Available online at www.sciencedirect.com
ScienceDirect
Progress in Oceanography 70 (2006) 407–415
Progress in Oceanography
www.elsevier.com/locate/pocean

Circulation and teleconnection mechanisms of Northeast Brazil droughts

Stefan Hastenrath *

Department of Atmospheric and Oceanic Sciences, University of Wisconsin – Madison, 1225 West Dayton Street, Madison, WI 53706, USA

Received 28 March 2004; received in revised form 28 February 2005; accepted 28 July 2005
Available online 21 June 2006

Abstract

The Northern Nordeste of Brazil has its short rainy season narrowly concentrated around March–April, when the interhemispheric southward gradient of sea surface temperature (SST) is weakest and the Intertropical Convergence Zone (ITCZ), which is the main rainbearing system for the Nordeste, reaches its southernmost position in the course of the year. The recurrent Secas (droughts) have a severe socio-economic impact in this semi-arid region. In drought years, the pre-season (October–January) rainfall is scarce, the interhemispheric SST gradient weakened and the basin-wide southerly (northerly) wind component enhanced (reduced), all manifestations of an anomalously far northward ITCZ position. Apart from this ensemble of Atlantic indicators, the Secas also tend to be preceded by anomalously warm equatorial Pacific waters in January. During El Niño years, an upper-tropospheric wave train extends from the equatorial eastern Pacific to the northern tropical Atlantic, affecting the patterns of upper-tropospheric topography and divergence, and hence of vertical motion over the Atlantic. The altered vertical motion leads to a weaker meridional pressure gradient on the equatorward flank of the North Atlantic subtropical high, and thus weaker North Atlantic tradewinds. The concomitant reduction of evaporation and wind stirring allows for warmer surface waters in the tropical North Atlantic and thus steeper interhemispheric meridional thermal gradient. Consequently, the ITCZ stays anomalously far North and the Nordeste rainy season becomes deficient.

Regional Index Terms: Tropical Atlantic; Northeast Brazil; Equatorial Pacific

Keywords: Sea surface temperature; Temperature gradient; Atmosphere–hydrosphere system; El Niño; Southern Oscillation; Teleconnection

1. Introduction

The Northern Nordeste of Brazil (Fig. 1d) is a particularly attractive target for circulation and climate diagnostics. It has a semi-arid climate with a short rainy season narrowly concentrated around March–April and large variations of precipitation from year to year. The Secas, or droughts, have a severe human impact (Has-

* Tel.: +1 608 262 3659; fax: +1 608 262 0166.
E-mail address: slhasten@facstaff.wisc.edu.

0079-6611/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pocean.2005.07.004

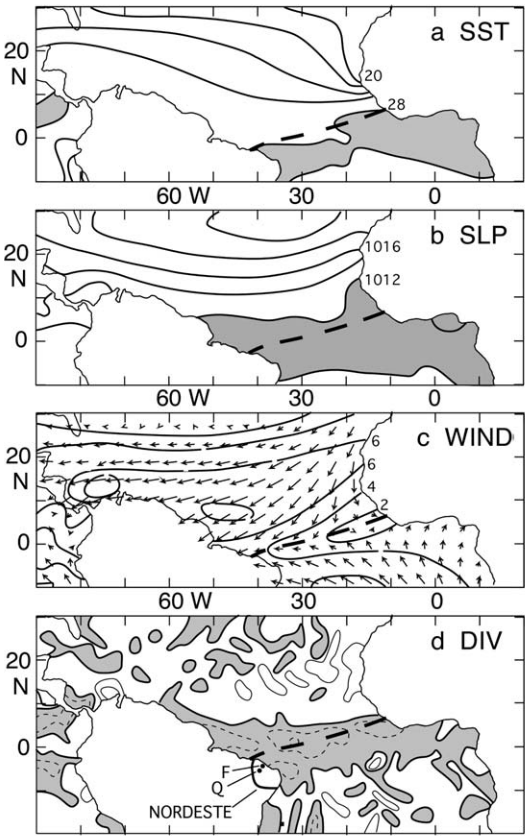

Fig. 1. Surface circulation over the equatorial Atlantic and eastern Pacific, March 1958–1997: (a) sea surface temperature, with isotherm spacing of 2 °C and with area above 28 °C shaded; (b) sea level pressure, with isobar spacing of 2 mb, and with area below 1012 mb shaded; (c) resultant wind direction and speed, with isotach spacing of 2 m s^{-1}; (d) divergence with isoline spacing of 5×10^{-6} s^{-1}, and convergence shaded. Bold solid line encloses Northeast Brazil (Nordeste), and F and Q denote the stations Fortaleza and Quixeramobim.

