An experiment on the initial conditions for a mesoscale forecast

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SUMMARY

A 6-h forecast starting at midday on a good sea breeze day has been repeated for seven different sets of initial conditions. The initial values for each field could either be given by an 8-h mesoscale forecast valid at 1200GMT or interpolated from a synoptic scale forecast valid at the same time. It was found that changing the initial temperature field had an important effect on the subsequent forecast, but the impact of changing the initial wind field was relatively small. Changing the initial surface pressures had no visible effect on any aspect of the subsequent forecast other than the forecast of surface pressure itself.

1. INTRODUCTION

In recent years there has been an increase in the use of high resolution numerical models to forecast atmospheric motion on local scales (30 to 300 km). (Anthes and Warner (1978), Fritsch and Chappell (1978), Perkey (1976), Pielke (1974)). The design and testing of a numerical model is usually the first step taken in developing the ability to produce numerical weather forecasts, but, in practice, the integration of the model equations is only one component in a complex system. In particular, numerical forecasts require initial values for the model variables, and the quality of the initial conditions often contributes at least as much to the accuracy of the forecast as the model itself.

Carpenter (1979) has described a case study in which a model developed by Tapp and White (1976) was used to forecast well-developed sea breezes over England and Wales. The forecast started at 0400GMT. During the first eight hours, sea breeze fronts developed along much of the coastline, and, by 1200GMT, they were well established and beginning to penetrate inland. The experiment described in this paper uses this forecast as a control and finds the degradation in the six hour forecast from 1200 to 1800GMT produced by replacing model data at 1200GMT by less detailed information. Seven new forecasts were made, each based on initial conditions degraded by taking various fields from a synoptic scale forecast valid at 1200GMT. These changes might be regarded as simulating the effect of using an inadequate network of observations. Experiments of this sort should indicate which meteorological parameters are most significant and need to be analyzed in detail, if necessary using indirect observations, to provide accurate short range forecasts.

The effects of water phase changes and latent heat release are not important in the sea breeze situation studied here, and they have not been included in the forecast model. However, it is likely that they are more significant in other mesoscale situations, and this should be investigated in future experiments. Kreitzberg and Rasmussen (1977) and Atkins (1974) have considered the impact of varying the initial humidity field on the regional scale (~1000 km).

The experiment itself is described in Section 2, and the results are presented in Section 3. The extent to which these results can be generalised is discussed in Section 4.

2. THE EXPERIMENT

The situation chosen for the study was a good sea breeze day over England, 14 June 1973, described by Simpson et al (1977). Carpenter (1979) has described an experimental forecast for this day, which provided the raw material for the present work. The initial conditions, at 0400GMT, were obtained from a synoptic-scale forecast with a resolution of 100 km by interpolation to the 10 km mesoscale model grid. The resulting fields were very smooth, but this probably had little effect on the forecast because the sea breezes were
locally generated and there was little development in the first few hours of the forecast. The information needed to calculate lateral and upper boundary conditions for the mesoscale forecast was also taken from the synoptic-scale forecast. It comprises the normal component of velocity and the gradients of potential temperature and the other two velocity components. Full details are given in Carpenter (1979).

Seven sets of initial conditions, valid at 1200 GMT, were generated by combining data from the original mesoscale model and the synoptic-scale forecasts for 1200 GMT. Each of the seven forecasts based on these initial conditions used the same computer code and had the same initial surface temperatures and solar warming. Thus differences between the forecasts could be attributed to the changes in the initial conditions.

Although the basic model equations are non-hydrostatic, in practice the hydrostatic relation is very closely satisfied in model calculations for systems of low aspect ratio so the temperature and pressure are not truly independent variables. The mass field is determined to a good approximation by the temperature at each level and a single reference pressure, which we may take to be the surface pressure. Similarly, since the vertical velocity is effectively determined by the horizontal velocities through the continuity relation, the vertical velocity was not varied independently of the horizontal velocities. Thus either the mesoscale model forecast or the large-scale model forecast was used to provide initial values for each of:

(i) the winds
(ii) the temperatures
(iii) the surface pressure

Pressures at upper levels were calculated using the hydrostatic relation except when all the temperatures and all the pressures were taken from the mesoscale model. Changes of a field from mesoscale to synoptic-scale data were made at all points and levels together with one exception: one variation was intended to find the effect of having no temperature observations other than those at low levels. In this case the mesoscale model forecast was used to provide the temperature at the lowest model level and the temperature at other levels was taken from the large-scale model forecasts. Any lapse rate instability that this implied was removed and a well-mixed layer of uniform potential temperature (calculated from the mesoscale forecast at the lowest level) was used.

