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ENERGETICS OF COLD AIR OUTBREAKS OVER SOUTH BRAZIL

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1. INTRODUCTION

Intense cold surge events over South America have great impact in the economy, mainly in the agriculture. These events created an interest of many authors to study the processes that caused extreme conditions associated with cold-air outbreaks. Theses events are associated with atmosphere mechanisms of complex interactions in different scales of time and space, for example, interaction wave-wave (Marengo et al., 2002) and interaction tropic-extratropics (Müller et al., 2005). The principal related factors to these interactions are: atmospheric circulation, balance of radiation, soil moisture and topographical characteristics.

The first studies of cold-air outbreaks in South America were limited to the data in the adjacent oceans. These works were appointed to individual cases, especially those that have been caused great impacts in the southern and southeastern Brazil (Fortune and Kousky, 1983; Marengo et al., 1997). Recent works using radiosonde data, global analysis and satellite images show the synoptic analysis of these events with more detail than in the previous ones (Krishnamurti et al., 1999; Garreaud, 2000; Lupo et al., 2001; Vera et al., 2002; Pezza and Ambrizzi, 2005; Müller, 2005).

One of the most recognizable synoptic features in the winter atmosphere in South America is the passage of intense cold fronts, being responsible for severe weather conditions. Cavalcanti and Kousky (2003) found two preferential cold front tracks, being the first one a long of the continent, that extends from northern Argentina to northwest of the Amazon region, and the other one along of the east coast of Brazil.

The passage of intense cold fronts over the south of Brazil happens with more frequency during the wintertime. These systems usually propagate by the continental track, and sometimes propagate until the tropics (Fortune and Kousky, 1983; Garreaud, 1999; Andrade, 2005). The cold fronts that arrive in the tropical areas usually propagate quickly and are characterized with less humidity and high radioactive loss. They do not generate strong convective activity, but occasionally they associated with cold-air outbreak and frost in southern, southeastern and central Brazil (Vera and Vigliarolo, 2000). In the summer, cold fronts produce less temperature variations, but they organize deep convection in band form of convective clouds, along their main border (Garreaud, 2000).

The southern and southeastern Brazil regions have a clear preference to the occurrence of surface frontogenesis (Satyamurty and Mattos, 1989; Mattos, 2003). The frontogenetic function over the Southeast of Brazil has an annual and interannual variability being more to north in the winter and weaker over the northeast region of Brazil and higher over the south of Brazil in El Niño years than in La Niña years (Mattos, 2003).

The cold-air outbreaks are usually accompanied by accentuated temperature falls. Escobar (2001) and Reinke (2005) studied the falls of the minimum temperature in Argentina and southern Brazil, respectively. The main results found by them were that in the most of the inland areas happen the largest minimum temperature falls. These authors divided the accentuated falls of the minimum temperature in 3 types: (a) cold-air outbreak events that are not able to provoke negative temperature anomaly, (b) events that represent the change of a warm-air anomalies for a cold-air anomalies and (c) events that correspond to the cold-air outbreak in a period with negative temperature anomaly. The type (b) is the most frequent observed by both researchers.

The Andes Cordillera is the most important topographic characteristic of South America, located along the part west of the continent from the tropics to 55ºS. The Andes and the mountainous region in the eastern Brazil were seen by Fortune and Kousky (1983) and Lupo et al. (2001) as the instrument to canalize the cold-air, and contribute to the propagation of the cold-air to the tropical region of South America. When a low-level transient disturbance crosses the Andes it suffers changes in its structure and track. The track becomes anticyclonic when the disturbance crosses the Andes and it has displacement to

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equator on the leeside of the mountain. Normally the low-level transient disturbances cross the Andes to south of 38ºS where the Cordillera is lower. The cold-air move trough the mountain and it suffers an increase of the low-level divergence and consequently subsidence is observed in a larger area. The topography function is block the air in the east side of the mountain and if this situation is associated with the anticyclonic anomaly, the result is the formation of an anticyclone circulation over the central Argentina (Vera and Vigliarolo, 2000).

It is important to emphasize the orografic forcing role and the front system dynamics in the evolution and in the structure of the cold surges over South America. In the winter season quasi-stationary Rossby waves coming from the tropical west region of South Pacific can represent an important mechanism of interaction tropic-extratropic that affects the weather and the climate of the middle-latitude of South America. The synoptic situation associated with the cold-air outbreak and the local topography are important to determine the degree of coldness (Marengo et al., 2002; Garreaud, 2000).

