A Diagnostic Study of the Potential Vorticity in a Warm Blocking Anticyclone

LODOVICA ILLARI[1]

Atmospheric Physics Group, Imperial College, London

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ABSTRACT

Dynamical features of the warm blocking anticyclone which persisted over Europe during the summer of 1976 are studied using National Meteorological Centre analyses. The dynamics are presented from the perspective of quasi-geostrophic potential vorticity q. The block is shown to be a region of anomalously low, almost uniform $\bar{q}$. Computed balances in the 300 mb monthly mean quasi-geostrophic potential vorticity equation show that the mean flow advection $\bar{\mathbf{v}}\cdot\nabla\bar{q}$ and the eddy forcing $\overline{\mathbf{v}'\cdot\nabla q'}$ of $\bar{q}$ are of comparable magnitude and have the tendency to balance one another. It is suggested that transfer by synoptic scale systems acts to maintain the $\bar{q}$ anomaly against its advection downstream.

1. Introduction

The problem of understanding and explaining the mechanism of blocking has always been considered crucial in meteorology, and many investigations and observational studies of the structure and climatology of blocks have been carried out. However, despite much effort a satisfactory explanation of the mechanism has yet to be found. This lack of understanding precludes any strict definition and so first we will only describe the phenomenon.

In synoptic terms "blocking" is an interruption of the midlatitude westerly flow by a slow moving ridge, or anticyclone, extending at least up to 500 mb. In most cases the upper level westerly jet is split over a range of longitude, one branch passing poleward of the block and the other equatorward, giving a high, low dipole structure. Blocks grow preferentially over the west coast of Europe and the United States, at the end of the Atlantic and Pacific storm tracks (see for example, Rex, 1950; Sumner, 1959; Austin, 1980; Dole, 1983). Typically they have a lifetime of about two weeks and only rarely do they persist for more than a month. The incidence of blocking varies considerably from year to year. It is not certain whether any trends or periodicity are involved, but it seems that late autumn and early spring are the most favorable seasons for blocking.

The study of persistent blocking anticyclones is important because they play an important role in determining regional climate. Because of their long duration and association with local temperature and the movement of synoptic systems, blocking ridges coincide with significant deviations from seasonal norms of temperature and precipitation [see for example, Berggren *et al.* (1949) and Namias (1947, 1964)].

The summer of 1976 was a vivid demonstration of the possible climatological impact of such anomalies. The westerly flow remained blocked over Northern Europe for almost the whole of June, July and August of 1976 and the resulting anticyclonic circulation gave very hot and dry weather. The rainfall pattern was well correlated with the splitting of the jet stream. The period is now remembered as the "1976 European Drought" in recognition of its extensive impact.

The observed structure of blocking is itself suggestive of mechanism. Edmon (1980) has shown that anomalies of geopotential height charts for several winters have vertical phase lines and are cold low or warm high modifications to the normal January mean climate. Thermal forcing is an unlikely mechanism since locally it must induce a pressure anomaly that changes sign with height. The only possible way in which thermally forced motion could be consistent with observations is if heating anomalies existed in the lower stratosphere. Lower stratospheric cooling could induce sinking motion and adiabatic warming, leading to a warm anticyclone. Green (1977) in a study of the July 1976 European block showed that the stratospheric cooling rates would have to be prohibitively large to account for the observed intensity of the blocking. Instead, Green suggested that the block could be mechanically driven by the action of eddies on the scale of weather systems: he supposed that depressions move to the north and south in the split jet and produce at upper levels anomalous vorticity forcing, which maintains blocking in that region and accounts for the vertical structure. Descent of air transfers anticyclonic vorticity from upper to

[1] Present affiliation: European Centre for Medium Range Weather Forecasts, Shinfield, Reading, England.

lower levels through vortex stretching, and ensures that the anticyclone becomes warm. Surface friction removes anticyclonic vorticity at low levels. The blocking anticyclone and the warming of the troposphere are therefore dynamically driven by the action of synoptic scale eddies. Because the weather systems are generated in the baroclinic zones, the split jet and their associated baroclinic zones are not only symptoms of blocking, as it is normally assumed in synoptic analysis, but become a dynamically significant feature of the maintenance of the system. Such a mechanism also recognizes that blocking is an essentially unsteady phenomenon.

An attempt to observe the importance of moving weather disturbances in the maintenance of quasi-stationary phenomena such as blocking was made by Savijarvi (1977). He compared vorticity and temperature balances for a blocking case, and for a non-blocking case. The effect of large scale Reynolds stresses was found to be important, but systematic differences between the two cases were not evident. However, his results were not conclusive, possibly because his choice of averaging period overemphasized the role of mean processes.

