The Nature of a Heat Wave in Eastern Argentina Occurring during SALLJEX

S. BIBIANA CERNE AND CAROLINA S. VERA

Centro de Investigaciones del Mar y la Atmósfera, CONICET, and Departamento de Ciencias de la Atmósfera y los Océanos, Universidad de Buenos Aires, Buenos Aires, Argentina

BRANT LIEBMANN

CIRES Climate Diagnostics Center, Boulder, Colorado

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ABSTRACT

This note describes the physical processes associated with the occurrence of a heat wave over central Argentina during the austral summer of 2002/03, during which the South American Low-Level Jet Experiment (SALLJEX) was carried out. The SALLJEX heat wave that lasted between 25 January and 2 February 2003 was punctuated by extreme conditions during its last 3 days, with the highest temperature recorded over the last 35 yr at several stations of the region. It was found that not only the activity of synoptic-scale waves, but also the intraseasonal oscillation variability, had a strong impact on the temperature evolution during this summer. During the weeks previous to the heat wave development, an intensified South Atlantic convergence zone (SACZ) dominated the atmospheric conditions over tropical South America. Temperatures started to increase in the subtropics due to the subsidence and diabatic warming associated with the SACZ, as depicted by SALLJEX upper-air observations. An extratropical anticyclone that evolved along southern South America further intensified subsidence conditions. By the end of January the warming processes associated with SACZ activity weakened, while horizontal temperature advection began to dominate over central Argentina due to the intensification of the South American low-level jet. This mechanism led to temperature extremes by 2 February with temperature anomalies at least two standard deviations larger than the climatological mean values. Intense solar heating favored by strong subsidence was responsible for the heat wave until 31 January, after which horizontal temperature advection was the primary process associated with the temperature peak.

1. Introduction

The analysis and prediction of temperature extremes and their persistence are quite important as they affect a wide range of human activities. It has been documented that intense heat waves over subtropical South America produce dangerous levels of thermal stress in the population (Campetella and Rusticucci 1998; Alessandro and de Garín 2003). Nevertheless, the nature and mechanisms associated with the occurrence of heat waves over this particular region have yet to be studied in detail.

Heat waves over subtropical South America have usually been associated with the activity of synoptic-scale waves. Rusticucci and Vargas (1995) and Alessandro and de Garín (2003) analyzed the synoptic situations associated with intense heat waves over subtropical South America and found that northerly winds occur during most of the cases, associated with the development of a trough over central Argentina. Frontal systems approaching the region from the south also contribute to an intensification of the northerly winds favorable for the occurrence of heat waves at the subtropics (Rusticucci and Vargas 1995).

There is also some evidence that positive temperature anomalies may persist for periods longer than synoptic time scales over central and northern Argentina (Rusticucci 1995). Campetella and Rusticucci (1998) described the occurrence of an intense heat wave that

Corresponding author address: Bibiana Cerne, CIMA, 2do piso, Pab. II, Ciudad Universitaria, (1428) Buenos Aires, Argentina.
E-mail: cerne@cima.fcen.uba.ar

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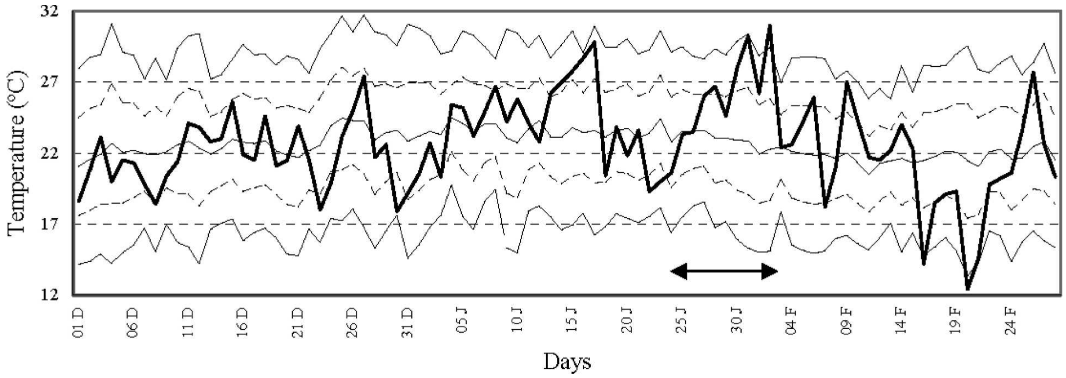

FIG. 1. 1200 UTC (0900 LST) surface air temperatures (°C) observed at Rosario city (Fig. 3) during austral summer 2002/03 (thick solid line) and climatologic daily temperature averages for the 1968–2003 period (thin solid line) with 1 std dev (short dashed line) and 2 std dev (long dashed line).

developed over central and northern Argentina that lasted for 2 weeks during March 1980. The persistence of an anticyclonic circulation over southeastern South America, in conjunction with continual low-level northwesterlies flowing into the region, accounted for the high temperatures. The mechanisms associated with persistent heat waves are not clear yet. Moreover, the intraseasonal variability of both temperature and temperature extremes has not received any attention yet, although several papers have already addressed the relevance of the intraseasonal variability of circulation and associated precipitation over subtropical South America (e.g., Liebmann et al. 2004, and references therein).

