Atmospheric Circulation Associated with Persistent Generalized Frosts in Central-Southern South America

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ABSTRACT

This paper describes the large-scale atmospheric circulation associated with persistent generalized frosts (GFs; at least 75% of the stations report frosts) in the east-central region of Argentina known as the Wet Pampa. The GF events are grouped according to their persistence, and NCEP–NCAR reanalysis data are used to create daily composites of mass and wind field anomalies during the 1961–90 winters. The GFs are caused by an anticyclonic anomaly that enters South America, generating southerly wind anomalies and cold air advection that are strengthened by the meridional layout of a cyclonic anomaly over the South Atlantic Ocean. In the case of the more persistent events the wind anomaly grows during the previous days and becomes quasi-stationary. Also, the study identifies at 250 hPa a double train of eastward-moving Rossby waves along the subtropical and subpolar latitudes, respectively, of the Southern Hemisphere. The layout of both wave trains favors the development of an intense southerly wind anomaly in the entire southern cone of the continent. On the other hand, the propagation pattern during the less persistent GFs shows only one arc-shaped Rossby wave train that reaches South America, and then propagates northeastward. Additionally, there is a subtropical jet entrance/confluence over the western side of the continent that induces a secondary meridional circulation whose subsiding branch facilitates the equatorward displacement of the low-level anticyclone, particularly in the case of the less persistent events. In the case of the more persistent GFs the confluence is located farther east and sustains essentially zonal wave train propagation, so that the surface anticyclone is not able to achieve a major equatorward penetration.

1. Introduction

Cold air outbreaks in subtropical South America, to the east of the Andes Mountains, are a frequent and very important feature of the synoptic climatology of the region. Often, they lead to frosts that have major, sometimes dramatic, effects on agriculture and other activities. In the past, the traditional approach was the study of individual frost events, while during the last decade the studies began to examine the mean synoptic structure and evolution of extreme cold episodes, grouped according to different selection criteria. For example, Algarve and Cavalcanti (1994) analyzed time series of minimum temperature at a group of meteorological stations in southeastern Brazil. They selected 19 cases among the most intense frosts that occurred from April to September 1980–89. The predominant atmospheric circulation feature noted by these authors is a bifurcation of the flow at upper levels (blocking pattern) over the southeastern Pacific Ocean—prior to most episodes—and a confluence over the continent (at relatively lower latitudes) during the frost.

Vera and Vigliarolo (2000) made a composite of nine events in the above-mentioned paper to study the evolution of synoptic-scale disturbances that led to cold air outbreaks in South America. The results show that the
circulation pattern is dominated by a long wave characterized by an anticyclonic perturbation in the southeastern Pacific Ocean and a cyclonic perturbation over South America. The composite shows, during the early stages of the frost events in southern Brazil, two additional features. There is an upper-level cyclonic perturbation associated with the subtropical jet, which is located farther north than its mean position that makes easier the equatorward incursion of the frontal system. In addition, a short wave trough at higher latitudes reaches the sub tropics and facilitates the cold air outbreak into the South Atlantic Ocean and thus leading to frosts over southern Brazil.

According to Krishnamurti et al. (1999), the large amplitude of the ridge–trough pair during the most intense frosts over south-southeastern Brazil results from the overlap of fast-moving synoptic waves and quasi-stationary planetary waves. The larger amplification of the wave at upper levels during the mature stage of the cold air incursion is mostly due to the baroclinic growth of the synoptic wave at low levels as it moves northward below the axis of the upper-level trough. Marengo et al. (1997) also indicate that the Andes Mountains contribute to the interaction of the lower and upper levels of the atmosphere in the early stages of the extreme episodes in subtropical latitudes. The approaching upper-level trough in midlatitudes intensifies when crossing the high mountain range and the enhanced southerlies result in increased cold air advection.

The cold air incursions that cause a significant temperature drop in central Argentina were analyzed by Escobar et al. (2004). The authors studied sequential patterns of geopotential height fields at 1000 and 500 hPa during the winters of 1979–93, and identify three typical situations related to cold air outbreaks in this region. One of them shows the classical upper-level pattern with a ridge to the west of the continent over the Pacific Ocean, associated with a postfrontal surface anticyclone. The other two patterns present a long-wave trough at upper levels that affects the continent, one of them with a postfrontal anticyclone moving at mid- and low latitudes and the other one with a migratory anticyclone incursion at lower latitudes.