Further case studies of intense blocks need to be carried out in order to gain an understanding of their initiation, maintenance and decay and so test dynamical hypotheses. Here a diagnostic study is presented of the warm blocking anticyclone which rested over Europe during the summer of 1976. We concentrate on the role of transients in the maintenance of the block and diagnose in terms of potential vorticity.

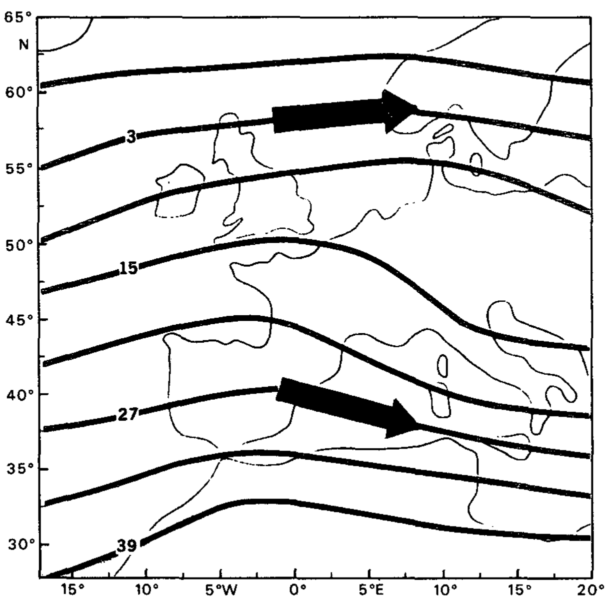

FIG. 1. Mean height of the 300 mb surface (in dam) for July 1976 as a deviation from a hemispherically averaged value of 927 dam. Black arrows indicate position of the split jet.

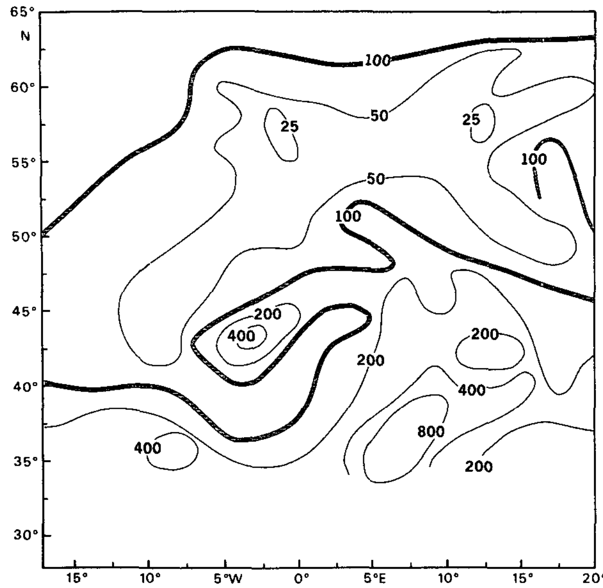

FIG. 2. The July 1976 rainfall expressed as a percentage of the 1931–60 average.

2. Synoptic situation

The westerly flow remained blocked over Europe for almost the whole of June, July and August 1976, giving anomalous weather. Depressions were steered to the north and the south by the two branches of the split jet (one at about 60°N the other at 40°N, see Fig. 1) with resulting low rainfall in between. July was particularly dry over northern Europe and the continental areas bordering the English Channel and the North Sea. To the south, over Italy and the Mediterranean, heavy showers were experienced (see Fig. 2). In July approximately seven depressions crossed the Greenwich Meridian north of the British Isles while two or three intense depressions passed southwards.

Analyses of daily synoptic charts for July 1976 show high pressure cells growing over the British Isles in the first days of the month. The ridge subsequently moved eastward over Northern Europe to reappear to the west of the British Isles at the end of the month. Although daily charts show the blocked flow and associated split jet, they also exhibit considerable variability reminding us that blocking is not a static phenomenon. Synoptic scale systems are evident: high pressure cells grow, block the flow and decay, and new systems replace them. Figure 3 shows the blocked configuration of 13 July 1976, with an intense depression upstream of the ridge. The southerly winds on its eastern flank transport air northwards into the block as noted in the early synoptic studies of Berggren *et al.* (1949) and Rex (1951). A study of a sequence of such charts strongly suggests that the blocking high is continually replenished with warm, low vorticity

