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Diurnal cycle in convergence patterns in the boundary layer east of the Andes and convection

Matilde Nicolini [a,b], Yanina García Skabar [a,c,d,*]

[a] Centro de Investigaciones del Mar y la Atmósfera, CONICET, Universidad de Buenos Aires, Pab. 2, 2ºPiso, Ciudad Universitaria, C1428EGA, Ciudad Autónoma de Buenos Aires, Argentina
[b] Departamento de Ciencias de la Atmósfera y los Océanos, FCEyN, Universidad de Buenos Aires, Pab. 2, 2ºPiso, Ciudad Universitaria, C1428EGA, Ciudad Autónoma de Buenos Aires, Argentina
[c] Servicio Meteorológico Nacional. 25 de Mayo 658, C1002ABN, Ciudad Autónoma de Buenos Aires, Argentina
[d] Facultad de Agronomía, Universidad de Buenos Aires. Av. San Martín 4453, C1417DSE, Ciudad Autónoma de Buenos Aires, Argentina

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ABSTRACT

The South American Low-Level Jet Experiment (SALLJEX) provided a unique dataset to investigate the existence of a mesoscale low-level circulation and of a diurnal cycle in its related convergence pattern over the Southeastern South American region east of the Andes, as well as its relationship with deep convection during the warm season. The present paper builds upon high-resolution analyses produced, assimilating the data collected during the SALLJEX field campaign using BRAMS, and explores their capability to reproduce mesoscale circulations not resolved by the low density observational network available in this region.

Results of the analyses show a diurnal oscillation signal in the mean boundary layer convergence pattern over the plains with a nocturnal (daytime) convergence (divergence) maximum. These results are coherent with previous findings of a nocturnal phase in the mature stage of organized deep convection and related precipitation in subtropical latitudes east of the Andes during the warm season. The diurnal cycle of convergence/divergence in the boundary layer is described over a 15-day period, during which different synoptic conditions occurred. During weakly forced environments a regime characterized by nocturnal eastward anomaly flow and convergence and daytime westward anomaly flow and divergence related to a mesoscale northwestern mountain–central plain flow regime dominates over the plains between the Andes Mountains, the Parana River Valley, and the southern Brazil mountain range. In contrast, during synoptic conditions dominated by the presence of a deep thermal low over northwestern Argentina and a related low-level jet, convergence at night is mainly accomplished by the predominantly meridional low-level jet, which exhibits an anomalous weak wind speed diurnal cycle with respect to its summer climatological mean. On the other hand daytime divergence is completely produced by the zonal wind component as in the previous synoptic situation. Mesoscale circulations are altered (still effecting mean divergence in the domain, which exhibits a diurnal oscillation) upon the initiation of deep convective circulations in the evening in an increasingly convectively unstable atmosphere driven by a persistent horizontal advection of heat and moisture at low levels and forced by convergence generated by the low-level jet and the presence of a frontal zone. Convection intensifies at night when its related convergence over the plains comes in phase with the convergence related to the nocturnal maximum in the low-level jet.

1. Introduction

Different processes related to the Andes mountain range and west-east gradients in surface characteristics influence the generation of mesoscale circulations that may be influenced by

* Corresponding author. Servicio Meteorológico Nacional. 25 de mayo 658, C1002ABN, Ciudad Autónoma de Buenos Aires, Argentina. Tel./fax: +54 11 51676767x18226.
E-mail addresses: nicolini@cima.fcen.uba.ar (M. Nicolini), yanina@smn.gov.ar (Y. García Skabar).

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surface friction and large-scale pressure gradients and may gradually force deep moist convection (Nicolini et al., 1987; Borque et al., 2010). These mesoscale circulations, often a response to slope-induced horizontal thermal gradients, are associated with divergence/convergence patterns in the boundary layer over the plains or over complex terrain (Ulanski and Garstang, 1978; Segal et al., 1989; Saulo et al., 2000; Pan et al., 2004; Barthlott et al., 2006, 2010; Kalthoff et al., 2009 and references therein).

This study used a set of analyses for a 15-day-long period included in the summer 2002-2003, during which the South American Low-Level Jet Experiment (SALLJEX) was performed in southeastern South America (Vera et al., 2006). SALLJEX aimed to monitor, quantify and analyze the low-level circulation over this region and its related precipitation typically located south of the South American Low-Level Jet (SALLJ, Nicolini et al., 2006), ahead of the maximum in wind speed where convergence dominates. The SALLJEX dataset provides a quantitative improvement in both spatial and temporal resolution over that of the operational network. Analyses were generated ingesting all available data with higher spatial and temporal resolution than that available for the region, following a downscaling methodology using the Brazilian Regional Atmospheric Modeling System (BRAMS).

With the purpose of advancing the study of the mechanisms that control the diurnal cycle of precipitation and convection in subtropical latitudes east of the Andes during summer, this paper focuses on exploring the diurnal cycle in mesoscale circulations within the boundary layer over northern and central Argentina that are not resolved by the low density observational network available in this region. The hypothesis is that nocturnal convergence over the broad valleys between the Andes Mountains, the Paraná River Valley, and the southern Brazil mountain range may be efficient in triggering or intensifying deep moist convection that may have started earlier during the afternoon if moisture was available and conditional instability prevailed (Nicolini et al., 1987). Different authors such as Nicolini and Saulo, 2006; Salio and Nicolini, 2006; Salio et al., 2007 showed evidence of a strong nocturnal phase in heavy precipitation and convection over central and northern Argentina. Besides lifting related to boundary layer convergence, the simultaneous existence of the other two ingredients necessary to initiate deep convection, namely, conditional instability and moisture availability, is also explored. The first question arises: Are the analyses with SALLJEX data (BRAMS-20) capable of reproducing a diurnal cycle of convergence/divergence as a means in the boundary layer? Other questions are: Can this diurnal cycle be related to a mesoscale northwestern mountains–central plain flow regime? Is there a relationship between the phase of convergence and of precipitation/convection in the area?

We also inquire the extent to which these circulations are sufficient by themselves to control deep convection or else other circulation patterns, more synoptically controlled like the ones related to strong SALLJ episodes, become more effective during the study period. Again, we investigate the relative timing of the onset and intensification of convection and of the diurnal oscillation in convergence related to these circulations. The paper is structured as follows: Section 2 describes the data, model and methodology used. A description based on BRAMS-20 of the synoptic evolution and occurrence of convection with emphasis in the low-level circulation, an analysis of the diurnal cycle in boundary layer convergence and divergence patterns in a reduced domain over northern and central Argentina and the relationship between this diurnal cycle and the timing of convection are presented in Section 3. Section 4 includes a summary and conclusions.

2. Data and methodology

2.1. Observations

The SALLJEX was conducted from 15 November 2002 to 15 February 2003, deploying a dense rain-gauge network and enhancing the spatial and temporal density of rawinsonde (RAOBS) and pilot balloon observations (PAOBS) in Southeastern South America (SESA). During the experiment RAOBS were made once a day at 06 UTC and PAOBSs, twice a day at 06 and 21 UTC. A special observation period (SOP) was held from 6 January to 15 February 2003, with 2 daily RAOBSs (06 and 21 UTC) and four daily PAOBSs in Argentina, Bolivia, Paraguay and Brazil. In addition, intensive observation periods (IOP) were defined, totaling to 23 days, with 3 or 4 RAOBSs and 8 PAOBSs per day at selected sites along the SALLJ axis. The location of observational stations is shown in Fig. 1.

To identify the convective systems and their life cycle, IR brightness temperature data were employed at half hourly intervals with horizontal resolution of 4 km over the area between 10°S–40°S and 40°W–75°W, data online at http://lake.nascom.nasa.gov/).

