

The February 1989 Pacific Block as a Coherent Structure

Abstract

Throughout the latter part of January and most of February 1989 a large-scale intense blocking event occurred over the Northeast Pacific Ocean. During its lifetime the block exhibited two distinct spatial configurations corresponding to Omega and dipole shapes, respectively. A time series of scatter diagrams of 5-day-averaged 500 mb geostrophic stream function versus potential vorticity is computed. It is suggested that both the Omega and dipole forms may correspond to free modes. It is shown that as the block develops the contribution of the gravest, quasi-barotropic mode dramatically increases and forms the dominant mode.

Introduction

Over the past decade, attempts have been made to model atmospheric blocking using idealized solutions of the quasi-geostrophic equations that can persist for times comparable to blocking durations. Because the timescale associated with a block (on the order of about 10 days; see Rex (1950)) and the horizontal amplitudes are larger than that typically associated with transient baroclinic disturbances, a reasonable conjecture is that blocking may correspond to the atmospheric attempting to configure itself into a localized, finite-amplitude free-mode that is rather stable to smaller eddy disturbances. In quasi-geostrophic dynamics, a free-mode is characterized formally by a functional relation $q = q(\psi)$, where q is the potential vorticity and ψ the stream function.

One way of testing whether or not a particular observed flow pattern is developing into a free-mode is to examine the *geostrophic scatter diagrams* for the flow (see Read *et al.*, 1986). Scatter diagrams are simply two-dimensional scatter plots of the observed stream function versus the observed potential vorticity from many points within a given geographical region at a given height.

Read *et al.* (1986) presented a technique for computing the area associated with a given scatter diagram. For a free mode, the scatter plot collapses onto a

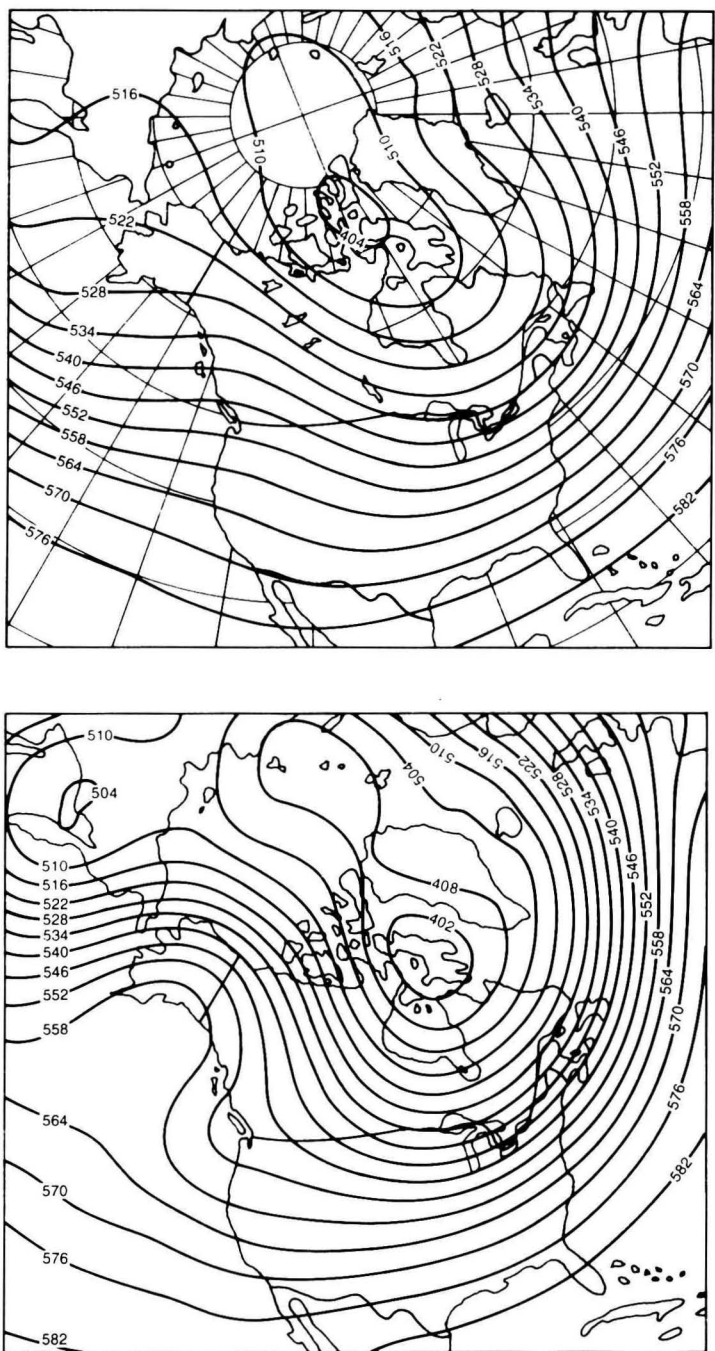


Fig. 1. Mean 500 mb geopotential height [dam.] for February; (a) climatological average; (b) February 1989. Adapted from Canadian Meteorological Centre, *Monthly Review*, May 1989.