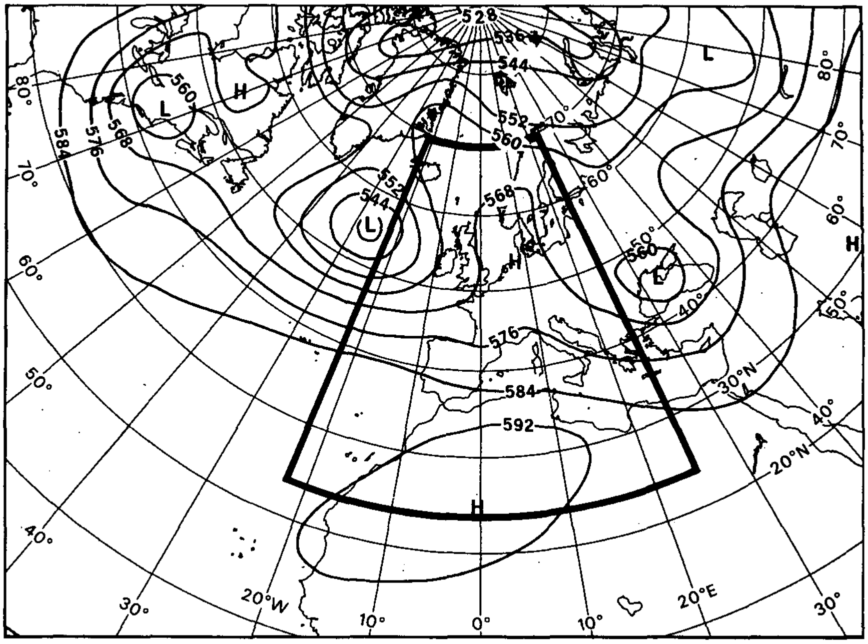

FIG. 3. The 500 mb chart for 13 July 1976 over Europe with contour heights at 8 dam spacing. Diagnostics have been computed within the area marked by the thick black line.

air by the southerly winds ahead of depressions as they approach from the west.

In the following sections we study the interaction between the synoptic systems and the split jet by separating the flow into time-mean and eddy components, and diagnosing in terms of potential vorticity.

3. Diagnostic approach

a. Potential vorticity and its conservation

The approximate conservation of potential vorticity is the single most powerful dynamical constraint on both mean flow and eddies. In particular, the interaction of eddies with mean flow is at its most unambiguous when viewed from the perspective of potential vorticity (see, for example Rhines, 1979). It is for this reason that we will discuss the dynamics of our blocking anticyclone in terms of potential vorticity rather than momentum or relative vorticity.

The following approximation to the full Ertel (1942) potential vorticity is appropriate to large-scale motion and is conserved in adiabatic frictionless motion in an isentropic surface (see for example Kuo, 1972)

$$P = (\zeta + f)\frac{\partial \vartheta}{\partial p},$$

where ζ is the vertical component of the relative vorticity; $f = 2\Omega \sin\varphi$ is the Coriolis parameter with Ω the angular rotation of the earth and φ the latitude; and ϑ is the potential temperature and p the pressure.

The quantity P has been used in diagnostic studies on isobaric surfaces (Lau and Wallace, 1979) but interpretation of maps, fluxes and flux divergences of P is difficult, because P is significantly advected out of the surface by vertical motion. To correctly calculate P, the relative vorticity must be evaluated on an isentropic surface. In this study, however, it is preferred to replace P by the potential vorticity appropriate to quasi-geostrophic motion and discuss the dynamics in terms of quasi-geostrophic potential vorticity q, quasi-conserved in isobaric surfaces:

$$q = \zeta + f - f_0 \frac{\partial}{\partial p}\left(\frac{\delta T}{S(p)}\right), \tag{1}$$

where

$$S(p) = -T_0(p)\frac{\partial}{\partial p}\ln\vartheta_0(p)$$

is the static stability with $T_0(p)$ and $\vartheta_0(p)$ the basic state temperature profiles; f_0 is a mean Coriolis parameter and δT the deviation from the basic state T_0.

The quantity q is conserved in adiabatic frictionless motion $\mathbf{v}$ in an isobaric surface

$$\frac{\partial}{\partial t}q + \mathbf{v}\cdot\nabla q = 0, \tag{2}$$

where ∇ is the gradient operator on an isobaric surface.

The connection between Ertel potential vorticity and the approximate forms P and q has been discussed by, among others, Charney and Stern (1962) and Green (1970).

The conservation of q is particularly useful in prognostic studies of large scale motion but recently has also been employed diagnostically in, for example, Holopainen *et al.* (1982). One should be cautious though, in the use of q in global scale diagnostic studies because of the rather crude assumptions that must be made. In particular the static stability $S = S(p)$ cannot be a function of horizontal position. However the use of q over the limited area of the block is a useful substitute for Ertel potential vorticity on ϑ surfaces, and clearly convenient here.

b. Calculation of q from data

The National Meteorological Centre (NMC) analyses provide a particularly convenient data base from which to build up large-scale circulation statistics. They incorporate observations from radiosondes, satellite, ships and aircraft. The particular NMC data set used here consists of the twice daily (0000 and 1200 GMT) analyses of geopotential height, wind and temperature on a 2.5° horizontal grid covering the globe at 12 standard pressure levels. Mean and eddy statistics are computed on a 20 × 20 grid, from 22.5 to 70°N and from 22.5°W to 25°E, covering western and central Europe and centered on the blocking anticyclone. The area is marked by the thick black line in Fig. 3.

