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On the Existence of Lloró (the Rainiest Locality on Earth): Enhanced Ocean-Land-Atmosphere Interaction by a Low-Level Jet

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Abstract. The department of Chocó, on the Colombian Pacific coast experiences 8,000 to 13,000 mm of average annual precipitation. Lloró (5°30'N, 76°32'W, 120m) has received above 12,700 mm (1952-1960). Using the NCEP/NCAR Reanalysis data, we show that the ocean-land-atmosphere interaction over the easternmost fringe of the tropical Pacific, enhanced by the dynamics of a low-level westerly jet ("CHOCO"), contributes to explain the existence of such record-breaking hydrological region. Deep convection develops from low-level moisture convergence by the CHOCO jet, combined with high-level easterly trade winds, orographic lifting on the western Andes, low surface pressures and warm air. Precipitation is organized in mesoscale convective complexes, in turn dynamically linked to the jet. The strength of the CHOCO jet (centered at 5°N) is associated with the gradient of surface air temperatures between western Colombia and the Niño 1+2 region, thereby exhibiting strong annual and interannual variability, which contributes to explaining Colombia's hydro-climatology and its anomalies during ENSO.

Introduction

One of the rainiest regions of the world is Chocó, located at the lowlands of the Pacific coast of Colombia, where average precipitation ranges from 8,000 to 13,000 mm per year. Although the density of the gauges does not meet standards, one can see that both average and record values are very impressive. Rainfall records show that the locality of Lloró (5°30'N, 76°32'W, 120m), received 13,473 mm of average annual precipitation during 1952-1954, dropping to 12,717 mm for the period 1952-58 [*Snow*, 1976]. The gauge was discontinued since then. In single years such as 1974, the nearby town of Vigía de Cuvaradó experienced total rainfall of 26,871 mm [*Eslava*, 1994]. Table 1 contains a summary of precipitation records from rain gauges in the region. Figure 1 shows the spatial distribution of mean annual isohiets. Many of those records surpass or at least are very close to Cherrapunji's, India and Mt. Waileale's, Hawaii, widely accepted as the rainiest locations on earth (see *Ahrens*, 1998, p. 355). The region is mostly covered by tropical rain forest, with mean air temperatures between 26-28°C, and mean relative humidity around 90% throughout the year. This harsh environment supports extraordinary biodiversity, but produces very hard living conditions, endemic malaria and extreme poverty for the very low population density of Chocó.

The existence of such a rainy region, just to the north of one of the driest regions of the world over western South America, deserves documentation and understanding. We explore the main mechanisms of the ocean-land-atmosphere interaction that may contribute toward those ends. The presence of the Intertropical Convergence Zone (ITCZ) is of course a major control, but finer analysis is in order.

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The low-level westerly "CHOCO" jet

The southerly trade winds over the Eastern Pacific cross the Equator due to the predominant position of the ITCZ north of the Equator [*Philander et al.*, 1996; *Waliser and Somerville*, 1994]. The corresponding change of the sign of the Coriolis acceleration, the predominant north-south coast orientation, the land-sea temperature, and friction gradients contribute to explain the westerly winds prevailing once they enter the northern hemisphere tropics [*Schott*, 1931; *Hastenrath and Lamb*, 1977; *Hastenrath*, 1991]. This explains the curvature of the trade winds coming from the Southern Hemisphere once they cross the Equator. However, it does not explain the curvature of the trade wind jet coming from the Caribbean, across the Central American isthmus and into the quasi-permanent low off the coast of Colombia (Figure 2). This observation, in turn, can be interpreted in terms of an anomalous pressure field existing in flows past bodies due to local topography.

Using data from the NCEP/NCAR Reanalysis Project [*Kalnay et al.*, 1996], we study the climatology of the wind field over western tropical South America. Figure 2 depicts the annual cycle of the 925 hPa wind field over the region. The winds penetrate into western Colombia as a low-level westerly jet, that we named as "CHOCO jet" (Chorro del Occidente Colombiano, or western Colombian jet). The annual cycle of the vertical distribution of the mean zonal winds at 80°W between 5°S and 20°N is shown in Figure 3. The winds of the CHOCO jet (shaded in gray) are almost absent during February-March, attain its maximum core wind velocities during October-November (6-8 ms^{-1}), and decrease onwards. The core of the CHOCO jet is located around 5°N throughout the year. A possible physical interpretation of this observation is discussed latter.

