly as possible in order to draw conclusions which may help to interpret experimental results on four-dimensional data assimilation, simulations of future observing systems, as well as give guidance on how to improve the efficiency with which we use the present observing system.

The evolution of an NWP model depends, to a very good approximation, only on the initial value of the slow (Rossby) modes of the model. The dynamics of the slow modes are characterized by the conservation of potential vorticity, and by the presence of a balance constraint. For a shallow water model on a β-plane, we can write the potential vorticity as

$$\eta = f_o + \beta y + \nabla^2 \psi - f_o \frac{\phi}{gD} \qquad (1)$$

where f_o is the mean Coriolis parameter, β is the gradient df/dy, ψ is the streamfunction of the rotational wind, and $\phi = gz$, the departure of the geopotential from its mean value gD.

The quasigeostrophic balance constraint is, in its simplest form, the geostrophic relationship

$$\psi_g = \frac{\phi_g}{f_o} \qquad (2)$$

For strongly nonlinear flows, equation (2) has to be replaced by the gradient wind equation or by a form of the nonlinear balance equation, both of which will also provide a relationship between ψ and ϕ.

Since the evolution of the forecast is determined by equations (1) and (2), it is clear that we have to provide the model with an initial field of a single variable, η or ψ, as accurately as possible.

The first argument that has provided insight on the importance of winds for "small scales" has been the geostrophic adjustment argument (e.g. Rossby, 1938; Blumen, 1972). It provides a very powerful theoretical framework, but we believe its interpretations have not always been completely appropriate (e.g., Washington, 1964; Daley, 1980).

Consider a small mass perturbation field $\delta\phi$ of horizontal wavenumber n introduced in the initial conditions of the model:

$$\delta\phi = Ae^{i(kx + \ell y)}, \quad k^2 + \ell^2 = n^2 = (2\pi/L)^2 \qquad (3)$$

After a short period of geostrophic adjustment, during which fast inertia-gravity waves disperse, the system reaches a new state of balance with the same perturbation potential vorticity:

$$-f_o \frac{\delta\phi}{gD} = \nabla^2 \delta\psi_g - f_o \frac{\delta\phi_g}{gD} \qquad (4)$$

where the wind and the mass are in balance:

$$\delta\psi_g = \frac{\delta\phi_g}{f_o} \qquad (5)$$

Therefore, the balanced geopotential height perturbation is given by

$$\delta\phi_g = \frac{1}{n^2R^2+1}\,\delta\phi \qquad (6)$$

where $R^2 = gD/f_o^2$ is the square of the Rossby radius of deformation.

Equation (6) indicates that for long waves ($n^2R^2 \ll 1$), $\delta\phi_g \approx \delta\phi$, ie, the model retains the mass data, and, from (5), the wind adapts to the mass field. For short waves ($n^2R^2 \gg 1$), however, $\delta\phi_g \approx 0$, the model does not retain the mass information, which disperses away as gravity waves. In effect, the model does not believe short wave mass information which is not in a state of balance.

Conversely, for a small wind perturbation $\delta\psi$ in the initial conditions,

$$\delta\psi_g = \frac{n^2R^2}{n^2R^2+1}\,\delta\psi \qquad (7)$$

which indicates that for short waves the model believes in the wind data ($\delta\psi_g \approx \delta\psi$), and the mass field adapts to the wind. For long waves, $\delta\psi g \approx 0$, the model does not retain wind information.

The traditional interpretation (Washington, 1964, Daley, 1980) has been similar to this: "Wind data must be used for short scales (e.g. tropics and small synoptic scales). For large scales mass data may be used". The reason why this interpretation is somewhat misleading, is that it does not exploit the fact that the atmosphere itself is in balance, and therefore the mass and wind data must also be in balance (Eq. (2)).

A more positive interpretation is the following: "In order to maximize the retention of useful information in the model, we should use the balance constraint on the data". Note that if

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for example, we apply the geostrophic wind correction on the data ($\delta\psi = \delta\phi/f_o$), we can force the model to retain all of the mass information even at small scales.

There are two comments that should be made. The first one is that, as pointed out by Daley (1980), most of the atmospheric waves can be considered short ($n^2R^2 > 1$). For an equivalent depth D = 10 km, typical of the external mode, waves are "short" if $L < 20{,}000$ km, i.e., even for planetary scale waves the model will tend to believe wind data much more than it will believe mass data. For the first baroclinic mode, $D \simeq 1$ km, waves are short if $L < 6000$ km, i.e., for most synoptic scale waves. For higher vertical modes, the mass data becomes increasingly important, but, with few exceptions, these modes do not have much energy.

