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Blocking: Observations, theory and modelling

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Lecture Series

Blocking:
Observations, theory and modelling

by

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Blocking : Observations, Theory and Modelling

In this lecture we will consider an important aspect of the extratropical general circulation associated with the phenomena of blocking for which the anomalous circulation is predominantly confined to a certain longitude sector and occurs in geographically preferred regions. Blocking typically has a timescale of a couple of weeks and tends to be most frequent at certain times of the year - e.g. western Europe in spring.

Blocking 'highs' are characterised by a region of warm air with higher than ambient pressure which extends upwards from the surface to the lower stratosphere. Within them the winds are generally light and the tropopause is higher than average. They are usually accompanied by a somewhat smaller region of low pressure with the opposite properties. This combined 'dipole' pattern is embedded in a diffluent flow field and tends to fluctuate in amplitude and phase (longitude) with the passage of travelling weather systems (Fig. 1). There is often a tendency for high pressure cells to collapse only to rebuild further to the west causing an overall westward translation of the pattern. A dynamically significant aspects of the blocked flow field is the reversed potential vorticity gradient (from the normal poleward gradient) as is clearly portrayed by isentropic analyses of Ertel potential vorticity $Q=\rho^{-1}(\zeta+f)\frac{d\theta}{dz}$, (Hoskins et al., 1985, Shutts, 1986). Potential vorticity within the blocking anticyclone is low relative to the ambient flow but high in the accompanying cut-off low further south. (Fig. 2).

One frequently gets the impression from studying sequences of synoptic charts that changes in weather type are often accompanied by an abrupt change in the configuration of the planetary scale flow and a new quasi-equilibrium pattern set up. Such behaviour is characteristic of some idealised non-linear systems containing quasi-equilibrium or 'attractor' points. The free-mode approach to representing blocking flow patterns involves finding time-independent solutions to approximated forms of the equations of motion and examining their sensitivity to governing parameters.

To consider the simplest nonlinear free mode solutions, consider a dissipation free barotropic atmosphere described by the barotropic vorticity equation

$$\frac{D}{Dt}(\zeta + f) = 0 \qquad (1)$$

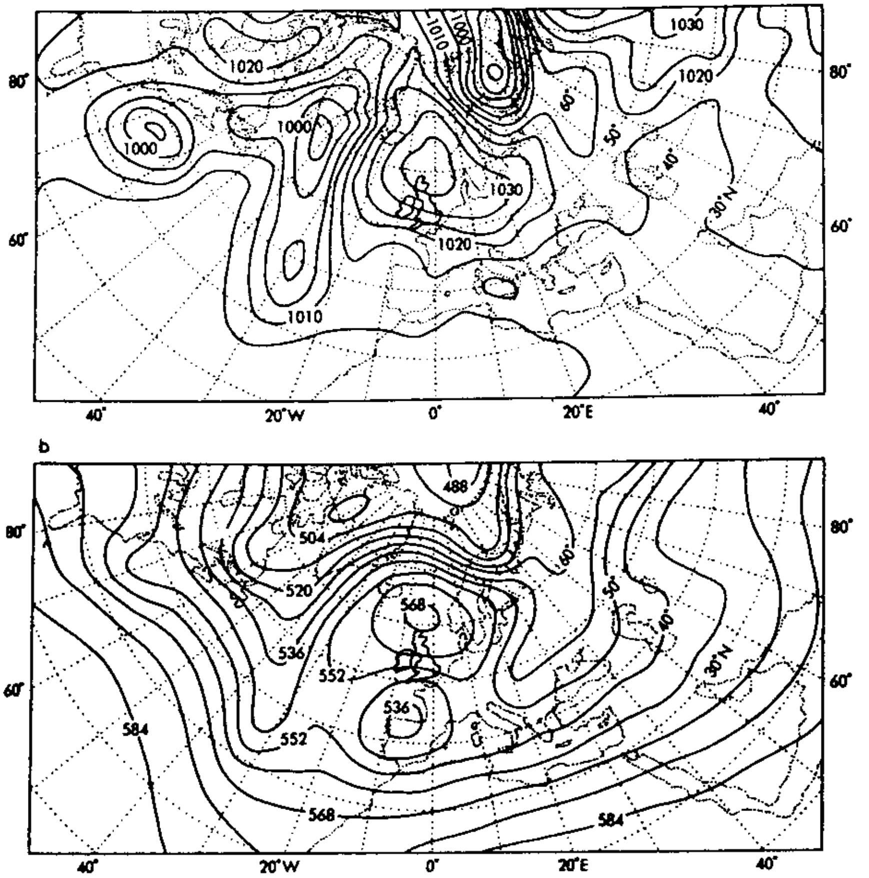


Fig. 1 Sea-level pressure field (top) and height contours of the 500 mb surface (bottom) for 15 February, 12Z, 1983.