These winds coming from the Pacific Ocean are colder and moister than the predominant upper easterly winds coming from the Atlantic and the Caribbean. Pacific sea air is cooler and moister than the continental air. This contrast favors the formation of Pacific sea breeze fronts with a clear diurnal cycle. *Arnett and Steadman* (1970) report on soundings of low level wind data over the region, during 1966-1967, with typical southwesterly low-level winds on the order of 4.6-7.2 ms^{-1}, around 1630 GMT October 18, 1967. The CHOCO jet causes strong moisture advection from the Pacific Ocean into Colombia. Figure 4 obtained from the *da Silva et al.* (1994) data set shows mean zonal moisture advection over northern

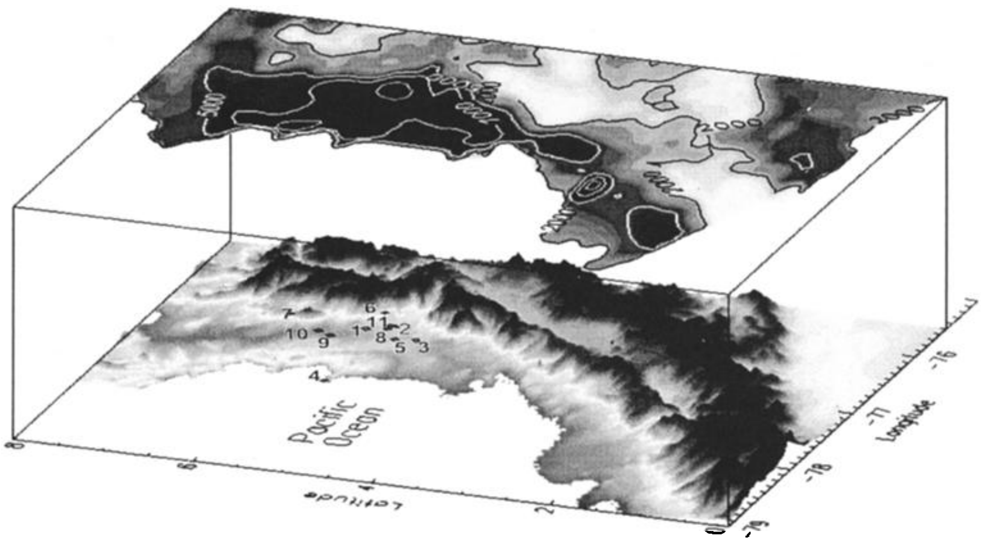

Figure 1. Map of western Colombia. Numbers denote location of rainfall stations whose monthly records are shown in Table 1. Average annual isohiets (mm) over the region are shown on top of the topography.

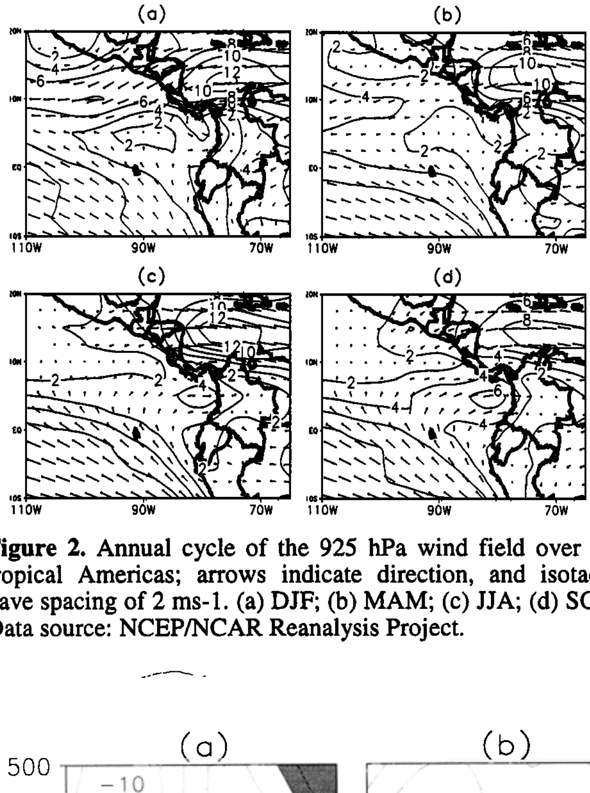

Figure 2. Annual cycle of the 925 hPa wind field over the tropical Americas; arrows indicate direction, and isotachs have spacing of 2 ms-1. (a) DJF; (b) MAM; (c) JJA; (d) SON. Data source: NCEP/NCAR Reanalysis Project.