Another comment is that although we can force the model to retain mass information even at small scales by imposing a geostrophic wind relationship on the data, we may only want to do so if we believe the mass data to be accurate at such scales.

This brings us to the subject of relative accuracy of mass and wind data, and to the second argument that emphasizes the importance of wind data at small scales: the differential versus integral measurement argument. From the geostrophic relationship $v = -k \times \nabla\phi/f_o$, winds are related to the gradient of the mass field, and therefore they should be more accurate at small scales. This is the argument that is implicit in the analysis by Phillips (1983), which we present here in a considerably simplified form.

We start, once again, from the premise that we want to estimate the initial value of the slow modes, or, equivalently, the geostrophic streamfunction. Consider a component of the streamfunction of horizontal wavenumber n: $\psi_n = B\, e^{i(kx + \ell y)}$, $k^2 + \ell^2 = n^2$. Suppose we have both mass (ϕ) and wind (v) measurements, with observational errors $\delta\phi_o, |\delta v_o|$ respectively. From these measurements we obtain two estimates of ψ, $\psi_g^{(mass)} = \phi/f_o$, and $\nabla\psi^{(wind)} = \underset{\sim}{k} \times \underset{\sim}{v}$, with corresponding errors

$$\delta\psi_n^{(mass)} = \delta\phi_o/f_o, \text{ and } \delta\psi_n^{(wind)} = \frac{|\delta v_o|}{n} \qquad (8)$$

Equation (8) provides a simple estimate of the relative accuracy of wind and mass measurements. Winds will be "more accurate" than mass data if $\frac{|\delta v_o|}{n} < \frac{g\delta z_o}{f_o}$.

For example, if we assume $|\delta v_o| \sim 3$ m sec^{-1}, and $\delta z_o \sim 10$ m, winds are more accurate than heights for $L < 2000$ km. We can combine optimally both estimates of ψ (with weights inversely proportional to the square of the error), and then the accuracy of the weighted average estimate will be the sum of the accuracies of the two measurements (Gandin, 1963, Phillips, 1983):

$$\frac{1}{|\delta\psi|^2} = \frac{fo^2}{g^2|\delta z_o|^2} + \frac{n^2}{|\delta v_o|^2} \qquad (9)$$

Equation (9) shows that the mass field will contribute very little accuracy at low latitudes, and that winds become increasingly accurate at short wavelengths.

From these theoretical arguments, it is clear that winds are extremely useful data at small scales (or in the tropics) because of two independent reasons: (a) they have higher accuracy, and (b) the model believes them better. However, if we have mass data that we consider reliable even at small scales (e.g. sea level pressure data or satellite temperature gradient data), we should force the model to retain it by imposing a balance constraint in the data itself.

2. FORECAST IMPACT EXPERIMENTS

Simulation experiments (Halem et al., 1985; Atlas et al., 1985) have indicated that 3-dimensional fields of horizontal wind data are more effective than mass data in reducing forecast errors. In this section we address the question: "Which data are more important in the present observing system, winds or heights?"

For this purpose we performed four real data assimilation experiments using the GLA Analysis/Forecast system (Baker, 1983, Kalnay et al., 1983).

In the first experiment, denoted "FGGE", we assimilated all available FGGE II-C data for the period 5 January - 2 February. These data include both rawinsonde and satellite (TIROS-N) temperature and moisture, and cloud-tracked winds data. In the other three experiments we omitted the assimilation of temperature and moisture ("NOTEMP"), of winds ("NOWIND"), and of cloud-track winds ("NOCTW"). We then performed seven 5-day forecasts from the different analyses every four days, and verified the forecasts against the ECMWF analysis.

Figures 1 and 2 present the extratropical (poleward of 20°) anomaly correlation averaged for the seven forecasts in the Southern and Northern Hemispheres respectively. It is clear from Fig. 1 that in the Southern Hemisphere, temperature data (mostly from satellite temperature soundings) are of essential importance. The forecasts which without temperatures are skillful for less than one day (correlation > 60%), become skillful for more than 3 days when the temperature data are utilized. Winds are useful in that they increase skill by about 9 hours, and cloud-track winds alone by less than six hours.