2.2. Methodology for analysis and data assimilation

Using the database of the SALLJEX, a set of analyses was generated for the warm season 2002–2003 assimilating all available data in the Global Data Assimilation System (GDAS) operational analyses from the National Centers for

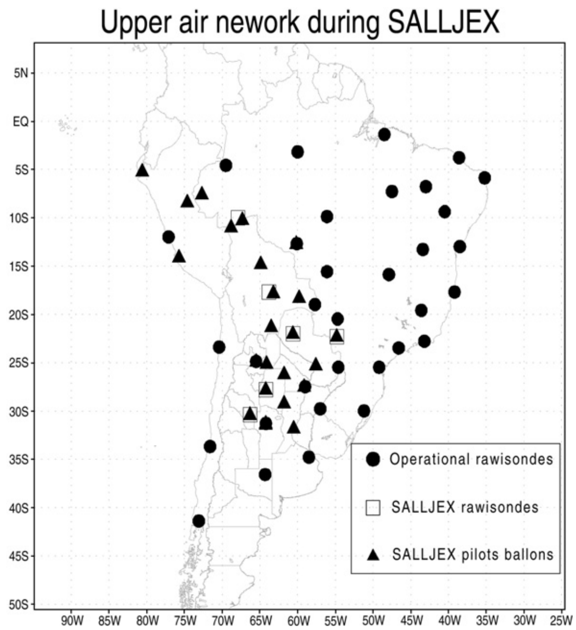

Fig. 1. Spatial distribution of upper air observations during SALLJEX.

Environmental Prediction (NCEP). These analyses improve the GDAS spatial and temporal resolution. The BRAMS model (Brazilian Regional Atmospheric Modeling System, Cotton et al., 2003), in its version BRAMS-3.2 (Freitas et al. (2009) and the BRAMS website (www.brams.cptec.inpe.br)), was used to generate the analyses BRAMS-20 for the present study. The data assimilation methodology included in the model, known as 4-D data assimilation scheme of the type "analysis nudging" was used. This technique modifies the model fields both at the points where there are observations and at the entire grid. This procedure makes it possible to obtain 3-hour-interval analyses with a resolution of 80 km for almost all South America and with a resolution of 20 km for the nested region comprising the center and north of Argentina and Chile, Uruguay, Paraguay, southern Bolivia and Southeast Brazil (Fig. 2). Twenty-nine vertical levels are used, with 18 levels in the first 12 km and the top of the model was located at approximately 23 km. The assimilation process started on 13 November 2002 and was carried out continuously in order to keep memory of previously assimilated data. The data assimilated are surface and upper level operational network, rawinsonde and special pilot balloon observations collected during the SALLJEX. Before assimilation, coherence analyses were performed on the datasets. A more detailed description of the methodology used to obtain the BRAMS-20 analyses can be found in the work of García Skabar and Nicolini (2009).

This paper aims at investigating the existence of a signal in the diurnal cycle of divergence–convergence patterns, and as only wide convergence zones are expected to be resolved given the low vertical and horizontal resolution of the analyses to reproduce fine horizontal-scale patterns and vertical structure, only vertically averaged boundary layer values are analyzed. Despite these limitations in resolution, Borque et al. (2010) have successfully compared the wind, temperature and dew point analysis profiles with real soundings within the boundary layer pointing out that the vertical structure was better represented by BRAMS-20 than by GDAS.

In order to calculate the mean boundary layer divergence fields during the study period, the height of the boundary layer was determined as the level where the vertical potential temperature gradient exceeds 1,7°/km—this value was selected as a threshold for transition to a more stable layer above. As expected, the obtained heights display a diurnal variability with minimum values at night. Given the low vertical resolution in the analyses, the minimum nocturnal value was set at 900 m, which approaches the maximum nocturnal height attained during the 15-day period (see a virtual potential temperature vertical-longitude cross section at 25°S and 12 UTC and vertical profiles at this latitude and 62°W in Fig. 3). Also, Borque et al. (2010) in an analysis of the environment associated with moist convection on 6 February 2003 found that the height of the boundary layer to the north of the convective area was closely related to the level at which maximum wind speed occurred and determined a diurnal oscillation between 2000 m at 18 UTC and as high as 1200 m at 06 UTC of the following day. Divergence values are vertical averages within the boundary layer for each grid point.

3. Results

3.1. Synoptic-scale analysis

The present study is organized around a two-week period during SALLJEX (since January 24 up to February 7/2003) that followed a cold incursion and during which different environmental conditions prevailed. A heat wave occurred between 25

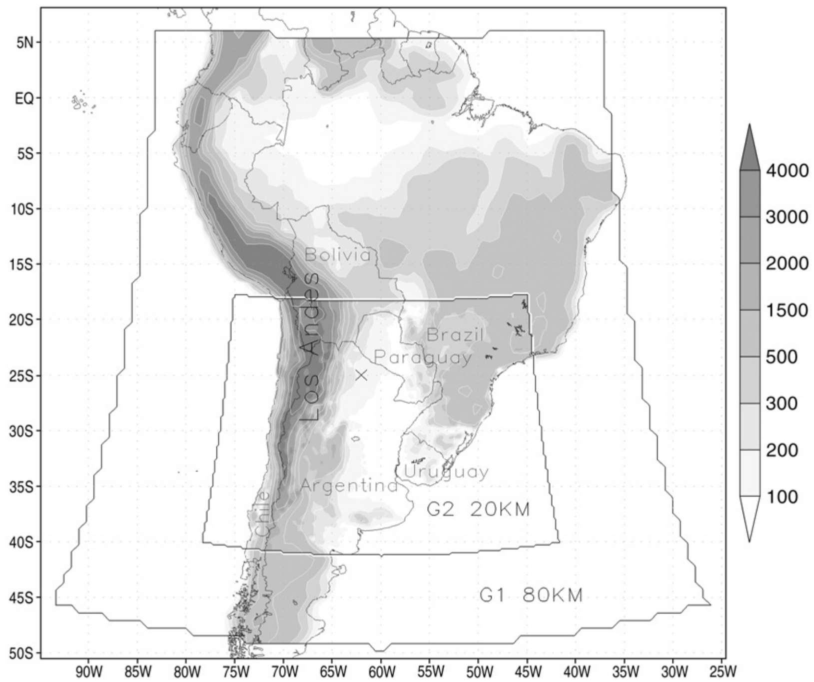

Fig. 2. Nested domains over South America and adjacent oceans. Topography is shaded and indicated in meters. A cross indicates the location of the vertical profile in Fig. 3.

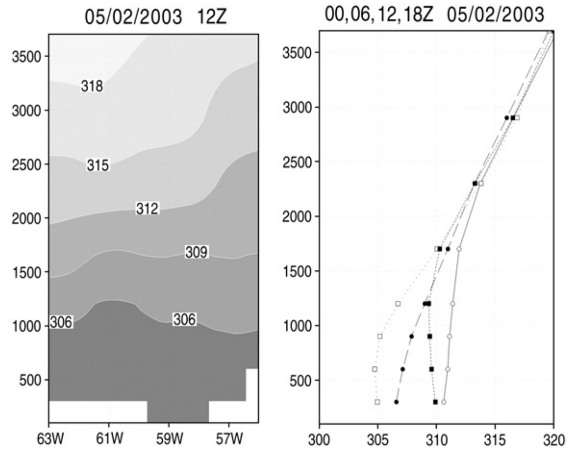

Fig. 3. Virtual potential temperature (°K) for February 5. Left: vertical cross section at 25°S at 12 UTC. Right: vertical profiles at 25°S 62°W at 00 (solid line), 06 (long dash), 12(dotted) and 18 (short dash) UTC. The altitude is indicated in meters.

January and 2 February 2003, producing the highest February temperatures over Argentina in the last 35 years. It was documented by Cerne et al., 2007. These authors found an intraseasonal oscillation with an intensified South Atlantic Convergence Zone (SACZ, Nogués-Paegle and Mo, 1997) during the period January 24 to 28. They identified subsidence and diabatic warming in the subtropical boundary layer as the main processes related to the strong SACZ presence that favored relatively dry conditions over central Argentina.

The following synoptic description centers the analysis on the 27 January and 2 February as dates representative of the synoptic-scale situation prevailing during the first and the second half of the period, respectively.