South America for October, showing large amounts of humidity input from the Pacific Ocean to the continent. Moisture convergence is constrained to the lower atmosphere (up to 850 hPa), as attested by the high horizontal wind divergence at 700 and 200 hPa over the region (not shown here).

The encounter of the low-level moisture-laden westerly jet and the easterly winds aloft, along with the effects of surface warming and orographic lifting produces a highly unstable atmospheric profile [*Emanuel*, 1994]. The associated dynamics causes strong deep convection and high amounts of precipitation along the western flank of the Andes. Figure 5 shows the annual cycle of average precipitable water over the region in kgm^{-2}, according to the NCEP/NCAR Reanalysis Project, in good agreement with the extraordinary high values observed in raingages over western Colombia and southern Panama throughout the year.

The CHOCO jet is bounded by the mid-tropospheric easterly jet at 700 hPa [*Hastenrath*, 1999] that appears to emanate from the continent towards the Pacific Ocean (Figure 3). These two jets might be interacting to enhance upward motion throughout much of the troposphere, and thus

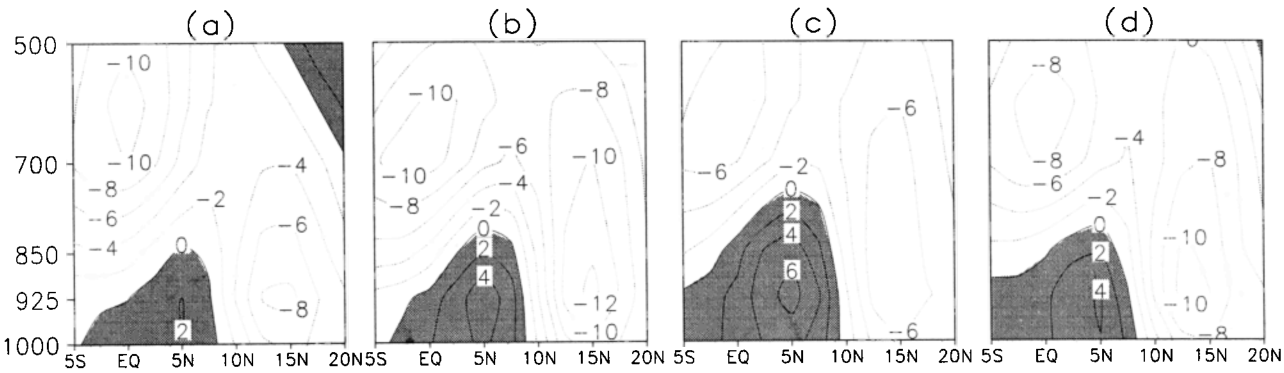

Figure 3. Annual cycle of zonal winds at 80°W (5°S-20°N, 1000-500 hPa); isoline spacing is 2 ms-1. Positive values (westerly winds) are shaded. Note the CHOCÓ low-level jet around 5°N. Data source: NCEP/NCAR Reanalysis Project.

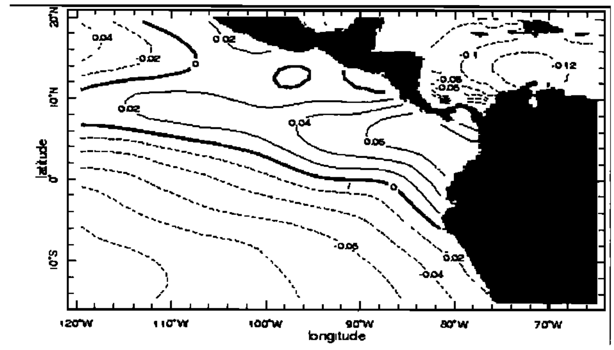

Figure 4. October field of moisture advection over tropical America, during 1945-1989. Moisture advection is estimated as the product of the surface zonal wind velocity and the air mixing ratio; dimensions are in ms^{-1}. Data source: *da Silva et al.* (1994).