In the Northern Hemisphere (Fig. 2) there is much more redundancy in the data, but it is clear that the 3-dimensional wind fields provided by rawinsondes are the most important component of the observing system. Their absence results in a degradation of about 6 hours. The absence of temperature has a smaller effect, and cloud-track winds have actually a small negative impact. If we look at the North American region separately (Fig. 3), the impacts are larger, with a small positive impact of cloud-track winds, and larger impact of temperatures and especially winds.

In the tropics, Fig. 4, the winds are useful throughout the 5-day forecast, and the temperatures have a positive impact on the first two days, although the skill, measured by the S1 score of the geopotential height, is small throughout the period.

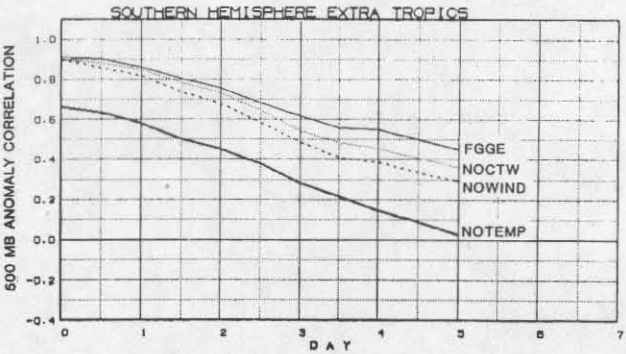

Figure 1. Average of anomaly correlation as a function of forecast day for seven forecasts each from the "FGGE", "NOTEMP", "NOWIND" and "NOCTW" assimilation experiments. Verifications are made against the ECMWF analysis and the region of verification is the extratropical Southern Hemisphere (polewards of 20°).

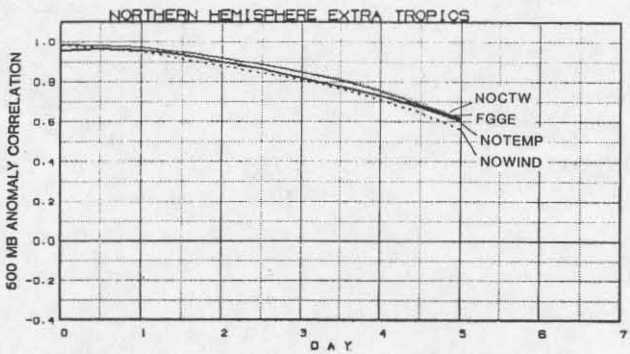

Figure 2. Same as Fig. 1 but for the Northern Hemisphere.

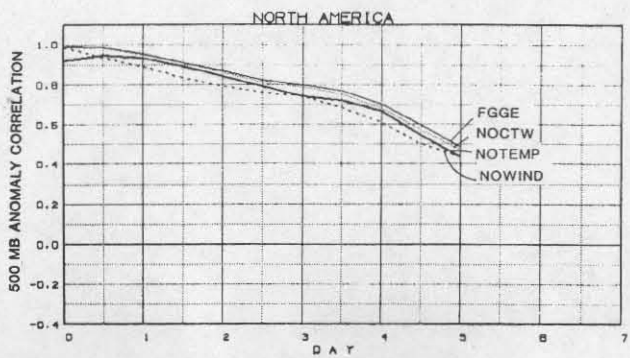

Figure 3. Same as Fig. 1 but for North America.

3. DISCUSSION

We have reviewed, in a very simple fashion, two independent arguments that emphasize the importance of wind observations for small scales and in the tropics: the geostrophic adjustment argument, and the differential measurement argument. They indicate that winds are very effective at small scales and in the tropics because (a) the model "believes" the wind data better than the mass data and (b) winds observations are more accurate than mass observations. As pointed out by Daley (1980), in the geostrophic adjustment argument, "small scale" includes most of the energy-containing modes of the atmosphere. This is especially true for the barotropic model, which explains why sea level pressure data were found to be quite ineffective in specifying the initial state (Smagorinsky et al., 1970). On the other hand, simulation studies of Halem et al. (1985) and Atlas et al. (1985) show that wind data are extremely effective.