In particular, frost events that cover large spatial extensions have been analyzed by Müller et al. (2005), who define a generalized frost (GF) as when at least 75% of the stations over a region report minimum temperatures less than or equal to 0°C. The authors studied the mean atmospheric circulation associated with GFs over east-central Argentina, in the region known as the Wet Pampa (Pampa Húmeda), in particular for the years with extreme frequencies of events during the period May to September 1961–90. The analysis shows that the intensification of the subtropical jet in South America contributes to a higher frequency of GFs, which may be related to the amplification of the pressure gradient in the region of the subtropical jet due to the increase in Rossby wave activity. A numerical study of Müller et al. (2003a) shows a mechanism of tropical–extratropical interaction in which the anomalous convection observed over the western tropical Pacific Ocean acts as a source of Rossby waves that propagate to the South American continent. As a result, the north–south pressure gradient intensifies in the region of the subtropical jet in South America. Müller et al. (2005) also analyzed the structure and evolution of the synoptic systems that produce GFs during winters with maximum frequency of events, by means of composites of daily fields. The results show the development of an upper-level midlatitude wave with a large amplitude trough over South America that extends up to the tropical latitudes, and the progressive amplification of another trough located upstream over the Pacific Ocean.

The referenced papers describe the atmospheric circulation associated with cold air outbreaks in subtropical South America; however, they do not analyze the conditions that determine the duration or persistence of the events, as well as their spatial extension. The aim of this paper is to study the differences in the regional and large-scale atmospheric circulation patterns that make a GF event more persistent or less persistent over the Wet Pampa, one of the most productive agricultural regions of South America. The originality of this paper is based on two elements, the first one being the precondition that the frost events must have a large spatial extension—that is, they must be generalized frosts—and the second one being the dependence of the cold surge duration, that is, the days of persistence, on the structure of the atmospheric circulation in different spatial scales.

In section 2 the GFs are identified in sequences of consecutive days with frost during the winters for the period 1961–90, and are grouped according to their persistence. The number of consecutive GF days implies, in principle, the persistence of a synoptic situation that causes and maintains the cooling over a large portion of the Wet Pampa. This hypothesis is used to study the atmospheric conditions associated with 1-day persistence (section 3a), 2-day persistence (section 3b), and 3-day or higher persistence events (section 3c). The study includes the analysis of 250-hPa Rossby wave propagation patterns in the Southern Hemisphere associated with each of the above-mentioned groups. Finally, section 4 presents a discussion of results and the conclusions, along with a conceptual model with the
2. Data and methods

The study is based on daily minimum temperatures from 41 synoptic and climatological stations operated by National Meteorological Service and the National Institute of Agricultural Technology, both of Argentina, during the period 1961–90. The meteorological stations are located in east-central Argentina (27°–40°S, 65°–57°W), a region known as the Wet Pampa (Fig. 1). At each meteorological station a day of frost is defined when the minimum temperature is less than or equal to 0°C. According to the criterion of Müller et al. (2000), a day of GF in the Wet Pampa is defined when at least 75% of the meteorological stations within the region report frost. GFs are particularly important because their spatial representation makes it possible to identify larger-scale phenomena.

GFs are grouped according to their persistence, which is defined as the number of consecutive days that follows the first day of the event and comply with the GF condition, and the list of events is shown in Table 1. One-day persistence indicates that the GF lasted 2 consecutive days; 2-day persistence indicates 3 consecutive days of GF, and so on. For each GF group, daily composites are made, starting three days before the first day of GF, which is identified as day 0, and ending one day after its completion.

For the analysis of the mean and the anomaly fields of the different variables, National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data are employed. The selected variables are as follows: mean values and anomalies of the geopotential height at 250 and 850 hPa; zonal and meridional wind anomalies at 250 and 850 hPa; vertical velocity anomalies at 500 hPa; and temperature anomalies at 850 hPa. Anomalies are calculated with respect to the period 1968–96, becaus
this was the climatology available on the Web page www.cdc.noaa.gov at the time when the data were processed. The results are tested by applying the Student’s t test.

