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A preliminary study of the observed vertical mode structure of the summer circulation over tropical South America

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ABSTRACT

In this paper we present a preliminary vertical modal decomposition of FGGE level IIIb data for the tropical sector over South America during the summer period 29 January–16 February. The vertical modes are defined by a linearized σ-coordinate primitive equation model as in Kasahara and Puri. The average flow during the analysed period is separated into 9 blocks covering tropical and subtropical South America and the average energetics is computed as a function of the vertical mode index. It is shown that the external mode is dominant at higher latitudes and, as the equator is approached, an internal mode with equivalent depth of the order of 250 m becomes dominant. The basic characteristics of the tropical upper circulation over South America, such as the Bolivian High and the deep trough off the NE coast of Brazil, are clearly depicted by the 4th internal mode. The flow at higher latitudes in the southern hemisphere is represented by a combination of both external and 4th internal modes with a dominant external mode at higher northern latitudes. The transient behaviour of the energetics over the continental blocks is correlated with the convective activity over the region.

1. Introduction

The tropical upper circulation over South America during the summer is characterized by an anticyclonic vortex centered approximately over Bolivia, accompanied by a deep trough off the northeastern coast of Brazil. Fig. 1 shows the 6-years January mean (1975–1980) 250 mb circulation based on the NMC tropical analysis (Kousky, personal communication), which reveals the basic meridional character of the tropical circulation over the continents. Climatological studies of the upper tropospheric circulation have been made by Gutman and Schwerdtfeger (1965), Sadler (1975), Kreuels et al. (1975) and more recently by Kousky and Kagano (1981). The latter reference discusses the correlation between cloudiness and precipitation with the position of the upper level anticyclone, indicating that latent heat release plays an important rôle in the maintenance of the system.

The spatial and temporal resolution of wind observations have been increased more recently by the use of satellite-derived information (Virji, 1981). Virji's analysis shows that the maximum wind, vorticity and divergence can attain values much higher than the average and that the position of the Bolivian High can vary significantly. Recently, Silva Dias et al. (1983) considered the tropical response of a linearized, shallow water model to transient forcing, interpreting the results as an internal mode with equivalent depth of the order of 250 m. The time evolution of the circulation reproduces some of the observed transient characteristics of the Bolivian High, such as its westward displacement away from the heat source and the deepening of the trough over NE Brazil.

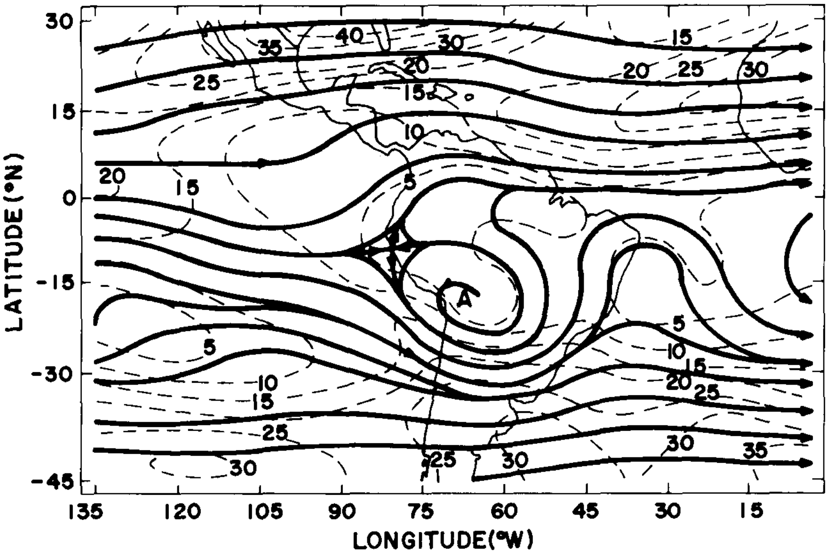

Fig. 1. Streamlines (full lines) and isotachs (m s^{-1}) (dashed lines) of the January mean 250 mb circulation derived from the NMC tropical analysis (Kousky, personal communication).

In Silva Dias et al. (1983), the comparison between the model results and the observed upper tropospheric circulation was qualitative, and the choice of an equivalent depth of 250 m was based on the typical tropical heating function which is best represented by such an internal mode (Gill, 1980; Hack and Schubert, 1981). Thus, the purpose of this paper is to analyse the vertical modal partition of energy observed during the period 29 January to 16 February 1979 and verify the basic assumption in Silva Dias et al. (1983) concerning the representative of an internal mode with equivalent depth of the order of 250 m.

In Section 2 we briefly discuss the vertical structure equation of a σ-coordinate primitive equation model linearized about a basic state at rest which was considered by Kasahara and Puri (1981). In Section 3 we show the modal decomposition of the average structure during the above-mentioned FGGE period and its transient variation in different sectors of tropical South America. Section 4 deals with the implication of the results concerning the single equivalent depth modelling work. The particular choice of the eigenmodes of Kasahara and Puri (1981) model allows the comparison of our local analysis with their global vertical decomposition. Recent model diagnostics of the effect of convection on vertical modes (Puri, 1983) have also been related to the eigenmodes described in Section 2.