The quasi-geostrophic potential vorticity q, Eq. (1), evaluated at standard pressure levels in spherical coordinates using NMC analyzed winds and temperatures, rather than geopotential height. This choice is made not merely for convenience: computations directly in terms of the height field, although more consistent with quasi-geostrophy, lead to unacceptably large and noisy advective terms which are obviously unphysical. Evidently errors in the height field are sufficient to overwhelm the signal when it is thrice differentiated in order to compute balances in the quasi-geostrophic potential vorticity equation. Instead q is evaluated using analyzed winds and temperatures, and advected by the analyzed winds.

The relative vorticity is calculated using space-centered finite differences. The $\partial/\partial p(\delta T/S)$ contribution is computed using a carefully chosen finite difference expression which takes due account of the irregularly spaced standard pressure levels. The static stability S is computed from vertical profiles of time-mean temperatures, horizontally averaged over the domain of interest. It is observed to increase sharply between 300 and 250 mb, indication of the mean height of the tropopause over the blocking high.

c. Separation of mean flow and eddies

The underlying assumption of Green's blocking maintenance mechanism is that the time mean flow is not itself a solution of the equations of motion, the imbalance being made up through transfer by synoptic systems. Eddy transfer may be introduced formally by separating variables into time-mean and eddy components, substituting them into the advective terms of Eq. (2) and time-averaging to give

$$\overline{\mathbf{v}\cdot\nabla q} = \bar{\mathbf{v}}\cdot\nabla\bar{q} + \overline{\mathbf{v}'\cdot\nabla q'} \tag{3}$$

where an overbar represents a time-average, and a prime the deviation from the time-average. To the extent that $\mathbf{v}$ is horizontally nondivergent the $\overline{\mathbf{v}'\cdot\nabla q'}$ term can be thought of as an eddy q flux divergence $\nabla\cdot\overline{(\mathbf{v}'q')}$.

To study the interaction between transient systems and the time-mean a suitable averaging period needs to be chosen. There is always some ambiguity about this choice which defines mean and eddy. In our exceptionally persistent block one might expect the time-mean to be relatively well defined and behaved. The month of July 1976 was chosen as a suitable interval over which to average, since it is long enough to include several transient systems and yet not too long to average out the anomalous circulation. It should be noted that our eddy component contains variability over time scales of 12 hours to 30 days. However, although the July mean is itself changing, one would expect the trend in the mean to be small because the anomalous circulation persisted for a full three months, of which July was the middle month. It seems reasonable therefore to associate the eddy terms with synoptic scale systems which are dynamically distinct from the blocked larger-scale flow.

4. The block and its potential vorticity

a. Mean flow

The mean height of the 300 mb surface for July 1976 is shown in Fig. 1. A ridge is blocking the zonal flow, which is split into two branches one passing poleward and the other equatorward of the ridge in a typical blocking configuration.

The mean relative vorticity (Fig. 4) shows an extensive anticyclonic region covering a large part of northern Europe. It has two maxima of about 2×10^{-5} s^{-1} (or $1/5$ of the local planetary vorticity), one over the British Isles and the other to the east over northern Europe. Their position is consistent with our synoptic observation that highs formed predominantly over the British Isles during the first days of the month, but that the center of blocking activity quickly moved over northern Europe for the remainder of the month. The distribution of monthly-mean rainfall deficit (Fig. 2) is well correlated with the mean vorticity pattern: the rainfall tends to be anomalously low in the center of the anticyclone (10°E, 55°N) and anomalously high in the cyclonic center (15°E, 40°N).

The ridge and associated anticyclone extend through the whole depth of the atmosphere. It is particularly vertically coherent above 500 mb (the phase lines are

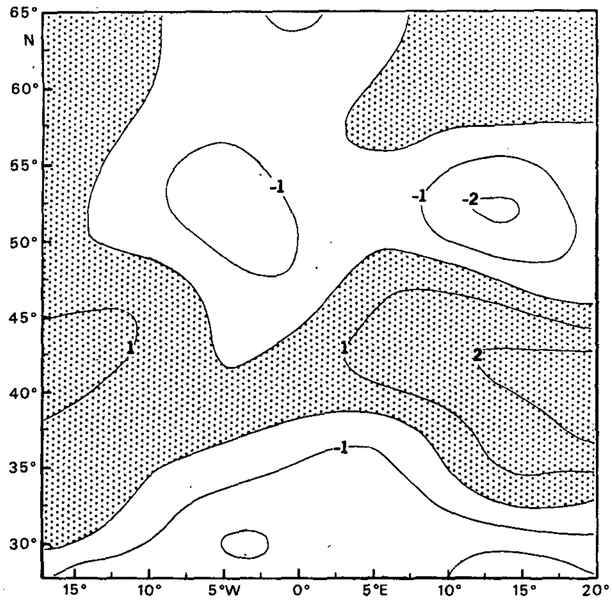

FIG. 4. Mean relative vorticity $\bar{\zeta}$ at 300 mb (10^{-5} s^{-1}). Dotted region indicates cyclonic vorticity and white region anticyclone vorticity.