This note will describe the physical processes associated with the occurrence of a heat wave that lasted for 9 days between 25 January and 2 February 2003 over north and central Argentina, with record high temperatures observed at several stations. The influence of the intraseasonal variability on the occurrence of this event is also addressed. Besides the extreme characteristics of this temperature heat wave, the event was also chosen because it occurred during the 2002/03 summer in which the South American Low-Level Jet Experiment (SALLJEX) was carried out by the World Climate Research Program/Climate Variability and Predictability/Variability of American Monsoon Systems Program (Vera et al. 2006). SALLJEX provided an unprecedented number of observations, which enabled a detailed description of the structure and temporal evolution of the circulation during this event.

The note is organized as follows. Section 2 describes the dataset used, while the main characteristics of the heat wave are assessed in section 3. The analysis of the intraseasonal variability and the discussion of the synoptic wave activity during the warm spell are presented in sections 4 and 5. A diagnosis of the thermodynamic energy equation is carried out in section 6 in order to identify the leading mechanisms responsible for the occurrence of this event. Finally, a summary and conclusions are presented in section 7.

2. Data

The datasets consist of December–February 2002–03 National Centers for Environment Prediction (NCEP) 6-hourly operational analyses [Global Data Assimilation System (GDAS)] with a $1° \times 1°$ grid resolution available at 17 vertical levels. Temperature fields from NCEP–National Center for Atmospheric Research (NCAR) reanalyses (Kalnay et al. 1996) were also used for comparison with GDAS and observed data. Daily averages of the National Oceanic and Atmospheric Administration (NOAA) satellite outgoing longwave radiation (OLR) field are used as precipitation proxy. Daily maximum and minimum temperatures and surface temperature for 1200 UTC at Rosario, Argentina, were supplied by the Argentinean National Weather

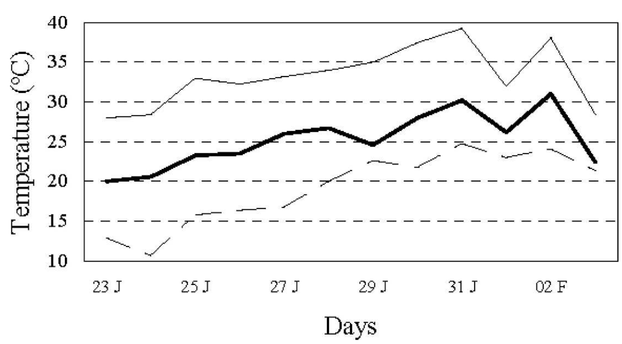

FIG. 2. Time series (°C) of daily maximum temperature (solid line), 1200 UTC surface temperature (thick solid line), and daily minimum temperature (dot–dashed line) recorded at Rosario between 23 Jan and 3 Feb 2003.

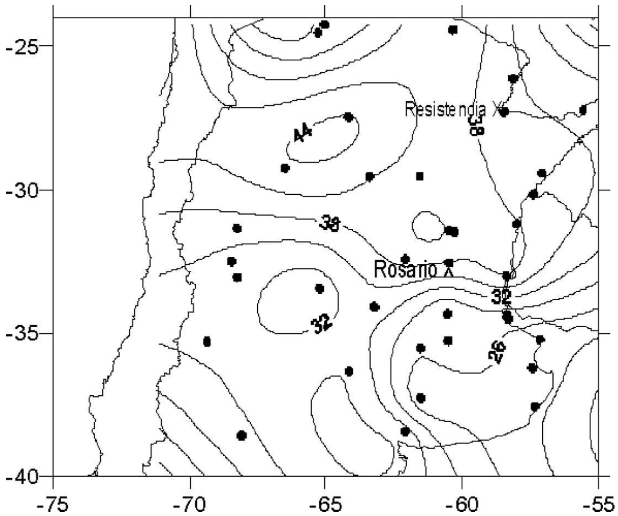

FIG. 3. Spatial distribution of maximum temperatures (°C) over central Argentina at 2 Feb 2003.

Service for the period 1968–2003. Radiosonde observations from SALLJEX are available at http://www.eol.ucar.edu/projects/salljex/dm/.

The temperature analysis was made through the study of the temporal evolution of the 1200 UTC (0900 LST) temperature at Rosario city (32°55′S, 60°40′W), which is located at the center of the region with largest positive temperature anomalies observed over the period of study (Fig. 3).

3. The SALLJEX heat wave

The time series of surface temperature recorded at Rosario city at 1200 UTC (0900 LST) during the austral summer of 2002/03 is depicted in Fig. 1, including the seasonal cycle (as described by the climatological daily temperature averages for the period 1968–2003). A persistent temperature increase characterized the period between 25 January and 2 February (hereafter referred to as "the SALLJEX heat wave") and was also observed in the time series of maximum and minimum temperatures (Fig. 2). Moreover, the positive temperature extreme that occurred on 2 February classifies in the 95th percentile and it is the highest recorded value for February over the 1968–2003 period. Figure 3 shows that on 2 February, the SALLJEX heat wave enveloped most of central and northern Argentina, with temperatures above 32°C. Maximum temperatures exceeded 40°C in the northwest.

Temperature began to increase on 23 January, and exceeded climatology between 25 January and 2 February. Anomalies larger than one standard deviation were observed by 30 January, while those occurring after 31 January exceeded the mean value by at least two standard deviations. Thus, the SALLJEX heat wave was truly an extreme event. The evolution of the standardized temperature and mixing ratio anomalies (departures from the mean divided by the standard deviation) shows that while the temperature anomalies increased during the event, the mixing ratio anomalies remained near zero (Fig. 4). The dry conditions associated with the SALLJEX heat wave are one of the most distinctive features of this event and are further investigated in the following sections. Figure 4 also shows that after 31 January, mixing ratio anomalies started to increase, suggesting the onset of a wet period.