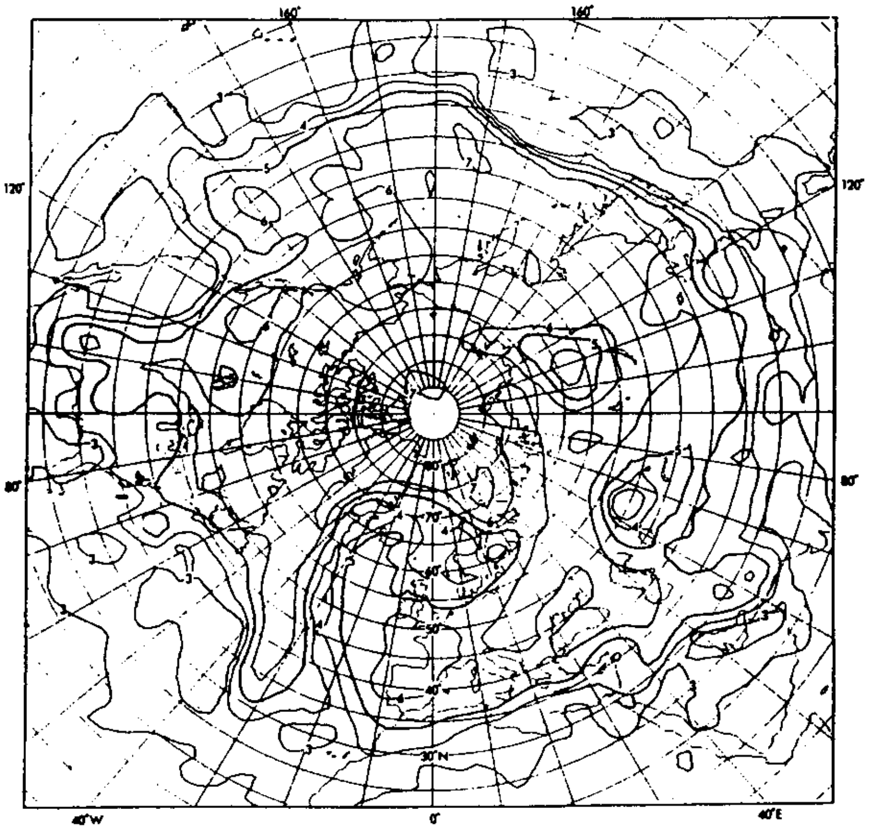


Fig. 2 Contours of the Ertel potential vorticity calculated on the 320°K isentropic surface on 15 February, 12Z, 1983. The contour interval is variable so as to enhance the detail in the potential vorticity field where gradients are small. The shaded regions are of high potential vorticity and represent stratospheric air.

In terms of the non-divergent streamfunction ψ, defined such that

$$u = -\frac{\partial\psi}{\partial y} \qquad v = \frac{\partial\psi}{\partial x}$$

then (1) becomes

$$\left(\frac{\partial}{\partial t} + \frac{\partial\psi}{\partial x}\frac{\partial}{\partial y} - \frac{\partial\psi}{\partial y}\frac{\partial}{\partial x}\right)\left(\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2}\right) + \frac{df}{dy}\frac{\partial\psi}{\partial x} = 0$$

or

$$\frac{\partial}{\partial t}\nabla^2\psi + J\,(\psi,\ f+\nabla^2\psi) = 0$$

where the Jacobian J is given by

$$J(A,B) = \frac{\partial A}{\partial x}\frac{\partial B}{\partial y} - \frac{\partial B}{\partial x}\frac{\partial A}{\partial y}$$