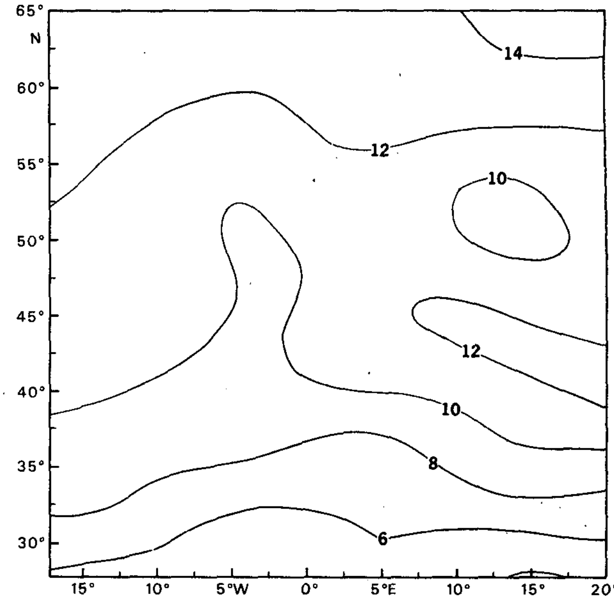

FIG. 5b. As in Fig. 5a, except for $\bar{\zeta} + \bar{f}$.

vertical), where it is most intense. The maximum anticyclonic vorticity occurs at 300 mb.

The monthly mean quasi-geostrophic potential vorticity $\bar{q}$ for July 1976 at 300 mb is shown in Fig. 5a. The background planetary vorticity f following latitude circles is distorted by the motion $\bar{\zeta}$ and temperature field $-f_0\partial/\partial p(\delta\bar{T}/S)$. In the blocking region the $\bar{q}$ contours are displaced northwards, showing that the block is a region of low potential, as well as low absolute vorticity. The anomaly in $\bar{q}$ is most pronounced at upper levels but is evident at all heights. The terms $\bar{\zeta} + f$ (Fig. 5b) and $-f_0\partial/\partial p(\delta\bar{T}/S)$ (Fig. 5c) are both small in the blocking region and collude together to make the block a region of almost uniform, anomalously low $\bar{q}$. We are interested in the processes which transported the low potential vorticity into the blocking region. Transfer by both mean flow and eddies must be considered.

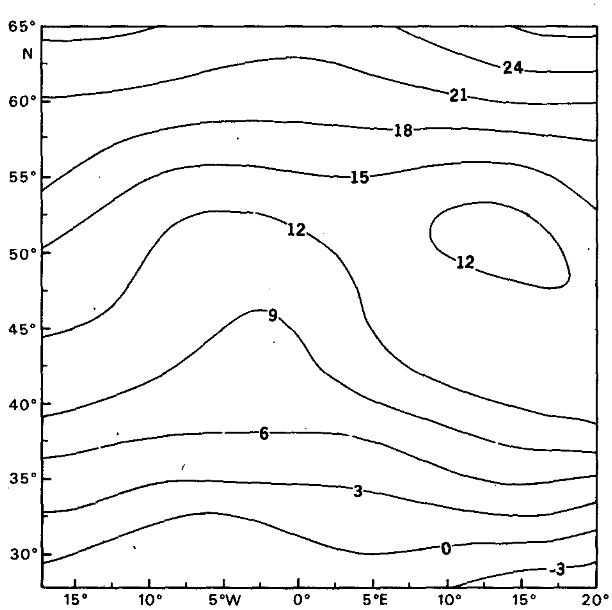

FIG. 5a. Mean quasi-geostrophic potential vorticity at 300 mb: $\bar{q} = \bar{\zeta} + \bar{f} - f_0\partial/\partial p(\overline{\delta T}/S)$ (10^{-5} s^{-1}).