tenrath, 1985, pp. 363–365). Work since the 1970s has progressively documented the annual cycle of circulation (Hastenrath and Lamb, 1977), has elucidated the circulation mechanisms of interannual climate variability (Hastenrath and Heller, 1977; Covey and Hastenrath, 1978; Hastenrath, 1985, pp. 293–300; Hastenrath and Druyan, 1993; Hastenrath and Greischar, 1993a; Curtis and Hastenrath, 1995; Hastenrath, 1995, pp. 302–309; Hastenrath, 2000a,b), and on this basis has developed methods for the seasonal forecasting of Nordeste rainfall anomalies (Hastenrath et al., 1984; Hastenrath, 1985, pp. 339–344; Hastenrath, 1990; Hastenrath and Greischar, 1993b; Hastenrath, 1995, pp. 359–362; Greischar and Hastenrath, 2000). Drawing on a sequence of studies at the University of Wisconsin, the present essay shall review the circulation mechanisms in the tropical Atlantic sector that control the rainfall variability in the Nordeste, and sketch the way in which Pacific El Niño events, through an "atmospheric bridge", affect the circulation of the Atlantic atmosphere–hydrosphere system, and thus the Nordeste.

2. Annual cycle

The rainy season in the Northern Nordeste of Brazil is short and narrowly concentrated around March–April, as is illustrated in Fig. 2 for two long-term stations. This particular seasonality in rainfall can only be appreciated from analyses of the large-scale circulation setting. The annual cycle of circulation in the tropical Atlantic sector has first been comprehensively documented in an atlas based on long-term ship observations (Hastenrath and Lamb, 1977). Fig. 1 presents a selection of maps for March, based on the Comprehensive Ocean–Atmosphere Data Set, COADS (Woodruff et al., 1987). The map of Fig. 1a shows

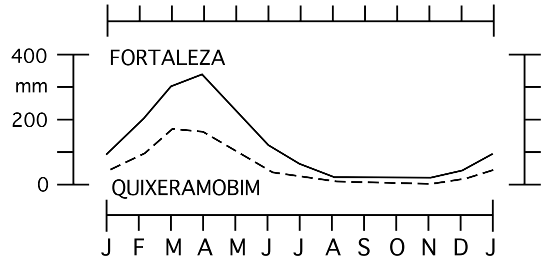

Fig. 2. Annual cycle of rainfall at Fortaleza and Quixeramobim (ref. Fig. 1d).

a band of warmest surface waters (>28 °C) across the equatorial Atlantic. A trough of lowest pressure (Fig. 1b) sits broadly over the warmest surface waters. Embedded in the low pressure trough is the confluence between the Northeast trades and the cross-equatorial airstream from the southern hemisphere (Fig. 1c). Also embedded in the low pressure trough is the zone of largest convergence (Fig. 1d), the Intertropical Convergence Zone (ITCZ).

The SST maximum hydrostatically favors the low pressure trough into which the airstreams flow from the two hemispheres, and thus the position of the ITCZ (Hastenrath and Druyan, 1993; Hastenrath and Greischar, 1993a). In boreal summer, the SST maximum, near-equatorial lowe pressure trough, and ITCZ, are all located far North, and the SST gradient is steep across the Equator. From September onward, the interhemispheric SST contrast decreases, and the complex of SST maximum, low pressure trough, and ITCZ, shift southward, reaching a southernmost position around March–April. The ITCZ is the major rainbearing system for the Nordeste and thus determines the timing and narrow concentration of the rainy season around March–April (Fig. 2). After April, the waters of the tropical North Atlantic warm, the interhemispheric SST gradient steepens, and the complex of SST maximum, low pressure trough and ITCZ migrate northward, away from the Nordeste.

3. Circulation mechanisms of droughts

The cartoon in Fig. 3 compacts the results from diagnostic research spread over two decades (Hastenrath and Heller, 1977; Moura and Shukla, 1981; Hastenrath et al., 1984; Hastenrath, 1985, pp. 293–300; Hastenrath and Druyan, 1993; Hastenrath and Greischar, 1993a,b). The maps of Figs. 3a and b illustrate the departures in the large-scale atmosphere–ocean setting characteristic of extremely DRY (Fig. 3a) and extremely WET (Fig. 3b) years in the Nordeste. Thus, during the DRY years the interhemispheric SST gradient is steepend, which Fig. 3a simplistically depicts by warm in the North and cold in the South. The steepened SST gradient entails a more northerly position of the SST maximum. As a consequence, the confluence between the airstreams from the two hemispheres sits far North, and along with that the rainbearing ITCZ. Fig. 3b for the Nordeste WET years shows departures broadly opposite to those in the DRY years, namely weakened interhemispheric SST gradient, a more southerly ITCZ position, and anomalously cold rather than warm Pacific waters.