The synoptic study of the cold-air outbreaks over South America was schematized by some authors as Garreaud (2000), Vera et al. (2002), Pezza and Ambrizzi (2005) and Müller et al. (2005). The fundamental changes during the cold-air outbreaks began when a low-level cold anticyclone moves from the Southeast Pacific to the southern Argentina, and a extratropical cyclone over the Southwest Atlantic deeps. Over the southern South America anomalous southerly winds intensify as a result of the geostrophic balance among the development of the migratory high, close by the southern coast of Chile, and the extratropical cyclone over the Atlantic Ocean. With that, the surface pressure begins to increase quickly over the continent. The anticyclonic moves to north in direction to the region of maximum of both cold-air advection and anticyclonic vorticity advection in high-level. The termically direct circulation in the entrance of the high-level jet in subtropical latitudes of South America is an instrument that intensifies the anticyclone and propagates the cold-air more to north. To the north of 20ºS the effect of the large-scale anticyclonic circulation and the increase of the surface pressure in the anticyclone boundary are explained mainly by the hydrostatic effect. In this area the blocking effect of the Andes decreases due to its form and because of the geostrophic adjustment that is weak in the tropical latitudes (Garreaud, 2000).

Concisely, the progress of the cold-air outbreak along of the subtropical Andes is organized by the topography that blocks the synoptic scale flow. The propagation to the lower latitude region suggests the interaction between the mass fields and wind: the strong pressure gradient accelerates the low-level winds which are parallel to the Andes range, while the horizontal advection of cold-air by ageostrophic southerly winds maintains the strong temperature gradient against dissipation by surface heat fluxes (Garreaud, 2000).

In the medium-level large-scale circulation of the cold-air outbreaks is observed a middle latitude long wave with a ridge over the west of the Andes and one trough over the South America southeastern coast. This situation results in a deep layer of northward meridional flow over the South America that contributes to the cold-air be canalized and the propagation to the equator. This system trough-ridge, during the incursions of cold-air has great amplification due to the overlap of the synoptic waves that move quickly a long of the quase-stationary planetary waves (Fortune and Kousky, 1983; Garreaud, 2000). In high-levels, during the mature stage of the cold waves, the amplification of the wave happens partly due the increase of the baroclinic instability in the cold wave, that in low-level moves to north below the axis of the high-level trough.

Besides the climatology and evolution of the cold-air outbreak, the energetics of these systems is also studied. Lau and Lau (1984) investigated the energetics of the cold surges in the east of Asia and they observed that the life cycle of this system is typical of the extratropical system with baroclinic growth, coinciding with the polar invasion and a decline phase which the barotropic processes. The structure of both high- and low frequency disturbances has different characteristics. The high frequency fluctuations have zonally propagation while the low frequency fluctuations propagate meriodionally and have more meridional extension (Lau and Lau, 1984). Gan and Rao (1999) calculated the energetics of the systems associated with high frequency anomalies over South America. This study showed that such systems grow for baroclinic conversion, could also grow in some cases over the South Pacific for barotropic instability and when they reach the maturity they decline barotropically.

Krishnamurti et al. (1999) associated the amplification of the middle-latitude high-level trough to the downstream development mechanism. In this study a wave decomposition associated with the freeze events in the southeast of Brazil was made. Using the prognostic of a high-resolution global model they observed that the growth of the stationary long wave during the frost events was due to the waves interaction. When they calculated the energetics of these events, they observed that interactions of non-lineal barotropic are important sources in the maintenance of the downstream amplifications; however, the baroclinic contributions dominate in larger magnitude.

To know the space and temporary evolution of the cold surges it is important to have a better knowledge of the mechanisms that involve the formation and the development of the transient disturbances. With that, the general aim of this work is to study the propagation and the energetics of the high frequency disturbances associated with cold surges during the wintertime of the south of Brazil.

2. DATA AND METHODOLOGY

In this present study we used the reanalysis of National Centers of Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) dataset for the period from 1985 to 2004. These data have temporary resolution of 6 hours (00, 06, 12, 18hs) and space resolution of 2.5^0 x $2{,}5^0$ of latitude and longitude. The meteorological variables used were: meridional and zonal wind, geopotential height, vertical movement and air temperature at the pressure standard levels from 1000 to 100-hPa. We used the software Grid Analysis and Display System (GrADS) to generate the graphs.

The criterion to select the study cases we used the high-pass filtered 925-hPa air temperature (T_h). First we calculated the average of the T_h in the area between 32.5ºS and 25ºS and 55ºW and 50ºW for the 1985-2004 winter months (June, July and August) ($\overline{T_h}$). The days in that the $\overline{T_h}$ was less than 2.5 times of the standard deviation and the period between two consecutives cases were more than 7 days we selected the cases.

The period of 7 days was attributed by being found in the literature that the front systems, in the south of Brazil has an approximate frequency of 5 systems a month, in the winter (Andrade, 2005).

The construction of the filtered and no filtered composed fields were built to analyze 7 days before and after the events. The days and time for the composed fields is defined like "Day-7, Day-6.75, Day-6.50,..., Day-0.50, Day0, Day0.50,..., Day7. The coldest day in south Brazil was labeled as Day0. The number after the dot is the period, the data are from four daily analyses, and then the periods are divided in DayX, DayX.25, DayX.50 and DayX.75. The period 0 was omitted.

