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Impact of tropical heat sources on the South American tropospheric upper circulation and subsidence

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Abstract. The nonlinear adjustment of the wind and mass fields to idealized tropical heat sources is studied with a simple nonlinear primitive equation model with emphasis on the upper level circulation over South America and neighboring oceanic regions during the austral summer. Numerical experiments are performed with (1) an idealized symmetrical heat source in the Amazon region, (2) the asymmetry induced in source (1) by the SACZ, (3) the effect of the Atlantic ITCZ off the Amazon mouth, (4) the African heat source, (5) the West Pacific source, and (6) the central Pacific source during the warm phase of ENSO. The linear response is obtained through the reduction of the heat source by a factor of 10 and subsequent multiplication of the results by the same factor. Two basic questions are discussed: (1) are localized heat sources important for the development of the observed cyclonic flow in the midequatorial Atlantic and (2) where is the compensating subsidence associated with the Amazon heat source located? The nonlinearity helps organizing a weak cyclonic curvature in the midequatorial Atlantic, with the inclusion of source (2). The basic state generated by the west Pacific source, and primarily by the central Pacific source, has a large impact on the cyclonic curvature on the equatorial Atlantic. The compensating subsidence associated with the Amazon source is concentrated on the southwest side of the source. The SACZ extension helps to enhance the subsidence over the northern Argentina, and the Atlantic ITCZ enhances the subsidence over northeast Brazil and central equatorial Atlantic. Nonlinearity weakens the subsidence at the 500 hPa level inducing a more barotropic structure in the dynamical response to the heating.

1. Introduction

Most of the tropical and subtropical South America receives more than 50% of the annual precipitation in the austral summer season (December-January-February) [*Nishizawa and Tanaka*, 1983; *Figueroa and Nobre*, 1990] in the form of convective rain with strong diurnal variation [*Silva Dias et al.*, 1987]. The daily rainfall amounts in the southern Amazon and central Brazil are of the order of 10 mm/d on the average over vast regions, reaching more than 30–50 mm/d during rainy episodes. Thus the release of latent heat is a large source of heating in the region and it has to be taken into account for explaining the regional summer circulation.

An approximate regional energy budget over the Amazon region in January shows an energy surplus of the order of 175 W/m^2. The precipitation gain and the infrared loss are of the order of 350 and 90 W/m^2, respectively. The significant reduction of the infrared loss compared to the clear sky typical value is due to the large fractional area covered by cirrus clouds during the austral summer. The regional energy balance shows a significant reduction in the net balance in July (approximately 45 W/m^2) due to the decrease in precipitation and the corresponding reduction in the cirrus coverage. The corresponding tropospheric warming is of the order of 1.8 and 0.5° C/d in January and July, respectively. A simple scale analysis of the thermodynamic equations reveals that the horizontal temperature advection cannot be responsible for the necessary cooling in the Amazon region primarily in January. Thus the vertical motion can be estimated as a residual of the thermodynamic equation with the further assumption of small storage, giving a mean pressure vertical motion of the order of 75 and 10 hPa/d in January and July, respectively.

Similar regional energy balances over the Atlantic Ocean (off northeast Brazil) and over the Pacific Ocean (off the coast of Peru) indicate substantial heat loss and the need for significant compensating subsidence, assuming that the horizontal temperature advection plays a minor role. The subsidence in the Atlantic region in January may be associated with the energy surplus over the Amazon and over the Intertropical Convergence Zone (ITCZ) in the Atlantic region. Similar reasoning is also valid off the coast of Peru, with the contribution of the east Pacific ITCZ and the Amazon/central Brazil precipitation. During the southern hemisphere winter, the enhanced convective activity of the ITCZ in the northern part of South America helps in sustaining the subsidence over the southern part of the Amazon and Central Brazil.

The picture that emerges from the analysis of the regional energy balance over the Amazon region indicates the need for intense upward vertical motion in the rainy months and compensating subsidence in the adjacent dry areas, primarily over the Atlantic and east Pacific Oceans. The regional balance suggests that the Amazon Basin/central Brazil during the southern hemisphere summer is a very important energy source which partially compensates the energy loss in the neighboring regions. This energy source may be also responsible for some remote impact associated with teleconnection

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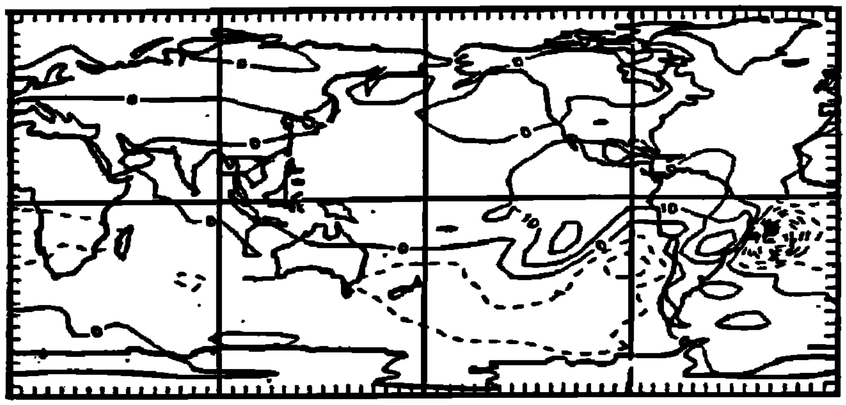

Figure 1. Influence function of a target point located just off the northeast coast of Brazil (indicated by solid circle). (Adapted from *Grimm* [1992].)

mechanisms [*Grimm and Silva Dias*, 1995, hereinafter referred to as GSD95]. GSD95, with a barotropic vorticity model, show that the upper level divergence over central Brazil during the summer season and the associated southeastward extension, known as the South Atlantic Convergence Zone (SACZ), act as a source region for some important teleconnection patterns in the northern hemisphere winter, such as the Eurasian pattern (EU). In this case, the western part of the wave train across Eurasia is particularly influenced by anomalous convection in the SACZ. Strong influences are also observed in the North Atlantic, affecting the eastern coast of the North American continent.

A basic difficulty in properly modeling the extratropical response with the barotropic vorticity model is the correct specification of the upper level convergence associated with the anomalous tropical heat sources. Tropical heat sources associated with the release of latent heating have a well-defined signature in the upper level divergence. However, the compensating upper level convergence also tends to be concentrated, especially in the subtropical region and not uniformly distributed at the same latitude of the forcing [*Sardeshmukh and Hoskins*, 1985] as specified in several model studies [e.g., *Branstator*, 1983]. The barotropic vorticity model is not able to properly reproduce this mechanism, and the anomalous divergent part of the wind has to be specified. Apparently, insignificant peculiarities of the anomalous divergence field seem to have substantial impact on the remote rotational response as clearly shown by GSD95. The upper level anomalous compensating subsidence, associated with tropical heat sources, may additionally come under the influence of mountains [*Gandu and Geisler*, 1991, hereinafter referred to as GG91], transients, and whether the subtropical response is linear or nonlinear [*Gill and Phlips*, 1986].

The atmospheric circulation over the South American region in summer presents some well-defined regional scale circulation systems such as the upper tropospheric large anticyclone centered over Bolivia, also known as the Bolivian high, a trough over the northeast Brazil in the upper troposphere [*Virji*, 1981; *Kousky and Kayano*, 1981; *Kousky and Gan*, 1981] and a low-pressure center over northern Argentina in the lower troposphere [*Schwerdtfeger*, 1976]. Previous model studies have shown that many basic characteristics of the upper tropospheric circulation can be reproduced by stationary and transient heat sources over the Amazon and central Brazil during the summer season [*Nobre*, 1983; *Silva Dias et al.*, 1983; *DeMaria*, 1985; *Paegle*, 1987; *Buchmann et al.*, 1990].

Although the basic features of the low-level summer circulation in the tropical region are described by simple linear models, subjected to the action of observed heat sources [*Zhang and Krishnamurti*, 1996], there are some significant discrepancies over South America which cannot be resolved with models that ignore the topographical effect [*Kleeman*, 1989; GG91; *Figueroa et al.*, 1995]. However, these studies indicate that the low-level flow is much more influenced by topography than the upper circulation. The study by *Figueroa et al.* [1995] indicates that the localized heating over Brazil may be responsible for the southeastward extension of the low-level trough associated with the Chaco low, in an orientation that resembles the South Atlantic Convergence Zone (SACZ) [*Kodama*, 1992, 1993]. However, *Silva Dias and Kasahara* [1987], with no topography, suggest that the southeastward extension of the low-level response to the stationary heating is tied to the interaction of the linear response with westerly basic state to the south of the heating.

The location of the upper level trough, to the east of the forcing, present in the linear simulations of the impact of the Amazon/central Brazil heat source is not in close agreement with the observed feature. Thus the compensating vertical motion in the linear simulations to the east of the forcing may not be properly located. In most of the previous model simulations, the trough is located over the continent, adjacent to the Bolivian high. Observations tend to indicate that in the mean the trough is located farther to the east, well over the Atlantic Ocean [*Chu*, 1985]. Nevertheless, observations indicate that during transient convective bursts in the tropical sector of South America there is a certain tendency to observe a westward displacement of the Atlantic trough, eventually penetrating into the continent [*Kousky and Gan*, 1981; *Silva Dias et al.*, 1983; *Horel et al.*, 1989]. Other mechanisms have been suggested by *Kousky and Gan* [1981], such as the intrusion of higher-latitude troughs in the equatorial region and the eventual formation of an upper cutoff low in the equatorial region.

Figure 1 [from *Grimm*, 1992] shows the influence function (GSD95) of a target point located just off the northeast coast of Brazil for the mean January 200 hPa basic state. The influence function allows the identification of the points where divergence is most efficient in producing a rotational response at the target point, in this case the point located off the northeast coast of Brazil. Figure 1 indicates that upper level divergence in the central/eastern Pacific Ocean during the southern hemisphere summer is favorable for the intensification of cyclonic vorticity in the equatorial Atlantic, off the northeast coast of Brazil. Thus it is clear that there the upper cyclonic vorticity off the northeast coast of Brazil can be generated by the upper level divergence and the associated compensating subsidence in other regions of the tropics besides the Amazon/central Brazil, as suggested by the numerical experiments of *Silva Dias et al.* [1983].

