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The Roles of Baroclinic and Barotropic Instability during Cyclogenesis and Atmospheric Blocking

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ABSTRACT

The application of three-dimensional instability theory to climatological and instantaneous atmospheric flows is discussed. New results on the roles of baroclinic (vertical shear) and barotropic (horizontal shear) instability in the formation of severe storms and atmospheric blocks are presented for particular synoptic situations in both the Southern and Northern hemispheres.

INTRODUCTION

In recent years, considerable effort has gone into analysing from observations the three-dimensional structures of atmospheric fluctuations of various time scales, such as developing extra tropical cyclones, blocks and other mature anomalies. Similarly, there has been a flood of literature on theories and numerical simulations aimed at understanding these phenomena.

For fluctuations with short time scales, of say less than about a week, there is little controversy about the basic mechanism operating. Since the pioneering studies of Charney (1947) and Eady (1949), the generally accepted theory of the formation of storms (or cyclogenesis) has been that of linear baroclinic (vertical shear) instability of the large-scale atmospheric flow field. These early investigations examined the instability of flows which had no longitudinal (also termed zonal) variations in the basic state or in the amplitude of the growing disturbances. Recent theoretical (Frederiksen, 1982, 1983b, 1984, 1985 and references therein) and observational (Blackmon et al., 1984, Trenberth, 1981) studies indicate that the geographical locations of storm tracks in both the Northern and Southern hemispheres can also be explained using instability theory with three dimensional basic states.

Recently, it was suggested (Frederiksen 1982, 1983a,c; Simmons et al., 1983; Schubert, 1985) that instability theory, with climatological averaged basic states having longitudinal as well as latitudinal (or meridional) variations, can also generate analogues of many other atmospheric fluctuations with longer time scales. Within baroclinic models (Frederiksen 1982, 1983c) as well as monopole cyclogenesis modes, there are onset-of-blocking dipole modes of slightly longer periods, very long period large scale mature anomaly pattern modes and modes of intermediate period and scale.

Comparison of the onset-of-blocking dipole modes with the observations of Dole (1983), and Colucci (1985) (Frederiksen, 1983c) and with model integrations (Frederiksen and Puri, 1985) has lent support to the proposal that these modes would be the precursors to the formation of mature anomalies (at least in some cases).

For the onset-of-blocking dipole modes the instability is combined baroclinic-barotropic (Frederiksen, 1983a), becoming increasingly barotropic (horizontal shear) instability for some of the intermediate modes. For the mature anomaly pattern modes it appears that the instability is essentially barotropic in nature (Simmons et al., 1983; Frederiksen, 1983c; Schubert, 1985) although there are differences between the modes obtained in baroclinic and barotropic models both in structure and growth rate and period (see Figs.1-5 of Frederiksen 1983c).

Our purpose here is primarily to examine whether instability theory can also pick out some of the important developments such as cyclogenesis and in particular blocking when the basic states are instantaneous flows representing particular synoptic situations, rather than climatological averaged flows. In section 2, the quasi-geostrophic equations used for the study are briefly summarized, while in sections 3 and 4 the instability properties of a Southern Hemisphere synoptic flow field for 24 August 1975 and of a Northern Hemisphere synoptic flow field for 6 November 1979 are examined. The conclusions are summarized in section 5.

2. MODEL DETAILS

The instability solutions presented in the following sections have been obtained by linearizing the spherical quasi-geostrophic equations about a three-dimensional basic state. These equations are as follows:

$$\frac{\partial \nabla^2 \psi}{\partial t} = - J(\psi, \nabla^2\psi + f) - \nabla\cdot(f\nabla\chi) - K(p)\nabla^2\psi - K'\nabla^6\psi, \quad (1)$$

$$\frac{\partial T}{\partial t} = - J(\psi, T) + \Sigma w \quad (2)$$

$$\frac{\partial \Phi}{\partial p} = - \frac{RT}{p}, \quad (3)$$

$$\nabla^2\Phi = \nabla\cdot(f\nabla\psi), \quad (4)$$

$$-\frac{\partial w}{\partial p} = \nabla^2\chi, \quad (5)$$

$$f = 2\Omega\mu, \quad (6)$$

$$\Sigma = -\left(\frac{\partial \bar{\bar{T}}}{\partial p} - \kappa\frac{\bar{\bar{T}}}{p}\right). \quad (7)$$

Here ψ is the streamfunction, χ velocity potential, T temperature, $\bar{\bar{T}}$ horizontally average temperature, Σ static stability parameter, p pressure, $w = dp/dt$ "vertical" velocity, Φ geopotential height, R gas constant for air, f Coriolis parameter, κ the ratio of the gas constant to the specific heat of air at constant pressure, $\mu = \sin$ (latitude), and $K(p)$ and K' surface drag and diffusion coefficients. The diffusion and drag coefficients used have the values $K' = 2.338 \times 10^{16}\ m^4 s^{-1}$, and $K(p) = 8.39 \times 10^{-7}\ s^{-1}$ at 900 mb and is otherwise zero.