2. Data and methodology

The data utilized in the following analysis consist of FGGE level IIIb wind, geopotential and surface pressure in a 3.75° by 3.75° latitude–longitude grid at 12 GMT during the period 29 January 1979 to 16 February 1979. The 3.75° × 3.75° resolution data were obtained at the National Center for Atmospheric Research (NCAR) taking every other grid point of the standard European Centre Medium Range Weather Forecasts (ECMWF) 1.875° × 1.875° analysis. The FGGE level IIIb data set is free from model influences except by the initial guess field. Thus, in regions where the observations are sparse, the analysed grid point data are more strongly model dependent.

The area of interest is limited by the following grid points: (30° N, 135° W), (30° N, 3.75° W), (45° S, 135° W) and (45° S, 3.75° W). In order to define the vertical modes, we linearize the primitive equations about a basic state at rest with a given mean temperature profile. This basic state mass field is defined by the average temperature at each standard pressure level over the region of interest. The vertical temperature (T_0) is then graphically interpolated at the sigma levels defined in Kasahara and Puri (1981). The mean surface temperature ($T_s = 294.16$ K) is graphically extrapolated and the mean surface pressure is taken as 1014.6 mb. The geopotential height at each level is hydrostatically determined (consistent with the model).

The basic state defined above allows 9 vertical modes $\psi_{n,k}$, where n is the vertical index and k indicates the vertical level. The vertical structure of each mode is shown in Fig. 2 and the associated equivalent depths (D_n) are also indicated. Evidently the vertical modes calculated here are quite