3. Persistence analysis

The atmospheric circulation associated with the GFs is analyzed according to their persistence, and Table 1 shows the dates of each GF group. The number of cases decreases as the persistence increases, for example, there are 20 cases of 1-day persistence, 9 cases of 2-day persistence, 2 cases of 3-day persistence, and only 1 case of 4-day persistence. GFs occur between May and September, although most cases take place in July, followed by June.

a. One-day persistence

Figure 2 shows the time evolution from day −3 to day 1 of mean geopotential height composites at 250 hPa (left panels) and 850 hPa (right panels) for GFs persisting one day, while Fig. 3 shows the corresponding anomalies. Over the eastern Pacific Ocean there is a wave approaching the continent during the days previous to the event that amplifies as it moves to the east. The upper-level winds flow associated with the ridge on the windward side of the Andes Mountains leads the low-level anticyclone on its way into South America from the southwest. This can be appreciated in the positive geopotential height anomalies observed from day −3 to day −1, which extend throughout the troposphere (Figs. 3a–c and 3f–h). On the first day of GF, the positive geopotential height anomaly reaches a value of 60 m (120 m) at 850 hPa (250 hPa) as shown in Fig. 3i (Fig. 3d). The anticyclonic anomaly at 850 hPa extends over a large portion of the southern cone of South America, covering almost all Argentina on day 0 when the GF starts (Fig. 3i), whereas on the first day of persistence (day 1; Fig. 3j) it only affects the Wet Pampa. The change in the lower levels from day 0 to day 1 is similar to the pattern of propagating low-level anticyclonic anomalies in the vicinity of north–south-oriented mountain ranges described among others by Gan and Rao (1994) and Garreaud (1999). The surface anticyclone moves to the east with the upper-level system, but its northern leading edge becomes increasingly detached from it, following an anticyclonic path along the lee side of the Andes. The concomitant cold air produces a low-level cooling over most of the subtropical part of the continent, and extending northward into the Tropics. According to Garreaud (1999), the ridging along the leading edge of the system is largely sustained by the hydrostatic effect of the shallow cold air dome replacing warm air.

The described anomaly pattern can be associated with the direct mode of pattern B (described below) in the climatic–synoptic classification of frosts in the Wet Pampa (Müller et al. 2003b). Müller et al. make a classification of atmospheric circulation features in order to obtain frost-related synoptic patterns for the Wet Pampa. They perform a principal component analysis (T-mode approach) and find that six synoptic situations account for 94% of the variance associated with frosts in the region. In particular the direct mode of pattern B, which corresponds to the second principal component (PC) and explains 30% of the variance, consists of a postfrontal anticyclone that enters the continent at latitudes poleward of 40°S. The associated south-southwesterly winds are accompanied by a marked advection of very cold and dry air into the area that favors the development of advective frosts. A similar pattern was found by Escobar et al. (2004), associated with the passage of cold fronts responsible for a significant temperature drop over central Argentina.

Downstream of the low-level anticyclonic anomaly there is a cyclonic anomaly that moves to the northeast toward the Atlantic Ocean, followed by the anticyclone that moves on the leeward side of the Andes Mountains (Fig. 3, right panels). Although midlatitude low-pressure systems coming from the Pacific Ocean across the Andes Mountains move east-southeastward over the Atlantic Ocean, the cold front associated with the low pressure center moves northeastward (Satyamurty et al. 1998), creating the above-mentioned cyclonic anomaly. The fast propagation to the northeast is a topographic effect of the Andes Mountains and it was identified by other studies of cold air outbreaks in South America (e.g., Garreaud 2000; Seluchi and Marengo 2000; Vera et al. 2002). The cyclonic anomaly is also seen in the upper levels (Fig. 3, left panels) and it becomes more intense on day 0 when it reaches a larger peak value (Fig. 3d) than that of its anticyclonic pair. The pattern of geopotential height anomalies in midlatitudes extends in an arc-shaped layout from the central Pacific Ocean to South America (Fig. 3, left panels). A similar pattern was found by Cavalcanti and Kayano (1999) in the third winter eigenvector for the Southern Hemisphere, which is similar, at the same time, to the typical wave train discussed by Hoskins (1983). This mode represents the passage of ridges and troughs associated with frontal systems and short transient waves that move across South America and are responsible for the changes in the weather conditions over the continent (Kousky and Cavalcanti 1997) with...
occasional cold air irruptions that can reach the tropical latitudes.