The initial conditions for the seven forecasts are summarized in Table 1. The nature

<table>
<thead>
<tr>
<th>Forecast</th>
<th>Initial winds</th>
<th>Initial temperatures</th>
<th>Initial surface pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MM</td>
<td>Mesoscale</td>
<td>Mesoscale</td>
<td>Mesoscale</td>
</tr>
<tr>
<td>2 SM</td>
<td>Large scale</td>
<td>Mesoscale</td>
<td>Mesoscale</td>
</tr>
<tr>
<td>3 MS</td>
<td>Mesoscale</td>
<td>Large scale</td>
<td>Large scale</td>
</tr>
<tr>
<td>4 SS</td>
<td>Large scale</td>
<td>Mesoscale at 50 m</td>
<td>Mesoscale</td>
</tr>
<tr>
<td>5</td>
<td>Mesoscale</td>
<td>Mesoscale at 50 m</td>
<td>Mesoscale</td>
</tr>
<tr>
<td>6</td>
<td>Large scale</td>
<td>Mesoscale at 50 m</td>
<td>Large scale</td>
</tr>
<tr>
<td>7</td>
<td>Large scale</td>
<td>Mesoscale at 50 m</td>
<td>Large scale</td>
</tr>
</tbody>
</table>

Source of the various fields in the seven sets of initial conditions. All the fields are valid at 1200 GMT. The calculation of the pressures, and of the temperature when 'mesoscale at 50 m' is specified, is described in the text. The labels SS etc. attached to four sets show the origin (S = synoptic, M = mesoscale) of the winds and temperatures.

of the differences between the three choices that were made for the temperature is illustrated by Fig. 1, which is a NS cross section passing just east of the Pennines and through the Midlands. The two choices that were made for the wind are illustrated by Fig. 2 (which is the same section), and the two choices for the surface pressure are shown in Fig. 3.
Figure 1. The initial potential temperatures on a NS vertical section: (a) the synoptic scale data; (b) the mesoscale data; (c) the result of inserting a mixed layer of uniform potential temperature (given by the mesoscale data) into the synoptic scale data. The figures on the vertical axis are height, in metres, for each of the model levels.
3. The Results

The purpose of the experiment was to compare the forecasts to come to some conclusion about the relative importance of the various fields in the specification of the initial conditions. An examination of Table 1 shows that there are three comparisons showing the effect of removing detailed wind information, two comparisons for both of the changes made in the initial temperature fields and one comparison (between 6 and 7) showing the effect of removing the detailed surface pressure information. In each case, the indications from pairs of similar forecasts were similar. Thus, for example, the effect of removing the detailed mesoscale temperature information can be found by comparing MM with MS or by comparing SM with SS, and the conclusions are the same.

(a) The effect of changing the initial wind fields

Figure 4 shows the 2-h low-level wind forecasts for SM (Fig. 4(a)) and MM (Fig. 4(b)), Fig. 5 shows these winds at 6 h and Fig. 6 shows the 2-h forecasts of vertical velocity.
Figure 3. The initial sea level pressure fields: (a) synoptic scale data; (b) mesoscale data.