During the mid-afternoon hours of 27 January 2003, a weak and quasi-stationary surface frontal zone aligned across Argentina at mid-latitudes was apparent in a gentle gradient in the 500/1000 hPa geopotential thickness field collocated with a sharp transition in the winds at 1000 hPa level (Fig. 4). Coherent with a cyclonic circulation centered around 53 W over southern Brazil, the region northward of the cold front was dominated by a weak south–southeasterly flow. Accordingly, relatively cold and dry air dominated the region (see the mixing ratio field at the 850 hPa level in Fig. 4) with the warm air receded to low latitudes over Brazil. On 27 January the western border of the surface anticyclonic circulation that followed the earlier frontal zone was characterized by northerly geostrophic winds. This circulation was related to the building of a still weak thermal-orographic low pressure system over northwestern Argentina, close to the eastern slopes of the Andes (Northwestern Argentina Low (NAL, Seluchi et al., 2003)). Mid-level analysis featured a prevailing southerly flow in advance of a pronounced NW–SE oriented ridge axis over central Argentina (Fig. 4, see 500 hPa geopotential and relative vorticity fields). Mid-level and upper level forcing for convection over the plains was negligible.

No convection developed over the subtropics before January 27. Convection initiated during the afternoon of the following day over the Andes and to the south of 35°S, over the east of the Andes. The generation of convection was favored by orographic lifting, convergence related to the quasi-stationary frontal zone and horizontal warm advection limited to a narrow region just east of the Andes. Convection evolved and dissipated during the night. There was no convective available potential energy (CAPE) over the plains north of this latitude and CIN values exceeded 250 J/Kg (not shown).

This synoptic situation was followed as from 31 January (second half of the period) by the dominance of a low-level jet (with its maximum oscillating around 25 S) strongly dominated by the evolving NAL circulation pattern. So far, previous studies indicate that the SALLJ is a central component of the tropical–extratropical exchange in South America, transporting humidity from the Amazon basin to the La Plata basin (Seluchi and Marengo, 2000) and increasing precipitation at the exit area of the jet. These studies also show that, although the SALLJ is an almost permanent pattern in the summer circulation, its meridional extension is highly variable. Salio et al. (2002) and Nicolini and Saulo (2006), recognized that the SALLJ penetration into high latitudes is associated with a deepening of the NAL and with a negative geopotential anomaly immersed in midlatitude baroclinic wave trains. Saulo et al., 2005 identified a deep NAL between 31 January and 6 February 2003, whose duration was anomalously long and which dominated the poleward penetration of the SALLJ. A predominant thermal component to the deepening of the NAL (limited by the −40 mgp contour at the 1000 hPa level on 2 February; see Fig.4) is apparent in the warm area in the 500/1000 hPa geopotential thickness field. Saulo et al., 2005 explained this deepening of the NAL mainly by high sensible heat flux values complemented by heating through orographic subsidence and the warming to the east of the NAL by warm advection. This deepening of the NAL forced a marked SALLJ penetration toward high latitudes, evident in the 850 hPa wind field with wind speed maxima throughout a region reaching as far south as 34 S (Fig. 4). This low-level jet core is located unusually southward of its warm season average position (around 17 S) found both in reanalyses and higher resolution forecast products (Douglas et al., 1998; Saulo et al., 2000; Marengo et al., 2004). This placed the central Argentinean region within a broad northerly flow of very warm, moist and increasingly unstable air. CAPE values increased during the day attaining magnitudes that exceeded 3000 J/Kg (not shown) at 18 UTC in a longitudinal band along 62 W from 26 to 33 S collocated with the low-level jet axis. A remarkable fact in the figure is the southward penetration of mixing ratio values higher than 15 g/kg at the 850 hPa level, which provided one of the ingredients necessary to initiate deep convection. No upper level forcing for the rising motion east of the Andes related to differential vorticity advection is evident from the geopotential height fields at low and mid levels, illustrated in Fig. 4.

The warm and moist advection to the east of the NAL that began to prevail from 31 January created the environmental conditions that gradually allowed convection to develop. A significant directional vertical wind shear might have contributed to the organization of convection. Mesoscale convective systems (MCSs) first developed on 2 February over the plains, south of 33 S, displaying a line structure during the night hours of 3 February-00TC to 12 UTC. During the following days, organized convection reached lower latitudes following the shifting of the NAL toward the NW and the withdrawal of the LLJ maximum toward the typical position that characterizes intense SALLJ events (around 22 S). Convection over the mountains started in the late afternoon of 2 February and propagated and intensified over the plains at night. An intensification of the stationary front

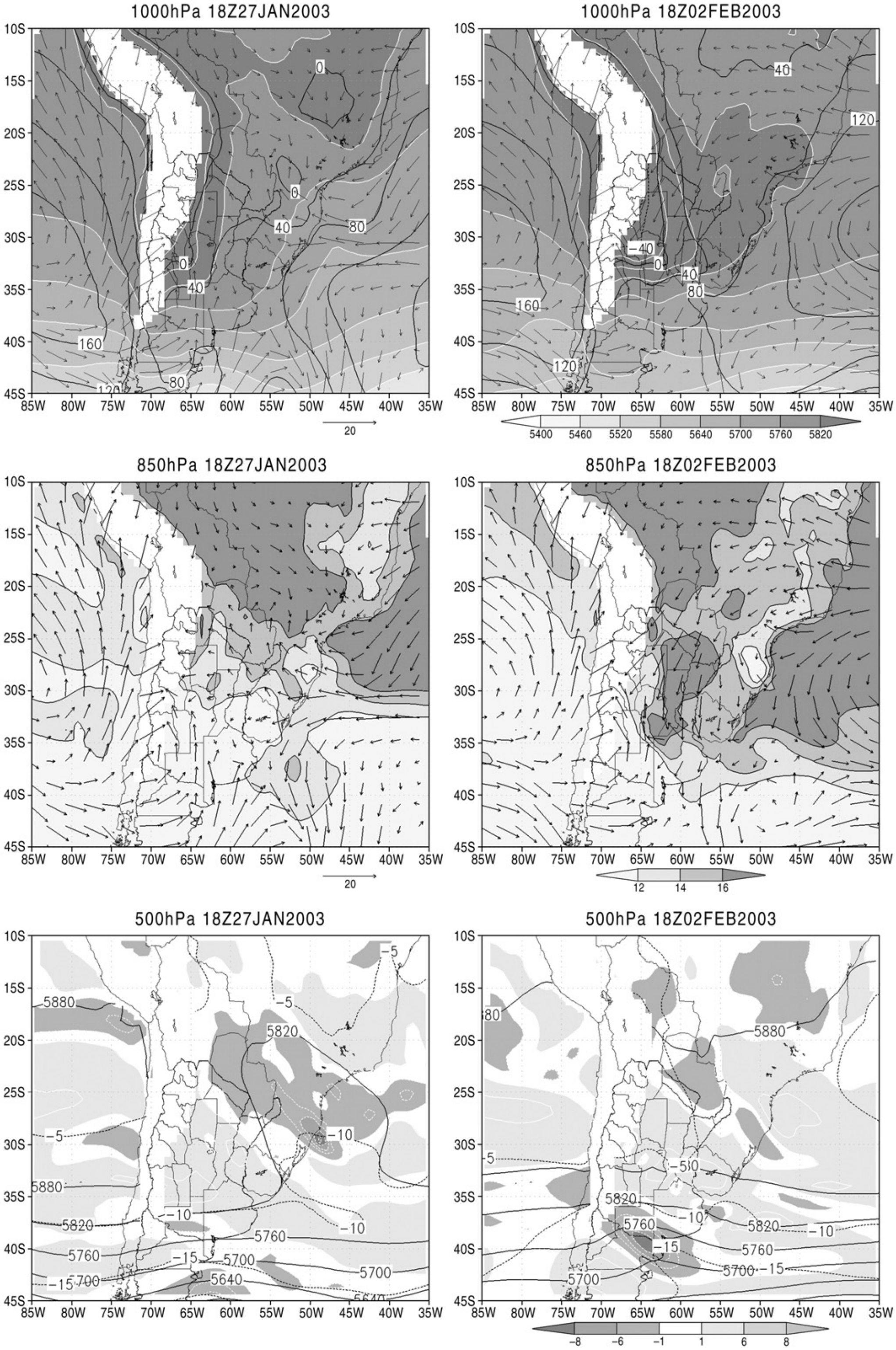

Fig. 4. Upper panels: 1000/500 hPa thickness (dmgp)(shaded), 1000 hPa geopotential height (mgp)(contours) and wind vector (m/s)(arrows). Center panels: 850 hPa wind vectors (m/s)(vectors) and mixing ratio (g/kg)(shaded). Lower panels: 500 hPa geopotential (mgp)(contours) and relative vorticity ($1/s*10^5$) (shaded). Left panels for January 27, Right panels for February 2nd, both at 18 UTC.

at 35 S and a new strengthening of the NAL during 6 February enhanced convergence which had developed from the merging of stronger and more severe MCSs. The propagation of the cold front together with a change in the orientation of the SALLJ from a prevalent meridional to a NW–SE orientation dominated at the end of the period.