The objective of this paper is to explore the dynamics of the subsidence field associated with the intense upward vertical motion required to regionally balance the energy budget in the tropical sector of South America during the southern hemisphere summer. Numerical integrations are performed with the primitive equation model described by GG91 in order to explore the location of the subsidence branch associated with a heat source with Gaussian horizontal distribution and a slightly skewed parabola in the vertical with maximum heating at 400 hPa, similar to the heat source described by GG91. The role of nonlinearities is explored with the Amazon/central Brazil heat source; in addition, the asymmetry of the heat source associated with the southeastward extension imposed by the latent heat release in the SACZ is also explored. The next step is to explore the eventual interaction between the main continental heat sources during the southern hemisphere summer, namely the western Pacific/Indonesian and the African heat sources. The nonlinearity of this remote influence is also considered under the constraints imposed by the model design.

2. Model Description and Experiment Design

The model has been previously described by GG91. The model employs the nonlinear, primitive equations in spherical coordinates and a sigma coordinate in the vertical. Horizontal finite differencing is performed in the Arakawa C grid with 2.5° in both latitude and longitude. The main differences with respect to GG91 are as follows: (1) the number of vertical levels has been increased to 9, (2) the domain is extended to the whole tropical belt limited at 60° N and 60°S. Thus cyclic boundary conditions are applied in the zonal direction, and the radiation boundary condition is imposed in the northern and southern boundaries. As in GG91, Rayleigh friction and Newtonian damping are applied with an e-folding decaying time of 5 days. The horizontal distribution of the heating function is defined by a Gaussian function with variable zonal and meridional e-folding radius. The vertical structure of the heating follows the prescription of *DeMaria* [1985], which is a slightly skewed parabola with a maximum at 400 hPa, independently of the location of the heat source.

The model atmosphere is initialized from the rest with the same horizontally uniform temperature basic state described by GG91 in order to avoid circulation spun up from the initial field. The steady heat source is turned on gradually to minimize the transient component of the response such that the constant heating is reached after 48 hours of integration. A virtually steady state solution is attained after 15 days of integration in most of the experiments.

The mean OLR field of January 1996 (Figure 2) is used to roughly define the location and shape of the main heat sources in the tropical region. Figure 3 shows the horizontal distribution of (1) the symmetric heat source over South America, (2) the asymmetric forcing associated with the southeastward extension of Amazon source, (3) a heat source similar to source 2 but with the Atlantic ITCZ, (4) the west Pacific, African, and South American sources, and (5) the South American and African sources with the Pacific source displaced toward the central Pacific. Each individual heat source is assumed to have a vertically integrated heating of 5°C/d at the center of the heat source, although observations indicate significant geographical variability of their strength (Figure 2). The level of maximum heating (400 hPa) does not show as much horizontal variability as suggested by *Pedigo and Vincent* [1990]. Some sensitivity experiments were performed in order to explore the impact of changing the relative magnitude of the heat sources as well as the level of maximum heating.

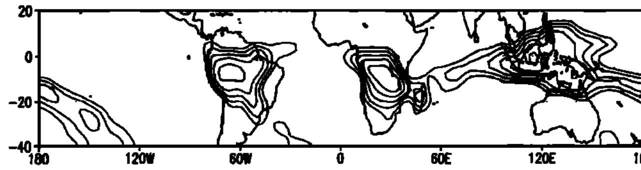

Figure 2. Mean outgoing long-wave radiation (OLR) field in January 1996. Contours from 190 to 230 W/m^2.

The different combination of these heat sources are selected in order to explore their impact on the subsidence field over South America during the southern hemisphere summer. The role of nonlinearity is explored with the same model but with a much weaker heat source (1/10 of the original value). The "linear response" is then obtained after multiplication of the final results by the same factor. Experiments with the initial heat source substantially weaker (1/20th) reveal the same characteristics. However, as the flow becomes less intense with even weaker heat sources, truncation errors in the finite difference solution tend to produce excessive noise primarily in the vertical motion field.

A summary of the experiments is shown in Table 1, which contains the location of the heat sources and the linear or nonlinear character of the numerical simulation. The linear experiment AL is a reference case since it reproduces previous model results [e.g., *Silva Dias et al.*, 1983]. The nonlinear effects are explored in experiment ANL. The role of the asymmetry of the heat source caused by the southeast extension associated with the SACZ is explored in experiment SANL. Figure 3 indicates that the Atlantic ITCZ may have a significant impact due to the asymmetry which causes an additional heat source near the equator where the partition of energy favors the excitation of fast modes. The combination of the major heat sources in the South American continent is explored in experiment ISANL. The impact of some remote heat sources on the upper tropospheric circulation in South America is the objective of the next experiments. The African heat source is studied in experiment AANL and the role of the west Pacific convection in combination with the African source is studied in experiment WPAANL; experiment WPAAL is its linear version. During the warm phase of the El Nino-Southern Oscillation (ENSO) the heat source in the Pacific Ocean is displaced to the central/east Pacific and its impact on the South American circulation is explored in experiment CPAANL.

3. Results

3.1. Impact of a Single Symmetric Heat Source in the Amazon/Central Brazil

The 200 hPa wind and the 500 hPa vertical motion (ω) associated with the nonlinear stationary response to the single

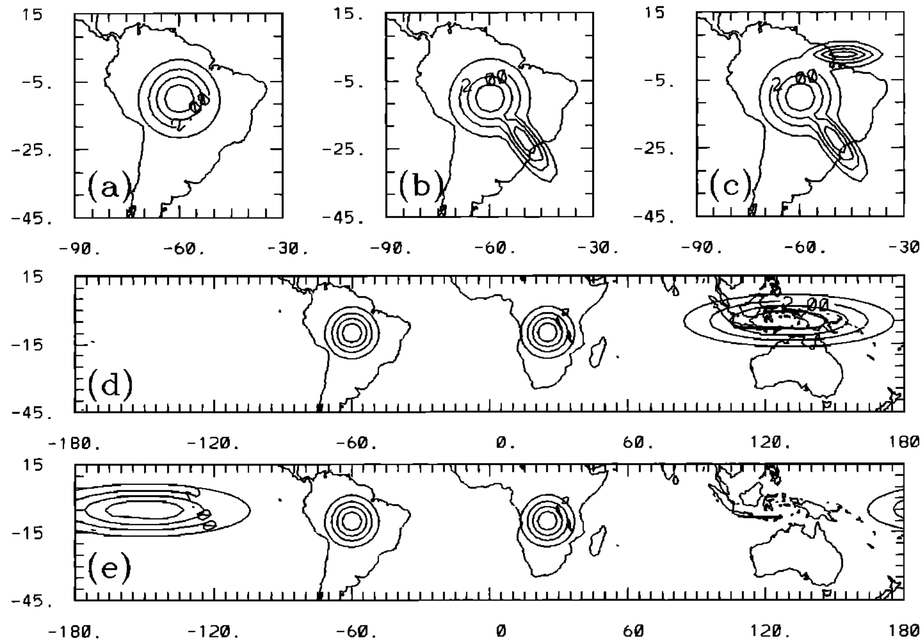

Figure 3. Contours representing the heating rate (K/d) of (a) the South American symmetrical source, (b) the asymmetrical source associated with the SACZ, (c) a heat source similar to Figure 3b but with the Atlantic ITCZ, (d) the three main equatorial sources (west Pacific, South America, and Africa), and (e) the South American and African sources with the Pacific source displaced toward the central Pacific.

symmetric heat source (Figure 3a) over Amazon/central Brazil is shown in Figure 4 (experiment ANL). The difference between the nonlinear and the linear responses (experiment AL) is shown in Figure 5. The contours of vertical motion are 20 hPa/d for the negative values and 1 hPa/d for the subsidence field for the total nonlinear response. The difference vertical motion field is shown with 1 hPa/d contours. The low-level circulation (figure not shown) is essentially the reversal of the 200 hPa flow in view of the dominance of the internal mode response to the imposed heating. The nonlinear response reproduces the basic characteristics of previous model works based on linear models, displaying the upper anticyclonic circulation associated with the Bolivian high and the trough immediately to the east (indicated by N in Figure 4). The compensating downward motion is concentrated to the west-southwest of the maximum upward motion, just off the southwest coast of Peru and northern Chile, extending westward. Another region of organized compensating subsidence is centered over the Atlantic in the equatorial region, with maximum intensity about half the magnitude of the Pacific region.

The largest differences between the ANL and the AL experiments are found in the upper level flow. The upper level cross equatorial flow near the heat source and the easterly equatorial flow, west of the forcing, are more intense in the nonlinear case (Figure 5a) exhibiting a short-wave structure over the equatorial Atlantic (including a weak SA, indicated in Figure 4a). The nonlinearity induces the formation of a slight cyclonic feature in equatorial North Atlantic (NA in Figure 4a). The southern (northern) branch of the upper level anticyclone is less (more) intense in the nonlinear simulation. However, the low-level cyclonic flow is more intense (not shown). Figure 1 supports the potential impact of the symmetric heat source on the development of cyclonic vorticity in the equatorial South Atlantic. In spite of the fact that Figure 1 was obtained with a barotropic model, linearized about a climatological basic and therefore with zonal and meridional shear, the nonlinear model generates a basic state which has significant similarity with the observed flow at 200 hPa, at least in the vicinity of the heat source.