Comparing forecast SM with MM shows the effect of removing detailed and accurate information about the winds. Eight areas or features in which it was reasonable to expect to see changes were identified and the results of these comparisons between integrations are summarized in Table 2. It appears that the effect of changing the initial winds is small, and qualitatively equivalent to a movement of the shear line in the direction of the synoptic wind.
In order to examine the nature of the differences between the two forecasts more precisely, the vertical velocity fields at 2 h (shown in Figs. 6(a) and 6(b)) have been smoothed, to remove numerical noise, and differenced. The result is shown in Fig. 7. The filter used was a seven point Shapiro filter (Shapiro (1970)) that has been found to have very little effect other than the complete removal of two grid length waves. Figure 7 supports the subjective impression that, in the absence of a mesoscale vortex (Fig. 2(b)) to maintain the position of the sea breeze fronts against the large scale winds, the temperature discontinuity is advected downwind in forecast SM (i.e. Figs 4(a), 5(a) and 6(a)). The movement of, for

![Figure 4. 2-h forecasts of 50 m winds, valid at 1400 GMT: (a) forecast SM (synoptic scale winds, mesoscale temperatures); (b) forecast MM (mesoscale winds and temperatures);](image-url)

Figure 4. 2-h forecasts of 50 m winds, valid at 1400 GMT: (a) forecast SM (synoptic scale winds, mesoscale temperatures); (b) forecast MM (mesoscale winds and temperatures);
example, the North Welsh convergence line corresponds to a mean speed over the two hours of about 4 m s$^{-1}$, which is rather less than the advecting synoptic scale wind speed. The differences in the 50 m wind at 2 h are shown in Fig. 8(a), and they should be compared with those in the initial data shown in Fig. 8(b).

There are theoretical reasons, based on geostrophic adjustment theory, for supposing that changes in the initial vorticities would have a more significant impact than changes in the divergent part of the wind field. Several of the mesoscale features present in these forecasts have associated maxima of the vertical component of vorticity in some cases as large as 3 f. It follows that there are significant small scale differences in the initial vorticities for SM and MM. Neglecting small positional changes of the sort identified above, these vorticity differences persist only slightly longer than other differences in the wind fields. The vorticity field at 2 h for forecast SM (i.e. derived from Fig. 4(a)) is shown in Fig. 9.

The three tests involving degradation of the initial wind fields indicated that the effect was small, i.e. equivalent to a positional error of about two grid lengths at most. Such an effect is comparable with errors due to other (e.g. numerical) deficiencies of the model.

(b) The effect of changing the initial temperature field

The effect of replacing detailed and accurate temperature fields can be seen by comparing forecasts MM and MS (or, with the same result, forecasts SM and SS). These two forecasts are shown in Figs. 4(b) and 4(c), 5(b) and 5(c), and 6(b) and 6(c). It appears that this change in the initial temperature fields leads to substantial differences in the subsequent forecasts. Some of these differences are shown in Table 2, but the forecasts are so dissimilar at 2 h that there is no value in comparing their treatment at that time of the eight features mentioned above.

As described in the previous section, the initial temperature fields were varied in two ways. The change shown as (ii) (a) in Table 2 was to replace the control mesoscale model forecast temperature for 1200 GMT with those from the synoptic-scale model forecast at all
### TABLE 2.

<table>
<thead>
<tr>
<th></th>
<th>2h</th>
<th>6h</th>
<th>2h</th>
<th>6h</th>
<th>2h</th>
<th>6h</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Stronger SW flow</td>
<td>Shear line to E moved N</td>
<td>*</td>
<td>10 km behind</td>
<td>Flow veered</td>
<td>Shear line further N</td>
</tr>
<tr>
<td>B</td>
<td>Shear line further N</td>
<td>20 km further N</td>
<td>*</td>
<td>10 km further N</td>
<td>5 km further N</td>
<td>10 km further N</td>
</tr>
<tr>
<td>C</td>
<td>Shear line further N</td>
<td>Further N</td>
<td>*</td>
<td>10 km further N</td>
<td>5 km further N</td>
<td>10 km further N</td>
</tr>
<tr>
<td>D</td>
<td>Slack winds become southerly</td>
<td>Shear line further N</td>
<td>*</td>
<td>N Devon sea-breeze under-developed</td>
<td>More penetration</td>
<td>More penetration</td>
</tr>
<tr>
<td>E</td>
<td>Coastal winds backed</td>
<td>V slight backing</td>
<td>*</td>
<td>Winds backed to S of shear line</td>
<td>5 km further N</td>
<td>10 km further N</td>
</tr>
<tr>
<td>F</td>
<td>No visible difference</td>
<td>10 km further N</td>
<td>*</td>
<td>20 km behind i.e. less penetration</td>
<td>More penetration</td>
<td>More penetration</td>
</tr>
<tr>
<td>G</td>
<td>All fronts 5 km further N</td>
<td>10 km further N</td>
<td>*</td>
<td>20 km behind i.e. less penetration</td>
<td>More penetration</td>
<td>More penetration</td>
</tr>
<tr>
<td>H</td>
<td>Shear line less developed, 10 km out to sea</td>
<td>10 km out to sea</td>
<td>*</td>
<td>10 km out to sea</td>
<td>10 km further inland</td>
<td>10 km further inland</td>
</tr>
</tbody>
</table>