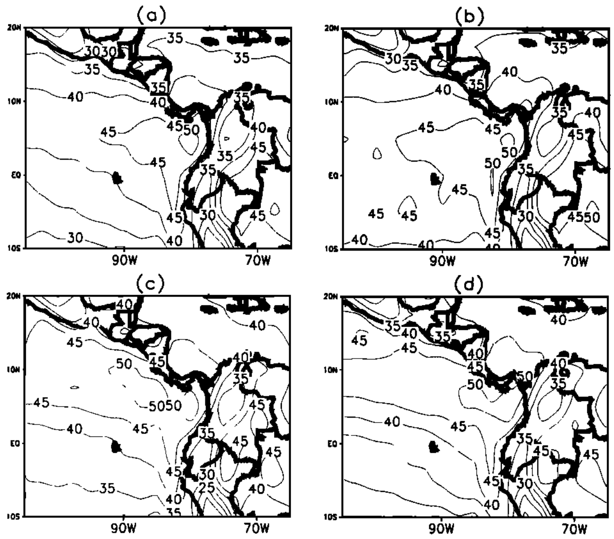

Figure 5. Annual cycle of average precipitable water; isoline spacing is 5 kgm^{-2}. (a) DJF; (b) MAM; (c) JJA; (d) SON. Data source: NCEP/NCAR Reanalysis Project.

contributing to development of deep convection [*Beebe and Bates*, 1955]. The CHOCO jet is also observed in the ECHAM-4 80-km resolution model of the Max Plank Institute for Meteorology of Hamburg (N. E. Graham, personal communication, 1999).

What mechanisms control the strength of the winds of the CHOCO jet during the annual cycle? Figure 6 shows the annual cycle of differences between average air temperatures over western Colombia (COLOM: 2°N-8°N; 75°W-77.5°W), the Colombian Pacific Ocean (COLPAC: 2°N-8°N; 77.5°W-82°W), and the Niño1+2 region in the Pacific Ocean (10°S-0°; 90°W-80°W) at 1,000 and 925 hPa. The largest temperature gradient is observed between continental Colombia and the Niño 1+2 region. Air temperature gradients between the two oceanic regions are slightly lower. All those gradients exhibit a clear annual cycle, with the largest gradient (925 hPa) during October-November, concomitant with the season of stronger winds at the CHOCO jet, and a minimum during February-March, consistently with the season of lowest strength of the jet. The largest land-ocean temperature gradient favors the circulation from the ocean to the continent, associated with the corresponding land-ocean pressure gradient. This mechanism sets up a permanent sea-land low-level circulation present in the climatology and is not reversed through the year. Besides, the role of the diurnal cycle is significant as most rainfall events over the region occur during the early hours (2-6 AM, local time), consistently with the activity of mesoscale convective systems (MCCs) over the region [*Velasco and Frisch*, 1987].

The CHOCO jet exhibits most characteristic features of low-level jets [*Stensrud*, 1996]: (1) it attains maximum wind velocities around 900-1000 hPa; (2) it is associated with strong ocean-land temperature gradients, and therefore with shallow baroclinicity; (3) it exhibits considerable vertical and horizontal shear (Figure 3); (4) it is related with the genesis

