The Llanos Low-Level Jet and its Association with Venezuelan Convective Precipitation

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National Weather Center Research Experiences for Undergraduates Final Project

10 August 2005

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Abstract

Low-level jets play an important role in transporting moisture and heat from one location to another. The NCEP North American Regional Reanalysis indicates the existence of a nocturnal low-level jet over the central Venezuelan plains, known as the Llanos, during the austral summer. Pilot balloon observations taken at San Fernando de Apure, Venezuela are used to validate the reanalysis data and verify the time of year and altitude at which upper-air Llanos wind speeds are greatest. Vertical profiles of pilot balloon-observed and regional reanalysis-estimated wind speeds during the dry and wet seasons of 2001 to 2004 show good agreement. Deep convection was expected to occur near the exit region of the Llanos low-level jet, close to the average position of the intertropical convergence zone during the austral winter. Cloud-top temperature frequency composites of northern South America during strong and weak low-level jet events in the dry and wet seasons are constructed to show that a strong Llanos jet is associated with deep convection in the southern Llanos.

1. Introduction

The South American Llanos, tropical savannah covering most of central Venezuela and east central Colombia, lie approximately between 3^{o}N to 9^{o}N and 63^{o}W to 73^{o}W at an altitude of less than 300 meters above sea level. The Venezuelan Llanos, also known as the Orinoco River Plains, are bordered by the coastal Cordillera de Mérida (northeastern branch of the Andes Mountains) to the northwest, the Cordillera de la Costa to the north, the Caribbean Sea to the northeast, the Guiana Highlands to the southeast, and the Colombian Llanos and Amazon rainforest to the south (Figure 1). As the Llanos' tropical wet and dry climate is warm throughout the year, it is classified by precipitation rather than temperature. Venezuelan summer is considered to be the dry season of November through April while Venezuelan winter is considered to be the wet season of May through October (Figure 2).

During the dry season (austral summer), the region of maximum precipitation commonly referred to as the intertropical convergence zone (ITCZ) migrates southward and allows the northeast trade winds to gain strength over Venezuela. Responding to the stronger pressure gradient between the subtropical high over the Atlantic and the low pressure over Amazonia, the trade winds flow from the northeast to the southwest over Venezuela. It is hypothesized that the northeast trades undergo topographic channeling between the Cordillera de la Costa and the Guiana Highlands, and strengthen as a result (Vernekar et al. 2003). Heating and cooling of the Llanos produces changes in the vertical mixing of the air’s horizontal momentum, resulting in a thin layer of strong winds known as a low-level jet (LLJ) in the early morning hours. This jet is strongest near sunrise and weakens throughout the day, as daytime heating mixes the winds vertically through a deep layer.

Vernekar et al. (2003) have studied various LLJs in South America and their influence on the austral summer climate; they found areas experiencing a nocturnal LLJ simultaneously experience nocturnal rainfall maxima. Low-level jets play an important role in transporting moisture and heat from one location to another, and can promote deep convection at the surface near the jet’s exit region (Stensrud 1996). Factors causing summer precipitation in the Llanos are largely unstudied and as such unknown; however, observations made in similar regions of South America (Marengo et al. 2004; Vernekar et al. 2003) lead us to believe that the intersection of the nocturnal Llanos LLJ’s exit region with the ITCZ during the wet season (austral winter, when the ITCZ migrates northward) may be associated with convective precipitation over southwest Venezuela.

The National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) indicates the development of this dry season LLJ in the early morning is likely the result of the aforementioned topographical and climatological factors. Pilot balloon observations taken since 2001 as part of the Pan-American Climate Studies Sounding Network (PACS-SONET) and LlanoJet studies in the central Venezuelan Llanos have verified the existence of the Llanos LLJ (Douglas et al. 2005).

Presented in this paper is an analysis of pilot balloon soundings, reanalysis data, and satellite images to investigate how well the NARR simulates actual upper air winds over the Llanos and to determine if the Llanos LLJ promotes or rather inhibits Venezuelan convective precipitation, for the ultimate purpose of improving reanalysis products for future climate research and forecasts. Section 2 will describe the background and context of this research project within the larger PACS-SONET project. Section 3 will expand on the details of pilot balloon data collection and the reanalysis data and satellite imagery used. Section 4 will explain the Interactive Data Language (IDL) data processing methods. Section 5 will analyze the reanalysis and imagery results and section 6 will make some concluding remarks.