The impact of the SALLJEX heat wave on human comfort was assessed through the calculation of the relative strain index (RSI), defined as RSI $= [10.7 + 0.74(T - 35)]/(44 - e)$, where T is the air temperature in degrees Celsius, and e is the water vapor pressure in hectopascals (Lee and Henschel 1966). The index represents the ratio between the necessary perspiration to regulate the body temperature and the atmospheric evaporative capacity. Upper comfort thresholds for young and old people are associated with RSI values for 0.15 and 0.10, respectively. Cardiac and respiratory problems are expected for RSI values larger than 0.18, while RSI values greater than 0.3 represent the failure

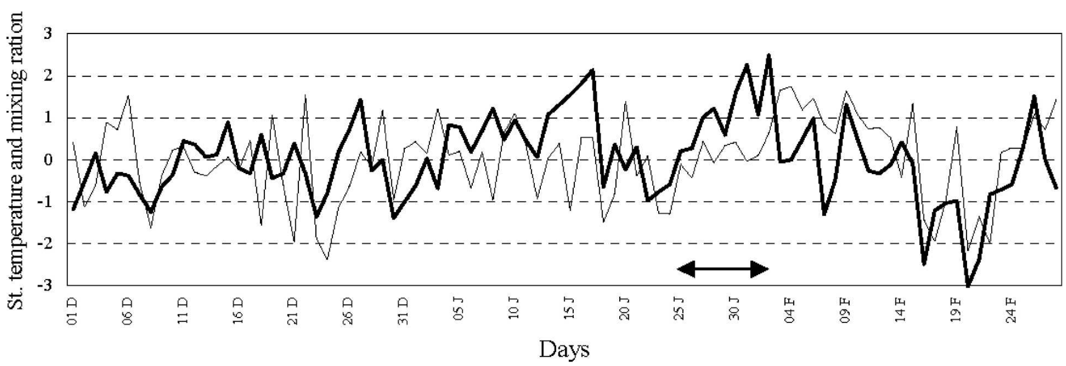

FIG. 4. Time series of 1200 UTC standardized surface temperature (thick line) and mixing ratio (thin line).

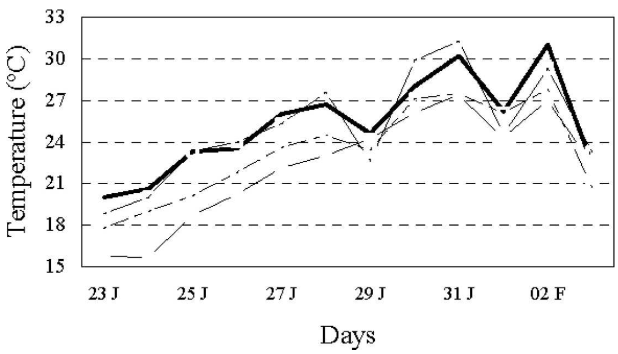

FIG. 5. Time series (°C) of observed 1200 UTC surface temperature (thick solid line), GDAS 2-m temperature (dot–long dashed line), GDAS 950-hPa temperature (dot–dashed line), and NCEP 995-sigma temperature (long dashed line) at Rosario city between 23 Jan and 3 Feb 2003.

threshold (loss of physiological thermal equilibrium). The analysis of the RSI evolution during the SALLJEX heat wave showed that from 28 January it monotonically increased from 0.23, reaching 0.56 on 2 February. RSI indices were even higher at the time of the maximum temperature (not shown), increasing the levels of discomfort associated with the SALLJEX heat wave.

The temporal evolution of the surface temperature observed at Rosario was compared with those described by GDAS analysis and NCEP reanalysis (Fig. 5), in order to assess the ability of these datasets to reproduce the SALLJEX heat wave. Both analyzed datasets are able to describe the main features of the temperature evolution, although both failed in reproducing the right values of surface temperature during the SALLJEX heat wave, being in general smaller than observed. In agreement, Rusticucci and Kousky (2002), comparing NCEP reanalysis maximum and minimum temperatures with station data over Argentina, found that reanalysis data underestimate the intensity of the extreme warm events.

4. Intraseasonal variability

Figure 6 shows that the time series of the standardized daily temperature anomalies at Rosario not only exhibit the typical synoptic variability, but also exhibit considerable intraseasonal variability (as described by the 10–90-day filtered time series of temperature anomalies). Moreover, it is evident that the SALLJEX heat wave was embedded in an intraseasonal oscillation event that lasted from middle January to the beginning of February. In agreement, the spectral analysis of daily temperature anomalies at Rosario during the austral summer of 2002/03 (not shown) exhibited significant variability on intraseasonal time scales, particularly around 20-day periods.

The intraseasonal evolution associated with the SALLJEX heat wave was explored through the analysis of the 5-day means of 950-hPa temperature anomalies, and OLR, wind, and moisture fields at 850 hPa (Fig. 7). The pentad that extends from 29 January to 2 February 2003 was considered as representative of the SALLJEX heat wave, and the previous pentads were defined in relation to this one.