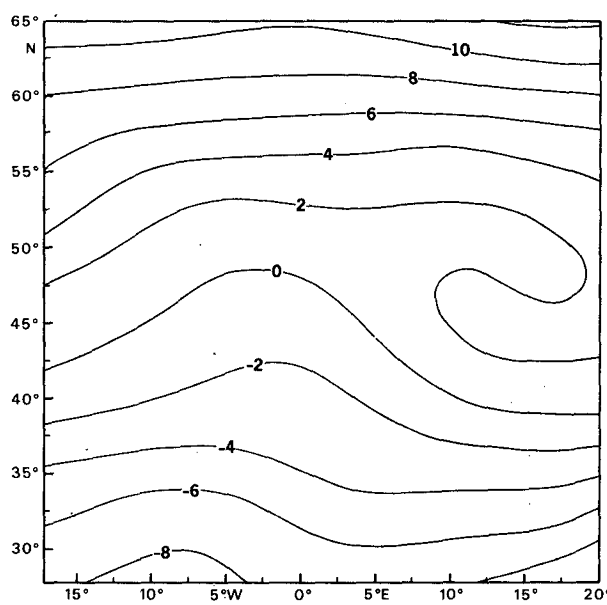

FIG. 5c. As in Fig. 5a, except for $-f_0\partial/\partial p(\overline{\delta T}/S)$.

b. Balances in the 300 mb monthly mean potential vorticity equation

We present the balance of terms in (3) at 300 mb for it is here, just beneath the tropopause, that the anomaly in $\bar{q}$ and the mean flow advection of $\bar{q}$ is large, and eddy transfer of q most active.

The 300 mb advection of $\bar{q}$ by the mean flow $\bar{\mathbf{v}} \cdot \nabla \bar{q}$ is shown in Fig. 6a. It is large in the upper tropopause and reaches a maximum at 300 mb. The $\bar{q}$ contours of Fig. 5a have been superimposed. The advection pattern is a result of the mean zonal flow "blowing through" the $\bar{q}$ pattern. The mean flow tends to advect the $\bar{q}$ pattern downstream with an advective time-scale of $\tau = L/u$, where $u = 20$ m s^{-1} is a typical 300 mb monthly mean zonal velocity, and $L = 2 \times 10^3$ km is the scale over which $\bar{q}$ changes, giving τ of order 1 day. If the low $\bar{q}$ is to be maintained, mean flow advection must be balanced; it could be balanced by either eddy transport or diabatic processes.

The eddy forcing term $\overline{\mathbf{v}' \cdot \nabla q'}$ (Fig. 6b) is fully comparable in magnitude with the mean-flow advection. A comparison of Fig. 6a with Fig. 6b shows that there is a marked tendency for eddy forcing to balance mean advection:

$$\bar{\mathbf{v}} \cdot \nabla \bar{q} + \overline{\mathbf{v}' \cdot \nabla q'} \approx 0, \tag{4}$$

suggesting that eddy forcing upstream tends to maintain the $\bar{q}$ anomaly from being blown downstream. Thus if a mean flow u moves through a region of eddy forcing of intensity F, then in a distance L, the mean potential vorticity is changed by an amount $\Delta\bar{q}$ given by

$$\Delta\bar{q} = \frac{FL}{u}.$$

So for values typical of the blocking region $F = 2 \times 10^{-10}$ s^{-2}, $L = 2 \times 10^3$ km, $u = 20$ m s^{-1}, $\Delta\bar{q}$ is of order 2×10^{-5} s^{-1} as observed.

If the motion were quasi-geostrophic, steady, adiabatic and frictionless, then the balance Eq. (4) would be satisfied exactly. The residual thus contains trends in the mean, diabatic and frictional terms and, of course, errors in the data and the quasi-geostrophic assumption. The residual is smaller than either term in Eq. (4) in the blocking region, although to the south, particularly over North Africa, the two terms have the same sign possibly due to diabatic warming effects.

A particularly significant feature of Fig. 6b is the north–south divergence-convergence dipole centered on and just upstream of the closed $\bar{q}$ contour. Shutts (1983) has argued that such a dipole forcing pattern is a natural consequence of the east–west compression of synoptic systems as they propagate towards a split jet. The deformation of the eddies by the split jet is associated with an enhanced enstrophy cascade and southwards down-gradient divergent eddy q fluxes. This is achieved synoptically through the large meridional displacement of air parcels brought from the south into the blocking high by synoptic systems. (This is also in accord with the remarks of Mahlman (1979) who described the transport of air from south-

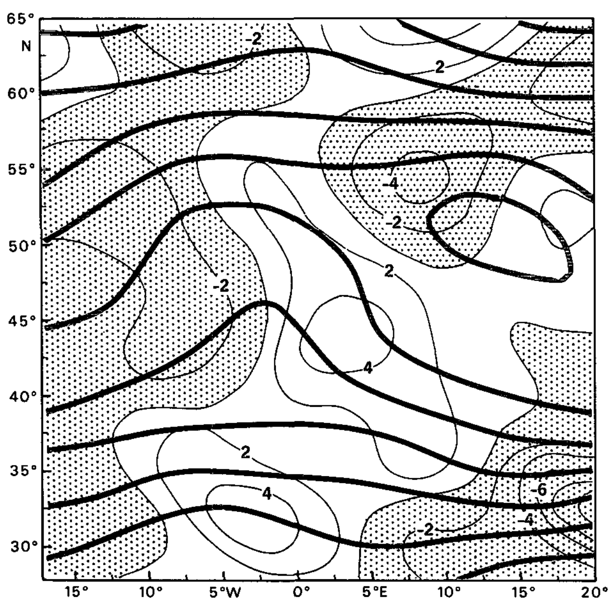

FIG. 6a. Mean flow advection of $\bar{q}$ at 300 mb ($\bar{\mathbf{v}} \cdot \nabla \bar{q}$) ($10^{-10}$ s^{-2}). The 300 mb $\bar{q}$ pattern has been superimposed. Dotted region indicates convergence and white region divergence.