Notice that if A is proportional to B then $J(A,B) = 0$. More generally $J=0$ if B is a functional of A ($B=B[A]$). Hence nonlinear time-independent free mode solutions of the barotropic vorticity equation are given by

$$J\,(\psi,\ f+\nabla^2\psi) = 0 \tag{2}$$

Now consider a stationary solution of the form

$$\psi = -Uy + A\cos kx\cos ly \tag{3}$$

This represents a superposition of a zonal wavenumber k Rossby wave on a uniform zonal flow with speed U. Writing $f=f_o+\beta y$ we have

$$f + \nabla^2\psi = f_o+\beta y - A\,(k^2 + \ell^2)\cos kx\cos ly$$

which is proportional to ψ providing

$$(k^2 + \ell^2)\,U = \beta \tag{4}$$

Hence the solution (3) with k and ℓ satisfying (4) is a nonlinear free mode solution ($J=0$) of the barotropic vorticity equation.

This particular solution does not describe well the geographically localised blocking phenomenon; it is a hemispheric solution. However, Stern (1975) and McWilliams (1980) have show that there exists a class of non-linear spatially isolated solutions which they name 'modons'. An example of this modon solution is shown in Fig. 3. The correspondence between this dipole behaviour and observed blocking is certainly suggestive.

The modon solutions equivalent to (3) contain Bessel functions of the distance from the centre of the dipole, instead of cosine functions of x and y. The functional form changes at some radius $r=a$. Nevertheless, both the inner ($r<a$) and outer ($r>a$) solutions satisfy $J=0$. Unlike linear wave solutions the modon is a shape preserving non-dispersive structure. It is therefore appealing to imagine the modon to describe at least to lowest order, the atmospheric block.

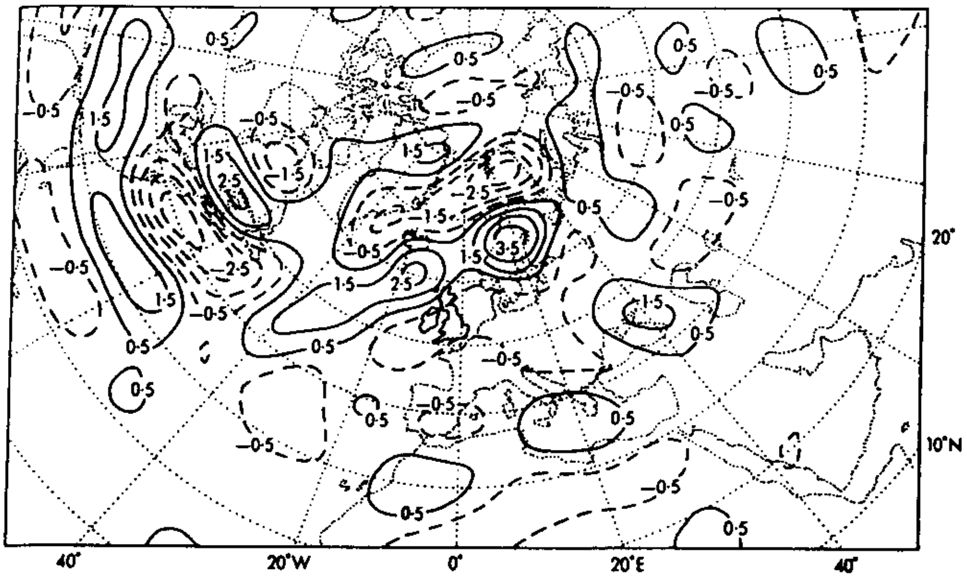


Fig. 3 Spatially smoothed eddy vorticity flux divergence at 300 mbar (high pass filtered in time) for the period 5-22 February 1983.

In reality, however, dissipative processes would tend to 'spin-down' and destroy these modon solutions. However, recent research has shown that injection of low potential vorticity into the block by transient eddies, can maintain the block against dissipative processes. Using our barotropic model, letting the overbar be a time average, primes being departures therefrom, we can write

$$J(\bar{\psi},\ f+\nabla^2\bar{\psi}) = \bar{F} - \nabla.(\overline{\underset{\sim}{v}'\zeta'})$$

where $\bar{F}$ represents all dissipative processes. The convergence of a flux of anticyclonic vorticity

$$\nabla.(\overline{\underset{\sim}{v}'\zeta'}) > 0$$

will offset the effects of dissipative processes decreasing mean anticyclonic vorticity ($\bar{F} > 0$). Fig. 4 shows the transient eddy vorticity flux divergence at 300 mb during the blocking period shown in Figs. 1-2. Only 'High-pass' transient eddies were included in this calculation to emphasise the contribution made by travelling weather systems with time periods of 6 days or less.