curve, and the area *must* be identically zero because the integrated or net flux of vorticity is zero. The *observed* scatter diagram area can therefore be viewed as a measure of the degree of departure of the observed flow from a quasi-geostrophic free-mode state.

Butchart *et al.* (1989) presented a theoretical and diagnostic study of an atmospheric block over central Europe. One of the most important conclusions of their study was the clear indication of the development of a simple non-analytic pattern in the scatter diagrams which had a striking resemblance to the scatter diagram for a geostationary modon solution. The principle purposes of this extend abstract is to very briefly present the results of a similar study for a blocking episode over the Northeast Pacific Ocean (see Figure 1). The reader is referred to Ek and Swaters (1993) for a complete description of our methods, analysis and conclusions.

The time series of 5-day-averaged scatter diagrams that we present shows a tendency for the scatter diagram area to decrease as the block develops; strongly suggesting that the blocking configuration observed is more free-mode like than either the pre- or post-block configurations. The baroclinic evolution of the block is also examined. Our results show a tendency toward a quasi-barotropic configuration as the block develops. This barotropic configuration is maintained throughout the life of the block. However, immediately prior to the formation of the dipole block we can identify a brief period with a slight increase in baroclinic activity associated with a transient cyclone. It is interesting to speculate that this baroclinic activity is associated with the eddy-straining process proposed by Shutts (1983, 1986) as a mechanism for driving atmospheric blocks into a dipole configuration.

The data set

The data (supplied by the Canadian Meteorological Centre) consist of objectively-analyzed archived data on a latitude-longitude grid, at a two-degree spacing. The full grid extends from 30°N to 80°N and westward from 20°W to 120°E (see Figure 2). Five levels were used: 850, 700, 500, 400, and 250 mb. At each level, 3 data fields were used: The geopotential height of the pressure surface denoted as Z ; the temperature denoted as T ; and the dew-point depression given by $T - T_d$. There are normally four data-sets for each day (one for every 6 hours), running for 39 days from 21 January through to 28 February, 1989. The initial preparation consisted of time-averaging (at each grid point) each data field, over the four synoptic periods per day. This smoothed out the smallest-scale disturbances.

The geostrophic stream function was calculated at each grid point (i, j) as $\psi_{i,j} \equiv f_0^{-1} g Z_{i,j}$, where f_0 is the Coriolis parameter at 60°N, g is the gravitational acceleration, and $Z_{i,j}$ is the geopotential height of the isobaric surface. The vertical component of absolute vorticity was calculated as $\nabla^2 \psi_{i,j} + f$, using a centred finite difference scheme for the Laplacian term. We used a β - plane approxima-

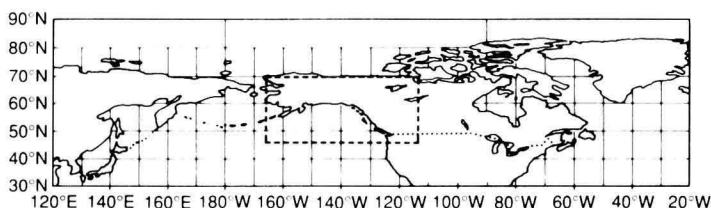


Fig. 2. The region covered by the data. The box over the Gulf of Alaska approximates the block's interior.

tion throughout our work. The baroclinic stretching term in the potential vorticity was computed using a finite-difference approximation.

We applied first a spatial and then a temporal smoother to the vorticity and stream function fields. The spatial smoother is a simple 5-point smoother, weighted to take into account the variable zonal grid spacing. The fields were then time-averaged over 5 days, with equal weights. All calculations in this paper begin with the 5-day mean fields, each centred on the date listed.

Throughout this study, the region occupied by the block was approximated by a horizontal box-shaped area, bounded by the latitudes 46°N and 70°N , and longitudes 114°W and 166°W . This box-shape was subjectively chosen to surround, as closely as possible, the portion of the block having closed stream function and vorticity contours, on as many days as possible.

