THEORIES OF BLOCKING

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1. ROSSBY WAVES

1.1 Stationary wave models

A suitable starting point for a discussion of the theories of blocking is the average N. Hemisphere upper tropospheric flow field for Dec - Feb. As shown by the 250mb streamfunction in Fig. 1, there is the westerly jet centred on the east coast of N. America, and the N. African maximum which continues into the major jet on the east coast of N. America. In the western ocean basins are the two regions of middle latitude westerly wind minima, and equivalently of diffluence in the streamfunction contours. These are the blocking regions of the N. Hemisphere. Blocking can be seen as an amplification of either or both of the climatological ridges.

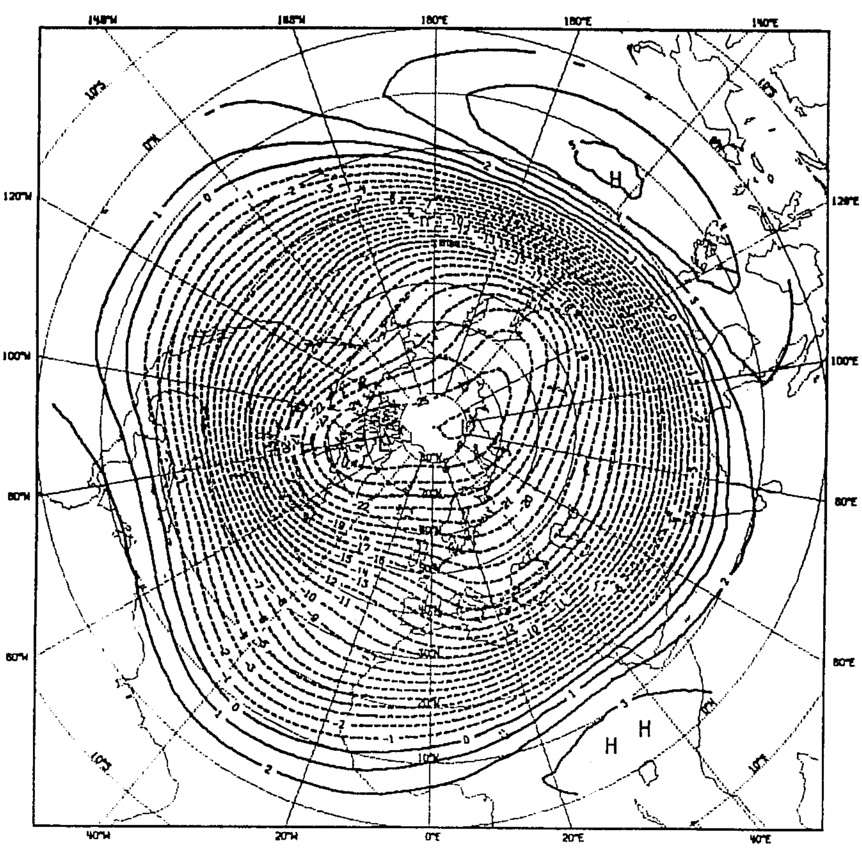

Figure 1.

Northern hemisphere 250mb streamfunction averaged over Dec-Feb for 1978-84. The contour interval is 5.10^6 m^2 s^{-1}. (ECMWF data)

The first obvious approach is then to consider the forcing of the climatological mean flow. One important process is uplift by the major mountain complexes. As described in Grose and Hoskins (1979), in a spherical, barotropic model linearised about a 300mb zonal flow, the anticyclonic forcing on the upslope and cyclonic on the downslope lead to a downstream train of Rossby waves. This train tends to split on the northern flank of the jet with a relatively lower wavenumber pattern poleward of this. The result is that about 90° downstream from a simple mountain there is an anticyclonic perturbation poleward of a cyclonic perturbation. The total streamfunction shown in Fig. 2 has a diffluence reminiscent of the blocking regions. Baroclinic models (Hoskins and Karoly, 1981) support this suggestion.