*The whole forecast is completely different (underdeveloped)*

The effect on the forecast of degrading the initial conditions by (i) using synoptic-scale wind data in place of mesoscale wind data (ii) using synoptic scale temperature data in place of mesoscale temperature data and (ii) (a) using synoptic scale temperature data except at the lowest model level, for which mesoscale data were used. (Lapse rate instability was removed by increasing the upper level temperatures.) The areas A to H are:

A. The general flow or the shear line north and east of the Isle of Man.
B. The shear line in N Wales.
C. The shear line in S Wales.
D. The general flow or the shear line in the South West Peninsula.
E. The wind direction along or north of the south coast.
F. The inland penetration of the south coast sea breeze.
G. The sea breezes in East Anglia.
H. The north east coast shear line.

A blank entry indicates that there was no effect.

Levels except the lowest, and then remove the convective instability. This gives initial temperatures that are qualitatively very similar to the mesoscale model forecast (see Fig. 1) and it had a small effect i.e. well within the range of errors due to other (e.g. numerical) deficiencies of the model.

On closer examination, particularly using a large number of charts not shown here, it is clear that all the forecasts are progressing through the same stages. Only forecasts SS and MS, in which the information about the development of a surface mixed layer due to convective heating and the inland penetration of cold air is not represented in the initial data, show any substantial deviation, and they appear to run about three hours behind the other forecasts. Given that the initial wind fields have little effect on the subsequent forecast this can be explained by observing that forecasts SS and MS must establish a temperature contrast between the land and sea air before any further development can take place, while in all other cases the temperature contrast exists in the initial conditions.

(c) The effect of changing the initial surface pressure

Throughout the 6-h period the two forecasts that showed the effect of this change were so alike that they could not be distinguished using graphical output, such as Figs. 4, 5 and 6.
except by looking at the forecast surface pressure itself. It is concluded that the details of the initial surface pressure field had no dynamical effect on the subsequent forecast for this sea breeze day.

4. DISCUSSION

It would be desirable to appeal to some general theory that explained the results of these

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**Figure 5.** 6-h forecasts of 50 m winds, valid at 1800 GMT: (a) forecast SM; (b) forecast MM;
Figure 5.(c) forecast MS.

Figure 6. 2-h forecasts of vertical velocity at 225 m, valid at 1400 GMT: (a) forecast SM;
Figure 6.(b) forecast MM; (c) forecast MS. The solid isopleths are $+4 \text{ cm s}^{-1}$, $+12 \text{ cm s}^{-1}$, the hatched isopleths are $-4 \text{ cm s}^{-1}$. The regions of ascent mark the sea breeze fronts.

experiments, but that does not appear to be possible. Geostrophic adjustment theory (eg Temperton 1973) is usually said to show that the mass field adjusts to the wind field for small horizontal scales, so the results are superficially surprising. However that theory is only appropriate when the phenomena of interest are geostrophic and when the basic linearization assumptions are reasonable. Neither of these requirements is satisfied in the
Figure 7. The difference in the 2-h forecasts of vertical velocity between forecasts MM and SM (i.e., Fig. 6(b) − Fig. 6(a)). The fields have been smoothed before differencing. The solid isopleths are \(+2\,\text{cm}\,\text{s}^{-1}\), \(+6\,\text{cm}\,\text{s}^{-1}\) and the hatched isopleths are \(-2\,\text{cm}\,\text{s}^{-1}\), \(-6\,\text{cm}\,\text{s}^{-1}\).