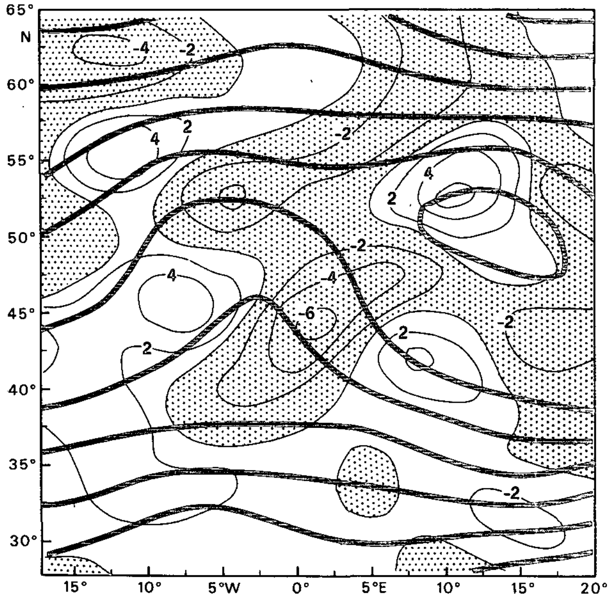

FIG. 6b. As in Fig. 6a, except for eddy forcing of $\bar{q}$ at 300 mb ($\overline{\mathbf{v}' \cdot \nabla q'}$).

erly latitudes into the western flank of a numerically simulated block.) As described in Illari and Marshall (1983), southward fluxes centered on the split jet are a dynamically important signature in the eddy flux statistics; their divergence leads to a north–south dipole in the eddy forcing as in Fig. 6b, which "splits" the jet.

5. Discussion

Our diagnosis in terms of quasi-geostrophic potential vorticity has highlighted the following features of the blocked 300 mb flow which must be accounted for by any proposed mechanism:

1) the blocking high is a region of anomalously low, almost uniform $\bar{q}$;
2) the $\bar{\mathbf{v}}\cdot\nabla\bar{q}$ and $\overline{\mathbf{v}'\cdot\nabla q'}$ terms are of comparable magnitude and tend to balance one another and, in particular,
3) upstream of the $\bar{q}$ minimum there is a divergence-convergence, north–south dipole in $\overline{\mathbf{v}'\cdot\nabla q'}$.

It is significant that the eddy forcing pattern is structured to maintain the $\bar{q}$ anomaly from being advected downstream, and suggests that transfer by synoptic systems is important in maintaining the blocking anticyclone. Indeed, it is very likely that the upper level low-q air is of tropical origin and is transported into the blocking high by synoptic scale systems. In the same way displacement of high-q air from polar regions can maintain the lower level trough to the south. This repeated sweeping of air into the block first northwards (low-q) and then southwards (high-q) by synoptic scale systems appears as a southwards eddy q flux whose divergence gives the characteristic divergence–convergence, north–south dipole in the eddy forcing pattern. This tends to generate low $\bar{q}$ to the north and high $\bar{q}$ to the south.

Shutts (1983) and Illari and Marshall (1983) have argued that the split jet, acting as a deformation field on the synoptic eddies, can organize the eddies in such a way that it can be sustained by them. Thus the eddy forcing pattern seems consistent with our theoretical expectations of the transfer properties of synoptic systems propagating in split jets and, furthermore, is in accord with our synoptic experience.

Such a view contrasts with the mathematical analysis of, for example, Charney and De Vore (1979) and McWilliams (1980) who find mean flow solutions (some aspects of which resemble blocks) without explicitly considering the effects of transient phenomena. Our data analysis may not be necessarily incompatible with these quasi-steady mean flow solutions, for it has been suggested that smaller-scale motions can change the number and position of the multiple equilibrium states (Kallen, 1982), and influence the transition from one state to another (Malguzzi and Speranza, 1981) but without acting to support the final steady state. Further study needs to be carried out to find closer links between these ideas. The present study suggests that transfer by synoptic scale systems is an essential feature that must be taken into account by any theory.