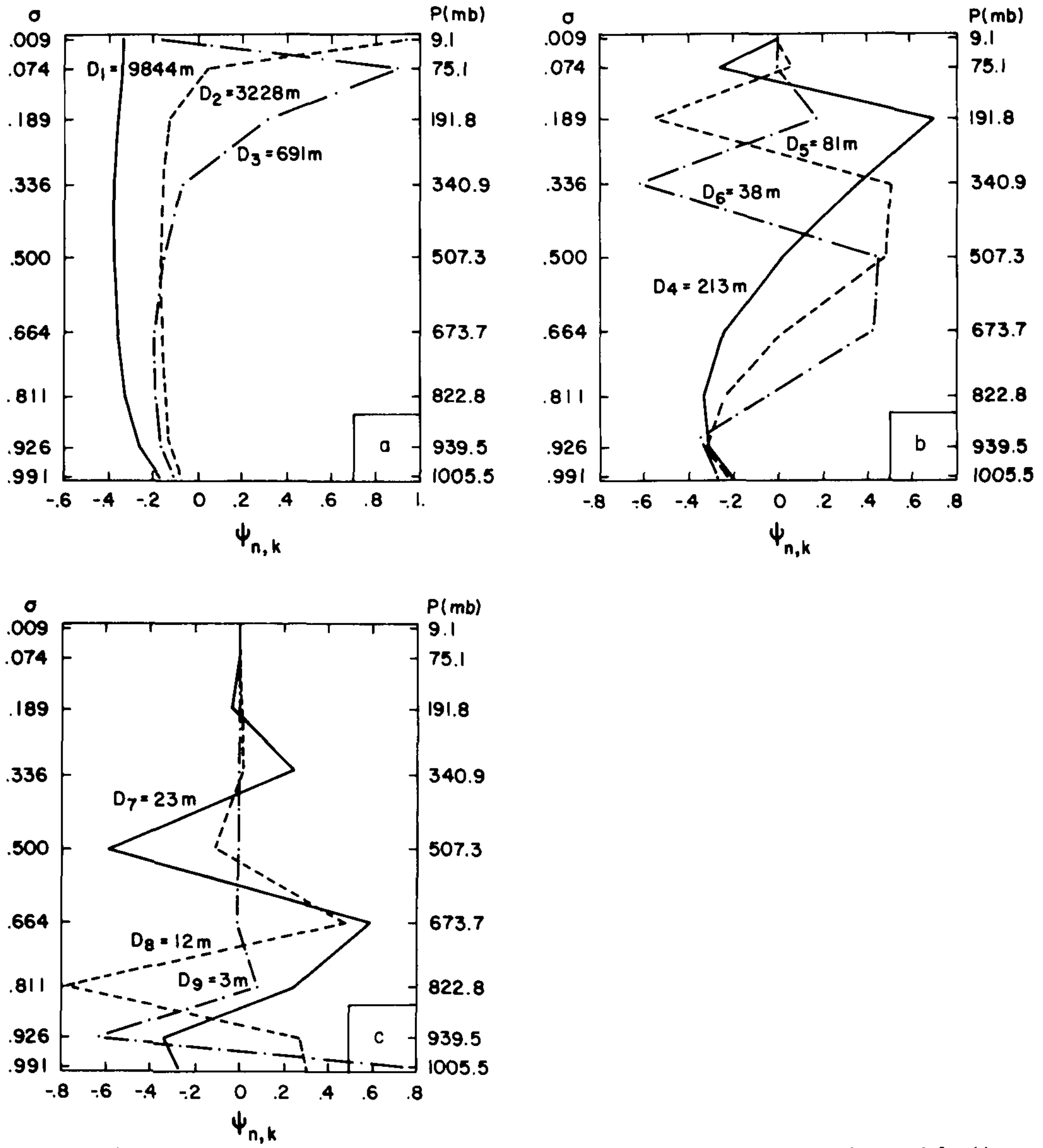

Fig. 2. Vertical structure of eigenfunction $\psi_{n,k}$ corresponding to equivalent height D_n for the basic state defined in text.

similar to those obtained by Kasahara and Puri (1981).

The external mode ($D_1 = 9844$ m) presents a vertical structure which is almost independent of height and is therefore referred to as the barotropic divergent mode (Kasahara, 1976). The vertical structures of the internal modes become more complicated and confined to the lower boundary for higher values of n. In particular, it is convenient to note that the 4th internal mode ($D_4 = 213$ m) attains a maximum value at $\sigma = 0.189$ (approximately 200 mb), thus having convergence/divergence up to approximately 500 mb and the reverse above, up to 100 mb. The 4th mode closely resembles the convergence/divergence profiles usually observed in active tropical regions (Yanai et al., 1973). It is important to note that the structure of the vertical modes is model dependent. A sensitivity test was performed increasing the number of vertical levels. The order of the mode with the typical tropical tropospheric convergence/divergence changes, but the equivalent depth remains approximately the same. Similar results were discussed by Puri (1983).

The vertical decomposition of level IIIb FGGE data in the vertical modes of the primitive equation level model requires interpolation at pressure levels which are determined by the surface pressure (P_s). This was accomplished by cubic spline interpolation and linear extrapolation at the boundaries whenever necessary. The resulting level gridded data were decomposed as a series of the vertical eigenfunctions as:

$$\begin{bmatrix} u_n \\ v_n \\ \\ z_n \end{bmatrix} (\lambda, \phi) = \sum_{k=1}^{9} \psi_{n,k} \begin{bmatrix} u_0(\lambda, \phi, k)/\sqrt{gD_n} \\ v_0(\lambda, \phi, k)/\sqrt{gD_n} \\ \left(z_0(\lambda, \phi, k) - z_\sigma(k) \right. \\ \left. + \dfrac{RT_0(k)}{g} \ln \dfrac{P_s(\lambda\phi)}{P_0} \right) \Big/ D_n \end{bmatrix}, \tag{1}$$

where u_0, v_0 and z_0 are the zonal component, meridional component of the wind and the height (in meters) at the levels; z_σ is the average height of the particular σ-level; g is the acceleration of gravity; R is the gas constant; and ϕ and λ are the latitude and longitude, respectively. In eq. (1), p_0 is the average surface pressure over the area under consideration. The method of decomposition is discussed in Kasa-hara and Puri (1981) and in Bonatti et al. (1983). The kinetic energy and available potential energy at each grid point, associated with each vertical mode, are defined by

$$k_n = \frac{gD_n}{2} (u_n^2 + v_n^2), \tag{2a}$$

$$P_n = \frac{gD_n}{2} z_n^2, \tag{2b}$$

respectively. It is also useful to define the parameter P_{e_n} which represents the percentage of the total energy which is contained in mode n. This parameter is given by

$$P_{e_n} = \frac{(K_n + P_n)}{\sum_{n=1}^{9} (K_n + P_n)} \times 100\%. \tag{3}$$

3. Results

The mean 200 mb geopotential and wind fields over the tropical and subtropical South American sector, between 135° W and 0° W and during the analysed period, are shown in Fig. 3. A well-defined Bolivian High and an accompanying trough centered at 15° S–30° W are the main meridional features; we also observe strong westerlies entering at the western limit of the region and splitting into two streams towards the southern and northern westerlies at higher latitudes. The Bolivian High acts as a quasi-permanent blocking cell on the tropical, upper westerlies over the Pacific Ocean (Casarin, 1982).