A useful simplification is that the solid lines mark the fronts in MM, and the hatched lines mark the fronts in SM.

present study. In particular, it is difficult to use a general approach based on a linearization such as geostrophic adjustment theory, to describe a situation in which a region of vanishing static stability, e.g. a well-mixed boundary layer over land, is embedded in an environment with a reasonably large \((2 \times 10^{-2}\,\text{s}^{-1})\) static stability. Nevertheless, the usual normal mode analysis does explain the results concerning the change in surface pressure, which will be discussed in the last paragraph of this section. The results from geostrophic adjustment theory that are needed in the last paragraph are derived in the Appendix.

In order to understand the results we must concentrate on the dominant aspect of all the forecasts, the development of sea breezes. Simpson, et al. (1977) have explained sea breezes as gravity currents in which the release of potential energy is balanced by (i) an increase in the kinetic energy of the land air as it passes over the head of the sea breeze front, and (ii) dissipative effects. It seems obvious that the existence of a temperature contrast necessarily implies motion, in this case a sea breeze, and that motion that has developed in response to the existence of a temperature contrast must decay if the temperature contrast is removed. Of the seven forecasts, only MM and SS had initial conditions that were balanced. The entire initial conditions for MM were taken from the control mesoscale model forecast and the sea breezes were well developed. The initial conditions for SS were all obtained from the large scale model forecast and there is no land/sea temperature contrast and no sea breeze motion. The other five forecasts followed either MM or SS after a short adjustment period.

(a) The adjustment of unbalanced winds to an existing temperature contrast

The initial conditions for forecast SM are shown, in cross section, in Figs. 1 (b) and 2(a). The warm well-mixed layer over land and the relatively cold stable air over the sea imply a temperature contrast near the coast that has produced the sea breeze vortex shown in
Figure 8. The difference in 50 m winds between forecasts MM and SM (a) 2-h forecast (i.e. Fig. 4(b)–Fig. 4(a)), (b) initial conditions.

Fig. 2(b) and must be inconsistent with the initial winds. In order to find the time scale for the inland acceleration of the dense sea air, consider the equation for the component of vorticity $\zeta$ normal to the sections shown. With

$$\zeta = \partial w/\partial y - \partial v/\partial z,$$
$$\partial \zeta/\partial t = c_p \left\{ \left( \partial \theta/\partial z \right) \left( \partial P/\partial y \right) - \left( \partial \theta/\partial y \right) \left( \partial P/\partial z \right) \right\},$$

(1)

where non-linear and dissipative terms have been omitted. $\theta$ is the potential temperature,
Figure 9. The vertical component of vorticity in forecast SM M at 1400 GMT. This field has been smoothed to eliminate numerical noise. The solid isopleths are \( +0.5, +1.5, +2.5 \times 10^{-4} \text{s}^{-1} \), and the hatched isopleths are \(-0.5, -1.5, -2.5 \times 10^{-4} \text{s}^{-1}\).

and \( P \) is the Exner function \( (p/p_r)^{R/c_p} \) which can be calculated from \( \theta \) using the hydrostatic relation \( (c_p/\theta) \partial P/\partial z = -g \cdot p \) and \( p_r \) are pressure and a constant reference pressure, \( R \) is the gas constant and \( c_p \) is specific heat at constant pressure. In the present context, the first term on the right of Eq. (1) can be neglected, and

\[
\frac{\partial \zeta}{\partial t} = \frac{(g/\theta)}{\partial \theta/\partial y}.
\]

When this expression is averaged over a box circumscribed by the sea breeze vortex in Fig. 2(b) and containing the sea breeze front, we find \( \partial \zeta/\partial t \approx 1.5 \times 10^{-6} \text{ s}^{-2} \). (Note that although this box is about 1 km deep, the sharp temperature gradient is confined to the bottom two levels, i.e. a layer about 150 m deep.) Averaged over the same box, the vorticity \( \zeta \), approximately \( \partial v/\partial z \), of the sea breeze vortex is of order \( 5/1000 = 5 \times 10^{-3} \text{ s}^{-1} \). This indicates that the time-scale over which the sea air will accelerate and the adjustment take place is \( \zeta/(\partial \zeta/\partial t) \approx 60 \text{ min} \). In the integrations the process is almost complete in an hour, in good agreement with this simple analysis.