It is interesting to note a weak upper cyclonic flow immediately to the southeast of the forcing in the ANL experiment in comparison with the linear case (AL), as indicated in Figure 5a. The location of this trough (indicated by S in Figure 4) is quite close to the upper trough associated with the SACZ. Although this feature is weakly present in the linear simulation, it is better defined in the nonlinear case. This result corroborates the suggestion by *Kasahara and Silva Dias* [1986] and *Figueroa et al.* [1995] that the asymmetric circulation, southeast of the symmetric heat source over the continent, resembles the upper level trough usually associated with the SACZ. GSD95 further explore this idea with the use of influence functions and their Figure 7 supports the notion that the root of the SACZ is the convective activity which is anchored over the continent during the South American monsoon. The same Figure 7 of GSD95 indicates that there are remote sources of cyclonic vorticity in the SACZ, located in the Pacific

Table 1. Description of Experiments

Source Location	Mode	Designation
Amazon/central Brazil	linear	AL
Amazon/central Brazil	nonlinear	ANL
Amazon/central Brazil+SACZ	nonlinear	SANL
Amazon + SACZ + Atlantic ITCZ	nonlinear	ISANL
Amazon + Africa	nonlinear	AANL
West Pacific + Amazon + Africa	nonlinear	WPAANL
West Pacific + Amazon + Africa	linear	WPAAL
Central Pacific + Amazon + Africa	nonlinear	CPAANL

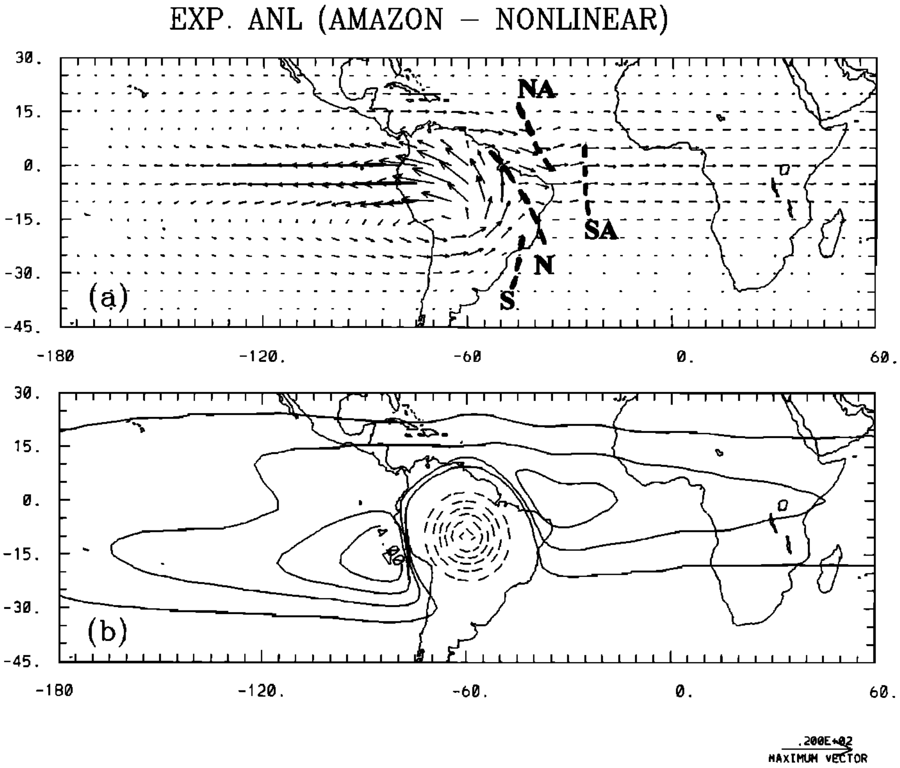

Figure 4. (a) The 200 hPa wind associated with the stationary response to experiment ANL (symmetric heat source over tropical South America) and (b) vertical motion in hPa/d at 500 hPa (contours are 20 hPa/d when $\omega < 0$ and 1 hPa/d when $\omega > 0$).

Ocean. This will be explored in a later section of this paper, considering the limitations of the current model.

There is a decrease in the magnitude of the upward vertical motion near the forcing and a corresponding decrease in the compensating subsidence in the nonlinear run (Figure 5b). However, the latter effect seems more noticeable in the Pacific Ocean. Thus it seems that the compensating subsidence over the equatorial area in the Atlantic, a feature essentially related to the Kelvin wave response, is less sensitive to the nonlinear processes. These results are similar to *Gill and Phlips* [1986] in spite of the differences in the model and experiment design.

The differences between the linear and the nonlinear simulations can be partially attributed to the barotropic effect associated with the nonlinear processes. Figure 6a shows a vertical cross section at 18.75° S of the geopotential perturbation of the nonlinear response and the difference between the nonlinear and the linear responses is displayed in Figure 6b. The difference field shows a significant barotropic structure. The corresponding cross section of the vertical motion field indicates that the maximum upward vertical motion is slightly displaced to higher levels with negligible impact to the east of the forcing at that latitude where the linear Kelvin response dominates (Figure 7).

The vertical cross section of the vorticity balance at 11.25° S associated with the nonlinear experiment ANL is shown in Figure 8. The Sverdrup balance (balance between the linear stretching and the meridional advection of planetary vorticity, i.e., $-\beta v = f\,\nabla \cdot \mathrm{V}$) is clearly dominating (Figures 8a and 8b). The horizontal vorticity advection $(-\mathrm{V} \cdot \nabla(\varsigma + f))$ has an important barotropic effect (anticyclonic tendency), as shown in Figure 8c. However, the major term responsible for the cyclonic tendency at higher levels is the nonlinear stretching, given by $\varsigma.\nabla \cdot V$ (Figure 8d), followed by the vertical advection of vorticity, the $-\omega\ \partial\omega/\partial p)$ term (Figure 8f), which is largest just below the 200 hPa level. The other terms of the vorticity balance are negligible at high levels. The barotropic structure of the nonlinear stretching term implies a strengthening of the low-level cyclonic vorticity reinforcing the heat low in northern Argentina (the Chaco low). In general, the nonlinear terms have the opposite sign of their linear counterpart as shown observationally by *Sardeshmukh and Held* [1984] and *Sardeshmukh and Hoskins* [1988].

In conclusion, the nonlinearity helps to enhance the cyclonic upper level vorticity in the Atlantic Ocean (indicated by SA in Figure 4), although much less intensely than the climatological feature. The horizontal advection of vorticity tends to enhance the cyclonic vorticity immediately to the east of the forcing, suggesting that the symmetric heat source anchored over the continent acts as a source of the upper trough usually associated with the SACZ. The subsidence field is primarily affected to the west of the source (less intense and practically no change in the position), and a minor effect is observed to the east, where the linear Kelvin response tends to dominate.

The inclusion of an Andean idealized topography does not seem to significantly modify the organization of the upper level flow associated with the Amazon/central Brazil heat source, as discussed by GG91 and *Figueroa et al.* [1995]. The strongest compensating subsidence remains to the west/southwest of the source and the upper level trough is not significantly altered.

The sensitivity of the model response to the location of the level of maximum heating was also explored. The maximum heating was lowered to 600 hPa (figures not shown). Although

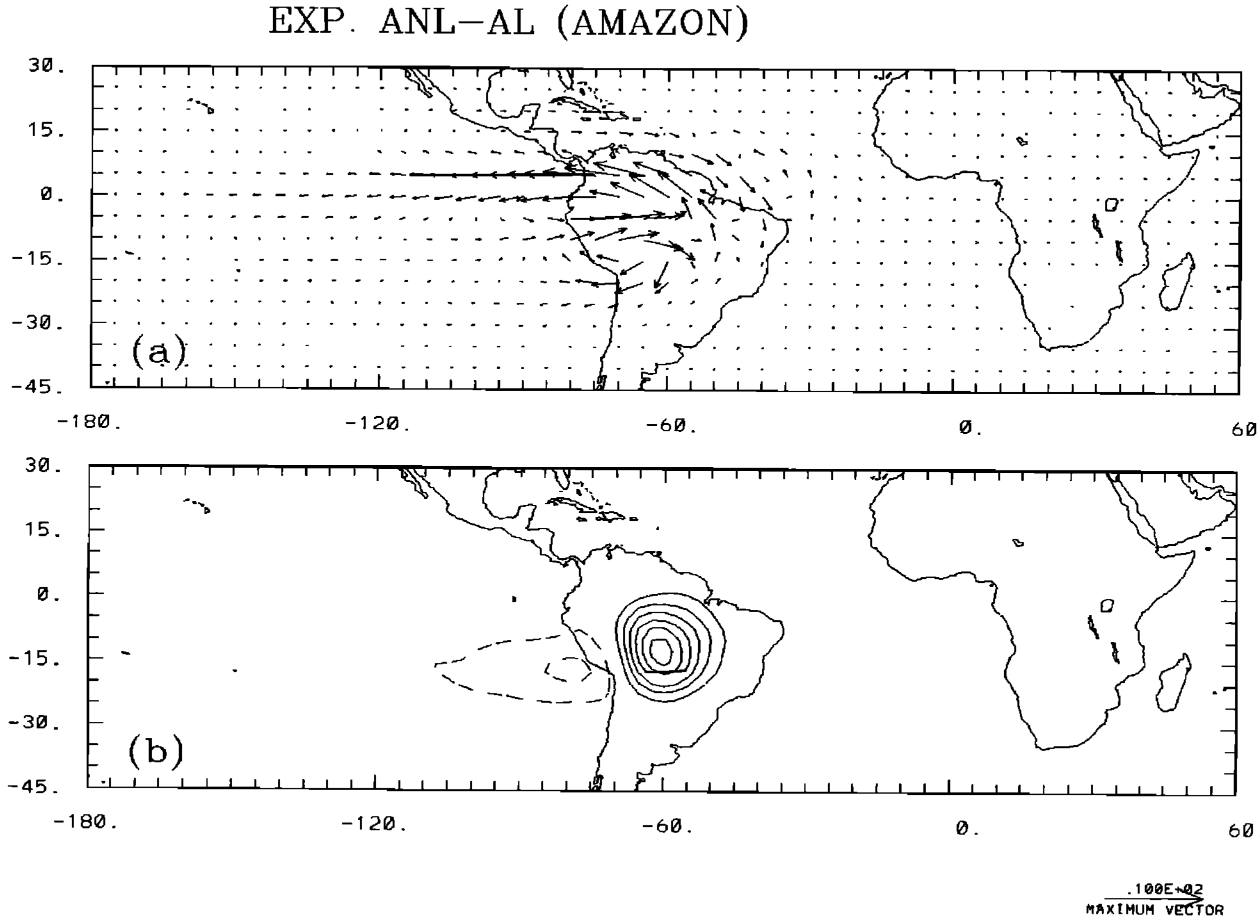

Figure 5. Same as Figure 4 except for the difference between the nonlinear and the linear experiments ANL and AL, respectively. Contours interval of 1 hPa/d.

the basic upper level response remains present, there is a significant intensification of the low-level flow. The maximum compensating subsidence at 500 hPa is kept to the southwest of the heat source, more intense, and closer to the heating. These results can be understood in terms of the slower energy dispersion associated with the higher order vertical modes excited by lower level heating [*DeMaria*, 1985]. However, the qualitative results are similar to the ANL experiment.