In context with the discussion in Section 2 it is noted that the circulation departure patterns characteristic of DRY and WET years broadly conform to the contrasts between the boreal summer dry season and late boreal winter rainy season in the course of the annual cycle; essential factors being the interhemispheric SST gradient and corresponding latitude position of the ITCZ. Apart from these indicators in the tropical Atlantic sector, Figs. 3a and b also show an association with SST in the eastern equatorial Pacific, with January Pacific warm (cold) anomalies accompanying DRY (WET) years in the Nordeste. The underlying circulation mechanisms are the subject of the next section.

4. Teleconnections with ENSO

The relation of climate anomalies in the tropical Atlantic sector with the Pacific El Nino phenomenon has been explored in a sequel of studies over the past three decades (Covey and Hastenrath, 1978; Curtis and Has-

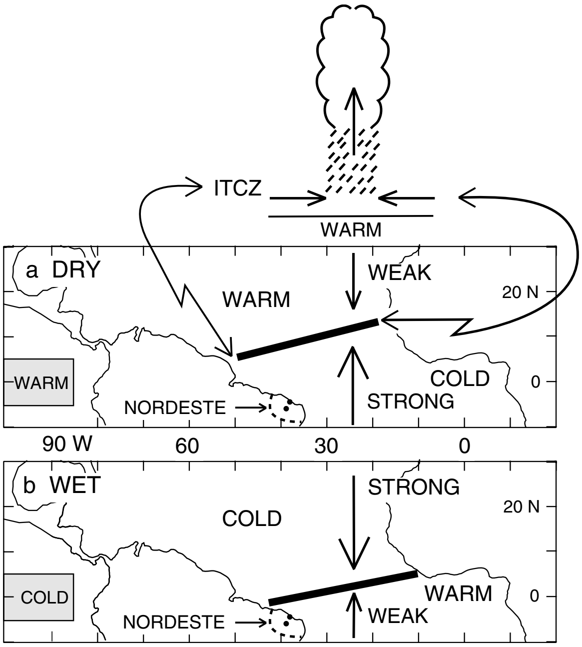

Fig. 3. Schematic illustration of the characteristic circulation departures during (a) DRY and (b) WET years in Northern Northeast Brazil. During DRY as compared to WET years the interhemispheric SST gradient is enhanced, the Northeast tradewinds weaker, the cross-equatorial airstream from the Southern hemisphere weaker, and the enclosed wind confluence along with the ITCZ are displaced northward. Along with this the pre-season rainfall in the Nordeste is reduced, and the equatorial Pacific waters are anomalously warm.

tenrath, 1995; Hastenrath, 2000a,b). A study in the 1970s (Covey and Hastenrath, 1978) showed that Pacific El Nino events are typically followed by warming in much of the tropical Atlantic, but the underlying mechanisms of such developments remained enigmatic.

Early theoretical and modeling studies (Egger, 1977; Opsteegh and Van den Dool, 1980; Webster, 1981; Hoskins and Karoly, 1981; Horel and Wallace, 1981; Nobre and Moura, 1984; reviews in Hastenrath, 1985, pp. 266–283; Hastenrath, 1995, pp. 282–288) suggested a role of the upper troposphere in large-scale linkages. These studies stimulated the notion of "atmospheric bridge" (Lau and Nath, 1996; Klein et al., 1999; Alexander et al., 2002).

A series of investigations (Hastenrath and Heller, 1977; Hastenrath et al., 1984; Hastenrath, 1990; Hastenrath and Greischar, 1993b; Greischar and Hastenrath, 2000) aimed at forecasting the precipitation anomalies of the March–June rainy season in Brazil's Nordeste from information through the end of January. The most indicative precursors of a deficient rainy season are deficient pre-season (October–January) precipitation in the region itself, steep interhemispheric southward thermal gradient, and basin-wide enhanced southerly (decreased northerly) wind component in the Atlantic, all manifestations of anomalously far northerly ITCZ position. Apart from this ensemble of Atlantic indicators, the Secas also tend to be preceded by anomalously warm equatorial Pacific waters in January.

In an attempt at understanding some of the mechanisms linking the Pacific SST to subsequent Nordeste rainfall, Curtis and Hastenrath (1995) documented the anomalous seasonal evolution of circulation in the Atlantic following warm Pacific in January. Nobre and Shukla (1996), Enfield and Mayer (1997), Klein et al. (1999), and Giannini et al. (2004) later confirmed their findings. Curtis and Hastenrath (1995) showed that from January to March Atlantic trade winds weaken anomalously, and that due to the concomitantly weakened wind forcing the tropical Atlantic surface waters warm anomalously through April. This sets the scene for an anomalously steep interhemispheric southward SST gradient, stronger southerly (weaker northerly) wind component, and thus anomalously far northward ITCZ position and deficient Nordeste rainfall. The study thus advanced the understanding to a new frontier defined in the question: what are the causes of the weakened North Atlantic tradewinds during Pacific warm events?