The time evolution of the 250- and 850-hPa geopotential height anomalies associated with the GF episodes can be illustrated by the conceptual model proposed by Marengo et al. (1997) and Garreaud (2000) for the evolution of circulation systems close to the surface during cold incursions in South America. The anticyclone center moves from the southeastern Pacific Ocean toward the continent, together with a cyclone.
located over the southwestern Atlantic Ocean. During the passage of anticyclones across the Andes Mountains, as indicated by Lichtenstein (1989), the low-level cold air cannot cross the high mountain barrier in the southwest part of the continent and consequently the systems go around the obstacle increasing their anticyclonic vorticity. To the south of 30°S the two pressure systems deepen mainly due to the vorticity advection at

Fig. 3. Anomaly of geopotential height composites from (top to bottom) day −3 to day 1 at (left) 250 and (right) 850 hPa, corresponding to 1-day persistence GF. Positive (negative) contours are shown in solid (dashed) lines every 20 gpm.
the upper levels within the midlatitude baroclinic wave. The geostrophic southerly wind (between the high and low pressure cells) produces low-level cooling along the east coast of South America and farther inland as far as 25°S (Garreaud 2000). Also, as the surface pressure increases over southern Argentina, a large-scale meridional pressure gradient is established between the migratory anticyclone and the continental trough farther to the north. The blocking effect of the Andes Mountains leads to an ageostrophic, topographically trapped southerly flow that advects cold air into the subtropics, as indicated by Garreaud (1999).

In Fig. 4 the meridional wind anomalies at 250 hPa (Figs. 4a–e) and 850 hPa (Figs. 4f–j) show a well-organized Rossby wave train propagating in midlatitudes of the Southern Hemisphere from the eastern-central Pacific Ocean to the Atlantic Ocean in a concave configuration as seen from the equator (Figs. 4a–c). The anomalies become more intense and statistically significant (99%), as can be seen in particular during the event (Figs. 4d,e). As indicated by Marengo et al. (1997), the upper-level trough in midlatitudes intensifies when crossing the high Andes Mountain range by a positive feedback mechanism between the low-level cold air advection and the upper-level cyclonic vorticity advection, which in turn increases the former one. Once the core of the southerly wind anomaly enters the continent, it develops the cold air outbreak as it moves to the northeast (Figs. 4i,j). The statistically significant (99%) positive meridional wind anomaly, as can be seen in Figs. 4f–j, is very extensive and reaches the tropical latitudes. An example of this case occurred in July 1981 when severe frosts were registered over a large region that extended as far north as the tropic of Capricorn (Haddock et al. 1981; Fortune and Kousky 1983). This episode took place in the Wet Pampa from 17 to 21 July 1981 and developed partial frosts—between 25% and 75% of meteorological stations in the Wet Pampa report frost (Müller et al. 2000), and GFs, in particular, on 18 and 19 July when 90% of the meteorological stations recorded frosts (Müller et al. 2003b).

The wind anomalies at 250 hPa are shown in Fig. 5 in which large areas with 99% statistically significant values of the zonal wind component can be appreciated. At the entrance region of the subtropical jet in South America, during the days previous to the event, there is a confluence of southwest and northwest wind anomalies in the upper-level wind field (illustrated by the arrows in Fig. 5a). This is an important large-scale feature of the more intense and lasting cold air outbreaks in the subtropical regions, to the east of high mountain ranges (Lau and Chang 1987; Schultz et al. 1998; Garreaud 2000; Vera and Vigliarolo 2000). According to Schultz et al. (1998) the direct Hadley cell–type secondary circulation that develops in the entrance region of the subtropical jet favors the subsidence in midlatitudes and contributes to the intensification of the surface anticyclone favoring its equatorward incursion. Uccellini and Johnson (1979) showed that the horizontal wind acceleration induces a direct secondary circulation on a vertical plane perpendicular to the subtropical jet axis with the downward (upward) branch over the polar (equatorial) side of the jet. Midtropospheric subsidence over east-central Argentina (Fig. 6a) and upper-level anticyclonic vorticity advection act together to intensify the low-level anticyclone, while the upward motion at lower latitudes induces a midlevel cooling, thus favoring the cold air outbreak (Garreaud 2000). In agreement with that, Marengo et al. (1997) and Vera and Vigliarolo (2000) found that low-level cooling is largely produced by horizontal cold advection. The resultant cooling in the subtropical part of the continent, and in particular over east-central Argentina, is shown in the temperature anomalies of Fig. 6b.

b. Two-day persistence

Figure 7 shows the time evolution from day −3 to day 2 of mean geopotential height composites at 250 hPa (Figs. 7a–f) and 850 hPa (Figs. 7g–l) for GFs persisting two days. Figures 7a–f (250 hPa) show, during the previous days, a large-amplitude wave with the ridge over the Pacific Ocean off the western coast and the downstream trough over the eastern coast of South America. At 850 hPa (Figs. 7g–l) there is a similar wave but with larger amplitude than the corresponding one of 1-day persistence (Fig. 2).