These arguments and results suggest that the gravity current balance described by Simpson et al. is achieved quickly, i.e. more rapidly than the production and enhancement of the land/sea temperature contrast by solar warming of the land.

(b) The response of the wind field when the temperature contrast is removed

The initial conditions for forecast MS include the sea breeze vortex (Fig. 2(a)) imposed on a uniformly stable atmosphere (Fig. 1(b)). The restoring effect of the stability means that the vortex will be dispersed as gravity waves. The gravity wave energy will move with the group velocity away from the sea breeze front, and will then either be damped by the
diffusion in the model or become indistinguishable from the 'noise' that is always present in real data atmospheric model forecasts.

The dominant horizontal and vertical wave numbers, $k$ and $m$ of the gravity waves are given by the horizontal and vertical scales of the vortex. Thus $k \approx \pi/(3 \times 10^4) \approx 10^{-4} \text{m}^{-1}$ and $m \approx \pi/(1400) \approx 2.25 \times 10^{-3} \text{m}^{-1}$. The Brunt-Vaisala frequency $N$ is about $1.5 \times 10^{-2} \text{s}^{-1}$, so the horizontal group velocity $\pm N/m$ is $\pm 7 \text{m s}^{-1}$, and the vertical group velocity $Nk/m^2$ is around $0.3 \text{m s}^{-1}$. Hence the gravity wave will propagate up out of the lower layers in which the sea breeze develops, i.e. through a depth of, say, 1800 m, in 100 min, and in that time the effect of the vortex will be spread, horizontally, over slightly more than three times the width of the original vortex.

Forecast MS has been examined at 20-min intervals and its behaviour bears out this discussion. Once again the adjustment of the wind field to the mass field is relatively rapid, i.e. more rapid than the boundary layer processes that are responsible for the development of sea breezes.

(c) The effect of changing the initial surface pressure

Two forecasts started with initial conditions which differ only in the surface pressure. In both cases the hydrostatic relation was satisfied, so the pressure change was uniform with height and spread well beyond the sea breeze, which affects only the lower part of the atmosphere. Thus the earlier objections to the use of geostrophic adjustment theory do not apply in this case, and we can use the results derived in the Appendix for the vertically constant $m = 0$ modes. This theory states that a vertically uniform pressure perturbation, on these horizontal scales, will manifest itself as sound waves (Lamb waves) only. As sound waves it will have a small effect on the winds and no effect on the potential temperature and this explains the lack of any visible difference between these forecasts.

The sound waves propagate rapidly, but are reflected at the boundaries so the only mechanisms that will remove them are the time filter and the lateral diffusion of momentum. The time filter (Asselin (1972), with a coefficient of 0.02) is quite weak. The highest frequency sound waves have a period of 4 $\delta t$ (because of the implicit time integration described by Tapp and White (1976) and are damped by the filter with an $e$-folding time of about 50 time-steps. The diffusion is non-linear so an accurate calculation of the effect is not possible. Using a typical value for the diffusion coefficient ($10^4 \text{m}^2\text{s}^{-1}$) suggests that the high frequency short wave length sound waves will be damped by diffusion with an $e$-folding time of about 100 time-steps. Thus we may expect differences in the surface pressures to persist. In practice, small scale features, e.g. a trough along the NE coast shear line, adjust within two hours, but substantial differences remain on larger scales after six hours. The important result is that these differences are confined to the surface pressure field itself and do not show themselves in any other way.

5. Conclusion

The initial conditions for a local weather forecast, which started at 1200 (local time) in a good sea breeze day, have been varied and the relative importance of specifying correctly the temperature, wind and surface pressure fields has been assessed. The result is that the forecast is controlled principally by the initial temperature field, and that the wind field adjusts to the temperature field within about an hour. Changes in the initial mesoscale surface pressure field had no effect on the forecast.

Whether these conclusions are valid in a wide range of circumstances must be determined by further similar experiments in other meteorological conditions. They are obviously limited by the fact that the model and forecast treated the air as dry, so the consequences of the formation of cloud and rain due to erroneous vertical motion in the initial conditions have not been studied. Nevertheless, it is quite clear that it is important that the initial
temperatures are realistic, and this is not surprising since the geostrophic control of small scale (of order 100 km) weather systems is weak.