2.1 The Calculation of the Energetics

The change in the structure of high frequency disturbance during its evolution is intimately linked with its energetics. Our energetics study is not focused in the energy balance but just in the kinetic and potential energy conversions. Then, we used the same methodology of Gan and Rao (1999), where the energy conversions are observed from the quasi-stationary component (represented by the low frequency) into the transient component (represented by the high frequency). The equations used were:

$$\frac{\partial APh}{\partial t} = CA - PK \qquad (3.1)$$

$$\frac{\partial KEh}{\partial t} = PK - CK \qquad (3.2)$$

$$APEh = \int_{p_{top}}^{p_0} \frac{T_h^2}{2\sigma} dp \qquad (3.3)$$

$$KEh = \frac{1}{2g} \int_{p_{top}}^{p_0} V_h^2 dp \qquad (3.4)$$

$$CA = -\frac{1}{g} \int_{p_{top}}^{p_o} \frac{1}{\sigma} \left(u_h T_h \frac{\partial T_l}{\partial x} + v_h T_h \frac{\partial T_l}{\partial y} \right) dp \qquad (3.5)$$

$$CK = -\frac{1}{g} \int_{p_{top}}^{p_o} \left(u_h u_h \frac{\partial u_l}{\partial x} + u_h v_h \frac{\partial u_l}{\partial y} + v_h u_h \frac{\partial v_l}{\partial x} + v_h v_h \frac{\partial v_l}{\partial y} \right) dp \qquad (3.6)$$

$$PK = -\frac{1}{g} \int_{p_{top}}^{p_0} \frac{R}{p} \omega_h T_h dp \qquad (3.7)$$

where: APEh and KEh are, respectively, Available Potential Energy and Kinetic Energy of the high-frequency disturbance; CA and CK are the conversion terms of the available potential energy and kinetic energy of the quasi-stationary flow into KEh, respectively; and PK is the conversion of the APEh into KEh. The subscript "h" and "l" indicates the high-pass and the low-pass filtered data, respectively; σ is the static stability of the flow quasi-stationary. The other symbols are usually used in the meteorology. The vertical integration is from 1000-hPa (p_o) to 100-hPa (p_{top}).

3. TEMPORARY EVOLUTION OF THE COMPOSITIONS

On Day–2.5 the 500-hPa high-pass geopotential height chart (FIG. 1a) shows a wave high frequency wave train starting around the 120ºW-40ºS and propagating to South America, with a wavelength of 60º long. This wave train intensifies when displaces to east with phase velocity of 18º long.day^{-1}. On Day–1.5 (FIG. 1b), the positive high frequency disturbance has its maximum intensity close to Chilean coast. On Day0 (FIG. 1c), the negative high frequency disturbance reaches its maximum intensity over the Atlantic Ocean jut to east of southern Brazil. After this day, this wave pattern weak.

The 925-hPa high-pass geopotential height charts (FIG. 2) show a wave train stating around the 115ºW-40ºS on the Day–2.5 (FIG. 2a). A comparison of the FIG. 1a with the FIG. 2a we can see that this wave train had a vertical inclination to west, showing a baroclinic structure. 24h later (FIG. 2b) there were two positive high frequency disturbances; one was crossing the Andes and the other was over the South Atlantic (FIG. 2b). A negative high frequency disturbance was also observed over the studied region. On the Day0 the western positive high frequency disturbance was over the South America with a northwest-southeast orientation, from the Amazon region to southeast region of South America. The negative high frequency disturbance is over the South Atlantic and it is more intense. After the cold-air outbreak over South America, the wave train begins to weak during its propagation to east.

In the 925-hPa high-pass streamlines composed charts (FIG. 3), we can see on Day-3 that the South Pacific subtropical high is a little bit displaced to west in relation to the previous day (not shown). It is also noticed on Day-3 a short wave trough located over Argentina close to the Buenos Aires's Province and other to west of Chile. Twenty-four hours later (not shown) these two troughs merged and become in a well-amplified trough. On Day-1, we can notice in 925-hPa the confluence of the north-northeast winds with the south-southeast winds at the downstream of the trough axis, showing characteristics of a cold front over the southern Brazil. On Day0, the high frequency anticyclonic circulation was observed over the central region of Argentina and the south of Brazil. The position of the anticyclone core contributed to have southerlies over southern Brazil, showing the entrance of cold and dry air in this region.