Scatter diagrams and free modes

A means of testing the applicability of free modes to blocking originates with an interesting result of Read *et al.* (1986). Suppose that we pick an arbitrary, simple horizontal curve enclosing a region $\mathcal{R}_{(x,y)}$, in physical (x, y) space. The net flux of vorticity across the curve, $\partial\mathcal{R}_{(x,y)}$, due to the geostrophic wind, can be written as

$$F_q \equiv \oint_{\partial\mathcal{R}_{(x,y)}} q\vec{v}_g \cdot \hat{n} dl, \quad (1)$$

where $\vec{v}_g \equiv \hat{k} \times \nabla\psi$ is the geostrophic wind, \hat{n} is the outward unit normal vector to the curve $\partial\mathcal{R}_{(x,y)}$, dl is the differential arc-length, \hat{k} is the unit vector pointing vertically upward, and $\nabla = (\partial/\partial x, \partial/\partial y)$.

A positive flux entails a net export of cyclonic vorticity. We can apply the two-dimensional divergence theorem to (1) to get

$$\begin{aligned} F_q &= \int \int_{\mathcal{R}_{(x,y)}} \nabla \cdot [q(\hat{k} \times \nabla\psi)] dx dy \\ &= \int \int_{\mathcal{R}_{(x,y)}} J(\psi, q) dx dy. \end{aligned} \quad (2)$$

The second integral in (2) may be directly transformed into an integral over the corresponding region $\mathcal{R}_{(\psi, q)}$, in (ψ, q) space as follows:

$$\begin{aligned} F_q &= \int \int_{\mathcal{R}(x, y)} \text{sign}[J(\psi, q)] |J(\psi, q)| dx dy, \\ &= \int \int_{\mathcal{R}(\psi, q)} \text{sign}[J(\psi, q)] d\psi dq. \end{aligned} \quad (3a)$$

The sign of the Jacobian is positive if the curve in (ψ, q) space is closed off in the same sense as the corresponding (x, y) space curve, which we take to be counter-clockwise. The sign is negative for (ψ, q) curves that are closed off in the

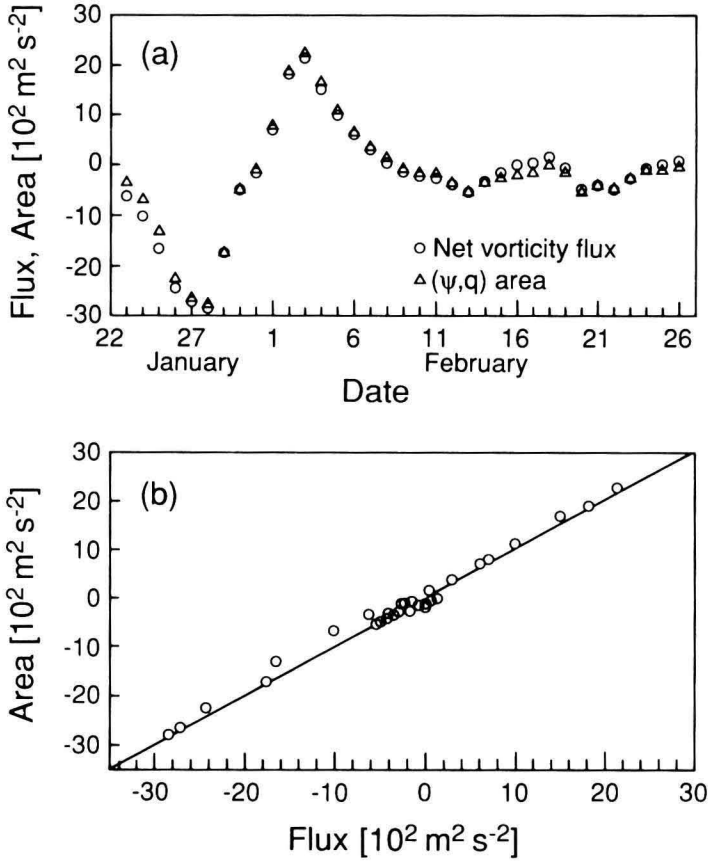


Fig. 3. (a) Time series of the area of the 500 mb net vorticity flux across the box bounded by latitudes 46° – 70°N and longitudes 114° – 166°W as computed directly from cartesian coordinate and q/ψ – scatter diagram representations, respectively. (b) The same variables as (a): net vorticity flux calculation in cartesian coordinates plotted against the q/ψ – scatter diagram calculation.