2. PACS-SONET Project

The Pan-American Climate Studies Sounding Network (PACS-SONET) is a NOAA-funded research project that began in 1997 by establishing 12 pilot balloon stations from Mexico to Peru. The goals of the project were to determine the upper-air wind circulations associated with wet and dry spells in the rainy season of Central

America, to validate reanalysis products commonly used in tropical climate studies of data-poor regions, and ultimately to arrive at a better understanding of global climate processes (Douglas et al. 2004).

The PACS-SONET project has since expanded, with more pilot balloon stations established across Latin America, including the San Fernando station in Venezuela in 2001. One of the smaller studies conducted within the PACS-SONET project was the LlanoJet experiment (Douglas et al. 2005). One radiosonde and six pilot balloon stations were set up for five days in March 2005 to augment the already existing San Fernando station, in order to study the diurnal variation and horizontal and vertical structure of the low-level jet that had been observed over San Fernando for the previous four years. Furthermore, researchers sought to further validate the regional reanalysis products that similarly showed a low-level jet over the Venezuelan Llanos.

3. Data

Pilot balloon soundings were taken at 1200 UTC (8am local standard time) at San Fernando de Apure, Venezuela, from March 2001 to May 2005. Despite fairly good temporal continuity at this station, a few months of data are missing, the largest gap being from November 2002 to mid-March 2003. The pilot balloons used for this study are relatively small, 30-gram red or white balloons typically filled with hydrogen. After their release, the balloons are tracked visually with a theodolite while an observer records the balloons’ elevation and azimuth angles in addition to the observation time. These three variables plus the ascent rate of the balloon (which is assumed to be constant throughout the observational period) are then used to calculate the upper-air wind speed and direction at different heights. One of the disadvantages of good pilot balloons observations when compared to radiosondes is their dependence on clear skies; if it is cloudy, the pilot balloon is too easily lost in the clouds and cannot be visibly tracked to high altitudes. Another disadvantage is the estimation of the pilot balloon ascent rate based on the balloon's size and the type of gas used to fill the balloon. The ascent rate is assumed to be constant, which may not always be the case. Radiosonde ascent rates are more easily and accurately determined. On the other hand, pilot balloons are more portable and much less expensive than radiosondes; the cost of pilot balloon observations is typically only 10% that of radiosonde observations.

As we did not have access to directly measured daily rain data for Venezuela, we inferred the location and extent of convective precipitation from cloud-top temperature frequency composites based on high-resolution infrared satellite images. Four satellite sectors were available: Caribbean (GOES-12), Full Disk (GOES-8 and GOES-12), Brazil (GOES-8 and GOES-12), and Peru (GOES-8 and GOES-12). There were tradeoffs to consider in spatial and temporal resolution and coverage by using any one of these sectors. The Caribbean sector, available from March 2004 to the present, has a good temporal resolution of thirty minutes and a spatial resolution of four kilometers for infrared images. However, the sector covers the Caribbean Sea, part of Central America, and only the northern half of Venezuela. The "Full Disk" sector, available from April 2002 to April 2004 and including the entire western hemisphere centered on South America, similarly has a spatial resolution of four kilometers for infrared images. However, this sector has a much coarser temporal resolution of three hours. The Brazilian and Peruvian sectors, both initially available for the longest period of April 2002 to the present and covering most of northern South America, have a better temporal resolution of thirty minutes. Nevertheless, shortly after we settled on the Brazilian sector as the best choice and began to analyze these infrared images, a hard disk failure caused us to lose all of the images from March 2004 to the present, leaving us with images from only 28 April 2002 to 18 February 2004.

We also worked with the NCEP NARR. The NARR has a spatial resolution of 32 kilometers and a temporal resolution of 3 hours. Although the entire country of Venezuela is not within the NARR's domain, the Venezuelan Llanos are just inside the southern border of the reanalysis. Zonal and meridional wind fields are two of the NARR's 45 parameters available from 1979 to 2004. As the comparable pilot balloon soundings ranged from 8 March 2001 to 31 May 2005 for 1200 UTC, we decided to include the two wind component parameters at 1200 UTC from 1 January 2001 to 31 December 2004 in our study.