3.2. Impact of Asymmetry Caused by SACZ

As discussed in section 2, the role of the heat source associated with the SACZ is explored in experiment SANL. The intensity of the heat source associated with the SACZ is assumed to be of the same order of magnitude as the Amazon/central Brazil source during the southern hemisphere summer (Figure 3). This assumption is realistic during active phases of the SACZ when substantial rain is associated with the southeastward extension of the convection over the central part of Brazil [*Paegle and Mo*, 1997]. The 200 hPa flow and the vertical motion field at 500 hPa are shown in Figures 9a and 9b, respectively. Subsidence remains concentrated to the west-southwest of the asymmetric heat source, with strongest downward motion on the northern coast of Chile, extending toward central/northern Argentina in the southeast direction. There is a slight southward displacement of the subsidence field compared to the previous case (Figure 4b). The equatorial subsidence in the Atlantic Ocean is practically insensitive to the addition of the heat source associated with the SACZ. This effect can be understood in terms of the forcing projection on the Kelvin mode: according to *Silva Dias et al.* [1983] the Kelvin mode is less excited as the forcing is displaced away from the equator. A simulation with the Amazon/central Brazil source removed confirms the confinement of the compensating subsidence to the west of the SACZ source (figure not shown).

Strong subsidence occurs in the poleward side of the heat source associated with the SACZ, as shown by *Casarin and Kousky* [1986] and *Paegle and Mo* [1997]. Figure 3 of Paegle and Mo, based on OLR data, implies that a strong SACZ is associated with rainfall deficit over the subtropical plains in northern Argentina, Uruguay, and southern Brazil. This observational result is consistent with Figure 9, and it can be explained in terms of Rossby and gravity wave dispersion associated with the localized heat source [*Silva Dias et al.*, 1983; *DeMaria*, 1985].

The cyclonic flow in the tropical equatorial region (marked SA in Figure 9a) is more intense than in the ANL experiment (compare with Figure 4a). Figure 1 supports the importance of the SACZ upper level divergence for generating cyclonic vorticity in SA. In addition, there is a southeastward displacement of the BH when the SACZ source is activated (compare Figures 4a with 9a), and the upper level trough induced by the SACZ (marked S in Figure 9a) is located southwest of its position in the previous experiment (Figure 4a). An upper level trough develops in the equatorial North Atlantic (NA in Figure 9a). The location is similar to the climatological feature observed in this region but much less intense. There is a minor hint of cyclonic curvature in this area in experiment ANL (Figure 4a).

Figure 10, taken from *Sugahara* [1991], shows a composite of OLR during wet and dry phases during the rainy season in the southeastern part of Brazil (Figures 10a and 10b, respectively), based on data from 1984 to 1987. The corresponding 200 hPa flow is shown in Figures 10c and 10d. The timescale associated with the dry and wet periods is of the order of 20 to 60 days and therefore compatible with the results of *Paegle and Mo* [1997]. Wet periods during the rainy season in the southeastern part of Brazil are associated with the presence of the SACZ and with drier periods in the southern part of Brazil, Uruguay, and northeastern Argentina. The upper level trough is clearly more developed in the case of enhanced activity in the SACZ with stronger southeasterly upper tropospheric flow to the east of the BH. This feature is quite similar to the model result displayed in Figure 9a. The observed eastward displacement of the BH during the wet phases of the rainy season (Figures 10c and 10d) also seems to be reproduced by the ASNL experiment. However, the stationary solution does not show a closed cyclonic flow in the equatorial Atlantic, off the northeast coast of Brazil.

3.3. Impact of Atlantic ITCZ

Figure 2 indicates that the Atlantic ITCZ in January is more active just off the Amazon mouth. Experiment ISANL was designed to explore the impact of the additional asymmetry induced upon the Amazon/central Brazil heat source with the southeastward extension associated with the SACZ. Figure 11a shows the 200 hPa stationary wind field and Figure 11b and the

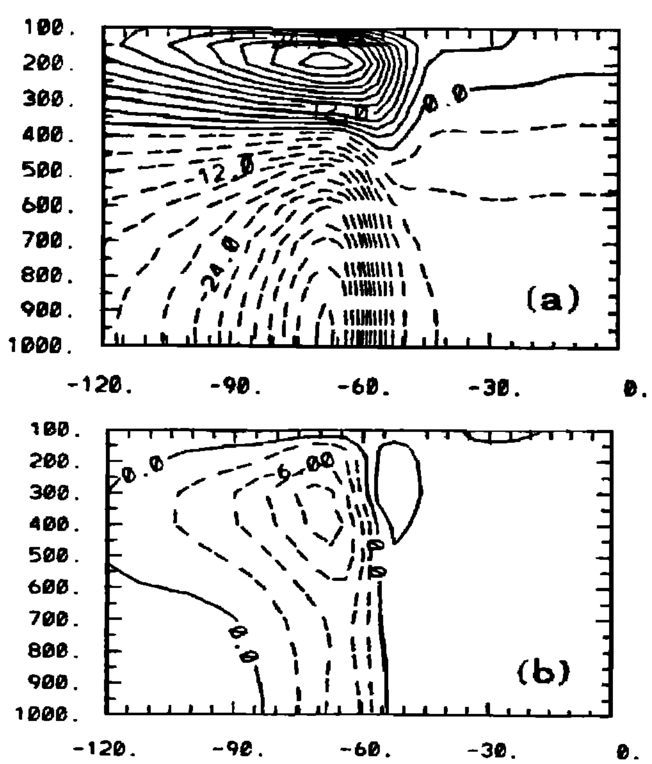

Figure 6. (a) Vertical cross section at 18.75° S of the geopotential perturbation of the nonlinear response in experiment ANL (3 m increment) and (b) difference between the nonlinear and the linear responses (ANL-AL) with 3 m increment.

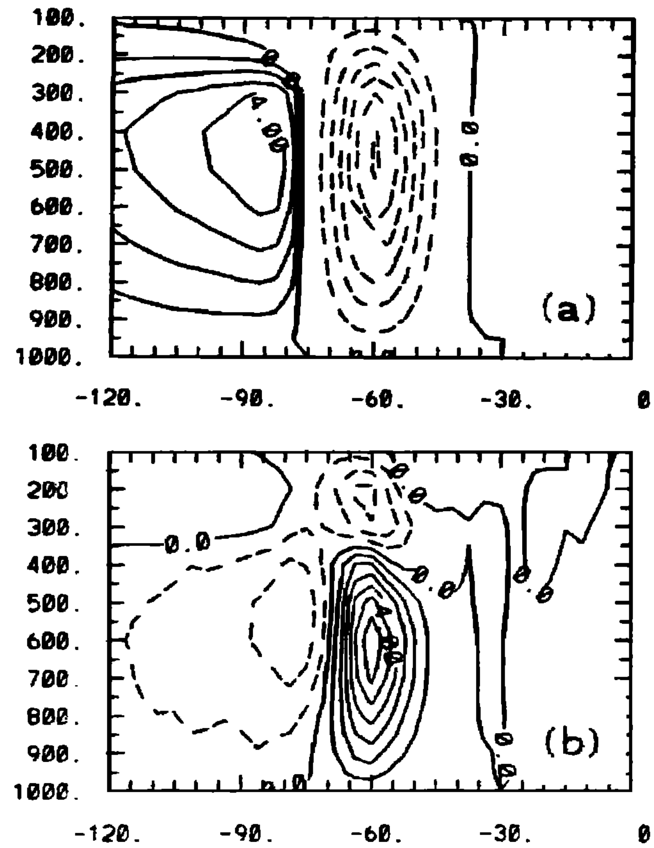

Figure 7. Same as Figure 6 but for the vertical motion field (a) for experiment ANL (contours every 10 hPa/d when $\omega < 0$ and 1 hPa/d when $\omega > 0$) and (b) for the difference between experiments ANL and AL (1 hPa/d increment).

500 hPa ω field. The Atlantic trough (SA in Figure 11a) is better defined in this case, and it is shifted to the east in comparison with Figure 9a. The eastward displacement of SA is related to the stronger upper westerly flow in the Atlantic Ocean, extending toward equatorial Africa, which is a significant feature of this experiment in comparison with the previous cases. The enhancement of SA is also supported by Figure 1, which shows that upper level divergence in the Atlantic ITCZ region in the Amazon region helps to sustain the cyclonic vorticity at the target point. In addition to the South Atlantic trough, this experiment suggests the eastward displacement of the cyclonic vorticity in the equatorial North Atlantic (NA in Figure 11a), another climatological feature of the upper level flow in January.

Subsidence of northeast Brazil is much stronger in this case (Figure 11b compared with Figure 9b). Enhanced subsidence is also observed over the central equatorial Atlantic, suggesting that the central and eastern Atlantic ITCZ is effectively suppressed by the Walker circulation set up by the monsoonal convection over South America in spite of the high sea surface temperature usually observed in this area. The equatorial subsidence associated with this experiment extends toward equatorial Africa. Midtropospheric drying can also be expected in this experiment near the northern part of South America.

3.4. Impact of Amazon and African Sources

The westward extension of the upper level flow and the intense subsidence off the west coast of South America in