3.2. Diurnal cycle in boundary layer divergence patterns east of the Andes

Fig. 5 shows the vertically averaged boundary layer divergence/convergence patterns for 27 January 2003 at 09 UTC (06 LST) and at 21 UTC (18 LST), representative of nighttime and daytime hours, respectively. The domain is limited by 20 S–70 W and 35 S–50 W, where organized convection typically prevails over SESA (Salio et al., 2007). A diurnal variation in this field is apparent during this day, which is representative of the period 24 January to 30 January. The variation is dominated by a persistent anticyclonic circulation. This field exhibits a marked diurnal cycle in divergence related to mesoscale zonal circulations coherent with a mountain/broad plain breeze regime with convergence prevailing over the plains at night. In contrast, the meridional component of the flow mostly opposes to convergence at night, whereas in the afternoon both wind components contribute to a

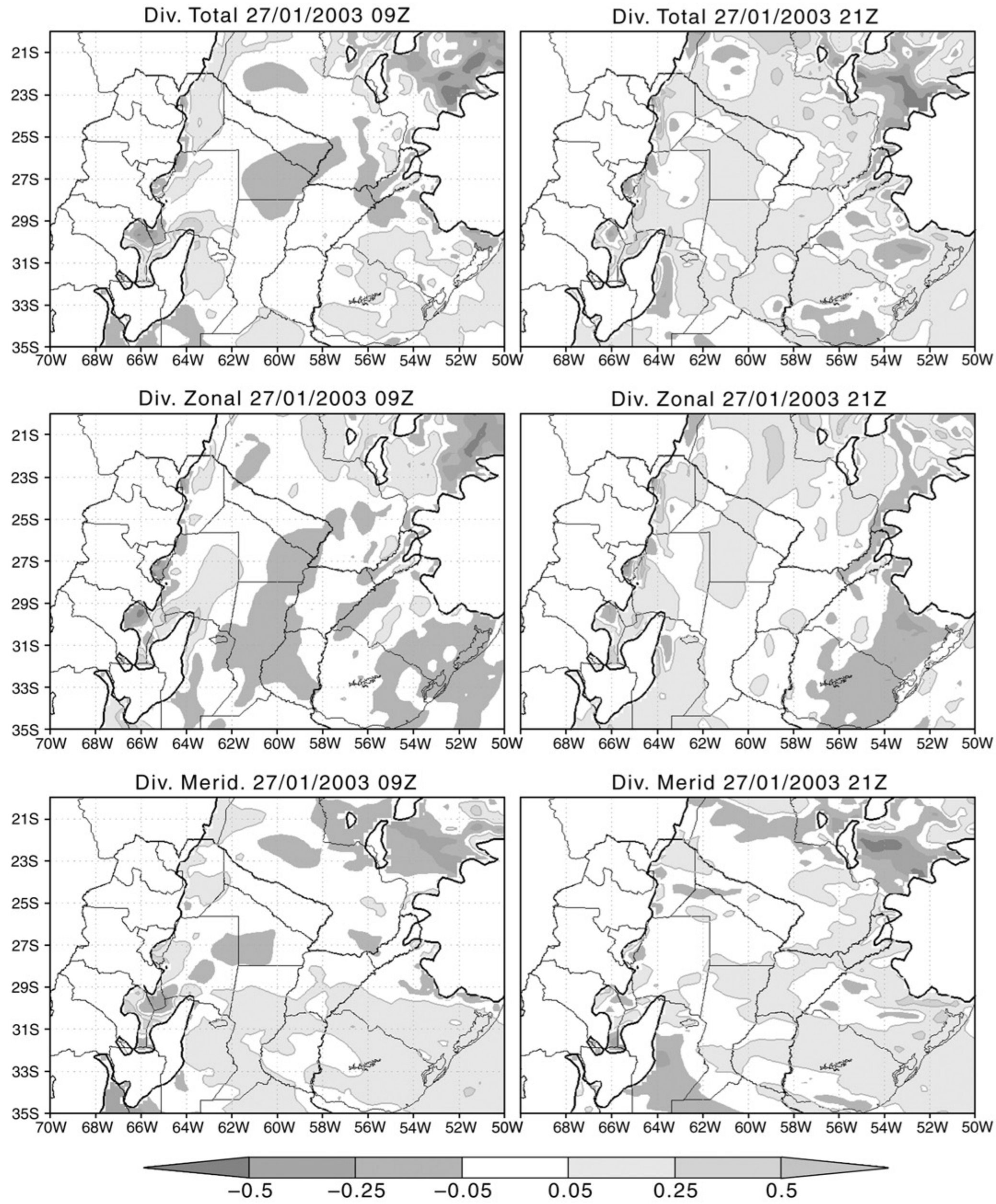

Fig. 5. Vertically averaged boundary layer divergence ($1/s^*10^4$) from top to bottom: total, zonal and meridional components for January 27. 09 UTC, left panels, and 21 UTC, right panels. No calculations were made for mountain areas higher than 500 m (white shaded and black contoured).

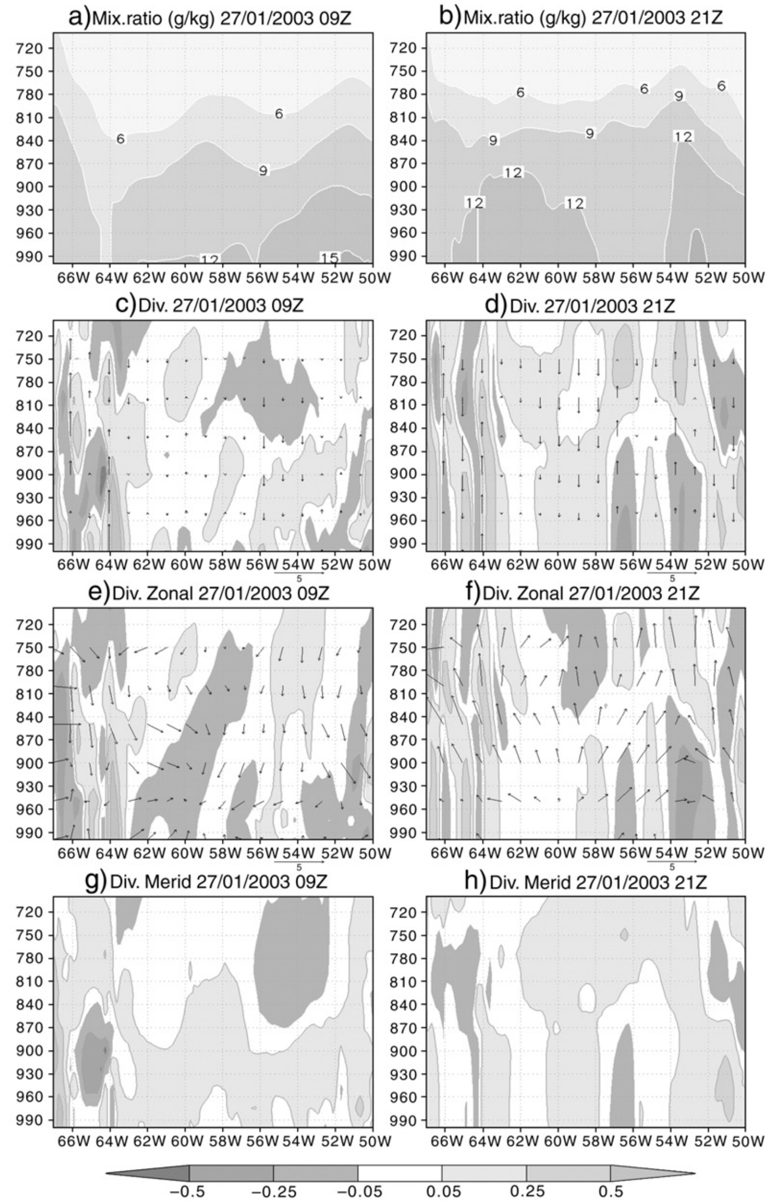

Fig. 6. Vertical cross section at 30°S from top to bottom: a) and b) mixing ratio (g/kg), c) and d) total divergence and vertical wind component (vectors) (cm/s), e) and f) zonal divergence and anomaly from the diurnal mean horizontal wind (vectors) (m/s) and g) and h) meridional divergence ($1/s*10^4$) (shaded) for January 27th, left panels at 9 UTC, right panels at 21 UTC.

net divergence. A persistent and strong convergence is present at both times in the northeastern corner of the domain related to the cyclonic circulation present over southern Brazil.