Between 19 and 23 January, weak positive temperature anomalies were observed over the subtropics (Fig. 7a). Convection was intense over tropical South America (Fig. 7b) with relatively strong low-level winds over Bolivia transporting moisture eastward into southeastern Brazil (Fig. 7c), where the South Atlantic convergence zone (SACZ) typically develops (e.g., Nogues-Paegle and Mo 1997). Warming conditions increased considerably over Argentina during the next pentad (Fig. 7d) associated with drier conditions in the vicinity of Rosario city. At that time, convection at the SACZ intensified (Fig. 7e), promoted by NW low-level winds flowing into the region (Fig. 7f). Between 29 January and 2 February, large positive temperature anomalies developed over Argentina (Fig. 7g). North-

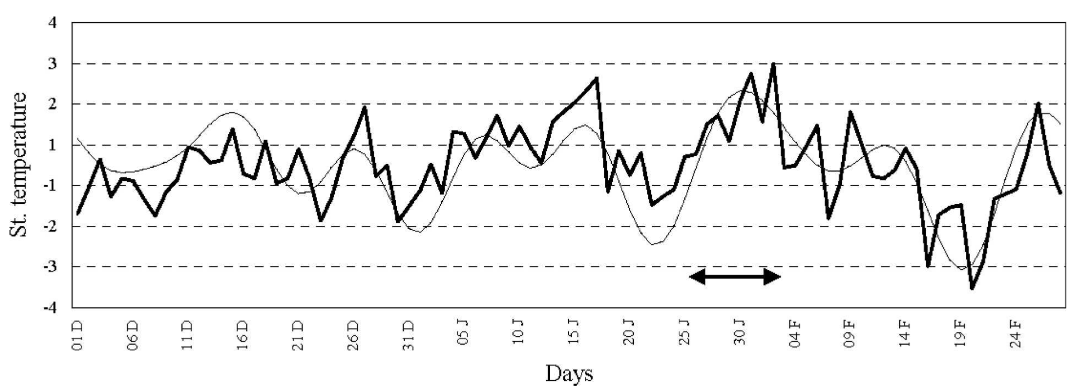

FIG. 6. 1200 UTC standardized surface temperature anomalies (thick line) and corresponding 10–90-day filtered anomalies (thin line) at Rosario city during austral summer 2002/03.