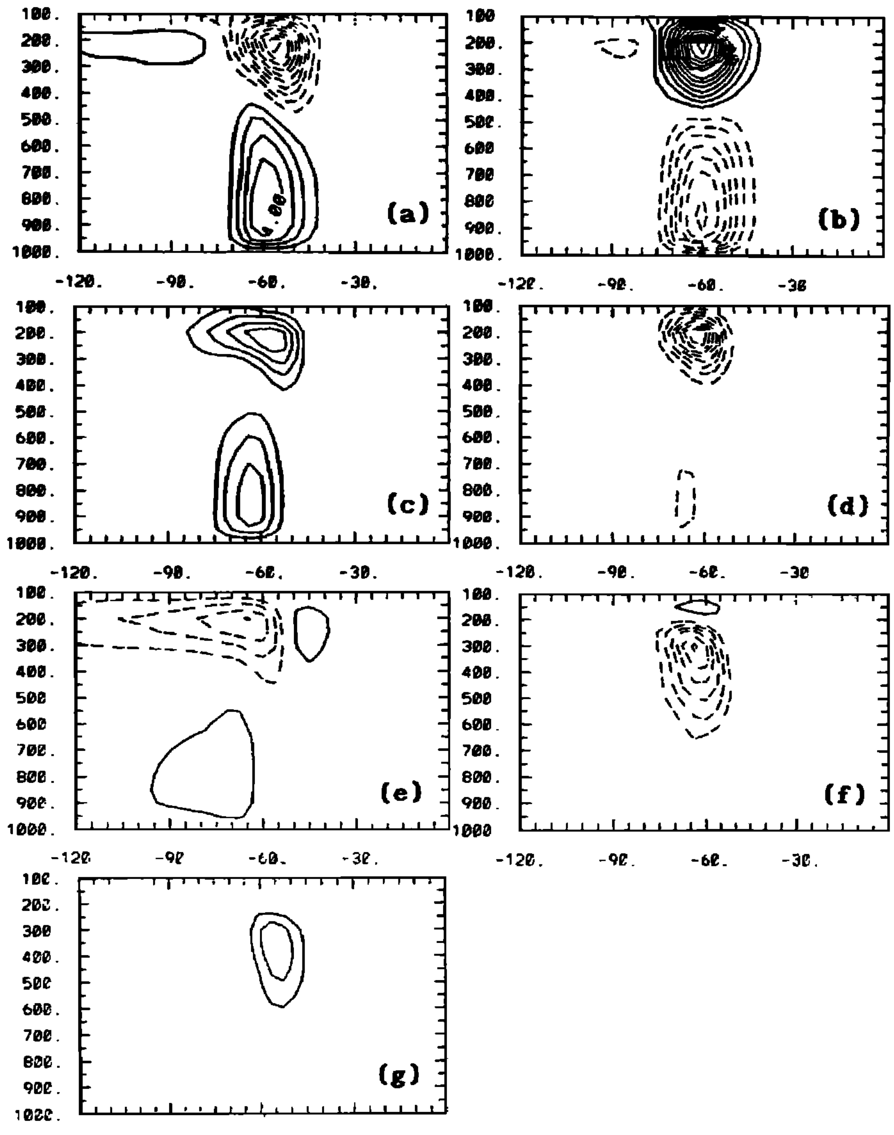

Figure 8. Vertical cross section of the vorticity balance at 11.25°S associated with the nonlinear experiment ANL for (a) the $-\beta\, v$ term, (b) the f $\nabla \cdot$ V term, (c) the horizontal vorticity advection $-\mathrm{V} \cdot \nabla (\varsigma + f)$, (d) the $-\varsigma$. $\nabla \cdot$ V term, and (e) the twisting term and the vertical advection of vorticity $(-\omega\, \partial\varsigma/\partial p)$. Contours increment of 1.0×10^{-11} 1/S^2 in Figures 8a and 8b and of 0.5×10^{-11} 1/S^2 in Figures 8c–8g.

experiment ANL suggest that the influence of the African heat source on the subsidence and upper level flow over South America and the Atlantic Ocean should be explored. Experiment AANL was designed to explore this hypothesis. The combined effect of the two major heat sources is displayed in Figures 12a (200 hPa wind) and 12b (vertical motion at 500 hPa). The compensating subsidence in the Atlantic Ocean is now spread over a larger area with maximum intensity just off the west coast of South Africa and Angola, in good agreement with observations. The subsidence over the northeast part of Brazil and neighboring oceanic area is stronger than in the single Amazon/central Brazil source (compare with Figure 4b). Compensating subsidence east of Africa shows an elongated extension over the Indian and western Pacific Oceans with larger values just east of northeast Africa in the Somali region. The intensification of the subsidence in this region is an effect of the superposition of the two heat sources. Thus the vertical motion in the equatorial part of Africa seems to respond to the convective activity over South America through the Kelvin response.

The nonlinearity associated with the response to the imposed heating can be identified in the location of the trough near Madagascar, marked I in Figure 12a. Assuming a linear response, trough I should be 10° west, taking as reference the location of the Atlantic trough SA (Figure 4a) since the African heat source is a replication of the Amazon/central Brazil heat source. Thus the insertion of the African source in the basic state produced by the Amazon/central Brazil source seems to have a significant impact on the location of the upper trough to the east of the heat source. This result suggest that the impact of the Pacific Ocean heat source on the South American circulation should be explored.

The upper equatorial westerlies in the Atlantic Ocean, present in Figure 4a, are disrupted in view of the strong equa-

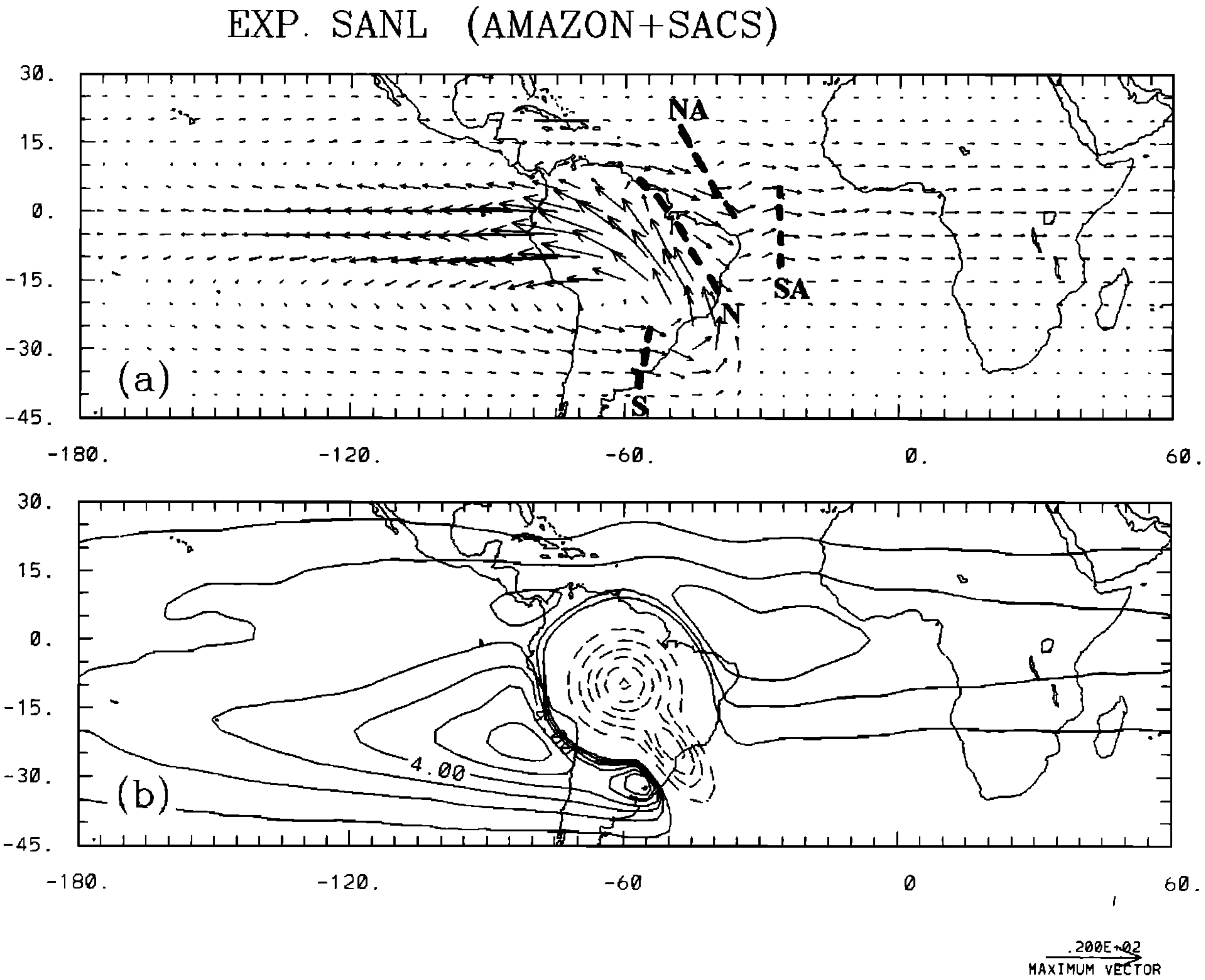

Figure 9. Same as Figure 4 but for experiment SANL (Amazon/central Brazil symmetric heat source and SACZ source).

torial outflow associated with the African source. Thus the Atlantic trough SA cannot be readily identified in Figure 12a. The reduction of the magnitude of the African source in relation to the South American one is sufficient to enhance the cyclonic vorticity in the central equatorial Atlantic region (figure not shown). Thus this experiment suggests that the dynamics of the trough off the northeast coast of Brazil is also dependent on the intensity of the African heat source.

3.5. Impact of South American, African, and West Pacific Heat Sources

A zonally elongated heat source is positioned in the equatorial west Pacific in addition to the Amazon/central Brazil and African heat sources (Figure 3d) in experiment WPAANL. The stationary upper tropospheric wind and 500 hPa vertical motion are shown in Figures 13a and 13b, respectively. The observed strongly difluent flow off the west coast of South America is well represented in this experiment. The upper tropospheric trough over northeast Brazil (N in Figure 13a) shows a more meridional orientation, displaced to the east, although to the west of the observed location. The west Pacific heat source is closer to the equator, and therefore more energy is projected on Kelvin modes, enhancing the equatorial subsidence in the east Pacific. The subsidence off the northeast coast of Brazil is enhanced in comparison with the experiment AANL (South American and African heat sources activated). Subsidence off the east coast of Africa is well concentrated over the Somali region and much more intense. The intensity of the mean zonal subtropical jet is strongly enhanced in both hemispheres in accordance with the increase in the mean zonal heating in the equatorial region showing three maxima over northern Argentina, South Africa, and just east of northern Australia, similarly to the observed feature. Thus the vorticity source associated with the nonlinear impact of the vorticity advection by the divergent component of the wind is enhanced, implying in a stronger higher-latitude impact of the tropical heat sources.