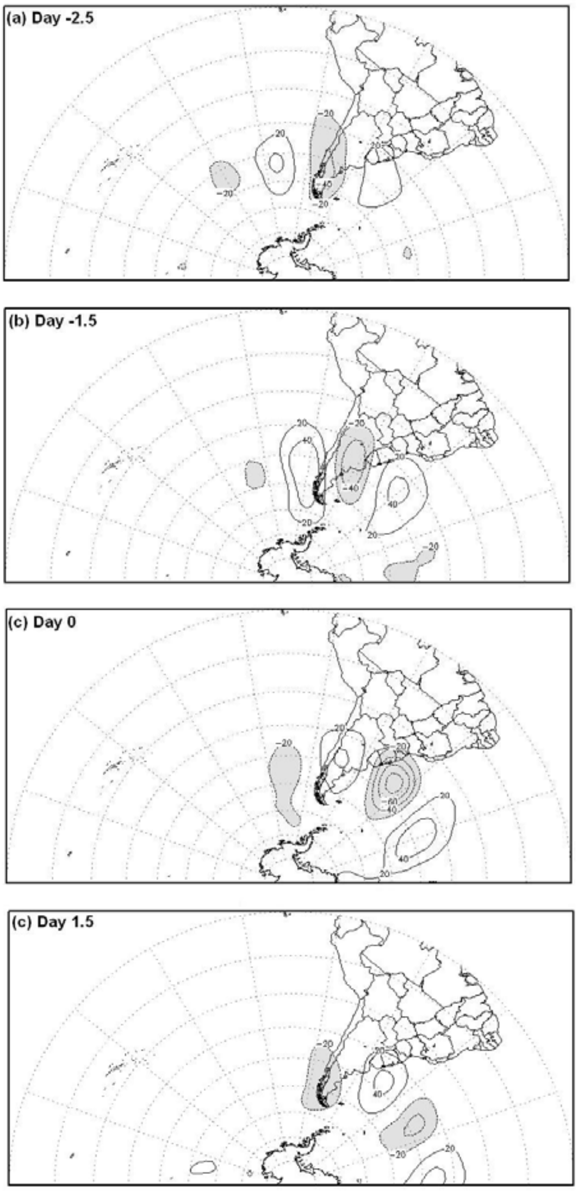

FIG. 1. Composite charts of the high-pass filtered 500-hPa geopotential height on (a) Day-2.5, (b) Day-1.5, (c) Day0 e (d) Day1.5. Shading indicates negative values.

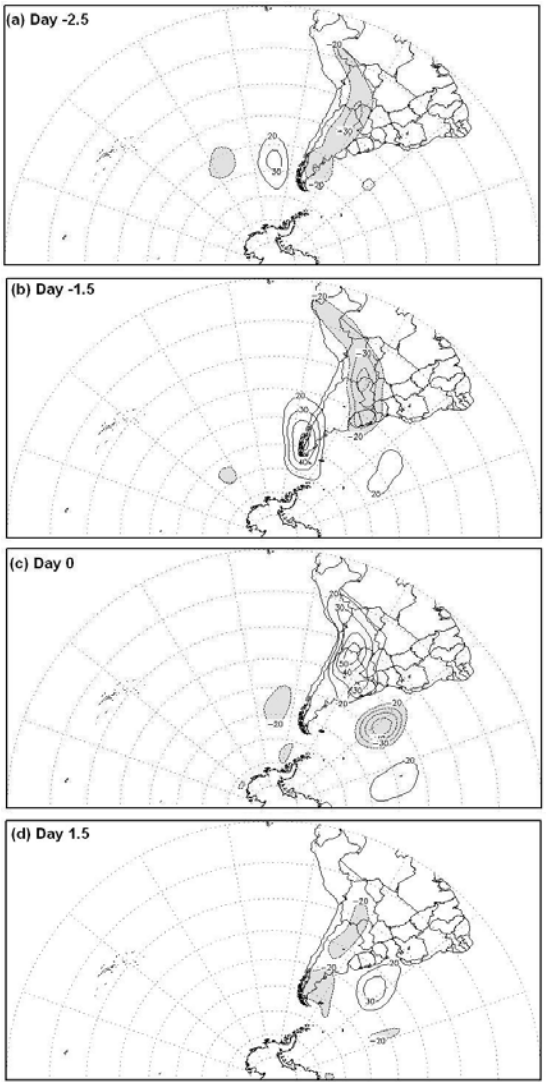

FIG. 2. Composite charts of the high-pass filtered 925-hPa geopotential height on (a) Day-2.5, (b) Day-1.5, (c) Day0 e (d) Day1.5. Shading indicates negative values.

The high x time section (FIG. 4) had two distinct periods. One period two days before of the incursion of warm air with positive anomaly and the other with negative anomaly until two days after the cold air incursion. The negative anomaly was deeper (up to 400-hPa) and more intense than the positive anomaly. In high levels the anomalies had opposite signal and were less intense than in low levels. Similar results were found by Lau and Lau (1984) for cold surges in the east of Asia.

The APEh composites (FIG. 5) show on Day–1.5 three maximum centers associated with the high frequency disturbance observed in FIGs.1 and 2. The most intense maximum APEh was located downstream the positive high frequency disturbance by ¼ of the wavelength at 925-hPa. This energy maximum moved together with high frequency disturbance when it was propagating to south of Brazil. After the Day0, the disturbance lost APEh when it propagated to the Atlantic Ocean.