Previous to the GF, an additional feature appears in the geopotential height fields at 250 hPa (Figs. 7a–c). At around 110°W there is a trough to the north of 40°S and a ridge to the south of that latitude, which in the anomaly fields (Figs. 8a–c) are seen as a pair of anomalies with opposite sign. The time evolution of the anomalies at low levels (Figs. 8g–i) clearly shows that the disturbance corresponds to the anticyclone responsible for the GF on the following days. A similar situation is observed in the 1-day persistence composites (section 2a), as well as in the GFs of the winters with maximum frequency of frosts (Müller et al. 2005), although in these cases the anomalies were much smaller than those obtained here, that is, 100 gpm at 850 hPa and 160 gpm at 250 hPa on day 0 (Figs. 8d and 8j, respectively). Therefore, the intensity of the anomaly seems to be important for the persistence of the GFs that affect the Wet Pampa during three consecutive
days. This figure also shows in the upper levels an increase of the zonal pressure gradient between the two anomalies as they approach South America. Between day $-1$ and day 0 the anticyclone begins to cross the Andes Mountains on the southwest as seen in Figs. 8i,j and 8c,d.

Figure 9 shows the meridional wind anomalies at 250 hPa (left panels) and 850 hPa (right panels). In the days
Fig. 5. Anomaly of zonal and vector wind composites at 250 hPa from (top) day −2 to (bottom) day 1 corresponding to 1-day persistence GF. Positive (negative) contours are shown in solid (dashed) lines every 2 m s⁻¹. The shaded areas indicate regions where the zonal wind anomalies are statistically significant at a 99% level of the Student’s t test. The thick arrows illustrate the confluence (see text for details).

Fig. 6. Anomaly of (a) vertical velocity (Pa s⁻¹) at 500 hPa and (b) temperature (°C) at 850-hPa composites on day 0, corresponding to 1-day persistence GF.
FIG. 7. Mean value of geopotential height composites from (top to bottom) day −3 to day 2 at (left) 250 and (right) 850 hPa, corresponding to 2-day persistence GF. Contours are every 100 gpm at 250 hPa and every 50 gpm at 850 hPa.
Fig. 8. Anomaly of geopotential height composites from (top to bottom) day −3 to day 2 at (left) 250 and (right) 850 hPa, corresponding to 2-day persistence GF. Positive (negative) contours are in solid (dashed) lines every 20 gpm.
Fig. 9. Anomaly of meridional wind composites from (top to bottom) day −3 to day 2 at (left) 250 and (right) 850 hPa, corresponding to 2-day persistence GF. Positive (negative) contours are shown in solid (dashed) lines every 2 m s\(^{-1}\). The shaded areas indicate regions with 99% statistical significance according to a Student’s \(t\) test.
previous to the GFs at 250 hPa there is a double train of eastward-moving Rossby waves along the subtropical and subpolar latitudes, respectively, of the Southern Hemisphere. The disturbance layout of both wave trains, which covers a large extension of western South America, turns the circulation more meridional as displayed by the southerly wind vector anomalies almost parallel to the Andes Mountains (Figs. 10a–c). This flow structure extends throughout the troposphere and sustains a markedly meridional polar air outbreak into the continent as seen at lower levels (Figs. 9g–l), since the system merges into a single large anomaly that persists during the following days. This configuration results in a large anticyclonic anomaly that channels the cold air coming from the south to the leeward side of the Andes Mountains, sustaining below 0°C temperatures (Fig. 11b) in the Wet Pampa during three consecutive days. On the last day of the GF, the northeastwardly moving anticyclone creates a weak northerly wind anomaly over part of the study area (Fig. 9l) and develops radiative frosts due to the clear skies and cold and dry air that arrived on the previous day.

As seen in the case of 1-day persistence and in the GF composites during winters with maximum frequency of frosts (Müller et al. 2005), the pair of upper-level cyclonic and anticyclonic anomalies intensify as the system evolves, although in the present analysis the cyclonic anomaly extends from high latitudes up to the Tropics (Fig. 8). The meridional layout of both anomalies makes easier the polar air incursion in the southern cone of South America for various days (Figs. 9j,k). According to the climatic–synoptic classification of frosts of Müller et al. (2003b), this situation can be associated with the direct mode of pattern C given by the third PC. This mode corresponds to a low pressure system on the eastern side of the continent and a high pressure system that enters from the Pacific Ocean and travels over the Wet Pampa creating a strong cold and dry air incursion from the south. This situation is often associated with an anticyclonic ridge that favors subsidence, clear skies, and nocturnal cooling, which adds a radiative component to the advective frost. Although the amount of variance explained by this pattern is low (5%), there was a situation on 15 July 1975 with a correlation coefficient of 0.86 with pattern C (Müller et al. 2003b).