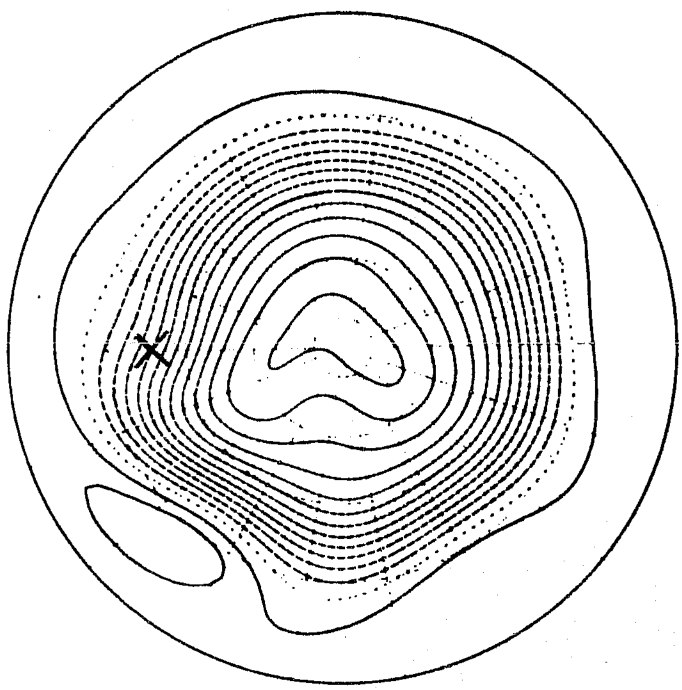

Figure 2. The total streamfunction for a barotropic model linearised about a Dec-Feb 300mb zonal flow and perturbed by a $2\frac{1}{2}$ km circular mountain, the centre of which is shown by a cross (Grose and Hoskins, 1979).

In a similar manner, simple heat sources and sinks in linearised stationary wave models lead to trains of Rossby waves. For certain distributions of diabatic heating these can be in phase with the mountain induced pattern, leading to an enhanced diffluence in the flow.

1.2 "Global" Rossby waves

Although a large amplification of the planetary waves is not necessary, the possibility of resonant growth is clearly appealing. For a steady barotropic model with $\underset{\sim}{v} = (\bar{u},0) + \underset{\sim}{k} \times \nabla\tilde{\psi}$, where $\bar{u}$ = cst., and with forcing $\mathcal{F}$ and dissipation $\mathcal{D}$, the governing equation is

$$\bar{u}\,\frac{\partial}{\partial x}\,\nabla^2\tilde{\psi} + \beta\,\frac{\partial\tilde{\psi}}{\partial x} + J(\tilde{\psi},\nabla^2\tilde{\psi}) = \mathcal{F} + \mathcal{D} \quad . \tag{1}$$

For free solutions to the linearised problem only the first two terms are retained and

$$\nabla^2\tilde{\psi} = -\,K_s^{\;2}\;\tilde{\psi}\;, \quad \text{where } K_s^{\;2} = \beta/\bar{u} \quad . \tag{2}$$

It is clear that the nonlinear term is zero for these modes. Equivalently they are solutions of the free nonlinear equation because the absolute vorticity $\zeta = f_0 + \beta y + \nabla^2\tilde{\psi}$ is a simple function of the total streamfunction $\psi = -\,\bar{u}y + \tilde{\psi}$:

$$\zeta - f_0 = -\,K_s^2\;\psi\,, \tag{3}$$

and therefore ζ is constant along a streamline. Given forcing in (1), there is the possibility of the resonant response of such modes.

Charney and DeVore (1979) exploited such a model with topographic forcing and damping. They included the feedback onto the zonal flow of the interaction of the wave with the mountain. Since, for westerly flow, the waves have high pressure west of the orographic peak and low pressure to the east, they act to force the mountain eastwards. The form drag on the atmosphere is therefore westwards. Charney and DeVore (1979) found two stable solutions: one with weak westerly flow and large amplitude waves and the other with strong westerlies and weak waves. The former has large form drag which is consistent with the weak westerlies and the latter has small form drag, consistent with the westerlies being only a little less than the forcing value.