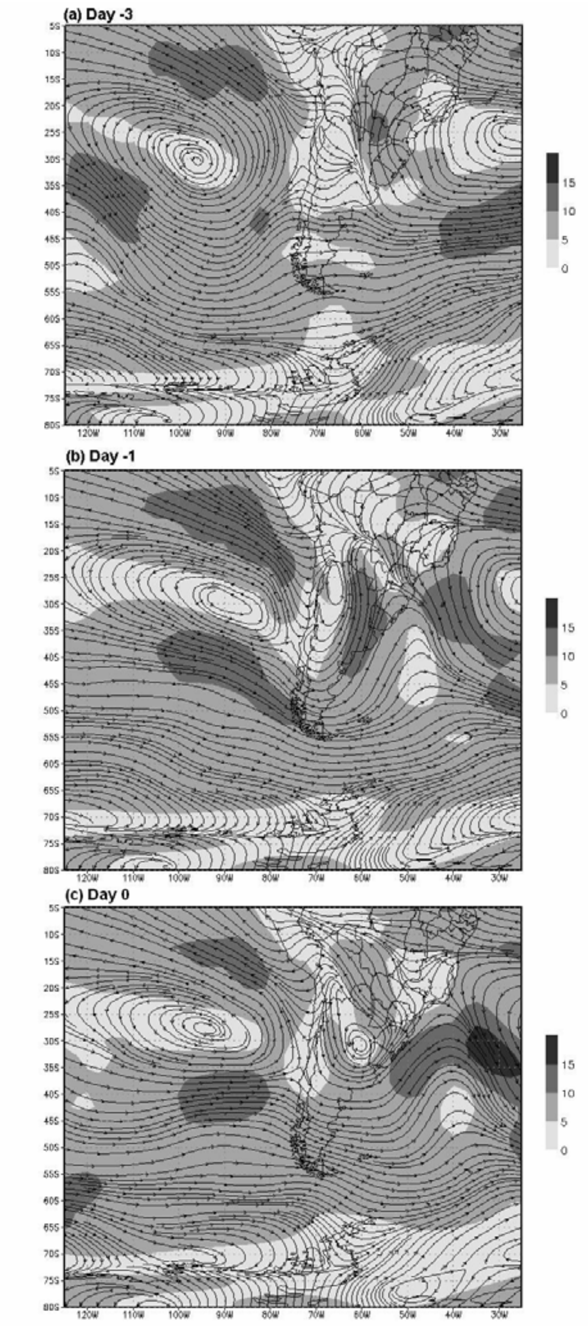

FIG.3. Streamline and wind magnitude (m/s) composite charts at 925-hPa on (a) Day-3, (b) Day-1, (c) Day0.

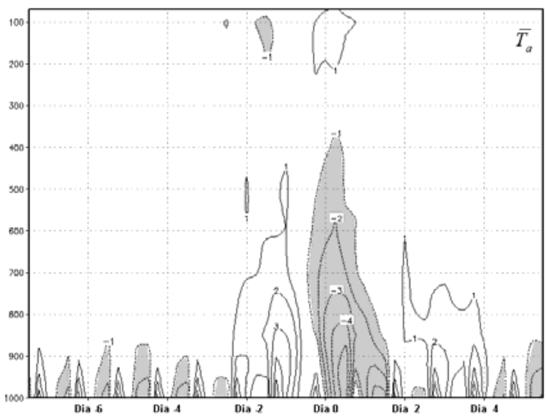

FIG. 4. $\overline{T}_h$ high X time cross during the 14-day composite period. Shading indicates negative values.

The APEh composites (FIG. 5) show on Day–1.5 three maximum centers associated with the high-frequency disturbance observed in FIGs.1 and 2. The most intense maximum APEh was located downstream the positive high frequency disturbance by ¼ of the wavelength at 925-hPa. This energy maximum moved together with high-frequency disturbances when it was propagating to south of Brazil. After the Day0, the disturbance lost APEh when it propagated to the Atlantic Ocean.

The KEh had been increasing since the Day-2.5 (FIG. 6a) with two maximum centers, one over the Pacific, close the western coast of South America in 40ºS, associated with the positive high frequency disturbance at 925-hPa. The other was located over the central region of Argentina and was associated with the negative high frequency disturbance at 925-hPa. Both KEh centers move to east and after the Day0 they weak when they are over the South Atlantic Ocean.