clockwise sense. Alternatively, we can relate the area of the q/ψ – scatter diagram, denoted by $A_{(\psi, q)}$, to the Jacobian as follows:

$$\begin{aligned} A_{(\psi, q)} &\equiv \iint_{\mathcal{R}(\psi, q)} d\psi dq \\ &= \iint_{\mathcal{R}(x, y)} |J(\psi, q)| dx dy. \end{aligned} \quad (3b)$$

In the case of a free mode formally defined by $q = q(\psi)$, we have $J(\psi, q) = 0$, and both the area of the (ψ, q) region, and F_q , must vanish. It is evident that either of the two quantities, F_q or $A_{(\psi, q)}$, may be thought of as a measure of the *departure* of the system from *any* free mode of the form $q = q(\psi)$.

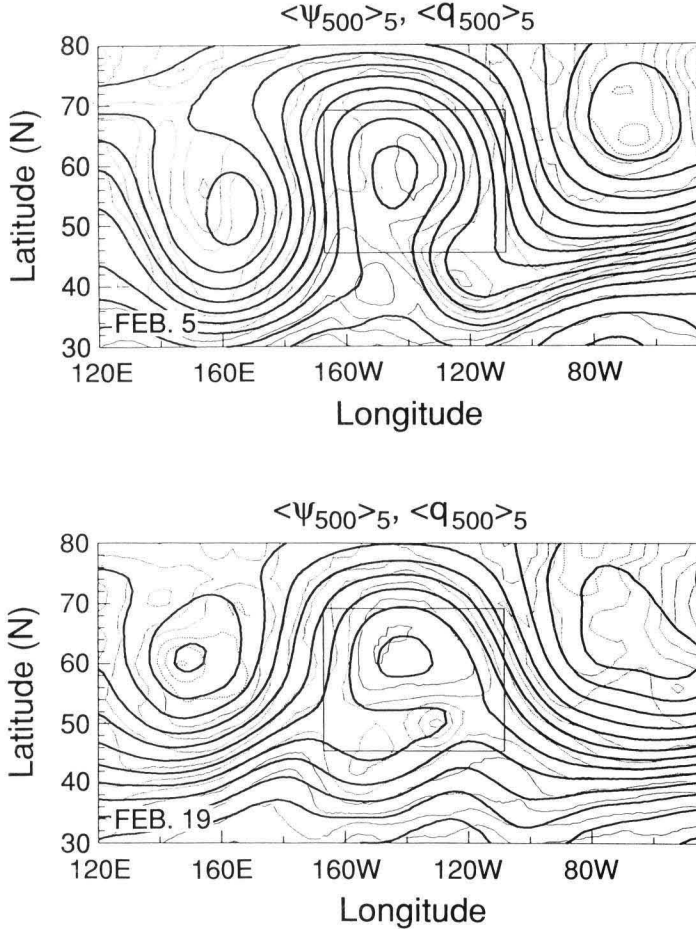


Fig. 4. Five-day mean 500 mb geostrophic stream function, ψ (solid contours), and potential vorticity, q (light dashed contours). Contour intervals are $6 \times 10^6 \text{ m}^2 \text{ s}^{-2}$ for ψ and $2 \times 10^{-5} \text{ s}^{-1}$ for q . a) Feb. 5, b) Feb. 20, 1989.

In Figure 3 we present time-series of the computed net vorticity flux using the cartesian representation (1) and the q/ψ – scatter diagram area representation (3a), respectively. The two quantities are in quite good agreement, as they should be, from which we conclude that it is possible to calculate the net vorticity flux using either representation as suggested by Read *et al.* (1986), and that our data are reasonably consistent. Repeating the calculations using a slightly larger box (Ek, 1992) produces nearly identical results, suggesting that the sensitivity to our choice of boundary, in this case, is not too severe.

The time series of the net flux clearly shows that it remains near zero values for the lifetime of the block. This suggests that the block is very near to an inertial free mode of the quasi-geostrophic equations, in the geostationary reference frame. The vorticity flux time series does not seem to distinguish between the dipole and Omega blocking configurations.

Based on the complete series of 5-day mean 500 mb charts, we may subjectively consider the block to have evolved between two states. From about February 1 to 14, the flow pattern had the familiar ‘Omega’ (Ω) shape (see Figure 4a). During the second, shorter period, February 18 to 21, shortly before it broke down, the block developed a discernible dipole-like form (see Figure 4b). The full series of 500 mb charts is given in Ek (1992).