With respect to the zonal wind anomalies that directly affect the continent, Fig. 10 shows two positive anomalies, one at around 30°S (shaded areas indicate 99% statistical significance) that is related to the subtropical jet, and another one over the southwestern part of the continent at around 60°S that is related to the polar jet. This configuration would substantiate the role played by the polar jet in conducting the waves to the continent and thus creating the appropriate conditions for the development of the most conspicuous GF cases. In this respect, Ambrizzi et al. (1995) and Berbery and Vera (1996) demonstrate that the jets are waveguides in the Southern Hemisphere during wintertime. In addition to the intensity, it is of particular interest to analyze the spatial extension of the wind anomaly associated with the subtropical jet. Figure 10 shows, during the days of the episode, a downstream acceleration of the subtropical jet on the eastern side of the continent, together with a confluence of southwest and northwest wind anomalies. This differs from the case of 1-day persistence in which the confluence is already observed on the days previous to the event and at the entrance region of the subtropical jet over the western end of the continent (Fig. 5). Schultz et al. (1998) indicate that the subtropical jet acceleration, and the consequent secondary circulation, causes the intensification of the anticyclone. In this analysis, the secondary circulation generated on the vertical plane has its downward branch over the eastern side of the continent—discussed in more detail below—thus contributing to strengthen the surface anticyclone. For example, Fig. 11a shows an extensive region with upward motion at tropical latitudes over the east-central part of the continent and another region with downward motion at subtropical latitudes covering all the Wet Pampa. Consequently, the anticyclone responsible for the GF strengthens and causes the important temperature anomalies shown in Fig. 11b. Figure 12 facilitates the understanding of the differences by displaying the vertical velocity anomalies from day –1 to day 1, and corresponding 1-day persistence (Figs. 12a–c) and 2-day persistence (Figs. 12d–f). In the case of 1-day persistence, the region of maximum subsidence is always displaced to the northeast of the surface high pressure center and changes position from western Argentina on day –1 (Fig. 12a) to southeastern Brazil on day 1 (Fig. 12c), so that the surface anticyclone follows that displacement and quickly leaves the study area moving to the northeast. Instead, the 2-day persistence case shows that the region of maximum subsidence evolves more slowly eastward and therefore the surface anticyclone propagates more zonally and remains longer over the Wet Pampa.

Another distinguishing aspect between 1-day and 2-day persistence is related to the different easterly speed of propagation of the anomalies that can be appreciated in the Hovmöller diagram of 250-hPa meridional wind anomalies of Fig. 13. At around 70°W (eastern flank of the Andes Mountains), Fig. 13a (1-day persistence) shows a constant easterly speed of propa-
Fig. 10. Anomaly of zonal and vector wind composites at 250 hPa from (top to bottom) day -2 to day 2, corresponding to 2-day persistence GF. Positive (negative) contours are shown in solid (dashed) lines every 2 m s$^{-1}$. The shaded areas indicate regions where the zonal wind anomalies are statistically significant at a 99% level of the Student’s t test. The thick arrows illustrate the confluence (see text for details).
gation of the meridional wind anomalies of 8.25° longitude per day, from day −3 to day 1. Instead, 2-day persistence (Fig. 13b) displays a more stationary pattern particularly before the event (speed of propagation of 4° longitude per day on days −3 and −2) and after the first day of the event (speed of propagation of 1.8° longitude per day on days 1 and 2).

c. Three-day and four-day persistence

This group consists of only three cases found in the period of analysis, two of them persisted for 3 days and the other one persisted for 4 days. Despite the small number of cases, a general analysis reveals physical features that are similar to those already described in the previous section, although they are now more prominent. The wave around the midlatitudes of the southern cone of South America (Fig. 14) shows larger amplitude than that of 2-day persistence, and the anomalies (not shown) are therefore more intense. The northwest–southeast-oriented large-amplitude trough to the east of the continent, which developed a few days before the event, is an observed feature in transient extratropical waves when they propagate on the leeward side of the Andes Mountains as shown by Berbery and Vera (1996) and Seluchi et al. (1998), among others. The upstream ridge has a deep trough to the north, at approximately 110°W (Figs. 14a,b), as in the case of 2-day persistence.