Mitchell and Derome (1983) used a quasi-geostrophic model and sought resonant modes in which

$$q - f_0 = -\,K_s^2\,(p)\;\psi \quad , \tag{4}$$

where q is the quasi-geostrophic potential vorticity. They showed a variety of interesting solutions in a periodic channel. They then considered the possibility of such modes achieving large amplitude in the thermally forced problem.

The global resonance theories are attractive but, in a more realistic spherical troposphere with easterlies in the equatorial region and propagation into the stratosphere possible, stationary simple free modes do not exist. Whether the leakage from the region is small enough that some semblance of resonant behaviour is possible is not clear at this time.

1.3 Local theories

Other studies have concentrated on local solutions to equivalent barotropic models in which the perturbation potential vorticity $\tilde{q}$ is approximated:

$$\tilde{q} = \nabla^2\tilde{\psi} - K_R^2\tilde{\psi} \quad ,$$

where $K_R^2 = f^2/N^2H^2$ and H is a height scale for the mode. For $K_S^2 = \beta/\bar{u} = $ cst., free modes must now satisfy

$$\nabla^2\tilde{\psi} = -\left(K_S^2 - K_R^2\right)\tilde{\psi} \quad . \tag{5}$$

The modon type solution investigated in the blocking context by McWilliams (1980) is relevant to the situation in which "global" Rossby waves are not possible, i.e. $K_R^2 > K_S^2$ in an infinite domain or, in a channel of width π/ℓ, $K_R^2 + \ell^2 > K_S^2$. In the region outside the circle radius r_0 about the origin, the modon solution again satisfies

$$q - f_0 = -K_S^2\,\psi \tag{6}$$

but this now takes the form of a K-Bessel function with decay away from the circle. Inside the circle $r = r_0$ a different functional relationship is specified :

$$q - f_0 = -K_M^2\,\psi \quad , \tag{7}$$

where $K_M^2 > K_R^2$ (or $K_R^2 + \ell^2$). The J-Bessel function solution in this region is matched to the outer solution.

As seen in Fig. 3, the simple modon solution has an anticyclone poleward of a cyclone and an ambient westerly flow around them. The potential vorticity is discontinuous, that in the anticyclone and cyclone being similar to the ambient value far equatorward and poleward, respectively, of the dipole. The circulation around the cyclonic anomaly helps maintain the position of the anticyclone which otherwise would move downstream and vice versa. The modon solution cannot describe the onset of