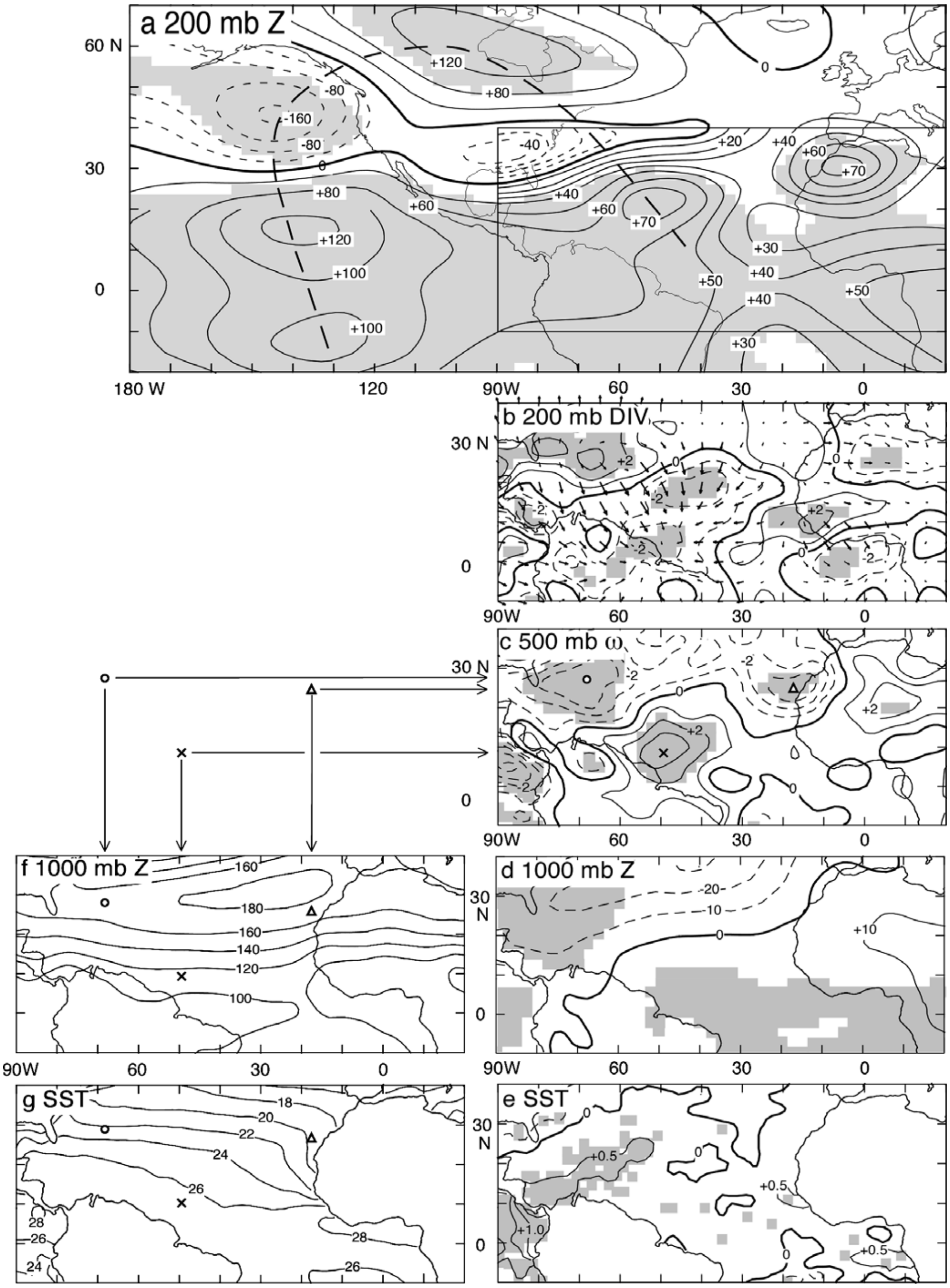

Fig. 4. January maps of differences between 10-year ensembles of Pacific WARM minus COLD (a–e), and of 1958–1997 mean conditions (f and g). The difference maps shown are of (a) 200 mb topography, with isoline spacing of 40 gpm (geopotential meters) poleward of 20°N, 20 gpm equatorward of 20°N, and 10 gpm for domain inside rectangle and thin dashed lines indicating negative values; heavy dashed line highlights wave train from equatorial Pacific to tropical North Atlantic; rectangle encloses domain shown in the maps (b–g); (b) 200 mb divergence with isoline spacing of 1×10^{-6} s^{-1} and dashed lines indicating negative values, and divergent wind component with arrows scaled at 2° latitude for 1 m s^{-1}; (c) 500 mb omega vertical motion, with isoline spacing of 10^{-4} mb s^{-1} and dashed lies indicating negative values or upward motion; (d) 1000 mb topography with isoline spacing of 20 gpm and dashed lines indicating negative values. The Atlantic 1958–1997 mean maps are of (f) 1000 mb topography with isoline spacing of 20 gpm; and (g) SST with isoline spacing of 2 °C. Open circle, triangle, cross, and accompanying arrows serve to identify extrema in the difference map (c) and to indicate their location in the mean maps (f and g). Shading and bold arrows denote significance of differences at 5% level according to *t*-test.

Exploration of this "atmospheric bridge" from the Pacific to the Atlantic had to wait for appropriate upper-air information. The issue of the NCEP-NCAR 40-year Reanalysis (Kalnay et al., 1996) opened new prospects. An evaluation for warm as compared to cold Pacific waters in January (Hastenrath, 2000a,b) revealed in the upper-tropospheric topographies a wave train from the equatorial Pacific to the tropical North Atlantic; the associated pattern of departures in upper-tropospheric divergent flow and divergence entails diminished subsidence on the equatorward flank of the surface North Atlantic subtropical high. This serves to decrease the pressure there, which weakens the meridional pressure gradient and thus the North Atlantic tradewinds. The further consequences of weak North Atlantic tradewinds following Pacific warm January are known from the earlier study (Curtis and Hastenrath, 1995).