A vertical cross section at 30 S is presented in Fig. 6 in order to emphasize the vertical structure of divergence and the anomaly from the diurnal mean wind components over the Argentinean plains (mostly between 58 W and 65 W) within and above a diurnally varying boundary layer at the same times as in Fig. 5. The vertical structure exhibits a diurnal variability in the zonal component (weakening of the easterly component at night and strengthening during daytime). A weaker signal in the meridional component contribution is apparent in Fig. 6, southerlies dominate the meridional component anomaly at daytime. Convergence and rising motions at night closer to the mountains are accomplished by northerlies that are stronger than the diurnal mean and dominate also in the other longitudes. Backing of the wind vector during nighttime was recognized in the region in previous studies (Saulo et al., 2000, among other authors) and is consistent with a diurnal variation in eddy viscosity that induces an inertial oscillation in the winds (Blackadar, 1957).

A vertical cross section of the mixing ratio field at the same latitude shows nocturnal values not exceeding 12 g/kg over Argentina and slightly increasing in the afternoon.

At night, even if convergence and rising motion are positively contributed by the mesoscale component that opposes large-scale subsidence, the total vertical velocities are less than 0.5 cm/s (around 60 W). This weak rising motion and the prevalent dry and stable conditions inhibit nocturnal convection in the area. The increase in moisture availability during the afternoon is counteracted by divergence and subsidence (Fig. 6), again creating conditions not favorable for daytime convection over the northern plains. Southward (around 37 S) convection is triggered in the evening of the day before and intensified at night (first hours of January 27) supported by meridional convergence in a narrow belt near the Andes, combined with convergence related to a quasi-stationary frontal zone at 37 S. Convergence over the mountains, related to zonal mesoscale circulations from 25 S to 32 S, starts to develop localized deep convection evident in the IR brightness temperature data for 19 UTC of January 27. This convection dissipates at night (not shown). Fig. 7 displays the absence of precipitation east of the Andes, except in the SACZ area located in the northeastern sector of the domain, where 6-hour accumulated precipitation values larger than 25 mm are reproduced both at nocturnal and daytime hours by BRAMS-20. Satellite estimations of accumulated precipitation compare satisfactorily well with BRAMS-20 fields (not shown).

The second half of the period (January 31 to February 7) was characterized by the presence of a well defined thermal low and a strong and substantially shifted to the south SALLJ with respect to its average summer position. The divergence patterns differ from the ones described for the first part of the period. At night, the vertically averaged ABL convergence/divergence in the area (Fig. 8) shows that the meridional component (more efficient to advect moisture) dominates (over the zonal one) in the contribution to the convergence line located southward of 33 S. This convergence region, mainly contributed by the poleward low-level jet, persists during daytime and propagates and intensifies during the following night covering an increasing area. The vertical structure of the meridional contribution at night, represented in the vertical cross section in Fig. 9, displays convergence extending up to the height of the boundary layer over Argentina and rising motions westward 60 W. While this structure persists in the afternoon, divergence and subsidence prevail eastward 62 W in a deeper layer. This divergence is due to the fact that the latitude of this section is located still in advance of the main convergence line and northward the southern core of the LLJ (Fig. 4). The presence of the broad warm area to the east of the NAL after maximum radiative heating and the extension of the NAL itself that attains its minimum pressure around 21 UTC (Fig. 4) are associated with the maximum in wind speed. This maximum extends after 12 UTC farther south of 30 S, evidencing the geostrophic nature of the late afternoon LLJ at this latitude. This weakening in the diurnal cycle of the LLJ that typically presents a nocturnal maximum at lower latitudes was previously found by Seluchi et al. (2003) and Saulo et al. (2004) in a summer NAL situation. Convergence and rising motions develop with an increasing horizontal and vertical extension and become stronger in the following 12-hour period (almost 10 cm/s). This intensification is substantially affected by the deep convection that developed and organized over the area. The contribution of zonal circulation is less evident in the net divergence pattern, particularly below 850 hPa, and the wind anomaly from the diurnal mean and its diurnal variability differ from the one described for January 27. BRAMS-20 was able to reproduce the precipitation field and its propagation within the domain (Fig. 10), consistent with the location of the organized convection observed in brightness temperature images (Fig. 11) and the accumulated precipitation field estimated by satellite (TRMM 3B42RT, Huffman et al., 2007), (see Fig. 10).

Higher moisture values favored by moist horizontal advection during this period (Fig. 9) and convergence related to the leading edge of the LLJ ahead a propagating frontal zone were efficient to trigger convection in the afternoon at 35 S. This convection propagated northward and intensified during the following night (Fig. 11). Accordingly, the convergence pattern is in phase with the time of maximum intensity of convection (09 UTC).

Segal et al. (1989) and Souza et al. (2000), among others, have recognized the role of surface heterogeneities in continental regions on the generation of mesoscale circulations. BRAMS-20 reproduces these inhomogeneities incorporating topographic, land use and vegetation, soil types and soil moisture data. These heterogeneities may possibly mask the orographic effects, which should manifest primarily as a nocturnal drainage/daytime upslope flow between the elevated area to the northwest and the eastern lowlands. The intensity and spatial scale of this circulation depends primarily on the characteristics of the complex terrain and is more easily identifiable in conditions of weak synoptic-scale flow (similar to those prevailing in the first half of the study period). Our divergence fields suggest a prevalence of the orographic effect due to the presence of the meridionally extended Andes mountain range over the obscuring effect of large spatial inhomogeneities over areas typically small. It is of particular relevance to recognize the possible existence of a dominant orographic signal in the scale of the study domain

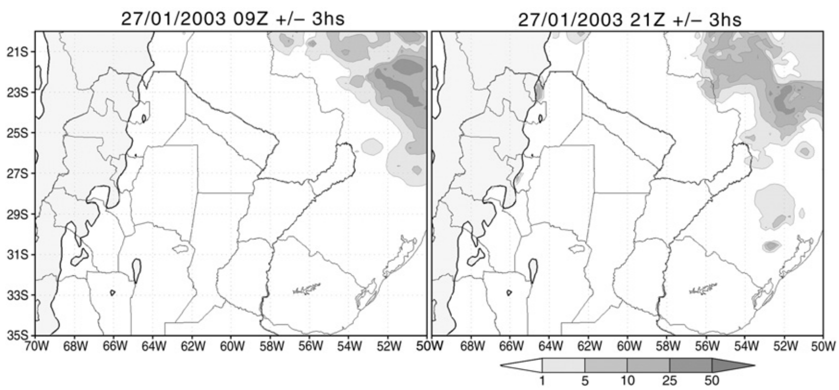

Fig. 7. BRAMS-20 6-hour accumulated rainfall for January 27. Left: from 06 to 12 UTC, right: from 18 to 00 UTC .