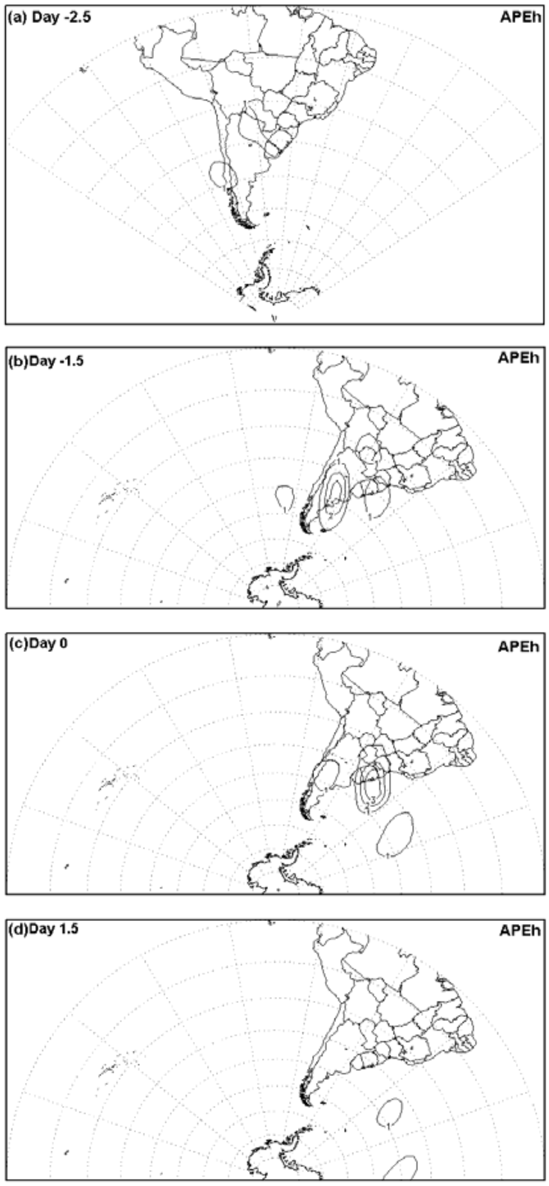

FIG. 5. Vertically integrated APEh terms: (a) Day-2.5, (b) Day-1.5, (c) Day0 e (d) Day1.5.

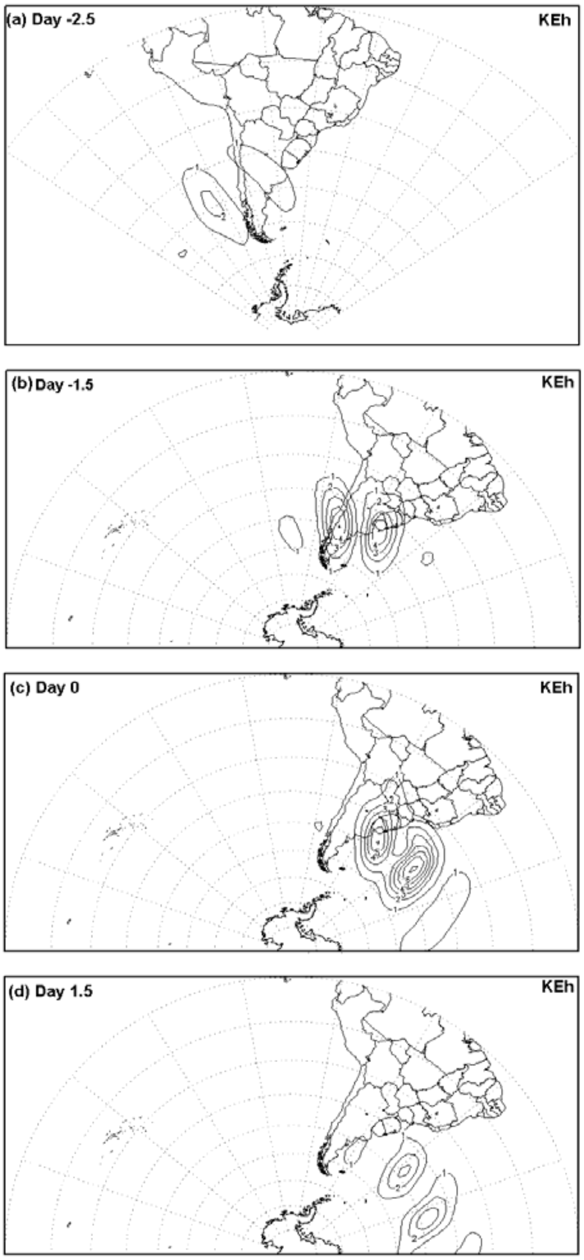

FIG. 6. Vertically integrated KEh terms: (a) Day-2.5, (b) Day-1.5, (c) Day0 e (d) Day1.5.

The CA and PK conversion terms explain the temporary variation of the maximum APEh center. The maps of term CA (the conversion of available potential energy from quasi-stationary flow into the APEh, FIG. 7) show a wave pattern with positive values located downstream of the high frequency disturbance at 925-hPa on Day–2.5 (FIG. 7a). The values of CA increased during the propagation of the disturbances, until the Day0. This conversion is associated with the poleward heat transport due to the air from the Subtropical South Atlantic high as we can see in the FIG. 3.