The role of the nonlinear terms can be evaluated with Experiment WPAAL. Figure 14 shows the 200 hPa wind difference between the nonlinear and the linear solutions. It is interesting to compare Figure 14 with Figure 5a since nonlinearity is expected to be larger in the WPAANL case than in the ANL because the Amazon/central Brazil heat source is now immersed in a strong basic state generated by the west Pacific source. The dipole structure of the difference wind field in the Bolivian high is similar but more intense in Figure 14. The southerly component of the cyclonic difference wind field

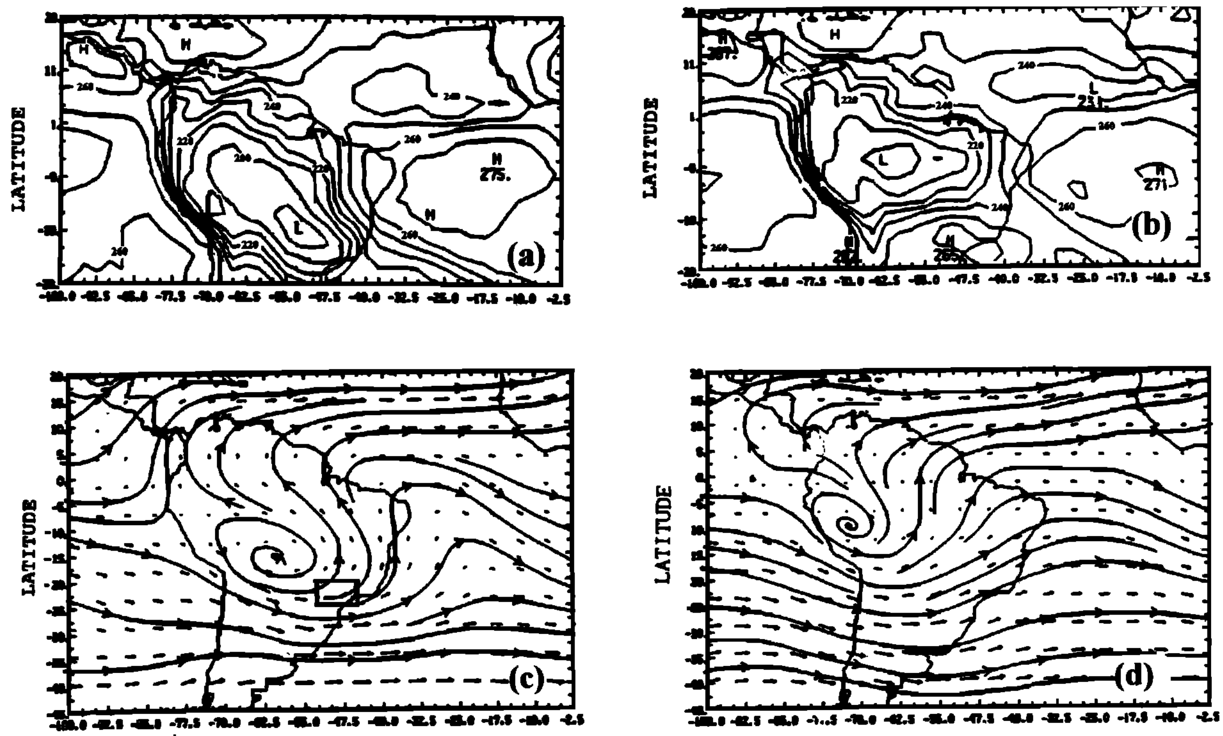

Figure 10. Composite of OLR during (a) wet and (b) dry phases during the rainy season in the southeastern part of Brazil, based on data from 1984 to 1987; (c) and (d) corresponding 200 hPa flow. (Adapted from *Sugahara* [1991].)

to the east of the Bolivian high is much stronger in Figure 14, enhancing the cyclonic flow off the southeastern coast of Brazil, near the SACZ region. Thus this experiment supports the idea that the SACZ trough is influenced by the upper divergence in the Pacific Ocean (GSD95). Figure 14 also confirms that the nonlinear effect is much larger to the west of the West Pacific heat source since the linear Kelvin solution is dominating to the east of the forcing.

The nonlinearity is responsible for the stronger meridional flow associated with the heat sources. As a result, there are indications of a stronger remote response, caused by the vorticity source associated with the advection of vorticity by the divergent component of the wind (figure not shown). The North Atlantic trough present (NA) in the nonlinear simulation (Figure 13a) is a clear indication of this process. A similar feature is found near the Somali region and in the central Pacific region. It is interesting to compare to position and strength of NA in this case and in the experiments with the symmetric South American heat source activated (ANL). The NA feature is present, in Figure 4a, but weaker and to the west of the NA in Figure 13a. The vorticity balance suggests that the enhancement of the meridional vorticity transport into the strong westerly basic state in the northern Atlantic acts as a strong vorticity source that is able to enhance NA.

3.6. Effect of a Warm-ENSO Heat Source

The eastward displacement of the west Pacific heat source during the warm phase of ENSO represents a major reorganization in the upper tropospheric circulation in the Pacific Ocean. Previous model work by *Buchmann et al.* [1986] indicated the potentially strong effect of a strong heat source in the East Pacific over the South American circulation. Experiment CPAANL was designed to further explore this effect. The lack of the physical feedback (present in the work of *Buchmann et al.* [1986]) allows a better identification of the purely dynamical processes involved in the connection between the anomalous ENSO heat source and the circulation over tropical South America.

The 200 hPa wind of the stationary solution of experiment CPAANL is shown in Figure 15. This figure should be compared with the previous experiment displayed in Figure 13a. The BH shows less longitudinal extent in the ENSO experiment and a large-amplitude upper level trough is located in the east Pacific, a feature commonly found during the negative phase of ENSO [*Kousky et al.*, 1984]. The trough just off the northeast coast of Brazil is wider and displaced to the east, compared to N in Figure 13a. This is a consequence of the enhanced advective effect associated with the stronger upper westerly mean state generated by the central Pacific heat source. The development of the upper cyclonic flow in the Atlantic Ocean in the CPAANL experiment finds theoretical support in Figure 1. The presence of the three major heat sources generates a basic state in the current simulation which captures the essence of the observed structure of the upper level flow in the tropical region, supporting the conclusion of *Zhang and Krishnamurti* [1996]. Thus the enhanced upper cyclonic flow in the Atlantic Ocean observed in Figure 15 can be identified with the effect of the anomalous upper level divergence in the central Pacific Ocean.

The subtropical jet is strongly enhanced over northern Argentina and southern Brazil (Figure 15 compared with Figure 13a), similarly to the observed effect [*Kousky et al.*, 1984]. However, no significant changes are observed in the location and intensity of the S trough contrary to the conclusion of

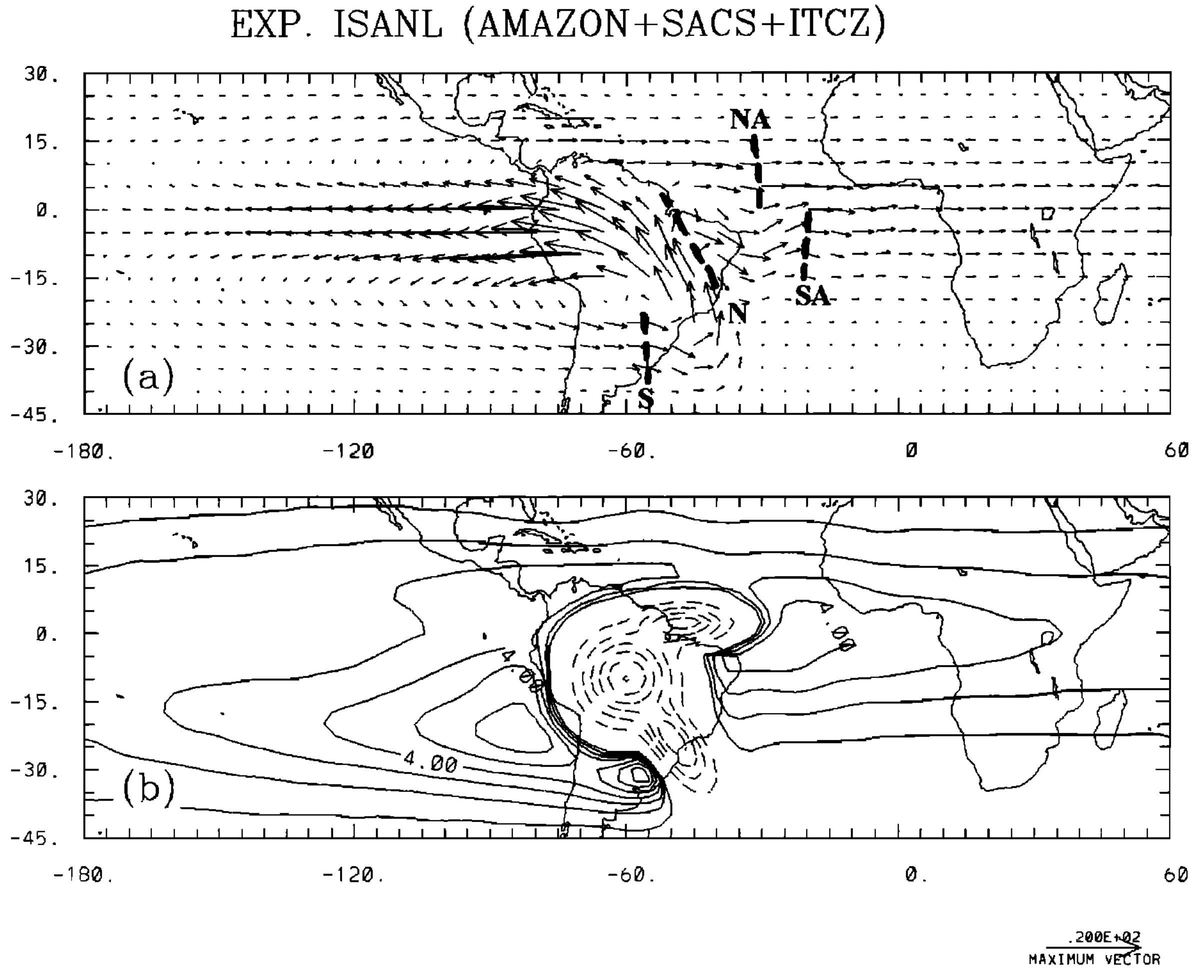

Figure 11. Same as Figure 4 but for experiment ISANL (Amazon/central Brazil heat source plus SACZ and Atlantic ITCZ sources).

GSD95 (based on their Figure 7) that the anomalous heating in the central Pacific favors the development of an anomalous trough in the southeastern/southern region of Brazil during ENSO events. This is a limitation of the current model which does not properly allow the energy propagation at higher latitudes.

The difference between the 500 hPa vertical motion in experiment CPAANL and WPAANL is shown in Figure 16. The largest downward motion impact is over central/eastern Amazon, extending along the northern coast of South America toward the equatorial Atlantic. Enhanced subsidence is also found over eastern equatorial Africa and Central America. There is a very close correspondence to the areas known to show precipitation deficit during warm ENSO events [*Ropelewski and Halpert*, 1987].