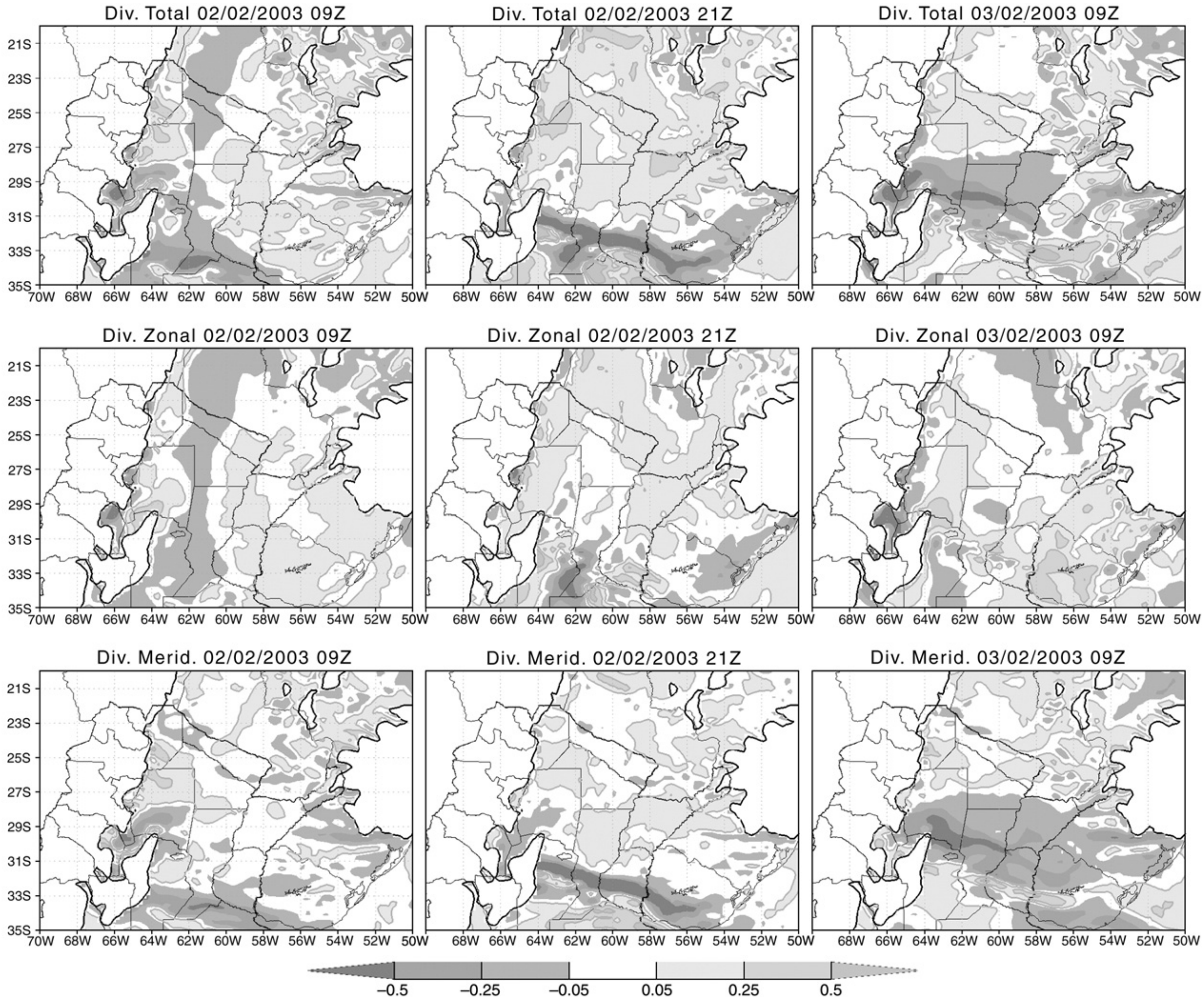

Fig. 8. Vertically averaged boundary layer divergence ($1/s^*10^4$) from top to bottom: total, zonal and meridional. From left to right: for February 2nd at 09 UTC, February 2nd at 21 UTC and February 3 rd at 09UTC. No calculations were made for mountain areas higher than 500 m (white shaded and black contoured).

associated with the normal to the Andes barrier component of the boundary layer divergence and explore its magnitude relative to that of the parallel component. In order to accomplish this, we calculated the average values in the domain of the zonal and meridional components and their total value. Besides, it is of interest to analyze the evolution of these three variables over the entire period of study in terms of the evolution of the synoptic scale circulation.

The temporal evolution of the overall domain mean divergence during the whole period displays a diurnal oscillation with maximum divergence at 18 UTC and maximum convergence between 03 and 12 UTC with stronger divergence values (upper panel in Fig. 12). Superposed to this diurnal cycle the evolution denotes a larger scale tendency to decrease since January 31 (beginning of the stronger synoptic period) and a dominance of convergence at 09 UTC (relatively weaker in magnitude especially during the first synoptic period). The 24-hour mean divergence is coherent with the prevailing anticyclonic conditions over the domain, which do not revert before the end of the period. The middle panel shows the net convergence at night (09 UTC) mostly responding to the zonal component up to January 29, followed by an evolution dominated by the meridional component with a weak opposite contribution from the zonal one. The afternoon evolution still shows during the first period a dominance of the zonal component that forces divergence. This dominance, in contrast with the nocturnal behavior, persists in the second half of the period, during which the meridional component opposes contributing to convergence. The onset of convection at this time is mainly related to this last component that prevails in the southern part of the domain.

This result shows that the orographic effect in the zonal circulation becomes evident during the first part of the period, when anticyclonic conditions without strong synoptic forcing dominate. In the second part, however, the presence of the meridional northerly component dominates over the local breeze in forcing night time convergence. Although weaker, this effect persists in the afternoon hours when zonal divergence governs. It

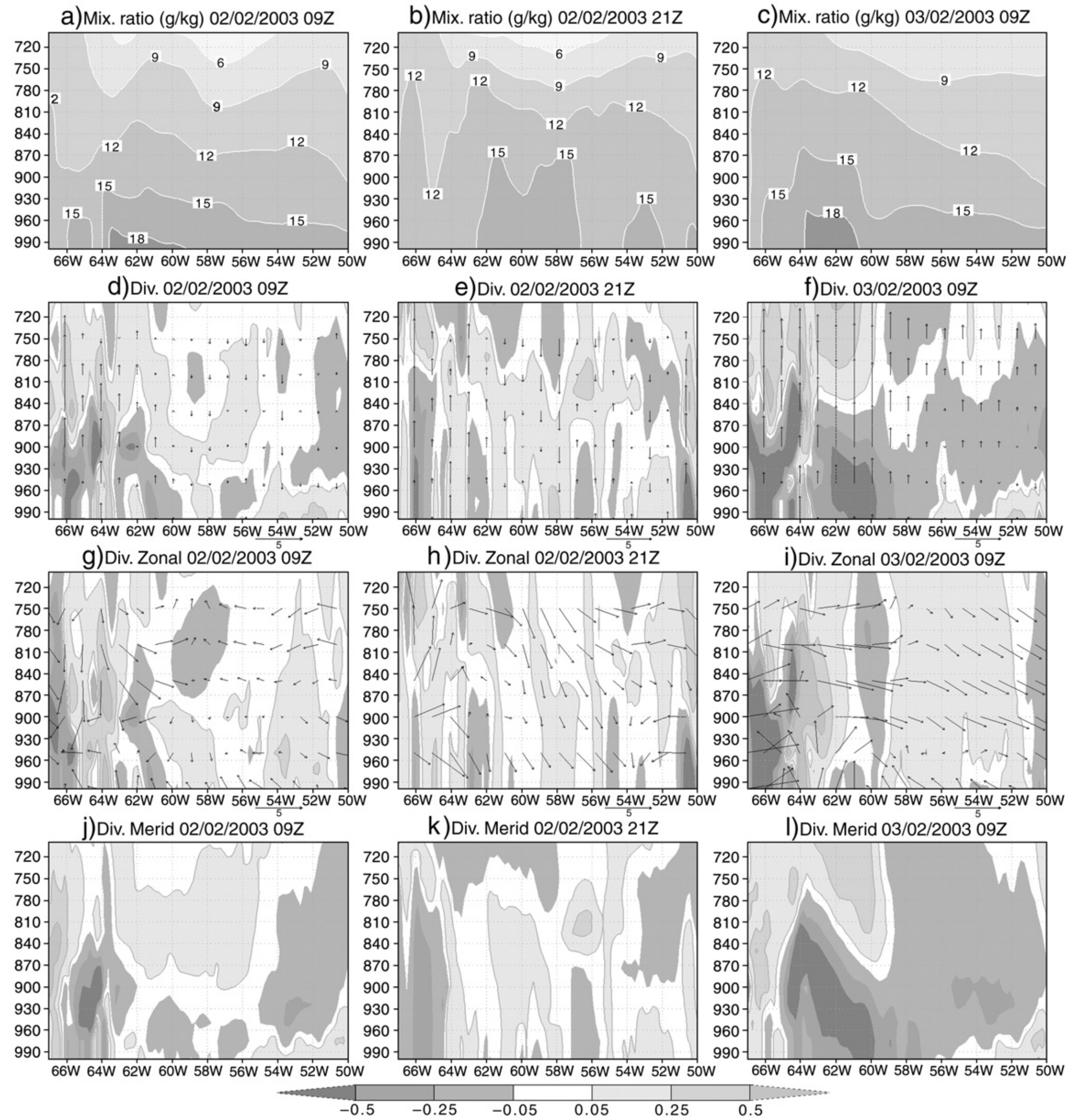

Fig. 9. Vertical cross section at 30°S from top to bottom: a)–c) mixing ratio (g/kg),d), e) and f) total divergence and vertical wind component (vectors) (cm/s), g)–i) zonal divergence and anomaly from the diurnal mean horizontal wind (vectors) (m/s) and j)–l) meridional divergence ($1/s^*10^4$) (shaded). From left to right: for February 2 at 09 UTC, February 2 at 21 UTC and February 3 at 09 UTC.