In order to analyse the vertical energy partition, in a compact representation, we defined 9 regions covering the tropical and subtropical sectors of South America, as indicated in Fig. 4. Blocks 1, 2 and 3 cover the northern portion of South America from west to east, north of the equator; just south of the equator and covering part of the Eastern Pacific we have block 4; the central part of Brazil is represented by block 5; block 6 covers part of northeastern Brazil and part of the Atlantic Ocean. Blocks 7, 8 and 9 cover the subtropical part of South America including the eastern Pacific between 26.25° and 45° S, northern Chile and Argentina, southern Brazil and the Atlantic Ocean

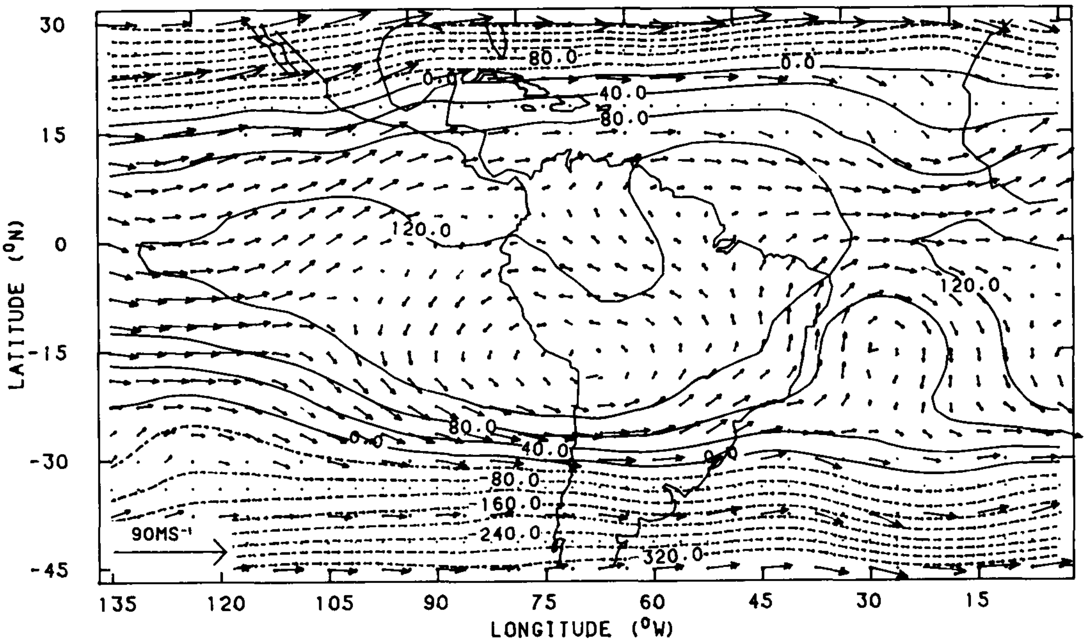

Fig. 3. Wind (arrows with magnitude (m s^{-1})) and the deviation of the geopotential height field (m) from mean value (positive in full lines and negative in dashed) for the averaged flow during the period 29 January to 16 February at 12 GMT and 200 mb.

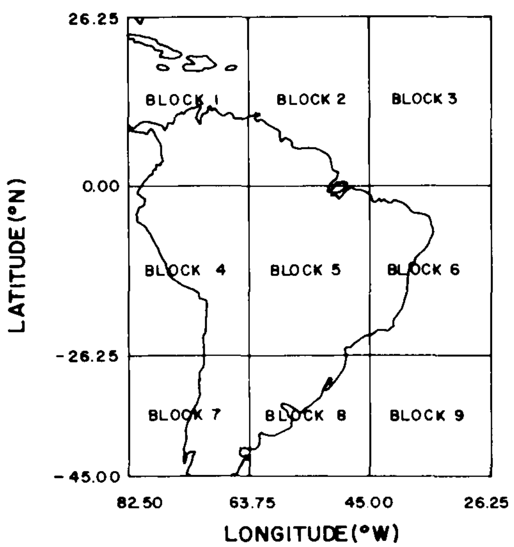

Fig. 4. Regions defined for vertical mode energy partition over South America.

up to 26.25° W. Block 5 is centered over the most convectively active region and block 6 covers part of NE Brazil which is a dry region. The other blocks are drawn in continuity. Fig. 5 shows the model energy as defined in eq. (2) (potential and kinetic forms) as a function of the vertical mode index or equivalent depth (D_n) for each of the 9 blocks indicated in Fig. 4. The grid point average total energy calculated in each box corresponds to the 12 GMT value. Also shown in Fig. 5 is the percentage contribution of each vertical mode (dotted line). The vertical partition is clearly concentrated in the 4th vertical mode ($D_4 = 213$ m) for the tropical region; as the latitude increases, the energy is distributed towards the lower order modes with the barotropic mode becoming dominant at higher latitudes. Previous vertical modal decomposition of northern hemisphere NMC Flattery daily data (Kasahara and Puri, 1981) have shown a larger percentage of energy in the external mode, although a relative minimum for the second internal mode followed by a relative maximum at the third internal ($D = 256$ m) was also observed.

The limited analysis presented in Fig. 5 suggests that the internal mode with $D_4 = 213$ m explains most of the total energy in the tropical sector under consideration, during the summer period analysed. As the latitude increases, the external mode becomes dominant, although a secondary maximum is found at the highest modes ($n = 8$ and 9).