Although these observations are explained by the traditional application of geostrophic adjustment theory to initialization (e.g. Washington, 1964, Daley, 1980), this theory also indicates that we can make much more effective use of mass data by imposing the geostrophic balance constraint on the data. If we have mass observations that are considered reliable we should force the model to retain them by forcing the wind to be in balance with the mass data. One effective way to do this is by the "geostrophic correction" of the wind, currently used at least in a partial form in many operational systems (Puri, 1981, Kistler and McPherson, 1975). However, if not performed carefully, this correction can easily result in an actual deterioration of the model's initial conditions. The use of mass data of heterogeneous origin (e.g. rawinsonde and satellite temperatures), which have different biases and are not even coincident in time, and the fact that the accuracy of geostrophic winds becomes poorer at small scales, can result in synthetic wind data which is not only inaccurate, but which is completely retained by the model. The use of multivariate optimal interpolation may be less desirable in data sparce regions, because the balance is introduced in a statistical fashion, assuming a "typical" correlation distance between mass and wind field rather than the observed wavelengths. The use of initialization methods, such as non-linear normal mode initialization, has no effect on the amount of information extracted, because their role is to filter out the information that the model would not retain anyway.

The second argument, that winds are more accurate at small scales because they are a measurement of the mass field gradient, (Phillips, 1983), provides a quantitative relationship with which both types of measurements can be optimally weighted.

It is possible that the application of these simple ideas, for example in the use of synthetic "satellite thermal wind" data together with appropriate filtering of the small scale noise in the temperature gradients (eq. 8) may be useful in increasing the amount of useful information extracted from the present observing system. A striking example of the potential improvement that the use of "satellite thermal winds" might produce, is presented in Fig. 5. We adapted a simulation system of an idealized data assimilation (Halem et al., 1985), where perfect data derived from a "nature" run are directly inserted into the GLA GCM. The figure presents the 12-hour 500 mb rms forecast error during the simulated assimilation cycle. The top two curves, adapted from Halem et al. (1985), show that perfect wind data is much more effective than mass data (surface pressure and complete temperature fields) in reducing the 12-hour forecast error. On the other hand, when we use mass data both directly and through the assimilation of geostrophic winds, the reduction of error is faster than with either mass or wind data alone.

Real data experiments with the current GLA Analysis/Forecast System show that in the present observing system, temperature data (mostly from polar orbiter satellites) is absolutely essential in the Southern Hemisphere. It is in this hemisphere that the use of satellite thermal winds has the largest potential for producing a significant improvement upon the current forecast skill. In the Northern Hemisphere, rawinsonde winds are already somewhat more important than temperatures. However, realistic simulation experiments (Atlas et al., 1985), indicate that lidar wind profile observations with a better geographical coverage will result in improved numerical weather prediction even in this hemisphere.

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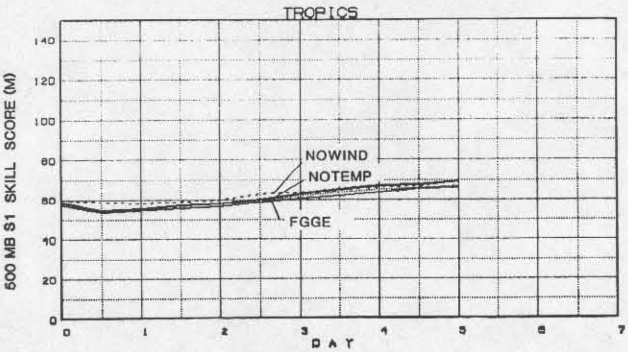

Figure 4. Same as Fig. 1 but for the tropics (30°S to 30°N). The skill score S1 measures the relative error in the pressure gradient forecast at 500 mb.

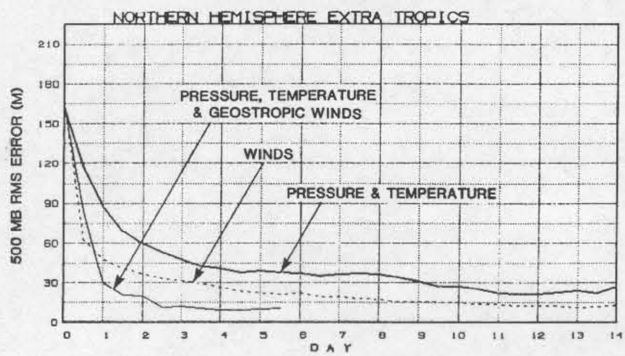

Figure 5. Idealized 12-hour cycle assimilation experiment using as data exact 3-D fields of a) surface pressure and temperature, b) u and v wind components, and c) surface pressure, temperature and geostrophic winds. Experiments a) and b) adapted from Halem et al. (1985).