4. Methodology

We first used IDL and the pilot balloon observations to generate a plot of the zonal wind speed's annual cycle from the surface to 5000 meters above ground level (Figure 3). This plot allowed us to more easily see what time of year and at what altitude the winds above the Llanos are strongest. We additionally used IDL to plot the interannual variation in pilot balloon-observed zonal wind speeds with height for both wet (May through September) and dry (November through March) seasons. Similar zonal wind speed plots were made from the 2001 to 2004 NARR data for comparison to the pilot balloon data (Figures 4 and 5). In order to examine the horizontal structure of the winds over the Llanos, NARR wind field maps were also produced with IDL for several pressure heights within the troposphere (Figures 6 and 7).

Next we selected the 100 strongest and 100 weakest observed LLJ events out of 441 days from 28 April 2002 to 18 February 2004, coinciding with the time period of available satellite images from the Brazilian sector of the GOES imagery from NASA's website. An IDL code was then written that used the infrared satellite images to construct half hourly frequency composites of cloud tops colder than -38^{o}C (235K) for strong LLJ events during the dry season (42 satellite images matched these days), weak LLJ events during the dry season (3 satellite images), strong LLJ events during the wet season (37 satellite images), and weak LLJ events during the wet season (70 satellite images). A threshold of -38^{o}C is often used in constructing such composites to estimate areas of deep convection in the tropics (Janowiak et al., 1994; Machado and Laurent 2004).

Diurnal cycle loops and daily averages (Figure 8) were constructed for each of these four cases, before subtracting the average strong LLJ composite from the average weak LLJ composite for both the dry and wet seasons. These two final composites represented the weak LLJ and strong LLJ convective anomalies during dry and wet seasons (Figures 9 and 10).

5. Results and Discussion

Figure 3 shows the San Fernando zonal wind speed's annual cycle, which illustrates the wind speed peaks at just below 1000 meters from late January to March, with a maximum of 15.5 meters per second from the east during the dry season, as expected. Wind speeds from the surface to 1000 meters above ground level are weakest in July and August during the wet season, also as expected.

The dry season pilot balloon zonal wind speed plot for San Fernando, seen in Figure 4, again shows the wind speed peaks at 14 to 15 meters per second at about 650 meters above ground level. At a corresponding pressure height of 925mb, the dry season NARR plot shows a similar wind speed maximum of 12 to 13 meters per second. The wet season pilot balloon zonal wind speed plot, seen in Figure 5, shows that wind speeds are much weaker during the wet season as compared to the dry season. Maximum zonal wind speeds are about 8 meters per second. The wet season NARR plot again shows a similar wind speed maximum of 7 to 8 meters per second. Apparent from these dry and wet season plots is how well the NARR does at reproducing the observed zonal wind speed profiles for at least the time period analyzed.

As the NARR shows the maximum wind speeds at San Fernando to be at 925mb, we looked at the spatial extent of the winds at 925mb during the dry and wet seasons. Figure 6 shows the horizontal structure of the wind field at 1200 UTC during the dry season, based on the NARR. A northeasterly wind speed maximum exists over the Llanos while weak winds exist over the northern Andes. Further evidence of a strong Llanos LLJ in the dry season and a weak or nonexistent Llanos LLJ in the wet season is seen in Figure 7, the NARR-based wind field at 1200 UTC during the wet season. The LLJ is noticeably weaker over the Llanos but again still stronger than the calm winds over the Andes.

Regardless of daily fluctuations in the strength of the Llanos LLJ, deep convection in the dry season is for the most part restricted to south of the Venezuelan border, as supported by the lack of cold cloud tops in the dry season frequency composites shown in Figure 8. However, the wet season frequency composites show a large patch of deep convection that migrates both north and south of the southern Venezuelan border depending on the strength of the wet season Llanos LLJ. The dry season convective anomaly composite (Figure 9) confirms there is no difference in convection (as it is nonexistent) in most of Venezuela from strong to weak jet events. In contrast, the wet season convective anomaly composite (Figure 10) shows there is deep convection occurring in most of Venezuela (especially east central areas) when the LLJ is weak and also occurring in the extreme southwest Venezuelan Llanos into the Colombian Llanos when the LLJ is strong. This region of convection in the southern Llanos during stronger LLJ events in the wet season is important to note. Referring back to the horizontal structure of the jet in Figures 6 and 7, it is apparent that the convective region in Figure 10 is near the LLJ's exit region and the ITCZ, as originally hypothesized.