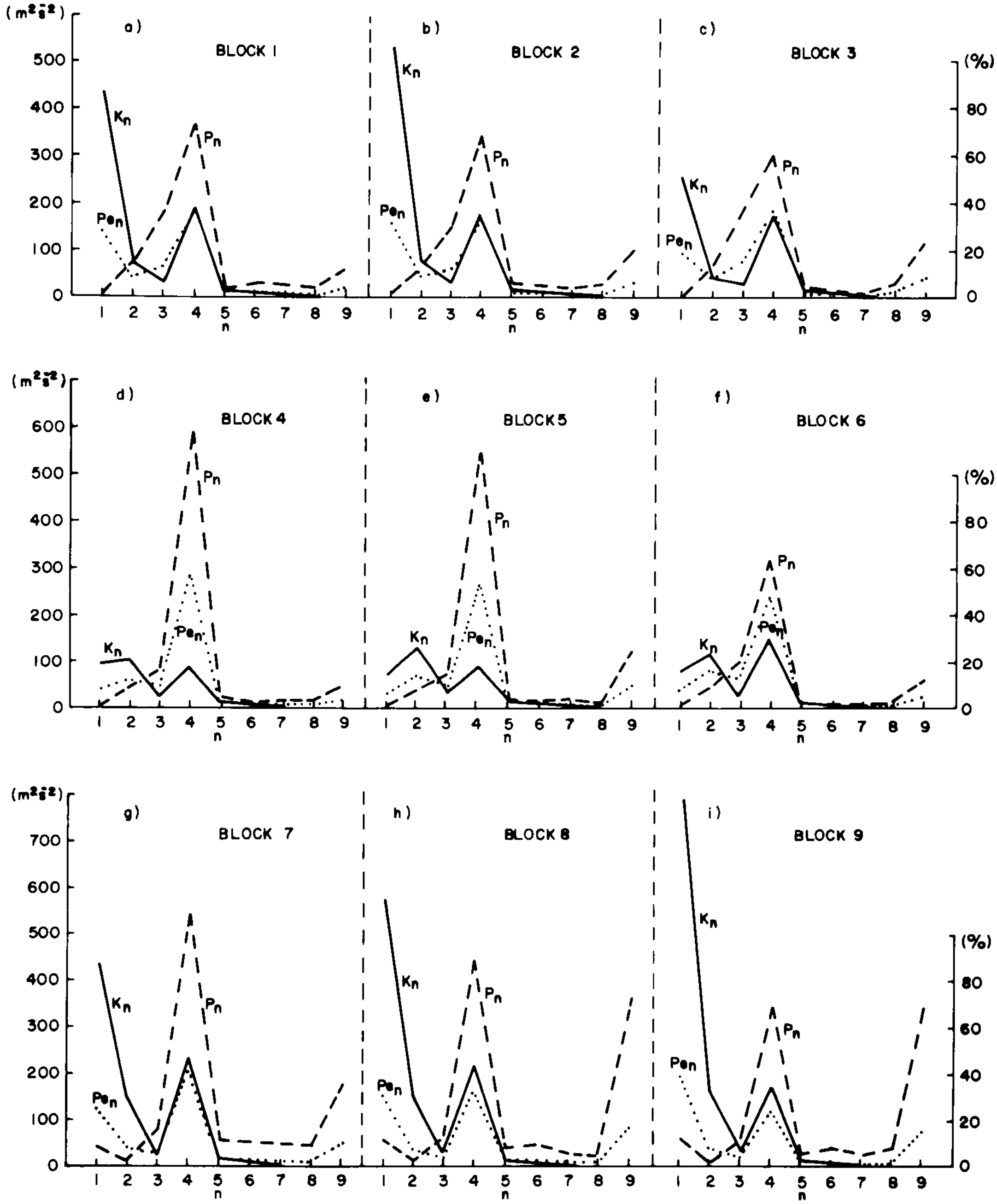

Fig. 5. Kinetic, available potential and percentage total energy (solid, dashed and dotted lines, respectively) as a function of vertical mode n for each of the blocks defined in Fig. 4.

According to Fig. 2, the higher-order internal modes have appreciable amplitude near the lower boundary and therefore tend to be a projection of boundary layer effects (Temperton and Williamson, 1981). The higher-order internal modes also show a marked diurnal variation primarily over land (not shown).

The relationship between the tropical circulation and vertical modes of model atmospheres has recently been discussed by Puri (1983). In comparative runs with the ANMRC spectral model with and without convective parameterization, Puri found that an internal mode with $D \cong 250$ m was the most affected by the inclusion of a convective parameterization scheme. The emphasis on that particular internal mode is due to the similarity between the inflow–outflow structure of the Hadley and the implied modal circulation (Fig. 2). The fact that the 4th mode dominates over the region experiencing the greatest convection activity (blocks 4 and 5) corroborates Puri's findings from an observational point of view.