The conversion of APEh into KEh corresponds to positive PK values in the FIG. 8. The two and half days before the cold air outbreak (FIG. 8a) we can see some positive and negative centers. The positive maximum close to the Chilean coast was associated with the positive high frequency disturbance at 925-hPa and the others two positive maximum over the continent were associated with the negative high frequency disturbance at 925-hPa. The results of the CA and PK terms show that both high frequency disturbances grew baroclinically extracting potential energy from the quasi-stationary flow and converting into KEh.

The CK term (barotropic term) shows the conversion of the quasi-stationary kinetic energy into KEh (negative values) (FIG. 9). Two centers of positive values of CK were found starting from Day-1.5, and both were associated to the two KEh maximum On Day0 a negative conversion was present over the Atlantic ocean just in the region of the negative high frequency disturbance at 925-hPa, showing that this system also grew by barotropic conversions.

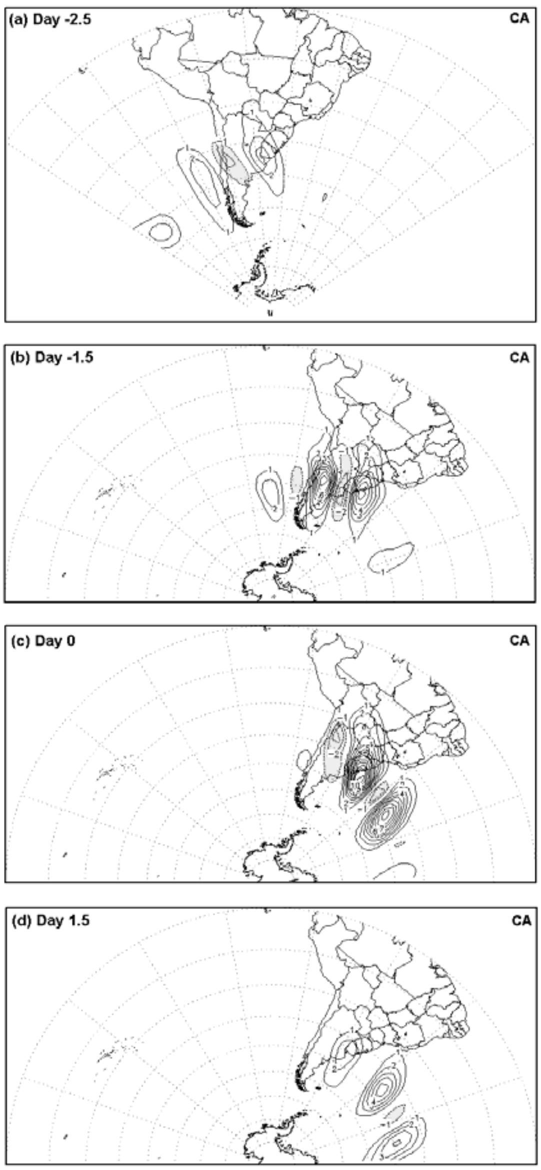

FIG. 7. Vertically integrated CA terms: (a) Day-2.5, (b) Day-1.5, (c) Day0 e (d) Day1.5. Shading indicates negative values.