6. Conclusions

Our study consistently identified a low-level jet over the Venezuelan Llanos that was strongest in the dry season at about 650 meters above ground level (or 925mb) and weakest in the wet season. We also found that the NCEP North American Regional Reanalysis was in good agreement with actual pilot balloon observations, and as such was a good estimate of upper-level winds over northern South America for at least the study period (2001 to 2004). Although our study showed that deep convection is practically nonexistent in Venezuela during the dry season when the jet is typically strongest, we did find that deep convection does indeed occur to the south, around the exit region of the jet and the ITCZ during the wet season. This result is similar to observations of other LLJs worldwide.

Acknowledgements

This work was funded by National Science Foundation Research Experiences for Undergraduates grant NSF 0097651. Pilot balloon data were obtained from the National

Oceanic and Atmospheric Administration (NOAA)-funded Pan-American Climate Studies Sounding Network (PACS-SONET) project. Reanalysis data were downloaded from the website of the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR): http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/index.html. Satellite images were obtained from NOAA's Geostationary Operational Environmental Satellite (GOES) 12.

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Figures

Figure 1. Venezuelan physical relief (right) and South America (left).

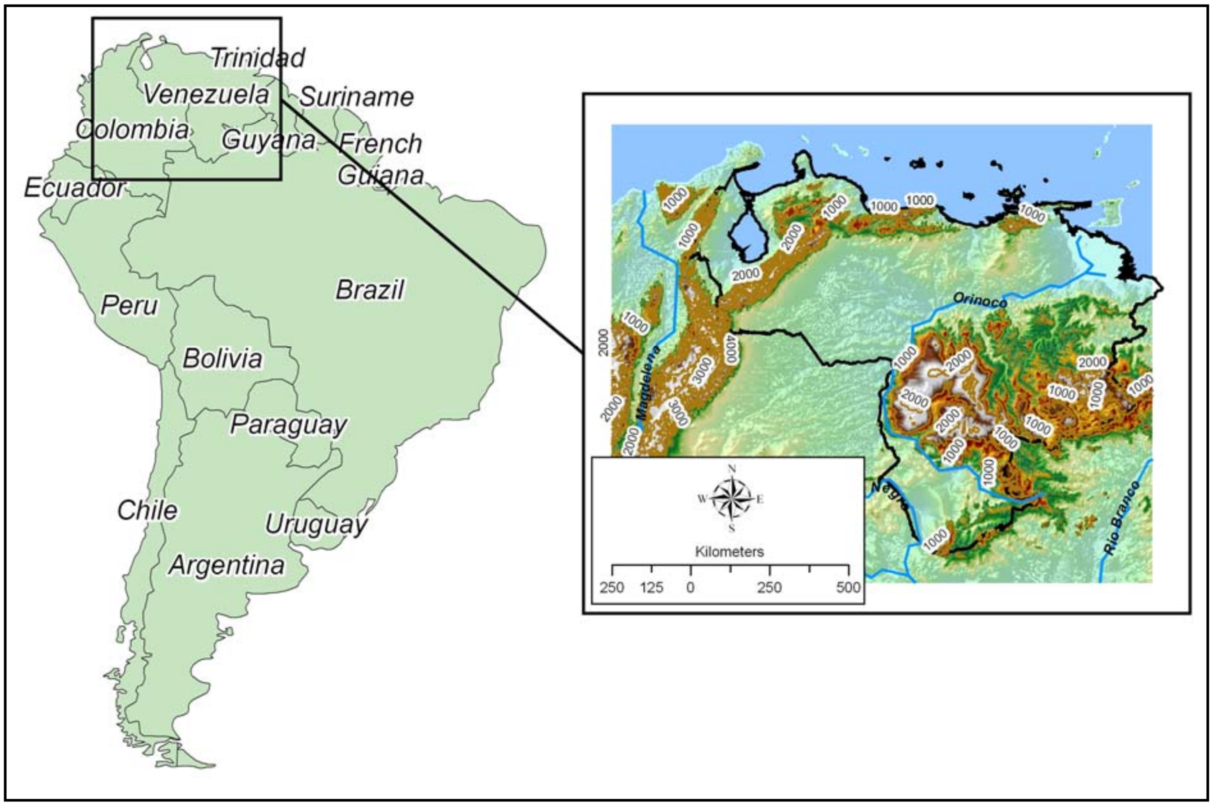


Figure 2. Climograph for San Fernando de Apure, Venezuela. Bars are precipitation in millimeters and curve is temperature in degrees Celsius.