It is also interesting to examine the participation of kinetic energy and potential energy in vertical modes (solid and dashed, respectively, in Fig. 5). The kinetic energy seems to be mostly represented by the lower-order modes mainly at higher latitudes, although it also shows a peak at the 4th mode in all blocks. The potential energy in the external mode is invariably negligible, with a strong peak at the 4th mode, which determines the dominance in the percentage distribution (dotted line in Figs. 5). This is evidently a simple reflection of the energy partition between kinetic and potential forms at each vertical mode according to eq. (2).

Figs. 6 and 7 show the upper level wind and geopotential fields associated with the mean field during the 16-day summer period, as attributed to the external mode ($n = 1$) and the 4th internal mode, respectively. Figs. 8 and 9 describe the percentage contribution of the $n = 1$ and $n = 4$ modes, respectively. Figs. 6 and 7 clearly depict the importance of the 4th internal mode, explaining the upper tropospheric circulation in the tropical region which attains peaks up to 80% in total energy partition (Fig. 9). The external mode, on the other hand, does not explain more than 15% of the total energy except on the eastern side of the upper trough off the NE coast of Brazil (maximum of 23.6%). At higher latitudes, the internal mode becomes gradually less important, being substituted for by the external mode except at southern latitudes between 90° W and 45° W where the 4th mode is large (Figs. 7 and 8). The equatorial westerlies over the Pacific Ocean as well as the Atlantic Ocean upper flow are basically represented by the 4th mode (Figs. 7 and 8).

The results presented in Figs. 7 and 9 support the basic assumption in Silva Dias et al. (1983),

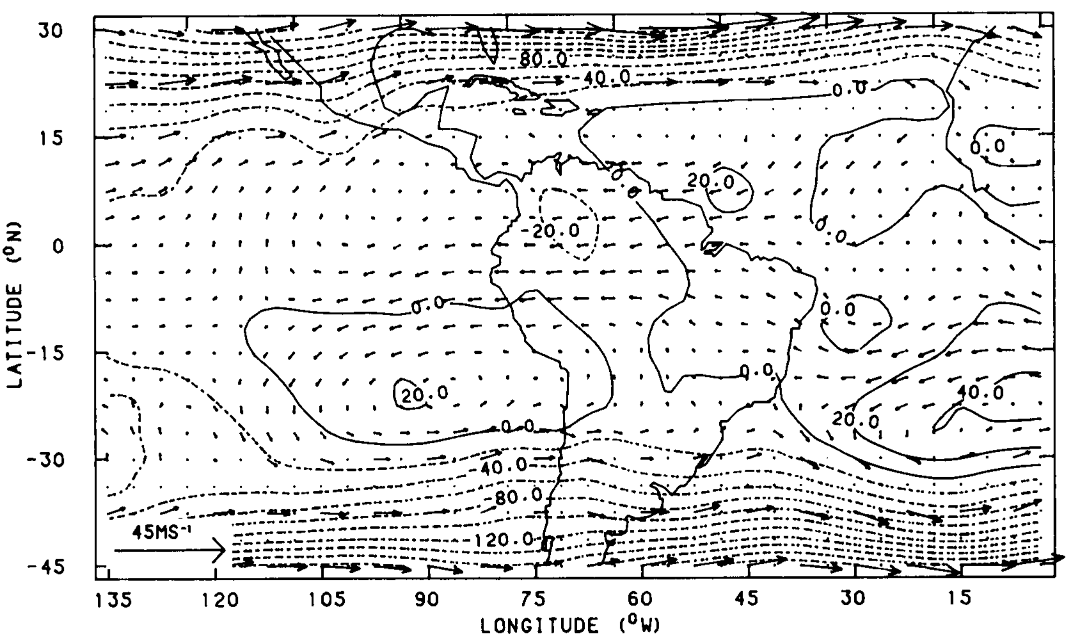

Fig. 6. Same as Fig. 3, but for the contribution of the external mode ($n = 1$).