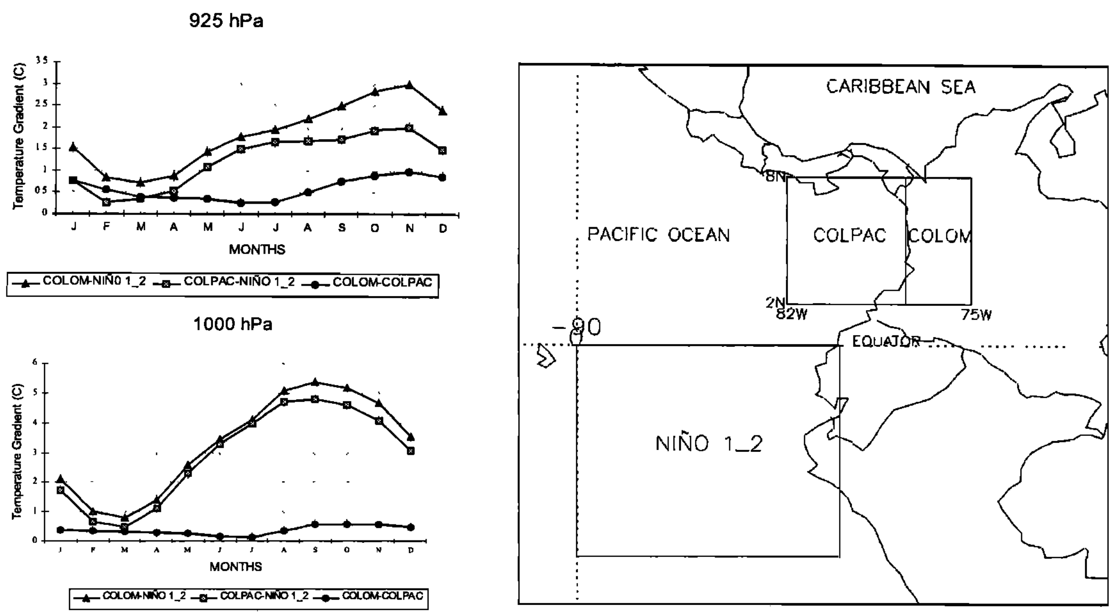

Figure 6. Annual cycle of air temperature gradients between western Colombia (COLOM: 2°N-8°N; 75°W-77.5°W), the Pacific Ocean off the Colombian coast (COLPAC: 2°N-8°N; 77.5°W-82°W), and the Niño1+2 region (10°S-0; 90°W-80°W), at 925 and 1,000 hPa. Data source: NCEP/NCAR Reanalysis Project.

Table 1. Mean annual rainfall and maximum monthly record values at diverse gauging stations in Chocó (Colombia). Numbers in the first column correspond to those in Figure 1.

No. Name	Latitude North	Longitude West	Height (m)	Average Rainfall mm (Period)	Record (mm/month) -Date
1. El Caraño	5°43'	76°37'	53	7831(1960-1995)	2030 - 07/1975
2. La Vuelta	5°27'	76°32'	100	8545 (1961-1995)	1438 - 07/1969
3. Andagoya	5°06'	76°42'	35	7268 (1961-1995)	1480 - 09/1974
4. Amargal	5°35'	77°30'	30	7119 (1993-1998)	1633 - 08/1995
5. Managrú	5°19'	76°44'	50	6343 (1978-1998)	1298- 03/1996
6. Bellavista	6°35'	76°35'	15	4950 (1967-1998)	1571- 05/1978
7. Tagachí	6°10'	76°44'	20	6540 (1967-1997)	1323 - 05/1971
8. Beté	6°00'	76°47'	25	8680 (1978-1997)	2854 - 07/1980
9. Lloró	5°30'	76°35'	90	7590 (1984-1997)	1472 - 08/1993
10.El Piñón	5°40'	76°23'	715	7689 (1959-1997)	2906 - 11/1970
11.Lloró Granja	5°30'	76°32'	120	12,541(1952-1960)	2676 - 06/1954

and development of strong deep convection; (5) it is associated with strong moisture transport over the eastern tropical Pacific (Figure 4) ; (6) it is highly intertwined with the development of MCCs (*Maddox*, 1980) over the Pacific Ocean that penetrate into Colombia and interact with the ITCZ. [*Poveda and Mesa*, 1997]; and (7) it is associated with the topographic gap that exists in the western branch of the Andes between 5°N and 5° 30'N, known as the Mistrató Pass, where mean heights decrease from around 3,000 to 1,500 m (see Figure 1). We hypothesize that this gap on the Andes acts as a flow convergence nozzle, where wind velocity increases and pressure decreases, thus contributing to focus, sustain, and enhance the jet itself. This in turn may explain why the core of the CHOCO jet is around 5°N throughout the year (Figure 3). Lloró lies at the foothills of the gap (Figure 1).

Analysis of the difference of the zonal winds at 80°W during extreme phases of ENSO [*Poveda et al.*, 1999] indicates that the strength of CHOCO jet winds diminish during El Niño, as compared with cold events. The strongest relative variation in the CHOCO jet occurs during JJA (year 0), with a weakening of the winds of the order of 2-3 ms^{-1}. The weakening of the CHOCO jet during El Niño is partly due to a diminished temperature gradient between surface air temperatures over the Pacific coast off Colombia and the Niño1+2 region, because of the anomalous air and SST warming on this region. Associated with the weakening of the CHOCO jet during El Niño events, moisture advection from the Pacific to Colombia diminishes. This contributes to explain negative anomalies in rainfall, river discharges and soil moisture during El Niño [*Poveda and Mesa*, 1997]. These local precipitation and atmospheric anomalies during ENSO, which in turn produce important land surface changes, may feedback into the global circulation and other oceans. Understanding the climate and interannual variations of this particular region contributes to disclose the complexities of global climate and large-scale phenomena like ENSO.

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