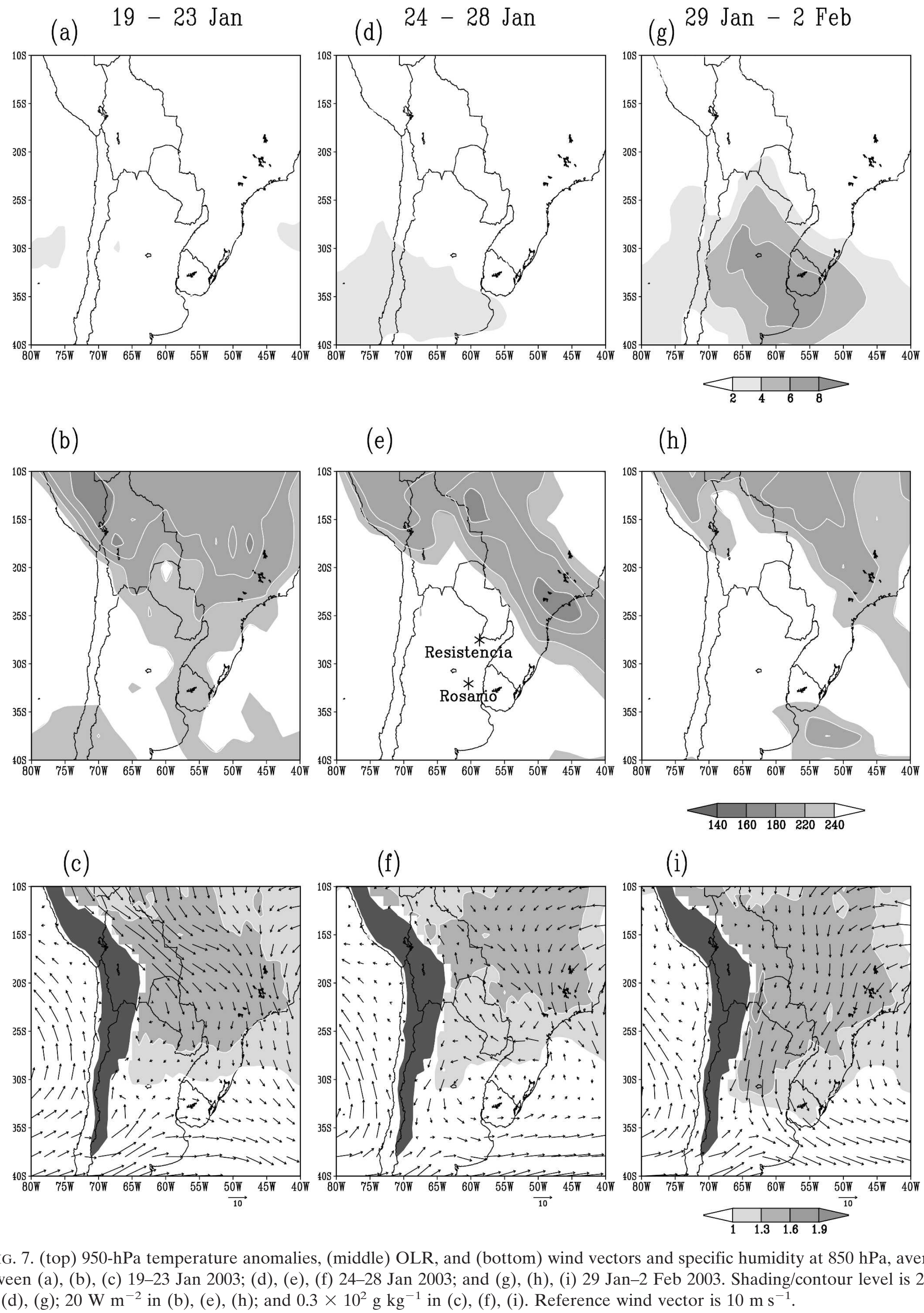

FIG. 7. (top) 950-hPa temperature anomalies, (middle) OLR, and (bottom) wind vectors and specific humidity at 850 hPa, averaged between (a), (b), (c) 19–23 Jan 2003; (d), (e), (f) 24–28 Jan 2003; and (g), (h), (i) 29 Jan–2 Feb 2003. Shading/contour level is 2°C in (a), (d), (g); 20 W m^{-2} in (b), (e), (h); and 0.3×10^2 g kg^{-1} in (c), (f), (i). Reference wind vector is 10 m s^{-1}.

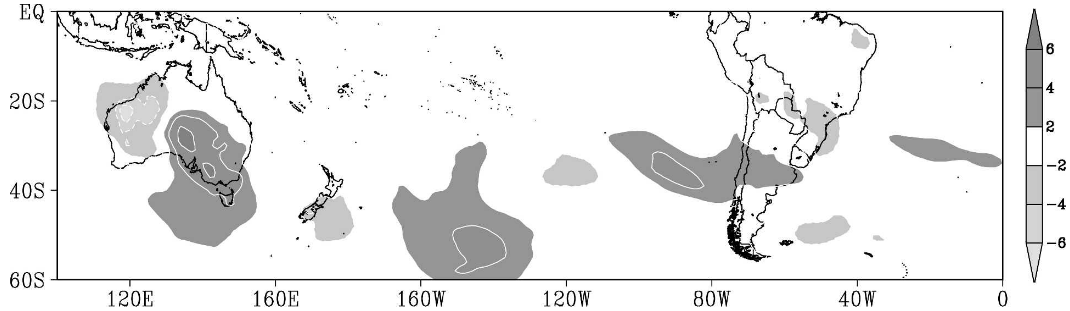

FIG. 8. 950-hPa temperature anomalies averaged between 24 and 28 Jan 2003. Shaded/contour level is 2°C, and the zero contour is omitted.

erly low-level wind anomalies were quite strong toward the subtropical regions where moisture increased considerably (Fig. 7i), while the convection over the SACZ region weakened considerably (Fig. 7h).

Both the circulation and OLR fields presented in Fig. 7 resemble those associated with the precipitation pattern known as the South America see-saw pattern (SASS; Nogues-Paegle and Mo 1997). SASS has been identified as the leading pattern of precipitation variability on intraseasonal time scales, and it is characterized by a dipolar structure. Enhanced precipitation over the SACZ, decreased rainfall in the subtropical plains, and a weakened SALLJ are the main characteristics of one of the SASS phases, like those displayed in Figs. 7d–f. On the other hand, the opposite phase is associated with a weakened SACZ, a southward intensification of the SALLJ, and increased rainfall at the jet exit (Figs. 7g–h). Therefore, the development of warm conditions over Argentina seems to be associated first with enhanced convection in the SACZ region and drier conditions at the subtropics, followed by a southward intensification of the SALLJ.

Previous works have shown that SACZ events may inhibit precipitation development over the subtropical regions due to compensatory subsidence mechanisms (Gandu and Silva Dias 1998). Cerne and Possia (2004) suggested that near the end of active SACZ periods, the temperature seems to increase over Argentina. Nevertheless, the impact of the subsidence mechanism on subtropical temperature changes has not been addressed yet and thus it will be explored for the SALLJEX heat wave in the rest of the note.

Temperature anomalies were also analyzed in a small-scale domain. Figure 8 shows a wave train extending from Australia to South America, linking the variability over South America with that over the western Pacific and SPCZ area, in agreement with previous works (e.g., Liebmann et al. 1999).

Figure 9 shows that the convection that occurred over the SACZ region between 24 and 28 January promoted subsidence conditions not only over central Argentina but also over eastern Brazil. The SALLJEX upper-air observations at Resistencia (27°27′S, 59°03′W) provided an excellent observational description of such subsidence conditions. On 22 January (Fig. 10a), the sounding shows moist conditions below 650 hPa associated with weak northerlies, while above, drier conditions and westerly flow are evident. Three days later, when the SACZ (Fig. 7e) and the associated compensatory subsidence mechanisms (Fig. 9) strengthened, the sounding displays very dry and warm conditions from surface upward, being particularly dry from 900 hPa (Fig. 10b). Greater stability from 650–900 hPa is also observed in the sounding compared with the previous one, presumably because of the increase in subsidence. By 31 January (Fig. 10c), the subsidence was weakened, the lower layer is more humid, and northerlies prevailed.