The five-level model used here is obtained by finite differencing Eqs.(1)-(7) in the vertical with the streamfunctions and geopotential specified at odd multiples of 100 mb and the temperatures and "vertical" velocities at even multiples of 100 mb. The basic states are represented by spherical harmonics at each level [Eq.(2.10) of Frederiksen, 1983b] and a rhomboidal truncation is used in which the zonal wavenumber ρ takes the values $|\rho| = 0,1,...15$ and the total wavenumber ν for the streamfunction takes the values $\nu = |\rho|+1, |\rho|+3,... |\rho|+15$. The basic state streamfunction is thus antisymmetric between the two hemispheres. The disturbances are also represented by spherical harmonics and have a time dependence $\exp(-i\omega^d t)$ where $\omega^d = \omega^d_r + \omega^d_i$ is the complex angular frequency [Eq.(2.11) of Frederiksen, 1983b]. Here we use truncation schemes in which the zonal wavenumber m takes the values $|m| = 0,1,...,15$ and for the antisymmetric streamfunctions the total wavenumber n takes the values $n = |m|+1, |m|+3,..., |m|+P$. Here $P = 9$ was used for the Southern Hemisphere flow and $P = 15$ for the Northern Hemisphere flow.

3. INSTABILITY OF THE SOUTHERN HEMISPHERE FLOW

For the Southern Hemisphere basic state we take the observed flow field at 2300 GMT on 24 August 1975. This is a few days before a blocking dipole wave train first occurred in the Tasman Sea region between Australia and New Zealand. Fig.1 shows the geopotential height of the 850 mb surface for 1100 GMT on 26 August 1975 by which time the dipole blocking wave train, which persists until about 2300 GMT on 29 August, is very evident between Australia and New Zealand.

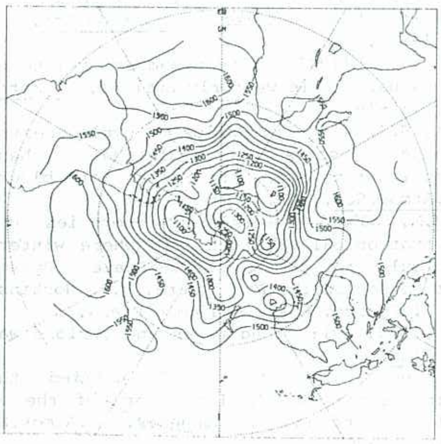

Fig.1: Geopotential height (m) of the 850 mb surface for 1100 GMT on 26 August 1975

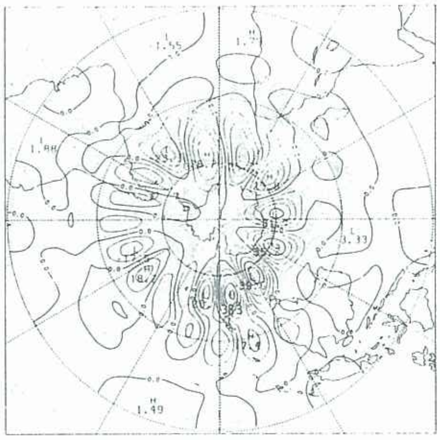

Fig.2: Instantaneous disturbance streamfunction at 700 mb for the fastest growing mode for the basic state at 2300 GMT on 24 August 1975.

The fastest growing instability mode obtained from the model in section 2 with the basic state taken on 24 August has a growth rate of $\omega^d_i = 0.342$ day^{-1} (e-folding time of about 3 days) and a phase frequency of $\omega^d_r = 127$ deg day^{-1}. The structure of the 700 mb streamfunction for this mode is shown in Fig.2. At other levels it has a similar structure but with the largest amplitude occurring at 300 mb. Combined baroclinic-barotropic instability appears to be responsible for the development of this mode. In the southeast Australian-Tasman Sea area we see the tendency towards the formation of dipole structures in this mode corresponding to the onset of blocking. This mode also picks out regions of development or deepening of troughs in the southwest Pacific and between Africa and Antarctica.

Of the other seven next fastest growing modes studied, we shall only consider the third (mode 3) and fifth (mode 5) fastest growing modes. Mode 3 is a fast propagating essentially baroclinic mode ($\omega^d_r = 228$ deg day^{-1}) with westward tilt with height and largest amplitude in the south Atlantic and Pacific ocean regions where it captures two of the major regions of deepening troughs. Its growth rate is 0.322 day^{-1} and it has a monopole cyclogenesis structure in which the wavetrain has a single maximum in the amplitude between the pole and equator. Mode 5 has high-low dipole structures with largest amplitudes east of New Zealand in the South Pacific Ocean; the maxima occur near the observed onset of blocking in this region. This mode has $\omega^d_r = 108$ deg day^{-1} and $\omega^d_i = 0.304$ day^{-1} and has nearly equal amplitudes at 900 and 300 mb.