In general, the pattern of anomalies (not shown) is similar to that of 2-day persistence; however, it must be remarked that the wave exhibits greater amplitude, particularly for the meridional wind. This reaffirms that the GFs are mainly advective and that the intensity of the anomalies seems to play a main role in the persistence of the events. As an example of an individual case, Fig. 15 shows the meridional wind anomaly of 1 July 1980, the first day of a 3-day persistent GF in which the double wave train is clearly seen.

4. Summary and conclusions

This paper presents a new approach in the study of cold air outbreaks in the southern cone of South America by considering the spatial extension of the event, that is, the concept of a GF, and the duration of the event, that is, its persistence. The GFs over the Wet Pampa region of Argentina are identified during the period 1961 to 1990 and they are grouped according to their persistence, that is, from 1-day persistence (two consecutive days with GF) to 4-day persistence (five consecutive days with GF). The study is based on the analysis, for each GF group, of a sequence of daily composites, from a few days before the event starts until one day after its completion, of different variables that describe the atmospheric circulation. The comparison between more persistent and the less persistent events brings out the distinctive features that explain the variable duration of the GF events, which is an original finding.

In general, the lower- and upper-level large-scale circulation over southern South America during the GFs typically shows a midlatitude wave with a ridge on the windward side of the Andes Mountains preceded by a trough, a configuration also found by other studies (e.g., Marengo et al. 1997; Krishnamurti et al. 1999; Garreaud 2000; Vera and Vigliarolo 2000). The present study adds to that common feature of the cold-air outbreaks the wave amplification before and during the
Fig. 12. Anomaly of vertical velocity composite (Pa s$^{-1}$) at 500 hPa from (top to bottom) day −1 to day 1 corresponding to (a)–(c) 1-day persistence and (d)–(f) 2-day persistence GF. Positive (negative) contours are shown in solid (dashed) lines every 0.02 Pa s$^{-1}$ (only absolute values greater than 0.07 Pa s$^{-1}$ are shown). The mean sea level pressure is shown in the background (darkest shading for values above 1025 hPa and no shading for values below 1015 hPa).
mature stage of the cold air outbreak, which reaches larger amplitude with more persistent events. In addition to that, the ridge–trough pair weakens the zonal wind component due to a decrease in the meridional pressure gradient previous to the more persistent GFs.

The GFs in the Wet Pampa are caused by an anticyclonic anomaly that breaks into South America, generating southerly wind anomalies and cold air advection. The permanence and the intensity of the anticyclonic anomaly depend on the characteristics of the event. The composite of the more persistent GFs reveals the presence of an anticyclonic anomaly over the eastern Pacific Ocean that deepens in the days previous to the event, similarly to what Müller et al. (2005) found during the winters with maximum frequency of GFs. However, the most persistent GFs are directly related to the quasi-stationary character of the anticyclonic anomaly as well as its intensity.

One of the main findings of this study is the identification of Rossby wave trains in the Pacific Ocean, whose propagation dynamics condition the synoptic characteristics of the GFs as well as their persistence. The time evolution of the wave patterns displayed by the sequence of daily composites reveals two basic forms of propagation. One of them presents an arc-shaped wave train that starts in the east-central Pacific Ocean and propagates across the midlatitudes of the Southern Hemisphere, initially poleward, and then curves toward the equator. Upon reaching the continent, the wave train continues to the northeast affecting all the southern cone of South America. This pattern, schematized in Fig. 16a, explains 1-day persistence GFs and is typically found in the literature to be responsible for the cold surges in South America (e.g., Marengo et al. 1997; Cavalcanti and Kayano 1999; Garreaud 2000). The other form of propagation shows a double wave train, schematized in Fig. 17a, that propagates across the subtropical and subpolar latitudes of the Pacific Ocean, respectively, and merges into a single wave train before entering the continent and previous to the GF event. This configuration favors the development of an intense southerly wind anomaly with large meridional extension that intensifies the anticyclonic circulation over its area of influence. The flow anomaly has barotropic structure and contributes to a sustained and markedly meridional polar air outbreak into the continent, which is typical during the more persistent GFs. This is depicted in the sequence of daily composites of mean geopotential height that shows, at around 120°W during the previous days, a trough at subtropical latitudes just to the north of a ridge at higher altitudes. The high-latitude ridge moves faster than the subtropical latitude trough, reaches the continent on the day before the event, and becomes quasi-stationary during the more persistent GFs.