5. Synoptic wave activity

Besides the strong modulation of the temperature variability at Rosario by the intraseasonal oscillation activity observed in this case, synoptic wave activity also played a role in determining the main circulation

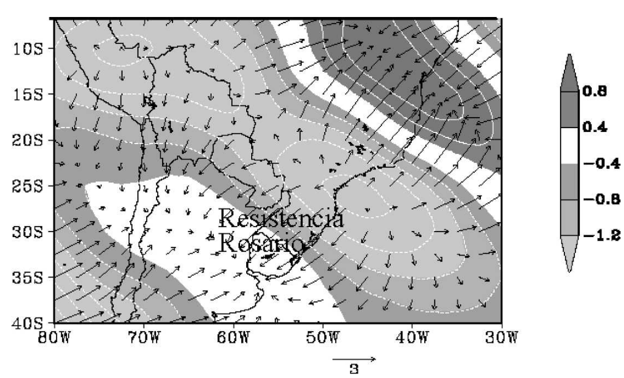

FIG. 9. Velocity potential anomalies (shaded) and divergent wind anomalies (vectors) at 200 hPa averaged between 24 and 28 Jan 2003. Shading/contour interval is 0.4×10^6 m^2 s^{-1}, and the zero contour is omitted. Reference wind vector is 3 m s^{-1}.

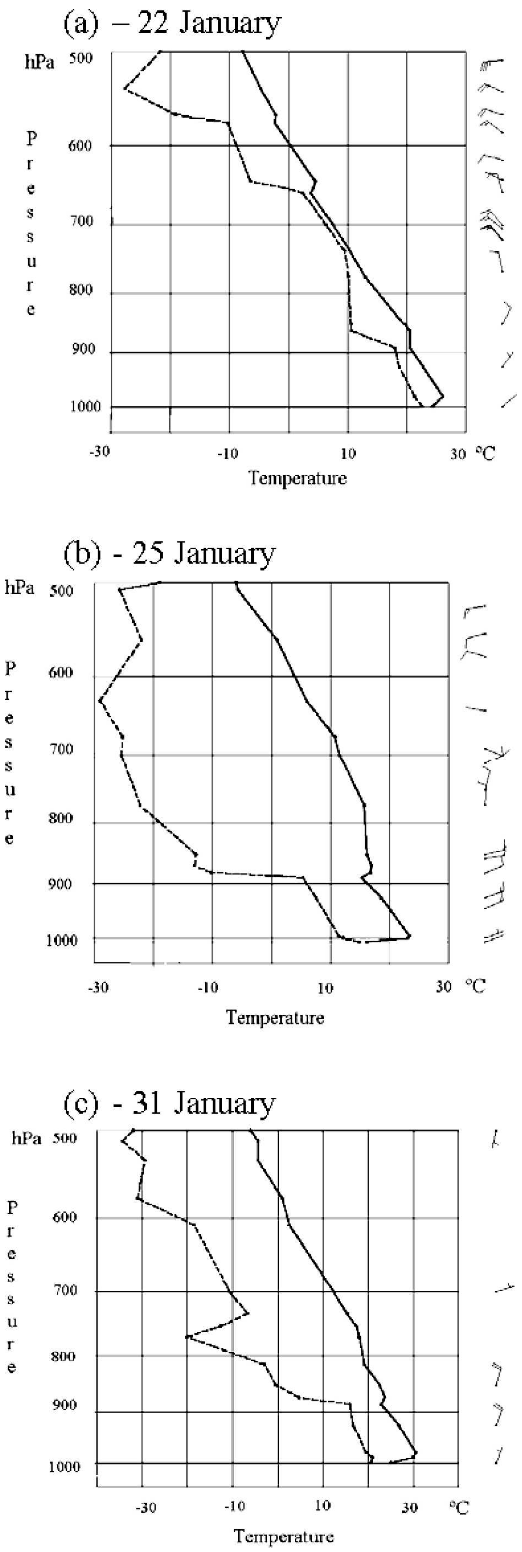

FIG. 10. Vertical profiles of temperature (°C; solid line) and dewpoint temperature (°C; dashed line). Wind velocities are represented by barbs (½ barb = 5 kt and 1 barb = 10 kt) at Resistencia station (27°27′S, 59°03′W) derived from SALLJEX radiosonde observations at 0600 UTC (a) 22 Jan, (b) 25 Jan, and (c) 31 Jan.

patterns that controlled the temperature changes. Figure 11 describes the synoptic conditions in the week preceding the occurrence of the temperature extreme of 2 February. On 27 January, the penetration from the South Pacific of an extratropical anticyclone into the continent (Fig. 11b) promoted additional subsidence in the extratropics besides that associated with the SACZ (Fig. 9). The Bolivian high was well developed over the eastern South Pacific, westward from its climatological position (Fig. 11a). The upper-level trough–ridge system, typically associated with the SACZ, was also well developed. On 29 January (Fig. 11d), the surface anticyclone moved over the southwestern Atlantic while a frontal system progressed eastward along the southern part of South America, linked with a distinctive cyclone located in the vicinity of the Antarctic Peninsula. By that time, the Bolivian high weakened as the extratropical trough over the southern tip of South America progressed eastward (Fig. 11c). On 31 January, the Bolivian high and the SACZ-related circulation considerably weakened as did the tropical convection (Fig. 11e). At lower levels, the extratropical front continued moving northeastward, promoting the strengthening of a low-pressure center over northwestern Argentina. This cyclonic feature, usually known as the "northwestern Argentinean low" (NAL; Seluchi et al. 2003), is, during summer, essentially a thermally driven system and seems to play a role in the southward intensification of the SALLJ (Saulo et al. 2004). By 2 February, the time at which the temperature extreme event occurred at Rosario, the northwestern Argentinean low continued strengthening and contributing to an intensification of the warm and moist northerly flow into central and eastern Argentina (Fig. 11h). The tropical circulation at upper levels is disorganized and the associated convection is rather weak (Fig. 11g). An extratropical upper-level trough remained over Patagonia contributing to intensify the low-level wind convergence over central Argentina. During the evening of 2 February, rainfall events occurred over eastern Argentina and temperature dropped 15.7°C in 6 h that night (not shown). Figure 6 shows that both the synoptic and intraseasonal signal of the temperature decreased considerably after 2 February.