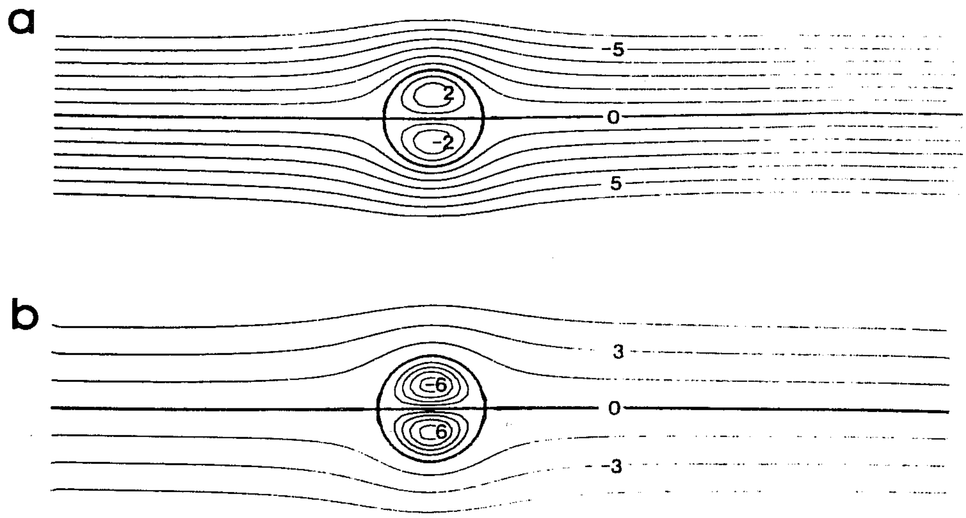

Figure 3. The total streamfunction, ψ, and $q - f_0$ for a modon with $K_M^{-1} \cong 500$ km, $L_R \cong 850$ km, $K_S^{-1} \cong 1000$ km and $r_0 \cong 2400$ km. Contours in (a) are in units of βL_R^3 and in (b) $1.5\ \beta L_R$. (Haines and Marshall, 1987).

blocking and the condition that free Rossby waves should not be possible is very restrictive. However the demonstration of the stability of an isolated potential vorticity couplet is very useful.

Pierrehumbert and Malguzzi (1984) have further investigated the barotropic model (1) in a situation in which no free Rossby waves are possible and there is small amplitude dipole forcing and small dissipation. They demonstrated the possibility of two solutions. One has a westerly flow over the forcing region and only weak waves downstream. The other exhibits modon-like closed streamlines in the forcing region with the weak forcing and dissipation averaging to zero in one complete cycle of the fluid around such a streamline.

2. INTERACTION WITH TRANSIENTS

2.1 Diagnosis of observations

Following Hoskins et al. (1983) one technique for understanding the sense of the momentum transports by transients is to consider the pseudo-vector

$$\underset{\sim}{E} = \left(\overline{v'^2 - u'^2}\ ,\ -\overline{u'v'}\right) \quad .$$

Where this vector converges the vorticity forcing of the mean flow is in the sense of decreasing the westerly wind. The synoptic systems in a storm track tend to be meridionally elongated with $\overline{v'^2} > \overline{u'^2}$. Downstream of their maximum amplitude they tend to force mean easterly winds. In a blocking situation the synoptic systems become very meridionally elongated before splitting and moving to north or south, and so this tendency to support the weak or negative westerlies in the block is very strong. Downstream of the block the succession of equatorward-moving zonally oriented cold fronts can lead to $\underset{\sim}{E}$-vectors pointing westwards, thus increasing their convergence and mean easterly forcing in the block.

There is no doubt that the major ingredient of a blocking high is the low potential vorticity (PV) in its interior, that this PV, even in time mean pictures, is typical of a latitude 20° or so nearer the equator and that the time mean flow is not in general sufficiently perturbed to perform such latitudinal excursions. Following Green (1977), it is clear that the divergence of the PV fluxes by the transient motions must be important. Illari (1984) and others have considered such flux divergences in blocking situations. A more direct approach, as given in Shutts (1986), Hoskins and Sardeshmukh (1987) and others, is to look at daily maps of PV on isentropic surfaces (see Fig. 4). Ahead of each cold front the poleward movement of subtropical air with its low PV into the mean anticyclone region is evident.