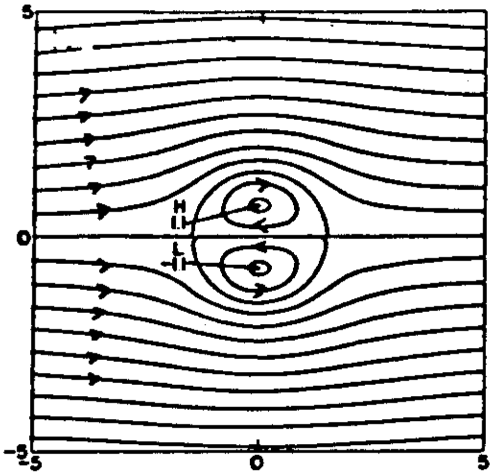


Fig. 4 Streamlines of a stationary equivalent barotropic 'Modon' taken from McWilliams (1980).

In the blocking region, the magnitude of vorticity forcing would be capable of spinning up the mean vorticity anomaly in about 2 days.

A more complete description of the role of transient eddies in maintaining blocks has been given by Shutts (1986), and Hoskins et al (1985) in terms of Ertel potential vorticity.

Hence a currently acceptable theoretical model of blocking would have it that the atmosphere, as a result of some possibly random perturbation, makes a transition from one almost free mode solution (non-blocked) to another free mode modon solution (blocked). Nonlinearity of the free mode prevents wave dispersion of the disturbance, and transient eddy forcing maintains the block against dissipation.

Since the existence of free mode solutions depends on the strength of the mean zonal wind (see e.g. equation (4), the theory might be able to explain the seasonal dependence on blocking.

So far we have concentrated on the phenomenon of European blocking. Blocking over NW America also occurs, though the 'modon' dipole anomalies are not observed; rather the Rockies ridge is strongly enhanced during a 'blocking' episode. However, a theory of such blocking phenomena, similar to the above, has been developed, where the atmosphere undergoes mode transitions from blocked to unblocked states. Interestingly the theory predicts a bimodal probability density distribution of atmospheric states which appears to be observed. This will be discussed in another lecture.

PREDICTION OF BLOCKING EVENTS

In order to assess how well the ECMWF model can simulate blocking events we present results from November 1983, as a basis for choice of specific examples of forecasts involving blocking. This material is taken from Simmons (1986).

Fig. 5 shows height anomaly correlations for 3-, 7- and 10-day forecasts performed from initial dates within November 1983. Particularly evident in the 7-day forecasts is a slow variation in forecast skill over the course of the month, with below-average performance at the beginning of the month and in the final week, and an accurate spell during the second and third weeks. This variation is discernible in the 3-day forecasts, and more so at day 10. Small daily variations in the accuracy of individual forecasts at day 7 are seen to be amplified at day 10.

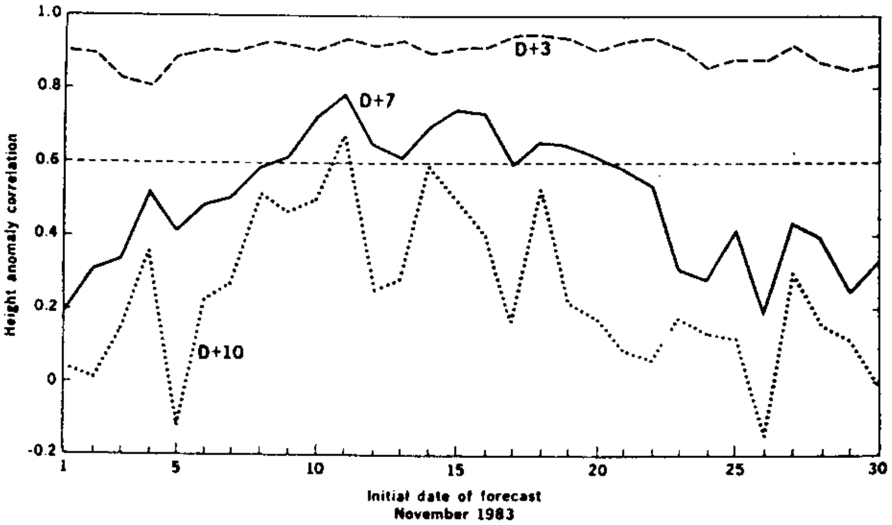


Fig. 5 Anomaly correlations of height for 1000-200 mbar and the extratropical Northern Hemisphere for 3-, 7-, and 10-day forecasts performed from initial dates within the month of November 1983.