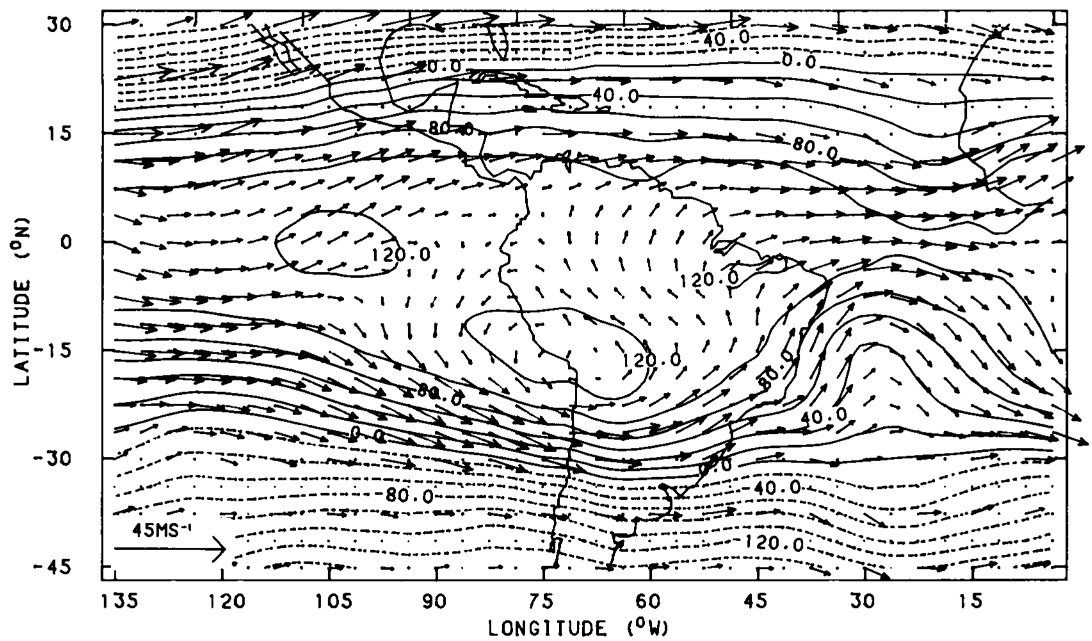

Fig. 7. Same as Fig. 3, but for the contribution of the 4th mode.

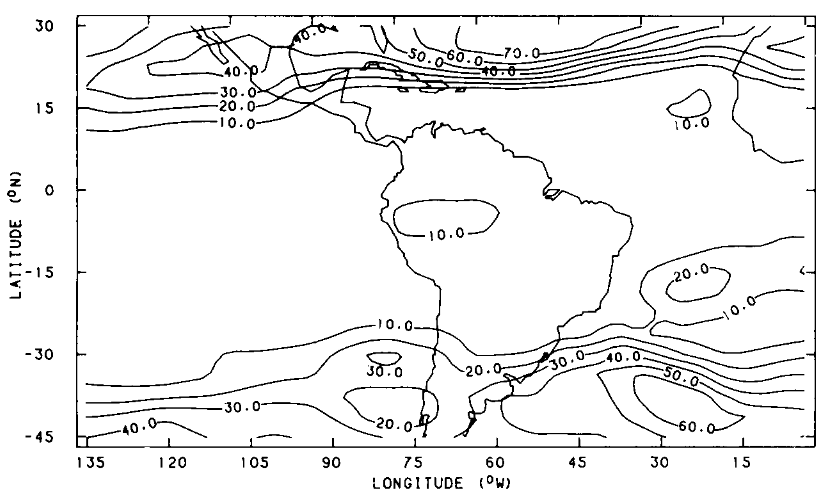

Fig. 8. Percentage of the total energy explained by the external mode for the average field shown in Fig. 3.

concerning the relevance of an internal mode with $D = 250$ m in describing the basic dynamics of the Bolivian High. Fig. 7 depicts the Bolivian High and the associated cross equatorial southerly flow with the subsequent intensification of the Atlantic Ocean upper westerlies. In Silva Dias et al. (1983), the upper westerly circulation is associated with Kelvin waves which are forced by convective bursts over tropical South America.

In order to study the transient partition of energy in vertical modes, we computed the kinetic energy, available potential energy and percentage total energy during the period under consideration for the basically continental blocks 4, 5 and 6 (solid,

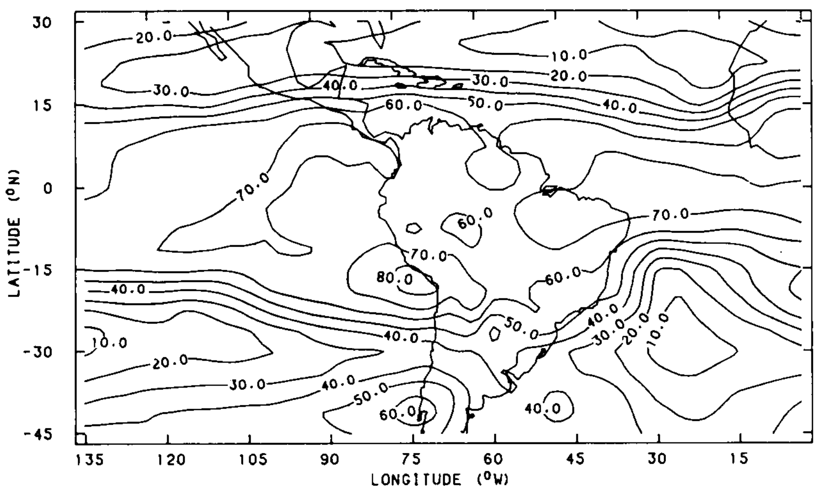

Fig. 9. Same as Fig. 8, but for the 4th mode.