The most interesting conclusion is that concerning the initial surface pressure field. It apparently contrasts with the results of Carpenter (1979) who found that a forecast for the same sea breeze day was very sensitive to the movement of the dominant anticyclone. However, even for scales as large as the whole model (600 km), geostrophic adjustment theory suggests that the pressure field will adjust to the wind field, and any residual tendency for the average wind field to adjust to the average pressure field will be minimized by the fact the normal component of the velocity is imposed at the model boundaries. On these scales, information about the synoptic situation can be conveyed through the wind field far more effectively than through the surface pressure field, and this is how it is done for the model used here.

This experiment was idealized in that it supposed full knowledge of all meteorological variables. In practice we have to interpret the observations that are available. Two forecasts were based on initial conditions that supposed qualitative knowledge of the boundary layer structure, which could be inferred from cloud type and height, satellite picture and current weather observations, and screen level temperatures only. It is encouraging that, in this situation, these forecasts were good. The result that changes in the surface pressure field have no impact on the subsequent forecast in this case does not imply that observations of surface pressure have no value, even in situations like 14 June 1973. It is well known that, in reality, it is possible to draw substantial conclusions from surface pressure observations alone. Rather, this result shows that the information contained in the surface pressure observations must be transferred to the other fields as part of the process of analysing the observations and calculating initial fields. If the initial fields of wind and temperature are not such as would produce the observed surface pressures, then the information content of the surface pressure observations will be lost, at least in sea breeze situations over the UK. It is likely that a great deal of work will have to be done to discover the best use to make of the large quantity of very high quality observations of surface pressure and tendency.

It is not possible to draw firm conclusions at this stage about which observations will prove useful in practice. Clearly, any observations of temperature or stability will be extremely useful. One of the most urgent problems is to discover the best use to make of screen level observations of temperature, but traditional surface based observations of boundary layer type must be considered seriously. Satellite and radar observations could well provide valuable information about boundary layer type and depth. Equipment installed in aircraft using major airports (ADSEL) Braybrook et al. (1976) could provide temperature measurements that will be a very valuable addition to the synoptic radio sonde network. It may be misleading to draw general conclusions about the value of wind observations from this experiment, but the usefulness of surface pressure observations probably depends on our ability to interpret them in novel ways.

ACKNOWLEDGMENTS

We are extremely grateful to Drs P. W. White and R. W. Riddaway for their useful comments on an early draft of the paper, and many conversations on this and other subjects.

APPENDIX

For systems with a vertical length scale much shorter than their horizontal length scale, atmospheric motion is effectively hydrostatic. If we use the hydrostatic approximation, the only waves that appear in a linearized analysis about the state of no motion are internal gravity waves and a horizontally propagating sound wave. Geostrophic motion appears as a stationary mode. In order to simplify the analysis, the variation of density and the speed of sound $c^2$ with height are ignored. The equations of motion are linearized about a basic state of no motion, in which the potential temperature $\theta = \theta_0(z)$ depends on height,
(g/\theta_0) \partial \theta_0 / \partial z = N^2 = \text{constant}, \text{and the Exner function } P = (\rho/\rho_0)^{k/\sigma} = P_0(z) \text{ is defined by its surface value } P_0(0) = 1 \text{ and the hydrostatic relation } (c_p\theta_0) \partial P_0 / \partial z = -g. \text{ Using the notation of Tapp and White (1976) the perturbation equations are}

\begin{align*}
\partial u / \partial t - f v + (c_p\theta_0) \partial P'/ \partial x &= 0 \quad \text{A1}
\partial v / \partial t + f u + (c_p\theta_0) \partial P'/ \partial y &= 0 \quad \text{A2}
(c_p\theta_0) \partial P'/ \partial z &= g \theta'/ \theta_0 \quad \text{A3}
\partial \theta'/ \partial t &= -w \theta_0 / \partial z \quad \text{A4}
(c_p\theta_0/c^2) \partial P'/ \partial t + \partial u / \partial x + \partial v / \partial y + \partial w / \partial z &= 0 \quad \text{A5}
\end{align*}