is only in areas where frontal zones or LLJ-related convergence dominate, that such mesoscale dynamic processes come to phase with the diurnal cycle of close-to-surface thermal stratification, which imposes more unstable conditions during radiative heating hours- allowing convection to start in the afternoon.

4. Summary and conclusions

Summarizing, the results based on BRAMS-20 for the period January 24 to February 7, 2003 indicate that during weakly forced environments characterized by anticyclonic circulation, a boundary layer regime dominates, characterized by nocturnal eastward anomaly flow and convergence and daytime westward anomaly flow and divergence over the plains. Even if this regime favors rising motions at night, stability and low values of specific humidity inhibit the development of convection. In contrast, during stronger environments (SALLJ conditions), diurnal oscillation in divergence exhibits no reversal of sign in both wind components. Daytime divergence is completely dominated by the zonal component while nocturnal convergence responds to the meridional component. During February 2, 2003 when convection initiates in the late afternoon and evening a persistence in convergence occurs downstream the predominantly meridional low-level jet which exhibits an

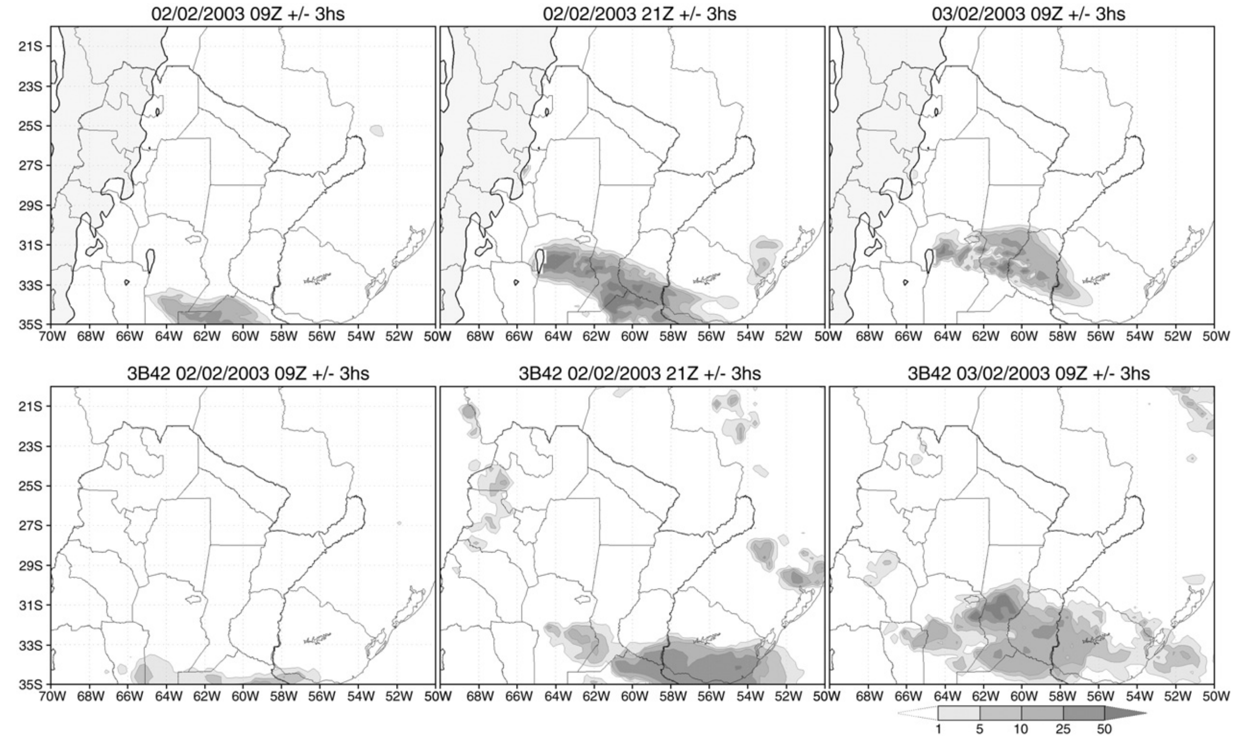

Fig. 10. Upper panels: BRAMS-20 6 hours accumulated rainfall. Lower panels: 3B42 accumulated precipitation estimation. From left to rigth: 06 to 12 UTC February 2nd; 18 UTC February 2nd to 00 UTC February 3rd; 06 to 12 UTC February 3rd.

anomalous weak wind speed diurnal cycle with respect to its summer climatological mean, whereas daytime divergence is completely accomplished by the zonal wind component.

Consistent with our results, Salio et al. (2007) identified low-level convergence effected (as in the period selected for the current work) by an anomalous all-day long strong low-level jet prior to the development of the system and a nocturnal phase of both mature MCSs and SALLJ maximum as essential features of the environment associated with large long lived MCSs during SALLJ events over SESA.

Mesoscale circulations are altered (still effecting mean divergence in the domain which exhibits a diurnal oscillation)

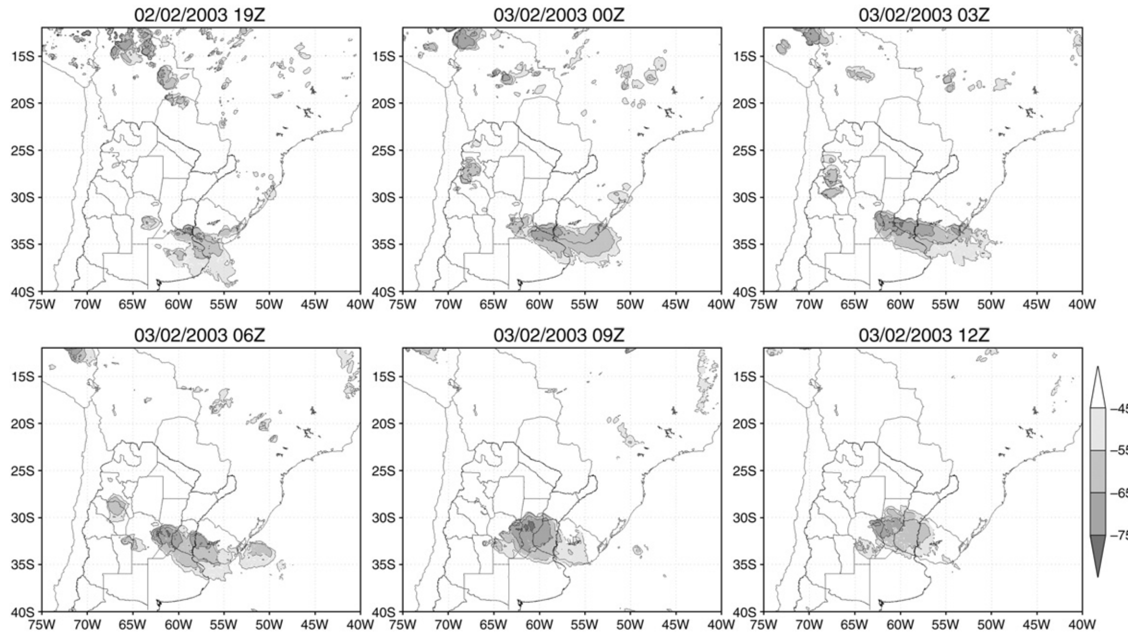

Fig. 11. IR brightness temperature data for February 2 at 19UTC and for February 3 at 00, 03, 06, 09 and 12 UTC.