While the present synthesis of our explorations over the past quarter century (Covey and Hastenrath, 1978; Curtis and Hastenrath, 1995; Hastenrath, 2000b) focuses on the eastern Pacific to Atlantic sector, recent papers on "atmospheric bridge" in part extend to larger domains. In particular, Klein et al. (1999) evaluated surface and satellite observations, whereas Lau and Nath (1996) and Alexander et al. (2002) used numerical modeling. Lau and Nath's (1996)maps do not capture the low-latitude Atlantic. Klein et al. (1999), Alexander et al. (2002), and Giannini et al. (2004) support the earlier findings of Enfield and Mayer (1997), Giannini et al. (2004) expand on the earlier results in the following respect. Instead of contrasting Pacific WARM against COLD years, they compare a reference normal with COLD and WARM ensembles, respectively, and on these grounds find a closer association for Pacific COLD years. The later papers (Lau and Nath, 1996; Enfield and Mayer, 1997; Klein et al., 1999) do not mention the earlier surface studies (Curtis and Hastenrath, 1995), and some (Alexander et al., 2002; Giannini et al., 2004) do not refer to the previous upper-air findings (Hastenrath, 2000b).

Figs. 4–6, place the chain of causality recognized in the three studies (Covey and Hastenrath, 1978; Curtis and Hastenrath, 1995; Hastenrath, 2000b) into context. Fig. 4 based on the NCEP-NCAR upper-air data set and COADS depicts the upper-air conditions for Pacific warm as compared to cold January (The WARM ensemble consists of the years 1958, 1966, 1969, 1970, 1973, 1983, 1987, 1988, 1992, 1995: and the COLD ensemble of the years 1963, 1965, 1967, 1968, 1971, 1974, 1975, 1976, 1985, 1989). A wave train from the equa-