The scatter plot of $\bar{\psi}$ against $\bar{q}$ in the blocking region shown in Fig. 7 (reproduced from Illari and Marshall, 1983) attests to the existence of a functional relationship between $\bar{\psi}$ and $\bar{q}$ and explains why solutions of $\bar{\psi} = \bar{\psi}(\bar{q})$ such as those of McWilliams (1980), can capture some of the characteristics of blocks. It is at first sight surprising that, despite the crucial role played by transient eddies in the maintenance of the mean flow, there remains a tight $\bar{\psi}(\bar{q})$ relation. This should not be interpreted, though, as suggesting that the $\bar{\psi}$ pattern can be understood without the need of eddy transfer. On the contrary the deviation of $\bar{\psi}$ from the $\bar{q}$ contours is small *but vitally important.* Indeed we suggest that it is only by invoking eddy transfer by synoptic systems that we can account both for the block's warmth and anticyclonic vorticity. The disturbance of the "modon type" solutions of McWilliams by transients is a vital component of the blocking mechanism, allowing air parcels to penetrate the closed $\bar{q}$ contours ventilating the block on trajectories which cut across the $\bar{\psi}$ contours. The recent study of Pierrehumbert and Malguzzi (1984) represents a significant attempt to

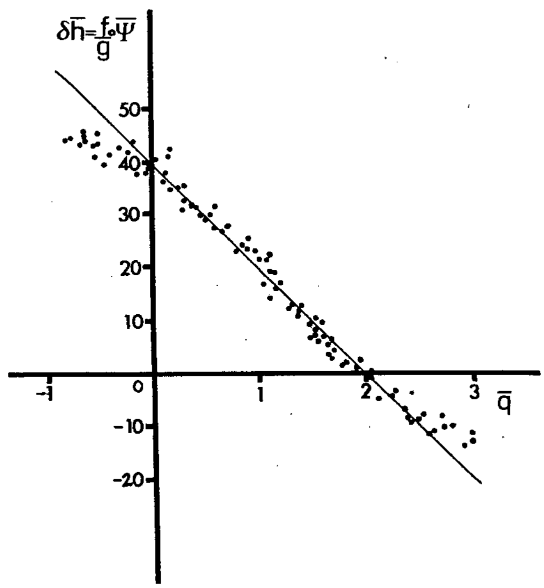

FIG. 7. Scatter diagram of the 300 mb $\bar{q}$ (in 10^{-4} s^{-1}) against the mean height of the 300 mb surface (in dam) showing their functional relationship.

reconcile the steady inviscid modon solutions of McWilliams (1980) with the growing observational evidence of the importance of the local eddy forcing of blocking. In assessment of the importance of the eddies it is interesting to consider the effect of removing the eddy forcing term—the $\bar{q}$ pattern would be blown away in the advective time scale of a few days.

There are other long wave features more permanent than blocking, which are usually thought of as stationary phenomena, but in which transients may be important. For example, conventionally we describe the Siberian anticyclone as thermally driven: an analysis carried out by Holopainen *et al.* (1981) indicates that eddy transfer is also important here. Holopainen has further shown that transient disturbances tend to maintain other stationary features typical of the wintertime circulation, such as the North Pacific low and the North Atlantic low. Eddy transfer into these systems can balance the whole of the dissipation of vorticity at the ground. The equivalent barotropic anomalies observed by Edmon (1980) in the wintertime circulation are unlikely to be a response to anomalous thermal forcing but could be forced by anomalous transient eddy vorticity transport.

Further diagnostic studies need to be carried out to see if similar dynamical processes are occurring in other blocking cases. Perhaps because of the adoption of quasi-geostrophy as a diagnostic framework our balance of terms is necessarily rather rough and certainly the present study cannot be regarded as a definitive one. The quasi-geostrophic framework must be relaxed to diagnose in terms of Ertel potential vorticity on ϑ surfaces. Such investigations are under way and Shutts (private communication, 1984) has found that eddy transfer is also in evidence in a winter blocking episode.

The dynamical insights gained from our diagnoses must be tested in models. For example, simplified but realistic forcing functions could be used in low resolution climate models in order to simulate blocking. We need to determine the extent to which the eddy transfer taking place in the block is anomalous. Further study of the transfer properties of the middle latitude synoptic scale, using real and model data is essential here. Our study of block maintenance should be extended to include the dynamics of block initiation and decay; of particular interest is the possible role of transients in the transition from blocked to unblocked flow. It will be necessary to diagnose blocking cases in the high resolution GCMs to see if the dynamical processes identified in our case study are also occurring in the models. It may be found that the difficulty the GCMs have in producing blocks is a result of their inability to resolve the eddy-transfer processes which we believe are crucial to the block maintenance (see for example Tibaldi and Ji, 1983).

Finally, other ways of treating the data need to be considered. For example, one approach would be to investigate the block in terms of parcel trajectories rather than the means at a point. This Lagrangian description could bear a closer relationship to the synoptician's view of blocking and give more insight into the transport of the warm low potential vorticity air into the blocking high by the moving air masses.

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