An additional element to be considered is that downstream of the above-mentioned anticyclonic anomaly, there is a cyclonic anomaly associated with the trough over the Atlantic Ocean and near the continent. This pattern is often associated with cold surges over central Argentina (Escobar et al. 2004) and in particular with frosts in the Wet Pampa (Müller et al. 2003b). However, the present study reveals that the role played by the cyclonic anomaly depends on its genesis. When the meridional flow increases over the western part of the continent (anticyclonic anomaly), it also does so farther...
Fig. 14. Mean value of geopotential height composites from (top to bottom) day −2 to day 3 at (left) 250 and (right) 850 hPa, corresponding to 3- and 4-day persistence GF. Contours are every 100 gpm at 250 hPa and every 50 gpm at 850 hPa.
east downstream (cyclonic anomaly) because both anomalies conform to a system that propagates across the Andes Mountains following a basically zonal trajectory, as shown by the double wave train. In this case, the meridional layout of the cyclonic anomaly over the Atlantic Ocean strengthens the polar air advection over South America. When the propagation pattern is a single train, on the other hand, the anticyclonic anomaly that affects the southern cone of South America moves northeasterly along with the cyclonic anomaly located downstream, following the typical trajectory of these synoptic systems leeward of the Andes Mountains. As a result, the cyclonic anomaly will create a southeasterly flow (maritime air) characterized by a weaker cold and dry air advection that does not favor the persistence of the GF episodes.

Another aspect related to the different wave train patterns is associated with the subtropical jet over South America. In the case of less persistent GFs there is a single wave train (Fig. 16a) and a meridional con-
fluence of wind anomalies at the entrance region of the subtropical jet in South America on the days previous to the event (Fig. 16b). At that place, the confluence of southwest and northwest wind anomalies accelerates the subtropical jet inducing a secondary meridional circulation with the upward branch on the equatorial side and the downward branch on the polar side of the subtropical jet (Fig. 16b). This provides additional strength to the surface anticyclone and, as a result, the whole system reinforces as it propagates to the northeast, extending the cold surge to lower latitudes, as noted by Schultz et al. (1998) for Central America and Vera and Vigliarolo (2000) for South America. On the other hand, when a double wave train is observed (Fig. 17a), the wind anomalies in the jet entrance region come from the west in the previous days, and the above-mentioned confluence is seen not before but during the event (Fig. 17b) and farther east. The jet accelerates on the eastern side of the continent inducing a secondary meridional circulation with a downward branch that moves slowly eastward along with the surface anticyclone, while in the case of 1-day persistence the downward branch is always displaced to the northeast of the surface anticyclone facilitating its equatorward displacement. In contrast to what is observed in the case of 1-day persistence, the region of acceleration of the subtropical jet now extends farther east and beyond 25°W. This configuration will sustain essentially zonal wave train propagation, in contrast to the 1-day persistence, and the surface anticyclone will not be able to achieve a major equatorward penetration. Another study of migratory surface anticyclone trajectories during winters (1976–88) with a maximum frequency of GF shows that none of them reached tropical latitudes, although they did cause temperature drops in southern Brazil.

From the above it can be concluded that the Rossby wave trains that propagate across the Pacific Ocean accelerate the subtropical jet when they reach South America. This influences the downstream propagation of the wave trains, which at the same time conditions the latitudinal penetration of the synoptic systems into the continent, as well as their persistence.

A final remark about the differences between 1- and 2-day persistence is related to the changes in the barotropic structure of the atmospheric circulation leading to GF events. Figure 18 shows vertical cross sections at 35°S of the anomaly of 250-hPa meridional wind composites from day −1 to day 1. Figures 18d–f (2-day persistence) show at around 70°W (eastern flank of the Andes Mountains) that the meridional wind anomaly

![Figure 17](image-url)
retains a basically barotropic structure throughout the event, in contrast to 1-day persistence (left panels) that starts to develop baroclinic characteristics on day 1. This evidence suggests that the GFs develop as a basically barotropic process and they persist longer when the atmospheric circulation is able to preserve such regional characteristic for several days.

As a concluding remark it is worth mentioning that the observed double Rossby wave train suggests the possibility of a remote origin for the more persistent GFs. If so, this would represent a possibility of forecasting such important events for the region several days in advance, so we will consider this topic in future research.
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