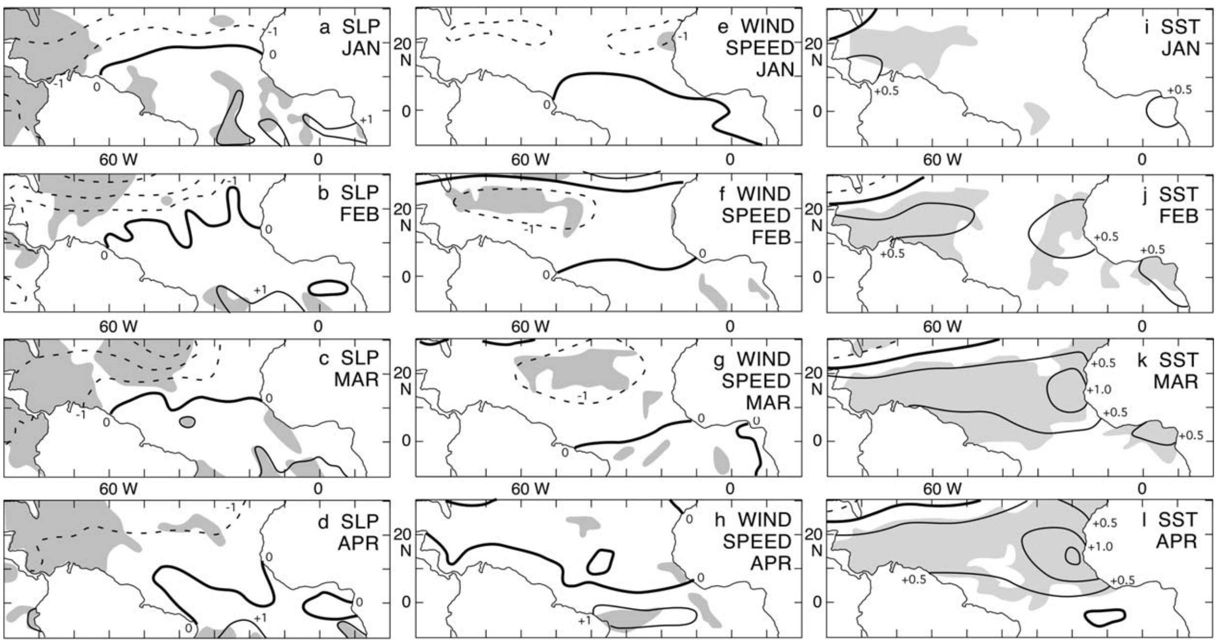

Fig. 5. Maps of differences between 10-year ensembles of Pacific January WARM minus COLD, for January (a, e and i), February (b, f and j), March (c, g and k), and April (d, h and l). The Atlantic maps shown are of sea level pressure (a–d), with isoline spacing of 1 mb; surface resultant wind speed (e–h) with isoline spacing of 1 m s^{-1}; and SST (i–l) with isoline spacing of 0.5 °C. Thick solid lines denote zero, and thin dashed lines negative values. Shading indicates areas for which the difference is significant at the 5% level according to t-test.

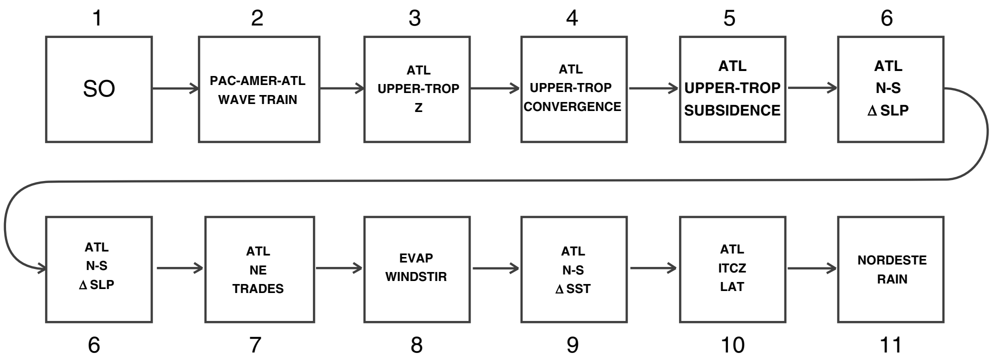

Fig. 6. Schematic diagram of mechanisms relating the Southern Oscillation to Nordeste rainfall: (1) Southern Oscillation; (2) Pacific-Americas-Atlantic upper-tropospheric wave train; (3) anomalies in Atlantic upper-tropospheric topography; (4) upper-tropospheric convergence on equatorward side of North Atlantic high; (5) mid-tropospheric subsidence on equatorward side of North Atlantic high; (6) meridional gradient of surface pressure; (7) strength of Northeast tradewinds; (8) evaporation and wind stirring in tropical North Atlantic; (9) interhemispheric southward SST gradient in Atlantic; (10) latitude position of Atlantic ITCZ; (11) Nordeste rainfall.

torial Pacific to the tropical North Atlantic is apparent in the map of 200 mb topography (Fig. 4a). Associated with this is the difference pattern of 200 mb divergent flow and divergence (Fig. 4b). Concordant with the upper-tropospheric divergence (Fig. 4b) is the mid-tropospheric vertical motion (Fig. 4c). Comparison with the map of long-term mean 1000 mb topography (Fig. 4f) shows that subsidence is reduced on the equatorward side of the North Atlantic subtropical high. This serves to decrease the 1000 mb topography in that latitude band during the Pacific warm as compared to cold years (Fig. 4d), resulting in a greatly weakened meridional pressure gradient. Fig. 4b should be compared to Fig. 4g: the largest warm differences are located to the North of the band of warmest surface waters in the long-term mean.