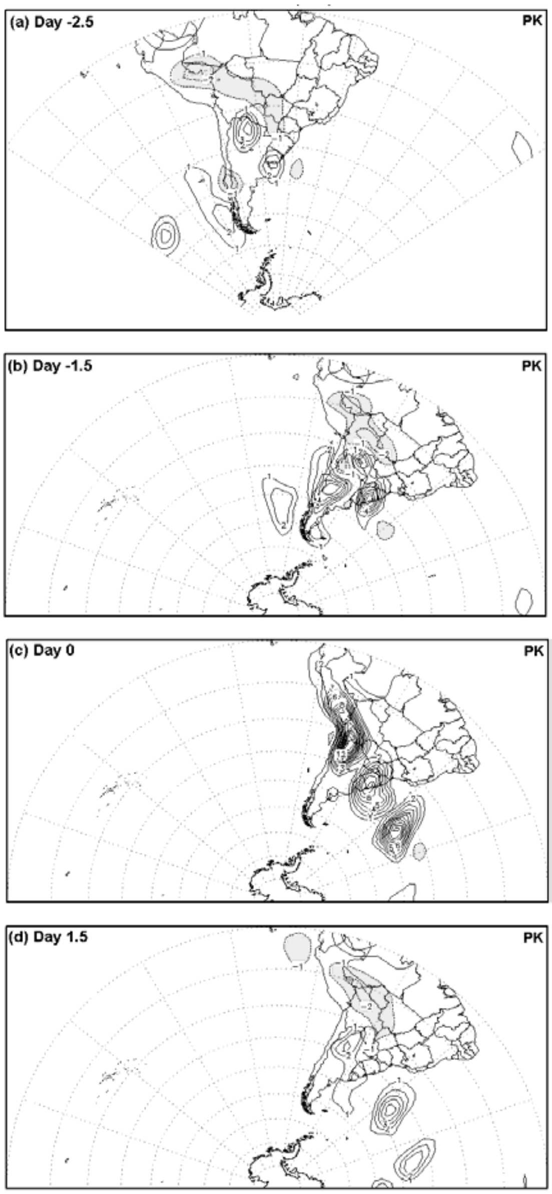

FIG. 8. Vertically integrated PK terms: (a) Day-2.5, (b) Day-1.5, (c) Day0 e (d) Day1.5. Shading indicates negative values.

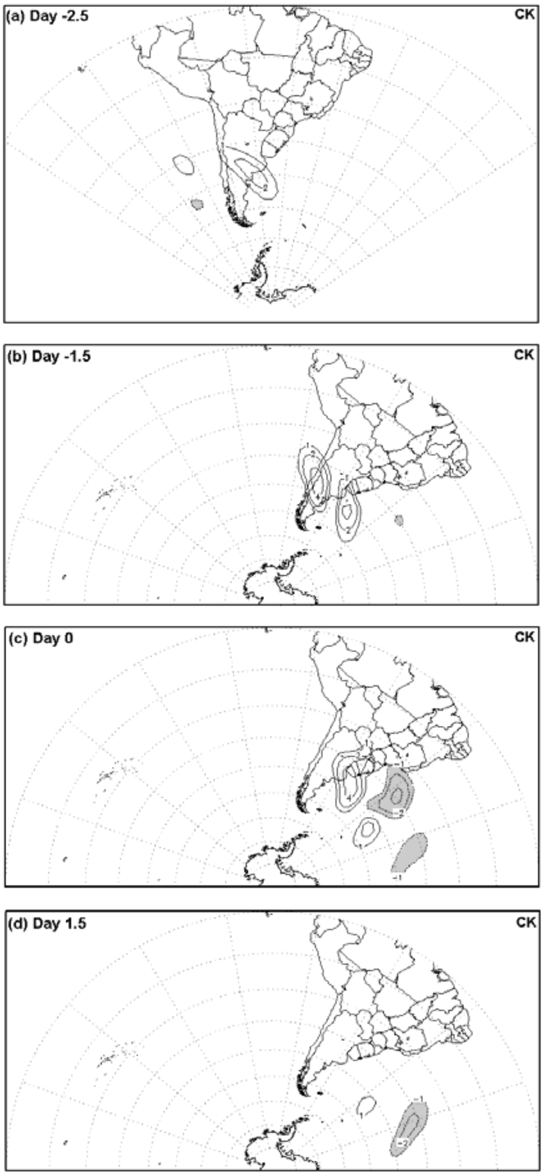

FIG. 9. Vertically integrated CK terms: (a) Day-2.5, (b) Day-1.5, (c) Day0 e (d) Day1.5. Shading indicates negative values.

4. DISCUSSION AND CONCLUSIONS

In this work were found 36 cases of high frequency extreme events. These events were selected from the high frequency air temperature and they were characterized by a positive anomaly of $\overline{T}_h$ two days before the event and a negative anomaly from Day0 to Day1.5 (FIG. 4).

In the high-frequency geopotential height composite at both levels 925-hPa and 500-hPa and in the high-frequency 925-hPa streamlines we observed that the atmosphere begins to modify over the South Pacific just three days before the cold surge events (FIGs. 1a and 2a) when a wave train pattern was observed in the geopotencial height composite at 925-hPa and 500-hPa levels. This wave train began to weak after the cold-air incursio cross the continent. These high frequency disturbances associated with the wave train showed a vertical inclination to west. These results are similar to the found in other South America cold air outbreak studies (Pezza and Ambrizzi, 2005; Müller et al., 2005). However, in these studies the geopotential height data was no filtered with a high-pass filter.

The 925-hPa streamlines composite shows that three days before the cold-air outbreak (FIG. 4a) there were two short waves, one over the coast of Chile and another over Argentina. These waves became in a unique amplified trough from Bolivia until the Atlantic Ocean, crossing the southern Brazil. This type of flow helps in the intensification of the cold-air outbreaks, because it channels the cold air from south of Argentina to the studied region. On Day0 (FIG. 4c) an anticyclone over the central region of Argentina contributes to in the south of Brazil have southerlies, characterizing entrance of dry and cold-air in this area.

The energetics study showed that the high frequency disturbance grew mainly by baroclinic conversion, as was observed in other similar works (Lau and Lau, 1984; Gan and Rao, 1999). During the development of these systems small barotropic contribution (PK) was also present to intensify the negative high frequency disturbance over South Atlantic.

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