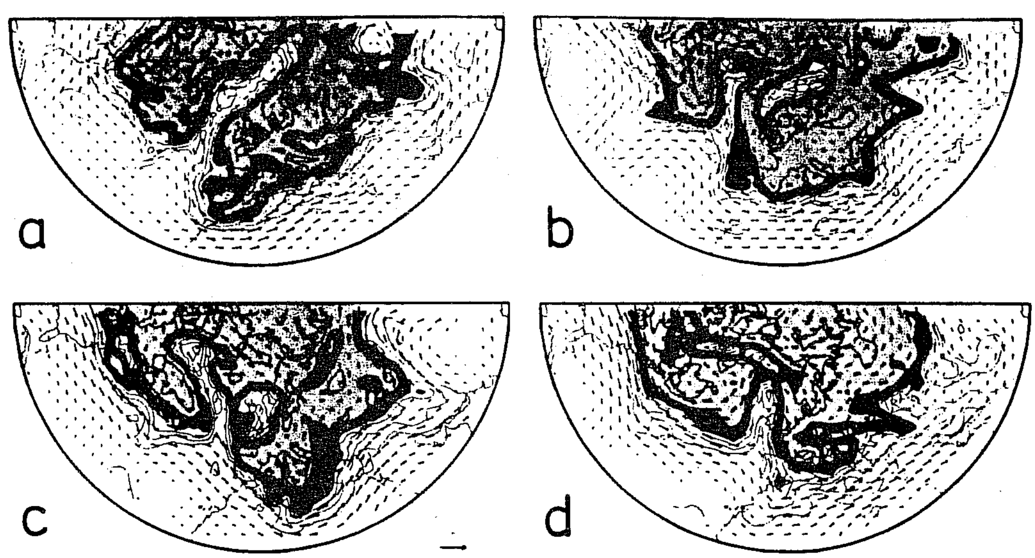

Figure 4. 315 K IPV maps for 3, 5, 8 and 10 February at 12 GMT, (a) - (d) respectively. Contours of potential vorticity are drawn every 0.5 units from 0.5-1.5 units. The region 2-3 units is blacked representing the likely tropopause position. The 'stratospheric' region greater than 3 units is stippled with contours every 2 units. The scale for the wind vector is such that the arrow underneath the figures would represent 100 m s^{-1}. The region shown is bounded by the 20°N latitude circle, 90°W and 90°E. (Hoskins and Sardeshmukh, 1987).

Each incursion lasts a few days, helping to maintain the anticyclone and to ensure that the next depression to move from the west behaves in the same manner. Sometimes the low PV appears to be completely renewed. At other times the terminology 'drip feed' seems to be more appropriate. High PV behind the cold front often moves equatorwards to reinforce the cyclonic part of the blocking PV dipole. High PV also sometimes moves into this region around the eastern side of the block.

2.2 Model studies

Haines and Marshall (1987) have used an equivalent barotropic numerical model to study the interaction of transients with a modon. They first showed that waves forced by a wavemaker, when they encountered a modon, had PV fluxes in the sense of reinforcing the modon. They then showed that these flux divergences did indeed force a modon when they were imposed on the undisturbed westerly flow. In an interesting extension to this they repeated the experiment with a flow that did not satisfy the modon condition: Rossby waves were possible. However a modon-like structure appeared over a period of a week or two before being weakened by Rossby wave energy dispersion.

A two level quasi-geostrophic model was earlier used by Foreman (1985). The initial state (see Fig. 5) contained a baroclinically unstable westerly flow with a region of weak diffluence which was maintained by a forcing. A very small initial wave perturbation grew by baroclinic instability. As it grew to finite amplitude the interaction of individual weather systems with the diffluent region was much as described above. Low PV was deposited in northern regions and high PV is southern regions, creating a strong blocking region which propagated westwards as is frequently observed. In a rerun of this experiment the diffluence forcing was turned off and the waves approached finite amplitude, but the interaction was similar. Thus the forcing is not important at the time of interaction.