4. Summary and Conclusion

Special attention was given in the previous sections to (1) the structure of the upper anticyclonic and cyclonic centers present over tropical South America and neighboring oceanic areas during the Southern Hemisphere summer and (2) the location of the compensating subsidence associated with the intense tropical convection over South America and its relation to the presence of the tropical heat sources located in the west Pacific, Africa, and in the Central Pacific during the warm phase of ENSO. The model is not able to properly simulate the higher-latitude remote response associated with the localized tropical heat sources in view of the limited latitudinal domain which is a manifestation of the long-distance energy propagation and/or the excitation of unstable baroclinic or barotropic modes. However, the model allows for the establishment of the near-source response and to the circulations associated with the larger group velocity modes. The tropical model response to the forcing is not significantly influenced by the location of the northern and southern boundaries provided they are located poleward of the current location. Since these modes are highly divergent, it is reasonable to expect that the subsidence areas associated with the localized heating are adequately represented by the stationary solution which is usually attained after 15 days of integration in most of the experiments. The lack of a realistic initial state based on the climatological flow also inhibits the transients associated with barotropic/baroclinic instability which could eventually feedback on the regional response with reduced damping. Nevertheless, the stationary response generated by the model with a more realistic distribution of heat sources is remarkably similar to the observed flow in the tropical region (Figure 16), as suggested by *Zhang and Krishnamurti* [1996] in the linear context.

Experiments ANL and SANL were designed to explore the

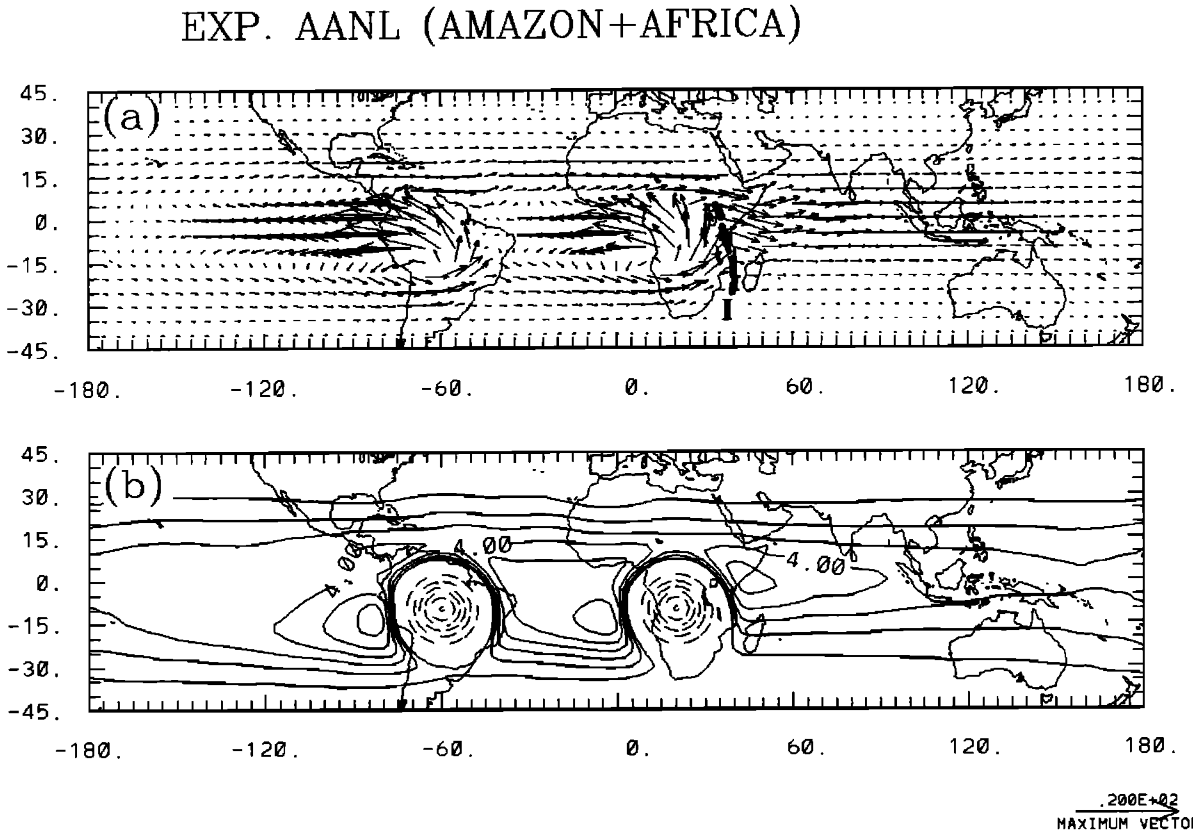

Figure 12. Same as Figure 4 but for experiment AANL (African and Amazon/central Brazil heat sources).

impact of symmetric and antisymmetric steady heat sources during the austral summer over the Amazon/central Brazil and the SACZ, respectively. Additional experiments were run to explore the potential impact of the Atlantic ITCZ, African, and west Pacific heat sources (ISANL, AANL, and WPAANL, respectively). The impact of an ENSO forcing, with the Pacific heat source displaced to the central Pacific, was also explored (experiment CPAANL). The linear impact of the localized heat sources was estimated after multiplying by 10 the stationary response of the nonlinear model forced by heat sources with one-tenth the magnitude of the nonlinear experiments (experiment AL and WPAAL).

The comparison between the linear and the nonlinear experiments with the symmetric heat source located in the Amazon/central Brazil indicate some significant differences such as intensification/weakening of the northern/southern branch of the Bolivian high. The enhancement of the cyclonic circulation southeast of the forcing is a feature of the nonlinear experiment which is relevant to the dynamics of the SACZ (trough S in Figure 4). The vorticity balance reveals that the barotropic nature of the nonlinear forcing, with intensification of the low-level cyclonic vorticity, is associated with the heat low over northern Argentina. The vertical distribution of the difference field between these two experiments shows a significant barotropic component as obtained by *Gill and Phlips* [1986]. Perhaps more important is the stronger cross-equatorial response in the nonlinear experiment which helps the establishment of significant distortions in the regional response over the equatorial Atlantic. The vorticity balance of the experiments suggests the importance of the nonlinear stretching term and the horizontal vorticity advection in order to explain the differences between the linear and the nonlinear results.

The nonlinear experiment shows an upward displacement of the maximum vertical motion associated with the heat source, with larger divergence at the upper troposphere with eventual impact in the remote response. The compensating upper tropospheric convergence occurs mainly to the southwest of the forcing, over the eastern Pacific off the coast of southern Peru, and northern Chile, extending over central/northern Argentina. Another area of compensating subsidence is oriented along the equator in the Atlantic Ocean, extending over Africa, associated with the Kelvin mode response to the localized steady heating. The inclusion of the asymmetry of the heat source associated with the southeastward extension of the SACZ enhances the subsidence in the poleward side of the SACZ, a feature commonly observed during episodes of enhanced convective activity in this region [*Casarin and Kousky*, 1986; *Paegle and Mo*, 1997]. Practically no effect is noticeable in the compensating subsidence in the equatorial Atlantic in view of the small Kelvin response associated with heat sources away from the equator such as in the case of the SACZ source. Remarkable similarity with the observed structure of the upper tropospheric circulation during wet and dry periods, during the wet season in the southeastern part of Brazil [*Sugahara*, 1991], was obtained with the symmetric and asymmetric heat source experiments.

The presence of the African and west Pacific heat sources have significant impact on the upper tropospheric flow over tropical South America. A linear experiment with the three heat sources shows that the upper trough, east of the Bolivian high, is intensified and shifted to the east in the nonlinear

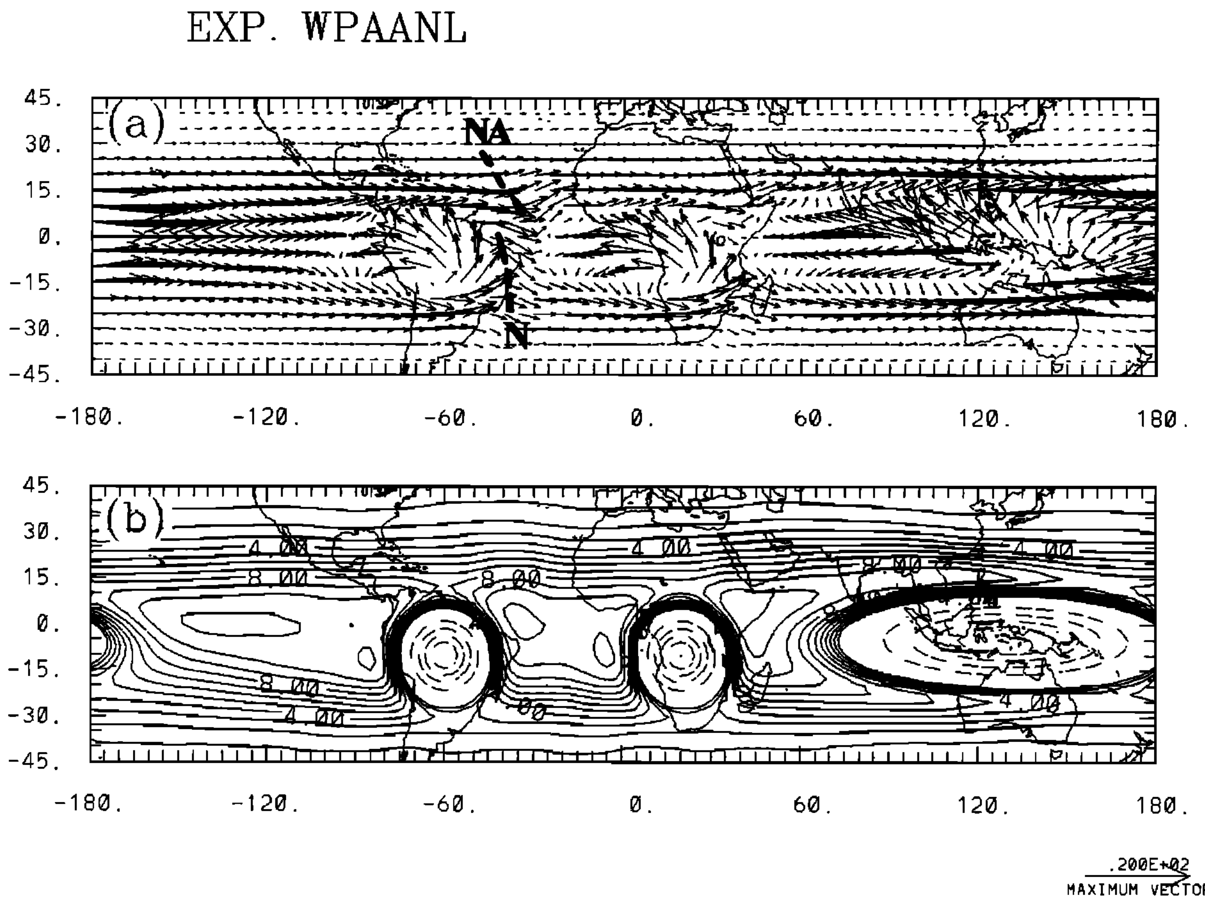

Figure 13. Same as Figure 4 but for experiment WPAANL (West Pacific Ocean zonally elongated heat source, African, and Amazon/central Brazil sources).