Baroclinic structure

In order to study the baroclinic evolution of the block we computed a time-series of spectral coefficients for the blocking stream function (defined to be the total dynamic stream function minus the stream function associated with the background zonal flow) associated with the orthonormalized vertical modes given in terms of pressure coordinates by (see Ek and Swaters (1993) for details of the derivation)

$$\frac{d}{dp} \left(\frac{1}{\sigma_r} \frac{d\Psi_n}{dp} \right) + f_0^{-2} (\gamma_n - A_0) \Psi_n = 0, \quad (4a)$$

$$\frac{d\Psi_n}{dp} - \frac{dU(p)/dp}{U(p)} \Psi_n = 0, \quad (4b)$$

on $p = p_r$ (250 mb) and $p = p_b$ (850 mb), respectively, and where

$$A_0(p) \equiv \left[f_0^2 \frac{d}{dp} \left(\frac{1}{\sigma_r} \frac{dU}{dp} \right) - \beta \right] / U, \quad (4c)$$

where $U = U(p) > 0$ is the eastward background zonal flow, and where σ_r , f_0 , and β are the static stability, and constant Coriolis and beta parameters, respectively.

In order to be able to compare the average contribution of each mode to the

vertical structure of the blocking eddy, we computed the root-mean-square (RMS) value of each coefficient, defined as

$$\langle a_n \rangle_{\text{RMS}} = \left[\frac{\sum_{x,y}^{(N \text{ points})} [a_n(x,y)]^2}{N} \right]^{1/2},$$

where the sum is understood to be over each horizontal grid point and $a_n(x,y)$ is the spectral coefficient associated with the n^{th} vertical mode.

Figure 5 presents a time-series for the first four root-mean-square coefficients. We can see that as the block develops, there is a significant increase in the relative contribution of $\langle a_0 \rangle_{\text{RMS}}$ suggesting a quasi-barotropic configuration.

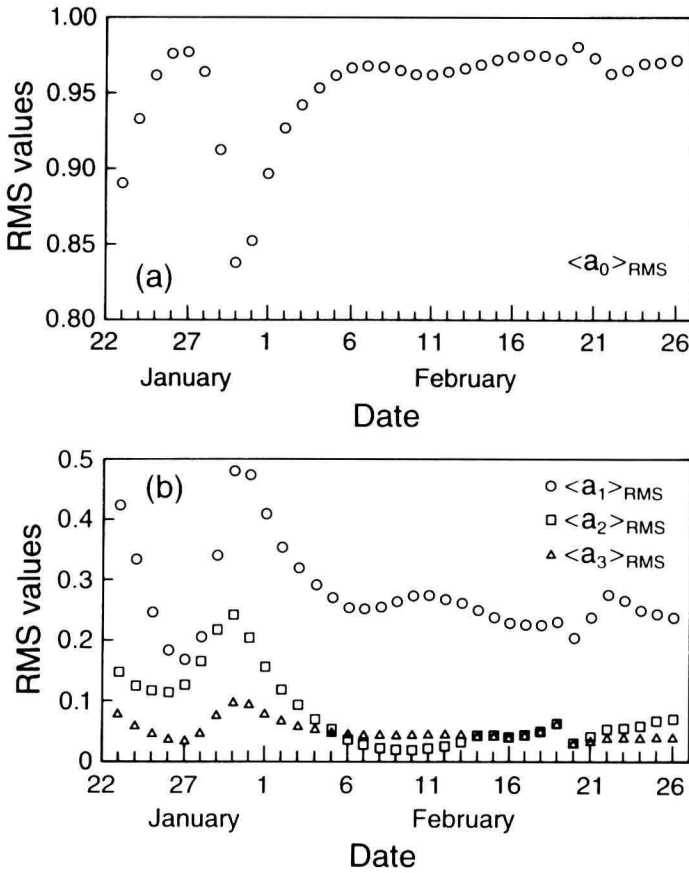


Fig. 5. Time series of normalized Root-Mean-Square (RMS) Fourier coefficients of the four gravest vertical normal modes. (a) Gravest mode. (b) First, second, and third modes. Normalizations are such that the sum of the squares of each day's four RMS values is unity.

Acknowledgement

Preparation of this manuscript was supported in part by research grants awarded by the Natural Sciences and Engineering Research Council of Canada and by the Atmospheric Environment Service of Canada.

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