To illustrate the range of accuracy of large-scale forecasts within this month, 5-day mean maps of 500 mbar height from analyses and two forecasts are shown in Fig. 6. The forecast from 11 November shown in the left-hand column is classified as the most accurate of the month according to the anomaly correlations at days 7 and 10 shown in Fig. 5. The right-hand forecast plot shows the result from the forecast from 26 November, which ranks as the poorest on the hemispheric scale.

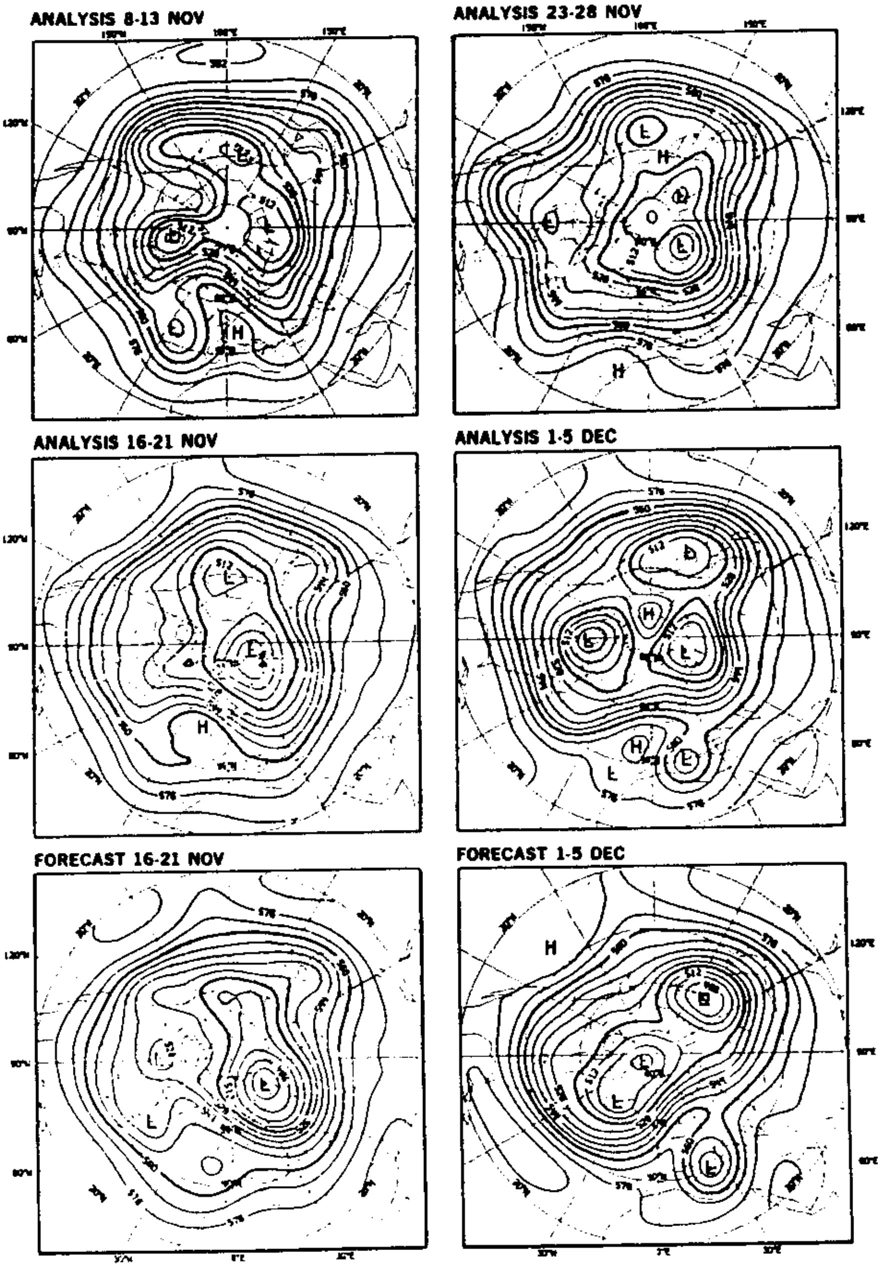


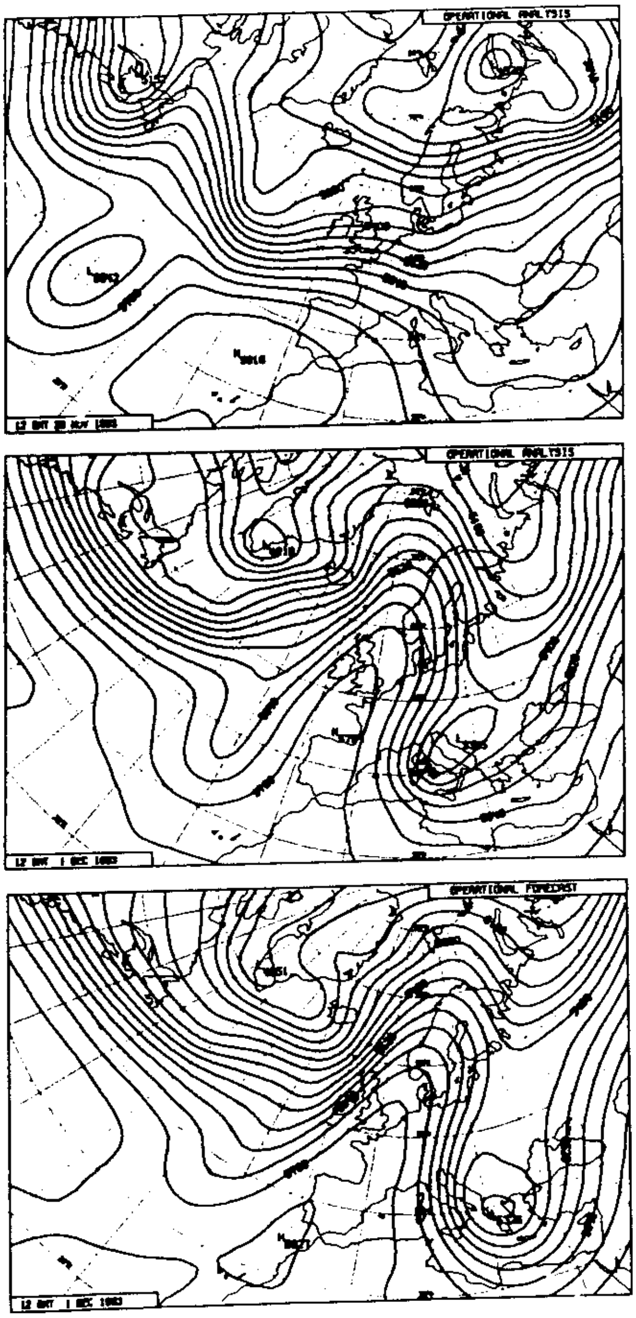
Fig. 6 Mean 500-mbar height analyses for the periods 8-13 November (upper left), 16-21 November (middle left), 23-28 November (upper right), and 1-5 December (middle right). Corresponding means for 16-21 November and 1-5 December are also shown for the forecasts from 11 to 26 November, respectively. The contour interval is 8 dam.

The forecast from 11 November is successful in its representation of most large-scale features present over the final 5 days of the forecast period, It has captured the retrogression of the block initially located over western Europe, the enhancement of the closed low to the northeast, and the decay of the low over northern Canada. Conversely, major error is seen in the forecast from 26 November. In particular, its evolution has produced a predominant zonal wavenumber 2 pattern in the high-latitude height field rather than the strong wavenumber 3 pattern which occurred in reality. The forecast is successful in its formation of a cutoff low in the European sector, but for practical application suffers from an important error in the position of this low, and in the eastward extension of the zonal jet over the Atlantic.

It is of interest from the viewpoint of systematic model errors (to be discussed) to examine in more detail the development of the latter features of the forecast from 26 November. Fig. 7 shows the initial 500 mbar height analysis for the European/Atlantic region, together with the corresponding maps for the 5-day forecast and its verifying analysis. At the 5-day range a pronounced ridge extends over western Europe, and the cutoff low has just formed to the southeast in both the forecast and reality, although it is already seen to be located further east in the forecast. To the west, the forecast exhibits a characteristic error in that the trough over the eastern Atlantic has a phase lag at southern latitudes, and fails to produce a weak cutoff west of the Iberian Peninsula.