The seasonal evolution of Atlantic patterns for WARM as compared to COLD Pacific January is presented in Fig. 5 based on COADS (The WARM ensemble consists of the years 1958, 1966, 1969, 1970, 1973, 1980, 1983, 1987, 1988, 1992; and the COLD ensemble of the years 1950, 1955, 1956, 1957, 1968, 1971, 1974, 1976, 1985, 1989). The maps of Figs. 5a–d show for Pacific January WARM minus COLD ever larger deficits of surface pressure over the tropical North Atlantic from January to March. Such evolution of the surface pressure field entails a progressive weakening of the meridional pressure gradient in the realm of the North Atlantic trade winds. Consistent with this, the total wind speed in the realm of the North Atlantic trade winds weakens from January to March (Figs. 5e–h); the positive differences in the equatorial belt in April (Fig. 5h) reflect the enhanced cross-equatorial flow from the southern hemisphere in response to the steepened meridional temperature gradient (Curtis and Hastenrath, 1995). The anomalous weakening of the northward SST gradient is mainly due to anomalous warming in the tropical North Atlantic. As detailed by Curtis and Hastenrath (1995), this stems from the combination of three forcings all related to the weakened North Atlantic trade winds during Pacific warm events. Most important are the reduced latent heat flux and wind stirring in much of the tropical North Atlantic and anomalous downwelling equatorward of 20°N, with a further contribution from increased net radiation resulting from the reduced cloudiness due to the diminished convergence in the downstream portion of the North Atlantic trades. Thus, the maps of Figs. 5e–h of wind speed should be compared with the SST maps of Figs. 5i–l, which bear out positive temperature differences in the tropical North Atlantic increasing from January through April. The implied steepening interhemispheric southward thermal gradient leads to a far northward ITCZ position and thus deficient rainfall in Brazil's Nordeste.

The causality chain from Southern Oscillation and El Niño to Nordeste rainfall documented in Figs. 4 and 5 is highlighted in the schematic flow diagram in Fig. 6. The Southern Oscillation (1) incites an upper-tropospheric wave train (2), which affects the upper-tropospheric topography (3) and divergence (4) and hence vertical motion (5) patterns over the Atlantic; the vertical motion (5) in turn influences the meridional pressure gradient at the surface (6) and thus the North Atlantic tradewinds (7); this through altered evaporation and wind stirring (8) modulates the interhemispheric meridional thermal gradient (9), which controls the latitude position of the ITCZ (10) and thus Nordeste rainfall (11). This causality chain also explains why the Atlantic near-equatorial low pressure trough sits anomalously far North during boreal winter of the low/warm SO phase (Hastenrath et al., 1987). Why the trough is located anomalously far South during the boreal summer of the low/warm SO phase is an intriguing pending question?

5. Conclusions

Rainfall in the Northern Nordeste of Brazil stems prevailingly from a single well-organized quasi-permanent component of the large-scale circulation, the Atlantic ITCZ. Both in the course of the average annual cycle and in interannual variability rainfall is least with a far northerly ITCZ position, which has as further manifestations a steep interhemispheric southward directed thermal gradient and basin-wide enhanced southerly (reduced northerly) wind component, as well as enhanced pre-season precipitation in the Nordeste. Apart from these Atlantic indicators, the Secas also tend to be preceded by anomalously warm conditions in the eastern equatorial Pacific. An "atmospheric bridge" from the Pacific to the Atlantic consists of an upper-tropospheric wave train, entailing anomalous upper-tropospheric divergence and vertical motion over the tropical North Atlantic, which affects the surface meridional pressure profile and thus the North Atlantic tradewinds; the altered windstress forcing modulates the SST pattern and particularly the interhemispheric thermal gradient. This, in turn, controls the latitude position of the ITCZ and thus Nordeste rainfall. Thus, the Pacific El Niño phenomenon aggravates the Nordeste Secas through a chain of mechanisms involving the Atlantic ITCZ. Ultimately, it is the strength and particularly the latitude position of the ITCZ which controls the short rainy season of the Northern Nordeste.

Acknowledgements

This work has been supported by National Science Foundation Grant ATM-0110061. I thank the anonymous reviewers for valuable comments.

References

Alexander, M.A., Blade, I., Newman, M., Lanzate, J.R., Lau, N.-C., 2002. The atmospheric bridge: the influence of ENSO teleconnections on air–sea interaction over the global oceans. Journal of Climate 15, 2205–2231.

Covey, D.L., Hastenrath, S., 1978. The Pacific El Niño phenomenon and the Atlantic circulation. Monthly Weather Review 108, 1280–1287.

Curtis, S., Hastenrath, S., 1995. Forcing of anomalous sea surface temperature evolution in the tropical Atlantic during Pacific warm events. Journal of Geophysical Research-Oceans 100 (C8), 15835–15847.

Egger, J., 1977. On the linear theory of the atmospheric response to sea surface temperature anomalies. Journal of Atmospheric Science 34, 603–614.

Enfield, D., Mayer, D.A., 1997. Tropical Atlantic sea surface temperature variability and its relation to El Nino – Southern Oscillation. Journal of Geophysical Research – Oceans 102 (C1), 929–945.