6. Diagnosis of the thermodynamic energy equation

To identify the dominant mechanisms responsible for the occurrence of this extreme warm case, the terms of the thermodynamic energy equation were computed. This equation is expressed as

$$\underbrace{\frac{\partial \theta}{\partial t}}_{\text{A}} = \underbrace{-\mathbf{V}_H \cdot \theta}_{\text{B}} - \underbrace{\omega \frac{\partial \theta}{\partial p}}_{\text{C}} + \underbrace{\frac{1}{Cp}\frac{\partial Q}{\partial t}}_{\text{D}}, \qquad (1)$$

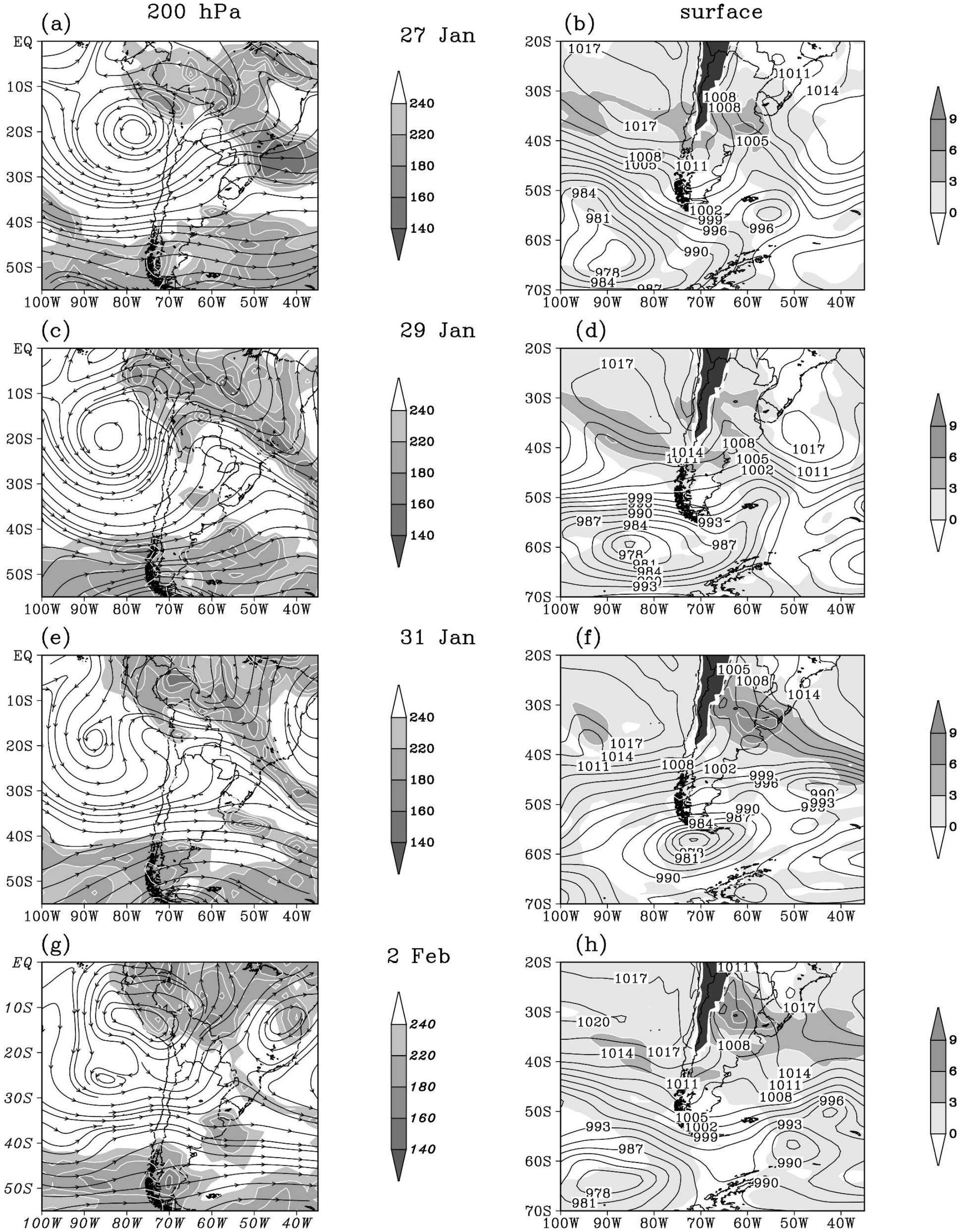

FIG. 11. (left) 200-hPa streamfunction (contour) and OLR (shaded), and (right) 950-hPa temperature anomalies (shaded) and sea level pressure (contour) at 1200 UTC (a), (b) 27 Jan; (c), (d) 29 Jan; (e), (f) 31 Jan; and (g), (h) 2 Feb 2003. OLR contour/shading interval is 20 W m^{-2} and only values smaller than 240 W m^{-2} are shaded. Contour interval is 3 hPa for sea level pressure. Shading interval is 3°C for temperature anomalies.