dashed and dash-dotted lines, respectively, in Fig. 10). The energy explained by the 4th mode shows more variation in blocks 5 and 6 (over Central and NE Brazil) after February 8. A close inspection of the geostationary satellite infrared pictures reveals a stronger convective activity starting after the 8th over Central Brazil. During the same period, the upper tropospheric circulation changed from an ill-defined Bolivian High to a fully developed circulation on the 11th (Fig. 6 of Silva Dias et al., 1983). The relationships between the heat source associated with the organization of the convective activity and the upper tropospheric anticyclonic circulation is shown to be plausible in Silva Dias et al. (1983). The available potential energy in blocks 4 and 5 is similar in magnitude and much higher than in block 6 over NE Brazil and the trend behaviour during the period is opposite after 7th February. It is also interesting to note the simultaneity in the decrease of available potential energy and increase in kinetic energy in block 6. The percentage of total energy explained by the 4th mode is approximately constant during the period in block 4 ($\simeq$60%), but blocks 5 and 6 show an increase and decrease, respectively, in the percentage of energy attributed to the 4th mode after 7th February.

The increase in potential energy in the central blocks occurs simultaneously with the convective heating over the region, which is accompanied by an increase in wind speed as a result of the

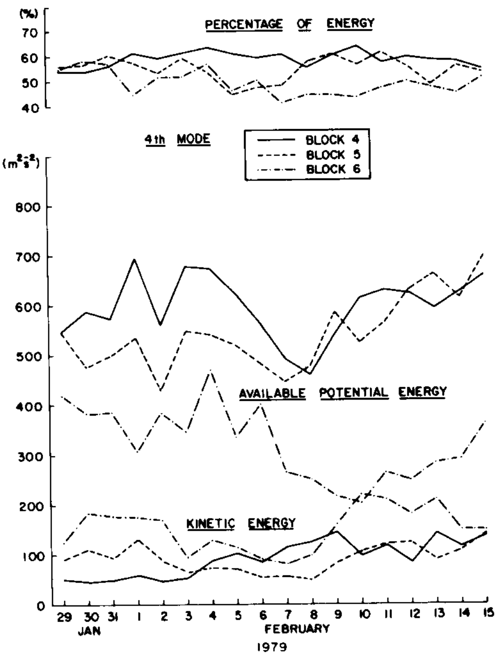

Fig. 10. Time variation of the energetics of the 4th mode in blocks 4, 5 and 6 as indicated.

tendency for geostrophic adjustment (Silva Dias et al., 1983). The opposite energetic behaviour of block 6 suggests that the formation of the trough over NE Brazil and the subsequent closed low does not have a local forcing, but is a response to a dynamical forcing elsewhere as discussed by Kousky and Gan (1981).

4. Conclusion

The modal decomposition of tropical level IIIb FGGE data over the South American sector indicates the prevailing contribution of an internal mode with equivalent depth of the order of 213 m, which is the 4th mode of Kasahara and Puri (1981) in the equatorial region. As the latitude increases, the external mode becomes dominant except near the southern border of the analysed region (45° S) The Bolivian High and the accompanying trough off the NE coast of Brazil are well reproduced by the 4th mode as well as the upper westerlies over the Pacific and Atlantic Oceans, as shown in Fig. 7.

Silva Dias et al. (1983) considered the effect of a transient and localized heat source in the tropical region using a linearized shallow water equation on an equatorial β-plane. Their results indicate that many aspects of the upper tropospheric circulation in the tropical sector of South America can be explained by considering the dispersive properties of the Rossby, mixed Rossby-gravity and Kelvin waves. The sharpening of the trough east of the Bolivian High is a consequence of turning on the heat source, and is related to the dispersive properties of mixed Rossby-gravity waves. The intensification of the upper equatorial westerlies is tied to the propagation of a Kelvin group, a result which is analogous to the stationary forcing circulation shown in Gill (1980). In both Silva Dias et al. and Gill's work, the shallow water equations were used with an equivalent depth of the order of 250 m and the justification for this particular choice was based on the projection of the typical heating function associated with convective systems in the tropical region (Yanai et al., 1973) onto vertical modes. Similar reasoning was also followed by Lim and Chang (1981) and Lau and Lim (1982).

The results presented in this paper substantiate the choice of the 4th mode with an equivalent depth of the order of 250 m, in single equivalent depth linear analysis of transient forcing as described in Silva Dias et al. (1983). It further illustrates the capability of such simple models in explaining the basic dynamics of the Hadley and Walker circulations. As an interesting application of these results, we mention the initialization problem in the tropical region. This latter subject has been recently addressed by Puri and Bourke (1982) and Puri (1983) in an attempt to retain the Hadley circulation during nonlinear normal mode initialization. The substantial latent heat release over tropical South America certainly has a great impact on the general circulation of the atmosphere and the modal decomposition is a simple approach to this problem which nonetheless yields useful results.

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