4. INSTABILITY OF THE NORTHERN HEMISPHERE FLOW

For the Northern Hemisphere basic state we take the observed flow field at 00 GMT on 6 November 1979. For this flow the rapid development of a major block off the west coast of North America in the Gulf of Alaska occurred during the next few days. On the 6th the blocking process had begun but distinct high-low dipole pairs only formed a few days later. Fig.3 shows the geopotential height of the 500 mb surface for 00 GMT on 9 November 1979; a very distinct dipole with the high centered over the Gulf of Alaska is evident at this stage. After about the 12th November the blocking ridge weakened and moved eastward.

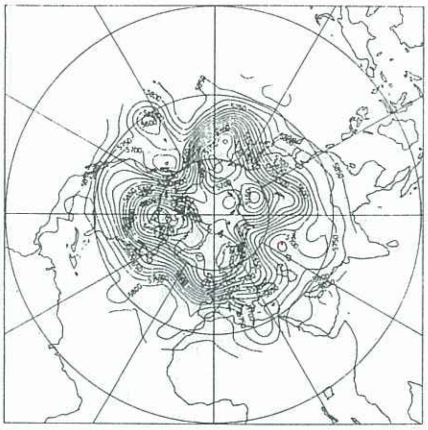

Fig.3: Geopotential height (m) of the 500 mb surface for 00 GMT on 9 November 1979

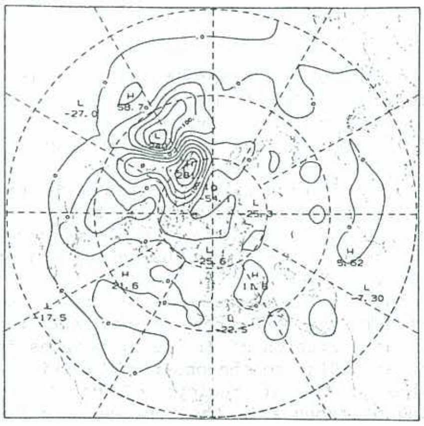

Fig.4: Instantaneous disturbance streamfunction at 500 mb for the fastest growing mode for the basic state at 00 GMT on 6 November 1979.

The fastest growing mode obtained from the model in section 2 with the basic state taken on 6 November has a growth rate of $\omega_i^d = 0.644$ day^{-1} (e-folding time of about 1.5 days) and a phase frequency of $\omega_r^d = 0.0$ deg day^{-1} corresponding to a mode which grows without phase propagation. The structure of the 500 mb streamfunction for this mode is shown in Fig.4; at other levels the structure is similar with the largest amplitude occurring at 300 mb. We see that the mode has the same large scale dipole structure as the observed block and occurs in practically the same geographical location. In this late stage of block formation, the nature of the instability is essentially barotropic. This was established by carrying out the instability calculation using a one layer model with the basic state field taken at the 300 mb level. The fastest growing instability mode obtained in this way has virtually the same structure as for the five level model at 300 mb. It again has zero phase frequency and a somewhat larger growth rate of $\omega_i^d = 0.932$ day^{-1}.

The same barotropic instability calculation was also carried out in the often used beta-plane approximation in which the full spherical geometry is replaced by planar geometry. With the beta-plane boundaries taken at the pole and equator and the Coriolis parameter evaluated at 45° latitude, we find that the fastest growing mode again has zero phase frequency and still larger growth rate of $\omega_i^d = 1.74$ day^{-1}. The structure of the fastest growing beta-plane mode is very similar to the spherical modes except that the equatorial high which accompanies the dipole block in Fig.4 is considerably stronger; it has an amplitude which is comparable with those of the primary high and low in Fig.4.

Of the ten fastest growing modes that we examined for the five-level spherical model, most are monopole cyclogenesis modes which have largest amplitudes at the surface and which are rather rapidly eastward propagating. They capture various features of developing or deepening troughs. For example mode 4 is an essentially baroclinic monopole cyclogenesis mode having westward tilt with height and a growth rate of $\omega_i^d = 0.4680$ day^{-1}, a phase frequency of 109 deg day^{-1} and largest amplitude in the northwest Pacific where there is also observed trough development. The eighth fastest growing mode is however similar to the fastest growing mode in its structure and the fact that it grows without phase propagation.

5. CONCLUSIONS

We have examined the three-dimensional instability properties of instantaneous atmospheric flows and found that many of the rapidly developing features such as extra tropical cyclones and blocks are captured by some of the fastest growing instability modes. For the monopole cyclogenesis modes studied, the nature of the instability is essentially baroclinic while for the smaller scale blocking-dipole modes characteristic of the Southern Hemisphere the instability is combined baroclinic-barotropic. For the final stages of development of large scale blocking in the Northern Hemisphere the nature of the instability is essentially barotropic.

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