Giannini, A., Saravanan, R., Chang, P., 2004. The preconditioning role of the tropical Atlantic variability in the development of the ENSO teleconnection: implications for the prediction of Nordeste rainfall. Climate Dynamics 22, 839–855.

Greischar, L., Hastenrath, S., 2000. The rainy season of the 1990s in Northeast Brazil: real-time forecasts and verification. Journal of Climate 13, 3821–3826.

Hastenrath, S., 1985. Climate and Circulation of the Tropics. Reidel, Dordrecht, Boston, Lancaster, Tokyo, 455 pp.

Hastenrath, S., 1990. Prediction of Northeast Brazil rainfall anomalies. Journal of Climate 3, 893–904.

Hastenrath, S., 1995. Climate Dynamics of the Tropics. Kluwer, Dordrecht, Boston, London, 488 pp.

Hastenrath, S., 2000a. Interannual and longer-term variability of upper-air circulation in the Northeast Brazil – tropical Atlantic sector. Journal of Geophysical Research-Atmospheres 105 (D6), 7322–7335.

Hastenrath, S., 2000b. Upper-air mechanisms of the Southern Oscillation in the tropical Atlantic sector. Journal of Geophysical Research-Atmospheres 115 (D11), 14997–15009.

Hastenrath, S., Druyan, L., 1993. Circulation anomaly mechanisms in the tropical Atlantic sector during the Northeast Brazil rainy season: results from the GISS General Circulation Model. Journal of Geophysical Research-Atmospheres 98 (D8), 14017–14923.

Hastenrath, S., Greischar, L., 1993a. Circulation mechanisms related to Northeast Brazil rainfall anomalies. Journal of Geophysical Research-Atmospheres 98 (D5), 5093–5102.

Hastenrath, S., Greischar, L., 1993b. Further work on the prediction of Northeast Brazil rainfall anomalies. Journal of Climate 6, 743–758.

Hastenrath, S., Heller, L., 1977. Dynamics of climatic hazards in Northeast Brazil. Quarterly Journal of the Royal Meteorological Society 103, 77–92.

Hastenrath, S., Lamb, P.J., 1977. Climatic Atlas of the Tropical Atlantic and Eastern Pacific Oceans. University of Wisconsin Press, 113 pp.

Hastenrath, S., Wu, M.C., Chu, P.S., 1984. Towards the monitoring and prediction of Northeast Brazil droughts. Quarterly Journal of the Royal Meteorological Society 110, 411–425.

Hastenrath, S., Castro, L.C., Aceituno, P., 1987. The Southern Oscillation in the tropical Atlantic sector. Contributions to Atmospheric Physics 60, 447–463.

Horel, J.D., Wallace, J.M., 1981. Planetary scale atmospheric phenomena associated to thermal and orographic forcing. Monthly Weather Review 109, 813–823.

Hoskins, B.J., Karoly, D., 1981. The steady linear response of a spherical atmosphere to thermal and orographic forcing. Journal of Atmospheric Science 38, 1179–1198.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society 77, 437–471.

Klein, S.A., Soden, B.J., Lau, N.-C., 1999. Remote sea surface temperature variations during ENSO: evidence for a tropical atmospheric bridge. Journal of Climate 12, 917–932.

Lau, N.-C., Nath, M.J., 1996. The role of the atmospheric bridge in linking tropical Pacific ENSO events to extratropical SST anomalies. Journal of Climate 9, 2036–2057.

Moura, A.D., Shukla, J., 1981. On the dynamics of droughts in Northeast Brazil: observations, theory, and numerical experiments with a general circulation model. Journal of Atmospheric Science 38, 2653–2675.

Nobre, P., Moura, A.D., 1984. Large-scale tropical heat sources and global atmosphere energy propagation associated with droughts in Northeast Brazil, pp. 83–86. In: Extended Abstracts of Papers Presented at the Second WMO Symposium on Meteorological Aspects of Tropical Droughts. September 1984, World Meteorological Organization, TMP Report Series No. 15, Geneva, Switzerland, 134 pp.

Nobre, P., Shukla, J., 1996. Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. Journal of Climate 9, 2464–2479.

Opsteegh, J.D., Van den Dool, H.M., 1980. Seasonal differences in the stationary response of a linearized primitive equation model: prospects for long-range forecasting. Journal of Atmospheric Science 37, 2169–2185.

Webster, P.J., 1981. Mechanisms determining the atmospheric response to sea surface temperature anomalies. Journal of Atmospheric Science 38, 554–571.

Woodruff, S., Slutz, R., Jenne, R., Steurer, P., 1987. A comprehensive ocean–atmosphere data set. Bulletin of the American Meteorological Society 68, 1239–1250.