Fig. 8 shows the 6-day forecast and verifying analysis. As in idealized studies of mature baroclinic waves (e.g. Simmons and Hoskins, 1978) the tilted eastern Atlantic trough in the forecast has decayed and enhanced westerly flow in this sector, whereas in reality a weak cutoff remains, with high pressure over southern England. In addition, the major Mediterranean cutoff has drifted slightly eastward in the forecast, rather than becoming established over the south of Italy.

Grønaas (1983) has carried out an extensive study of forecasts for the European/Atlantic area for the years 1980 and 1981. He identified 20 spells lasting 7 days or longer in which the anomaly correlation coefficient of



500-mbar height analysis for 12 GMT 26 November (upper) and ecember (middle), and the 500-mbar height field forecast for ecember (lower) from initial conditions for 26 November. The tour interval is 6 dam.

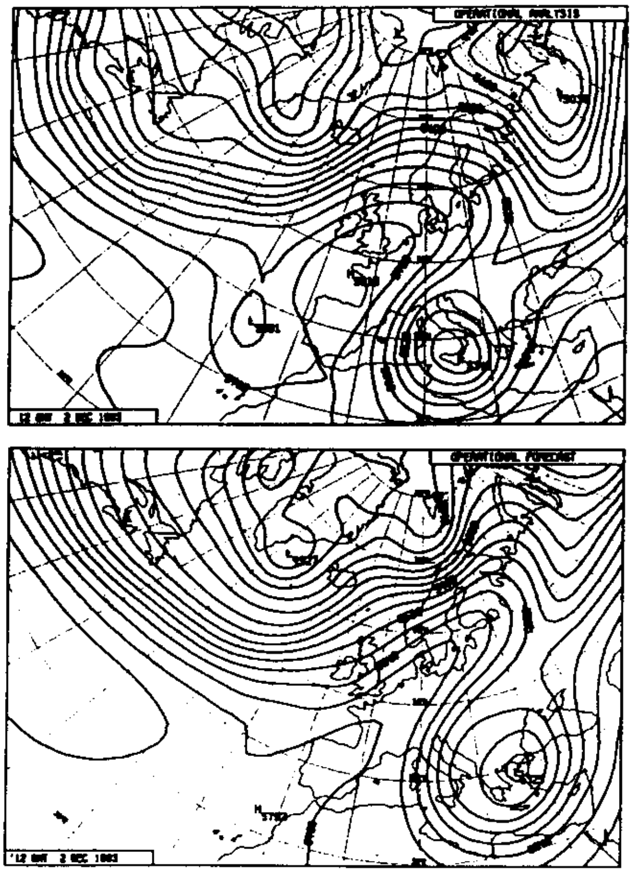


Fig. 8 The 500-mbar height field for 2 December (upper) and the corresponding 6-day forecast (lower) from 26 November.

500 mbar height for the European area indicated above- or below-average forecast quality. These spells were typed synoptically, and it was discovered that the best scores were found for situations characterized by some form of blocking, with poorest results in prevailing zonal situations. Mean scores for day 7 in blocking spells were comparable with those for day 5 in cases of zonal flow.

More specifically, Grønaas (1983) reports above-average forecast scores when persistent large-scale synoptic features such as blocking and cutoff lows are present in the initial analyses, or predicted within the first 3 days of the forecast. The poorer performance in zonal situations reflects not only phase errors of travelling disturbances, but also errors (which have a systematic element) in the cyclone tracks and in the range of filling of cyclones. The systematic errors appear to inhibit the formation of blocking later in the forecast period and give rise to a tendency for the cyclonic activity on the western side of a ridge or block to break down that feature. An indication of this has already been discussed with respect to the forecast from 26 November 1983.

Situations in which the development of blocking is accurately predicted may also be used to examine the mechanisms and interactions involved, and the features of the forecasting system which are of crucial importance. This can be achieved by controlled numerical experimentation, and case studies examining a range of sensitivities to such features as orography, model resolution, and parameterizations have been reported e.g. by Bengtsson (1981), Ji and Tibaldi (1983).

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