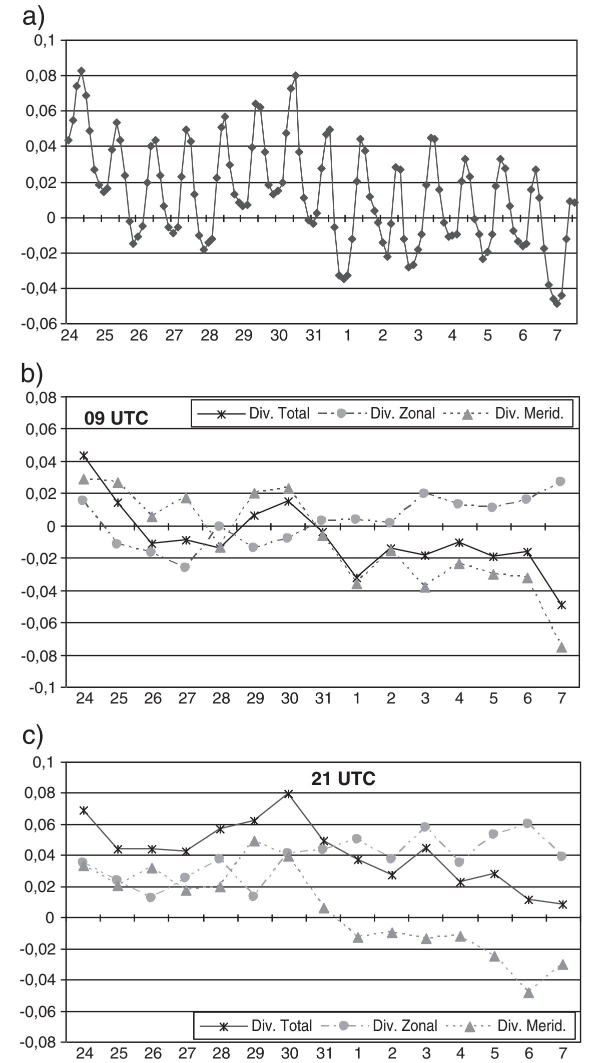

Fig. 12. Boundary layer divergence (1/s*10^4) averaged over the domain shown in Fig. 5. a)Total divergence from 24 January at 9 UTC to 7 February at 21 UTC every 3 hours. b) and c) Total, zonal and meridional divergence at 9 UTC and at 21 UTC, respectively.

upon the initiation of deep convective circulation in the evening within an increasingly convectively unstable atmosphere driven by a persistent horizontal advection of heat and moisture at low levels and forced by convergence generated by the low-level jet (acting during at least one diurnal cycle) and the presence of a frontal zone. Convection intensifies at night when its related convergence over the plains comes in phase with the convergence related to the nocturnal low-level jet maximum.

We have demonstrated the existence of a diurnal cycle in boundary layer divergence and a dependence of this cycle and related convection on the synoptic conditions during a 15-day period. Previous results bring into question two issues: one concerns the domain used and the other whether this signal is still present in the entire warm season (SALLJEX) period. In order to reduce possible sea-breeze and other diurnal circulations effects related to topography over Brazil near the eastern boundary and to concentrate on the plains region, the diurnal cycle has been recalculated for different domains, shifting the eastern border from 50 up to 57 W. Also, in one case the western border has been shifted to 64 W to reduce possible Andean slope breeze effects. We explored the potential domain dependence comparing the diurnal variation of the 15-day period average of the overall domain mean boundary layer divergence. No significant difference in the diurnal cycle behavior for the 15-day average has been obtained other than an increase in the amplitude for the reduced domain (see Fig. 13a for two different eastern boundary longitudes: 50 W, that is the one already used and 57 W). Concerning the second issue, we averaged the overall original domain mean boundary layer divergence in the whole SALLJEX period (15 November to 15 February) to obtain the warm season diurnal cycle and to compare it with the one corresponding to the 15-day period (Fig. 13b). The signal of the existence of a diurnal cycle in boundary layer divergence in the east of the Andes subtropical domain stands out well in both periods. The 15-day period shows a weaker convergence at night mainly contributed by a weaker meridional convergence and in both periods the diurnal oscillation is dominated by the zonal component, mostly perpendicular to the mountain range (Fig. 13c and d). This result shows that the diurnal cycle of boundary layer divergence is not a peculiar feature related to the particular synoptic situations included in the analysis but a common characteristic at least during the warm season.

It must be stressed that our conclusions regarding boundary layer divergence patterns and their diurnal oscillations east of the Andes over northern-central Argentina and the main mesoscale circulations that contribute to these divergences, as well as their relationship with convection are based on a short period and that horizontal and vertical resolutions, are still too limited to capture the fine-scale variability of these patterns. Higher resolution as the one used in previous observational and numerical studies in other geographical regions (mentioned in the Introduction) is necessary if interest is centered at capturing narrow convergence lines and other features that may favor and/or force convection and if the objective is focused on deep convective nowcasting. These analysis limitations and the lack of dense surface observation networks in the region preclude the comparison of the present work with other authors' previous results. Yet, this study based on BRAMS-20 provides the first documentation of the existence of a diurnal cycle in boundary layer divergences and mesoscale circulations related to the presence of the Andes mountains and gives confidence for future studies based on high resolution numerical simulations oriented to investigate processes responsible for the gradual destabilization of the atmosphere and the buildup of the required conditions to generate organized convection as the one observed over SESA. In particular, studies are required to determine the intensity of flow and moisture convergence related to thermally-induced circulations capable to generate regions favourable for initiation of deep convection in this region.

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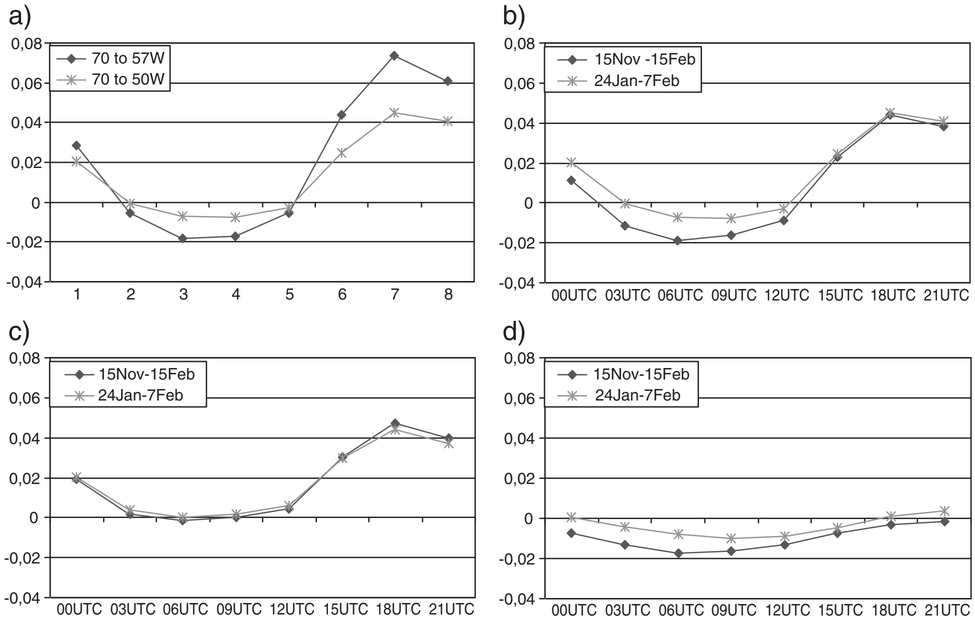

Fig. 13. Boundary layer divergence (1/s*10^4). a) Total divergence averaged for the 15-day period and over two different domains: one with the eastern border in 50 W (70 W to 50 W, same as in Fig. 5), and the other with the same border in 57 W (70 W to 57 W). b)–d) Total divergence, zonal and meridional divergence, respectively, averaged over the domain shown in Fig. 5 and for the 15-day period and for the SALLJEX period, respectively.

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