If, in order to be consistent with the assumption of constant density and c^2, we ignore the variation of \theta_0 with height, except in equation A4, we can find solutions

\[ \chi = \text{Re}[\bar{\chi} \exp\{i(\sigma t - kx - ly - mc)\}], \]

where \( \chi \) is \( u, v, w, \theta', \) or \( P' \) and \( \bar{\chi} \) is complex. After some algebra we find

\begin{align*}
\bar{u} &= (k\sigma - ilf)c_p\theta_0 P'/(\sigma^2 - f^2) \quad \text{A6}
\bar{v} &= (\sigma + ikf)c_p\theta_0 P'/(\sigma^2 - f^2) \quad \text{A7}
\bar{\theta'} &= -m\theta_0 gc_p\theta_0 P' \quad \text{A8}
\bar{w} &= -m\sigma/N^2 c_p\theta_0 P' \quad \text{A9}
\end{align*}

where

\[ \sigma/c^2 = (k^2 + l^2)\sigma/\{(\sigma^2 - f^2) - m^2\sigma/N^2 \}, \quad \text{A10} \]
i.e. \( \sigma = 0 \)

or \( \sigma_k^2 = f^2 + N^2 \frac{k^2 + l^2}{m^2 + N^2/c^2} \approx f^2 + N^2 \frac{k^2 + l^2}{m^2} \)

or \( f^2 + (k^2 + l^2)c^2 \quad \text{A11} \)

\( \sigma = 0 \) is the geostrophic mode. For \( m \neq 0 \), Eq. A11 gives the internal gravity wave mode and the approximation \( m^2 \gg N^2/c^2 \) is consistent with ignoring the variation of density with height. For \( m = 0 \), A11 gives the horizontally propagating sound waves.

Any initial conditions can be resolved into these modes. At first sight it appears that there are five variables and only three modes, but the hydrostatic relation removes one degree of freedom and Richardson's equation (Eq. A12, obtained by taking \( \partial / \partial t \) of

\[ \partial^2 w / \partial z^2 - N^2 w/c^2 = -((\partial / \partial z)(\partial u / \partial x + \partial v / \partial y)) \quad \text{A12} \]

Eq. 3 and \( \partial / \partial z \) of Eq. A5 and eliminating time derivatives removes a second degree of freedom. If the initial \( u, v \) and \( P' \) fields are given by \( \chi = \text{Re}[\chi \exp\{-i(kx + ly + mz)\}] \) then the geostrophic part of these fields is given by

\[ c_p\theta_0 P'_{\text{geostrophic}} = \left\{ f^2/c^2 c_p\theta_0 \bar{P} + if(k\bar{u} - \bar{l}v) \right\}/(f^2/c^2 + k^2 + l^2), \]

for \( m = 0 \),

\[ c_p\theta_0 P'_{\text{geostrophic}} \approx \frac{m^2 f^2 c_p\theta_0 \bar{P} + if(k\bar{e} - \bar{l}u)N^2}{m^2 f^2 + (k^2 + l^2)N^2}, \quad \text{A13} \]

for large \( m^2 \).

Finally it is supposed that after adjustment has taken place only the geostrophic mode remains. Thus, for \( m \neq 0 \) the wind field determines the adjusted state for \( f^2 m^2/(N^2(k^2 + l^2)) \ll 1 \). In the present study \( (k^2 + l^2) \sim 10^{-8}, \ m^2 \sim 10^{-5}, \ N^2 \approx 2 \times 10^{-4} \text{s}^{-1} \) (except within the well-mixed layer over land) so \( f^2 m^2/(N^2(k^2 + l^2)) \sim 10^{-1} \) and the mass field is expected to adjust to the wind field. However, this is not an appropriate application of the theory, as discussed in the text. For \( m = 0 \) the wind field determines the adjusted state for \( f^2/(k^2 + l^2)c^2 \ll 1 \). In the present study, this variable is \( 10^{-5} \), and in fact A13 gives \( P'_{\text{geostrophic}} \sim 10^{-5}P' \). Since a change in surface pressure affects only the
$m = 0$ components (through the hydrostatic relation), we expect it to be manifested only in sound waves, as discussed in the text.

REFERENCES


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