where A represents the potential temperature (θ) tendency, B the horizontal potential temperature advection, C the vertical potential temperature advection, and D the diabatic heating term. This last term includes the contribution of radiation, surface flux exchanges, large-scale condensation, and convection and friction; D was computed as a residual term of Eq. (1). Each term of Eq. (1) has been vertically integrated from surface up to 850-hPa level, as this layer is representative of the planetary boundary layer (not shown). Figure 12

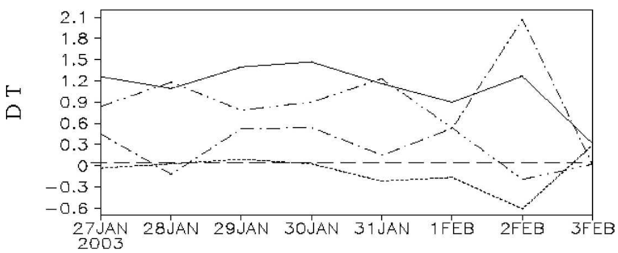

FIG. 12. Vertically averaged values [°C (6 h)$^{-1}$; between surface and 850 hPa] of the thermodynamic equation terms computed between 27 January and 3 February 2003: temperature tendency (solid line), horizontal temperature advection (dot–dashed line), vertical temperature advection (dashed), and diabatic heating term (dot–dot–dashed line).

displays the evolution of the different terms between 27 January and 3 February 2003.

The positive temperature tendencies occurring between 27 and 30 January were mostly associated with diabatic warming. Both the convection in the Tropics and extratropical anticyclone development (Figs. 11a–d), favored subsidence and clear sky conditions over Rosario. The intense sensible heat flux at the surface, promoted by the intense solar heating of the boundary layer and capped by a strong subsidence inversion, was responsible for the development of the heat wave. Between 31 January and 2 February, the horizontal advection term became dominant, favored by a strong northerly wind due to NAL intensification (Figs. 11e–h) that collaborated to weaken the contribution of the term C associated with the subsidence effect. Also, the diabatic warming started to decrease (likely due to an increase of cloudiness), and finally became negative. After 2 February, a cold air outbreak occurred that dropped markedly the values of both temperature tendency and temperature advection terms.

7. Conclusions

This note describes the main characteristics of a heat wave that occurred over central Argentina between 25 January and 2 February of 2003 that produced the highest February temperatures in the last 35 yr. Fortuitously, the SALLJEX experiment was occurring during this summer, which provided an unusually dense upper-level data coverage.

Temperature anomalies over central Argentina during that summer showed considerable variability on both synoptic and intraseasonal time scales. Moreover, it was found that the combined influence of synoptic waves and the intraseasonal oscillation (which resembled the known SASS pattern) contributed to set the warm environment over subtropical South America, favorable for the SALLJEX heat wave.

During the second half of January 2003, SACZ-like enhanced convection was observed over southeastern Brazil, which promoted dry and warm conditions over central Argentina. Associated subsidence favored clear-sky conditions, which in turn promoted intense sensible heat flux at the surface, resulting in the heat wave onset. SACZ activity was associated with a Rossby wave train extended between Australia and South America, suggesting an influence of tropical intraseasonal variability on the heat wave development. By the end of January the weakening of SACZ convection and the progressive intensification of the northerly low-level flow along the eastern slopes of the Andes into the subtropics contributed to decrease the subsidence conditions and to increase the warming processes by horizontal advection, resulting in a temperature peak that exceeded 40°C in central Argentina by the afternoon of 2 February. By the evening of that day, an extratropical anticyclone progressed into the region, causing a large temperature decrease on 3 February (in agreement with Garreaud and Wallace 1998).

The analysis of the vertically integrated terms of the thermodynamic energy equation confirms that intense heat flux at the surface, promoted by intense solar heating of the boundary layer capped by a strong subsidence, was responsible for the intensification until 31 January. After that, horizontal advection, associated with the southward intensification of the SALLJ and the enhanced NAL, was the leading term. Extratropical systems, SACZ development, and surface fluxes all contribute to heat wave occurrence. Numerical simulations separating the influences would be a useful methodology to assess the relevance of each term, but they are beyond the scope of this note and are included in future plans.

In addition, to our knowledge there are no previous studies addressing the influence of the intraseasonal evolution associated with the SACZ onto the daily temperature variability and temperature extreme event occurrence over this particular region. Therefore, future works are planned in order to assess whether the mechanisms discussed here are a more common characteristic of the tropical–extratropical interactions over South America, which would certainly contribute to increase the predictability levels in the region beyond the synoptic time scales.

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25269). We acknowledge the Environmental Research Service for supplying a free version of the RAOB to analyze the SALLJEX soundings. SALLJEX was funded by NOAA/OGP, NSF (ATM0106776), and funding agencies from Brazil FAPESP (Grant 01/13816-1) and Argentina (ANPCYT PICT 07-06671, UBACyT 055, and ANPCyT PICTs 99-76355 and 07-09950). NCEP—NCAR reanalyses and the OLR dataset were made available through the Climate Diagnostics Center (http://www.cdc.noaa.gov).

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