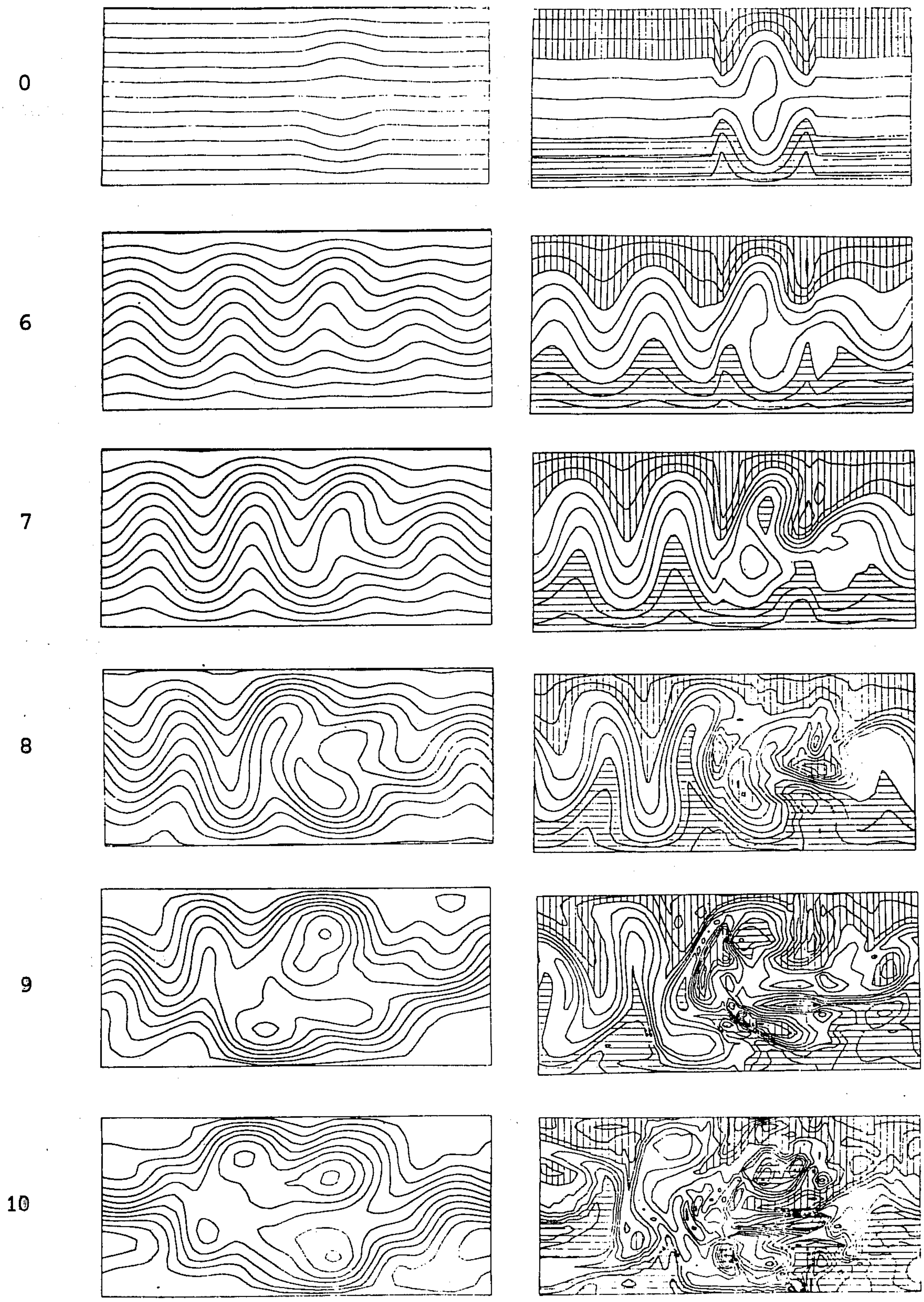

Figure 5. Upper level streamfunction (left) with contour $10^7\ m^2\ s^{-1}$, and potential vorticity (right) with contour 0.1f for days 0, 6, 7, 8, 9 and 10 of the 2-layer channel integration by Foreman (1985).

3. CONCLUDING REMARKS

We conclude with a short list of some features of theories on blocking, not all of which have been discussed in this lecture.

1. Blocking highs, being convectively stable regions with largest velocities away from the surface, are only weakly dissipated.

2. Dipole blocks have a stability as is illustrated by the modon solution.

3. Synoptic weather systems tend to feed back positively onto the existence of blocks.

4. Initiation and decay:
   - (i) favourable nature of the long-wave pattern
   - (ii) instability mode (Frederiksen, 1982)
   - (iii) formation and destruction by a major synoptic system is possible (the others tend to act as slaves, as in 3).

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