experiment. The upper westerlies in the east Pacific, associated with the Kelvin response to the west Pacific source, undergo strong diffluence when merging into the upper easterlies generated by the South American heat source over the eastern Pacific. Strong subsidence occurs in this area, shifting the area of maximum downward motion, previously found off the southwest coast of Peru, to the equatorial region in the eastern Pacific. The intensification of the subtropical jet in both hemispheres in the South American region, associated with the presence of the Pacific convection, has a significant impact on the location and shape of the upper tropospheric trough east of the BH and on the location of the subtropical jet which is displaced to the east of its former position in the single-source experiment. Stronger subsidence is found in the equatorial

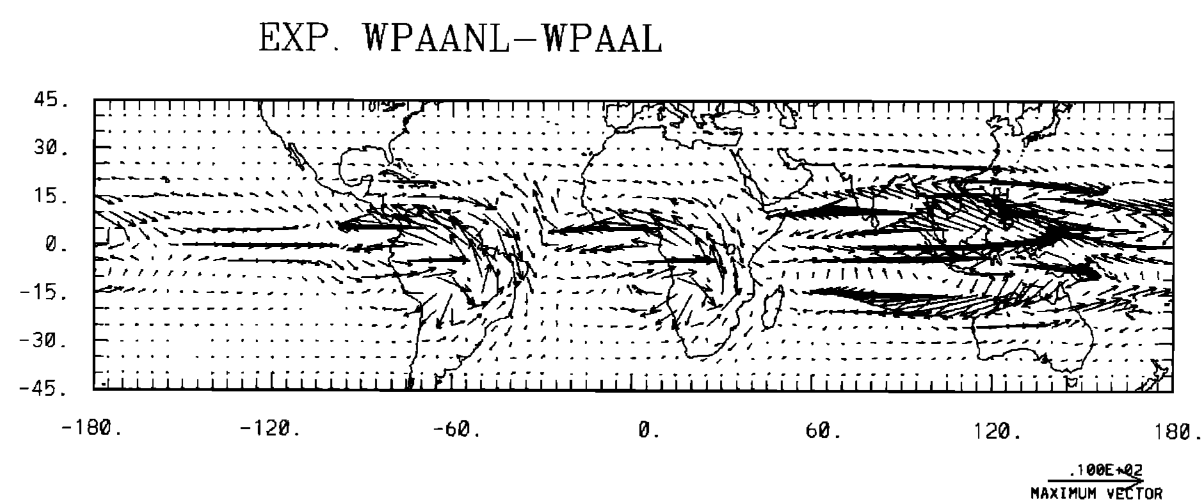

Figure 14. Difference between the 200 hPa flow in the stationary solution of the nonlinear experiment WPAANL and the linear version WPAAL.

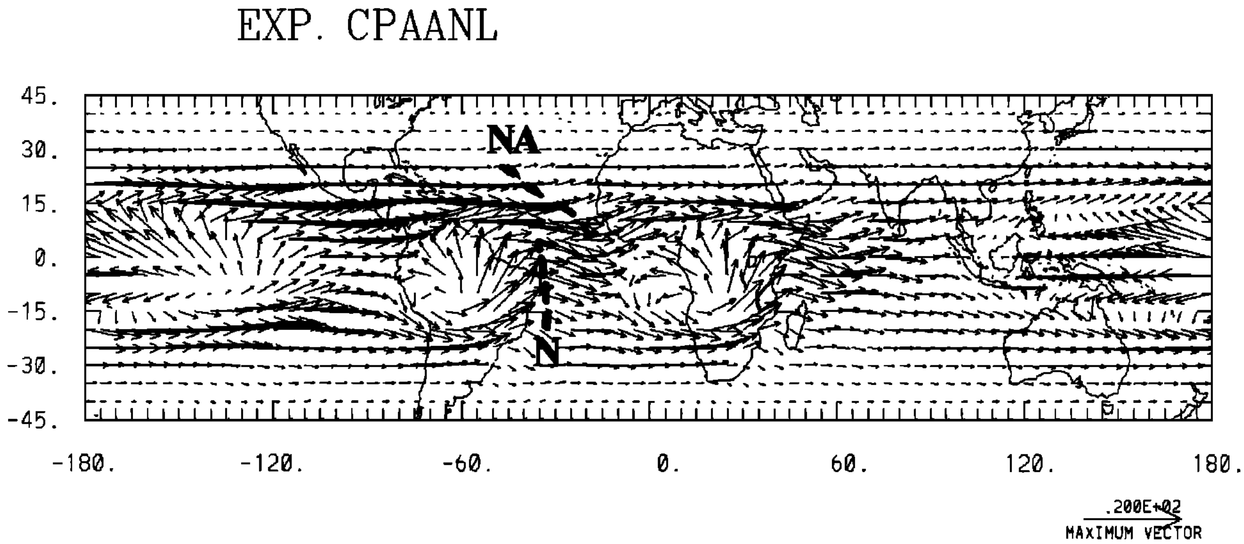

Figure 15. The 200 hPa flow in the stationary solution of experiment CPAANL (central Pacific heat source, African, and Amazon/central Brazil sources).

region in the Atlantic Ocean, extending toward Africa. The stronger subsidence in the Somali region seems to be related to the combination of the Amazon and west Pacific heat sources.

The African source has a significant impact on the subsidence field over the Atlantic Ocean, extending its influence to northeast Brazil where the downward motion is intensified, as verified in experiment AANL. The upper tropospheric cyclonic vorticity in the central equatorial Atlantic is also significantly influenced by the introduction of the African source. The nonlinearity in the African region, induced by the basic flow generated by the South American heat source, causes an eastward displacement of the upper trough over Madagascar, associated with the African source. This effect is quite negligible in the linear simulation.

The eastward displacement of the Pacific heat source associated with the warm phase of ENSO seems to enhance the cyclonic upper tropospheric circulation over the equatorial Atlantic. The trough off the northeast coast of Brazil appears as a broad open cyclonic flow. Intensified subsidence is observed throughout the Atlantic, from northeast Brazil, extending toward Africa and on to the Indian Ocean, confirming previous findings by *Buchmann et al.* [1986] with a complete general circulation model. The observed precipitation anomalies in the South American and African continents [*Ropelewski and Halpert*, 1987] are in remarkable agreement with the difference field associated with the subsidence at 500 hPa between the West Pacific and the central Pacific heat sources (experiments WPAANL and CPAANL).

Attention is focused in this paper to the regional response to localized heating in the tropical sector of South America and how the compensating subsidence is organized and influenced by other major tropical heat sources such as the African and the Pacific. The regional response is important not only for understanding the local climatological structure of the upper level flow. GSD95 indicated that the anomalous teleconnection patterns may be related to the anomalous upper tropospheric divergence/convergence associated with the convective activity over tropical South America. This is the case of the Eurasian pattern which is significantly influenced by upper tropospheric divergence/convergence in the Gulf of Mexico, extending southeastward toward the eastern part of Brazil, with opposing influence in Argentina (Figure 9 of GSD95). The upper diver-

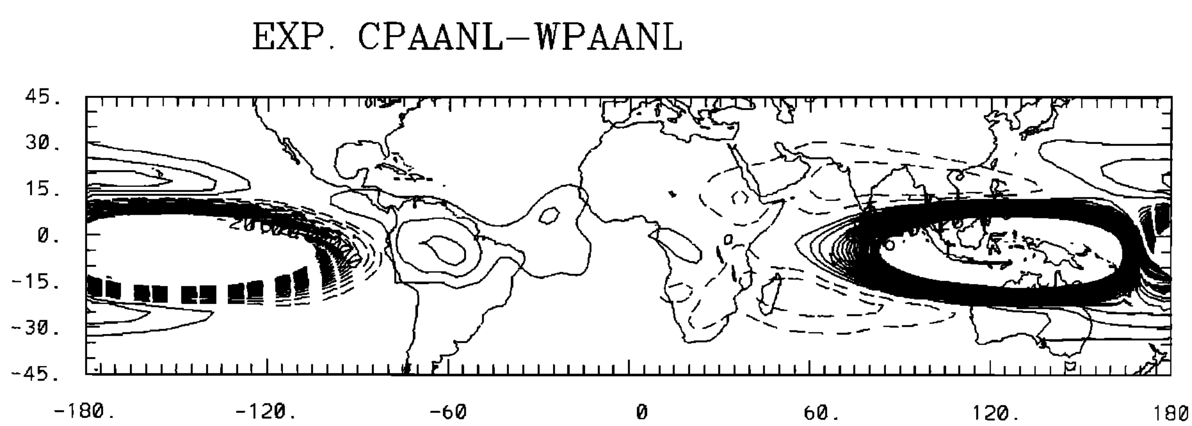

Figure 16. Difference between the 500 hPa vertical motion in the stationary solution of experiments CPAANL and WPAANL (1 hPa/d contours, when values are lower than 20 hPa/d).

gence associated with the Amazon/central Brazil and SACZ experiment (SANL experiment, shown in Figure 9a) shows a remarkable similarity with the influence function of the target points of the Eurasian pattern located over western Europe and western Asia. The compensating subsidence in this experiment shows a reasonable match with the opposing influence in Argentina for the same target points.

The target points of the PNA pattern, located in the northern part of the central Pacific and just off the east coast of North America, also bear some relationship with convection in South America. Their influence functions (shown in Figure 5 of GSD95) show relatively large values oriented in the northwest-southeast direction over the tropical sector of South America. Opposing signs are observed in the influence function, primarily in the case of the North Pacific target point.

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