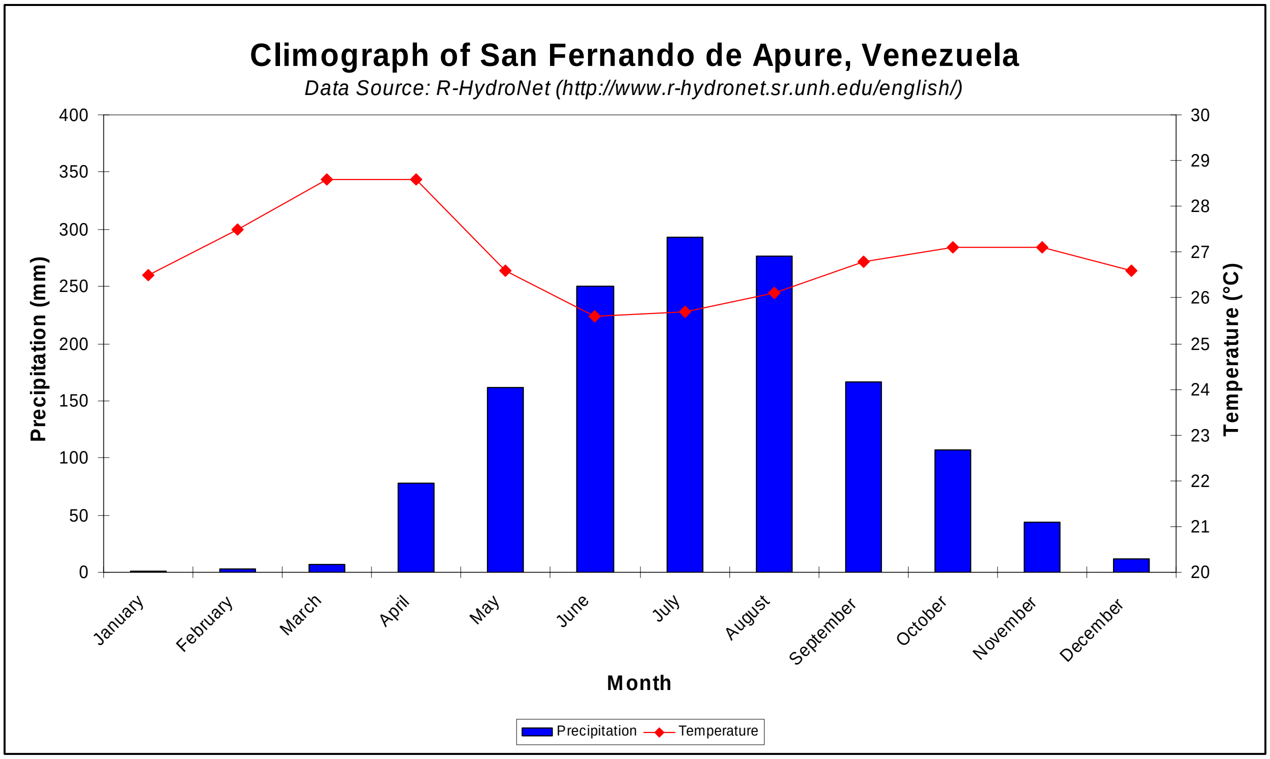


Figure 3. Annual cycle of the zonal wind speed at San Fernando for 1200 UTC, averaged from pilot balloon soundings taken from 8 March 2001 to 31 May 2005. Numbers on the contours represent wind speed in meters per second. Negative numbers correspond to easterly winds. Note the 15.5 meters per second wind speed maximum in late February at about 650 meters above ground level. Wind speeds at the same altitude are at a minimum in July and August.

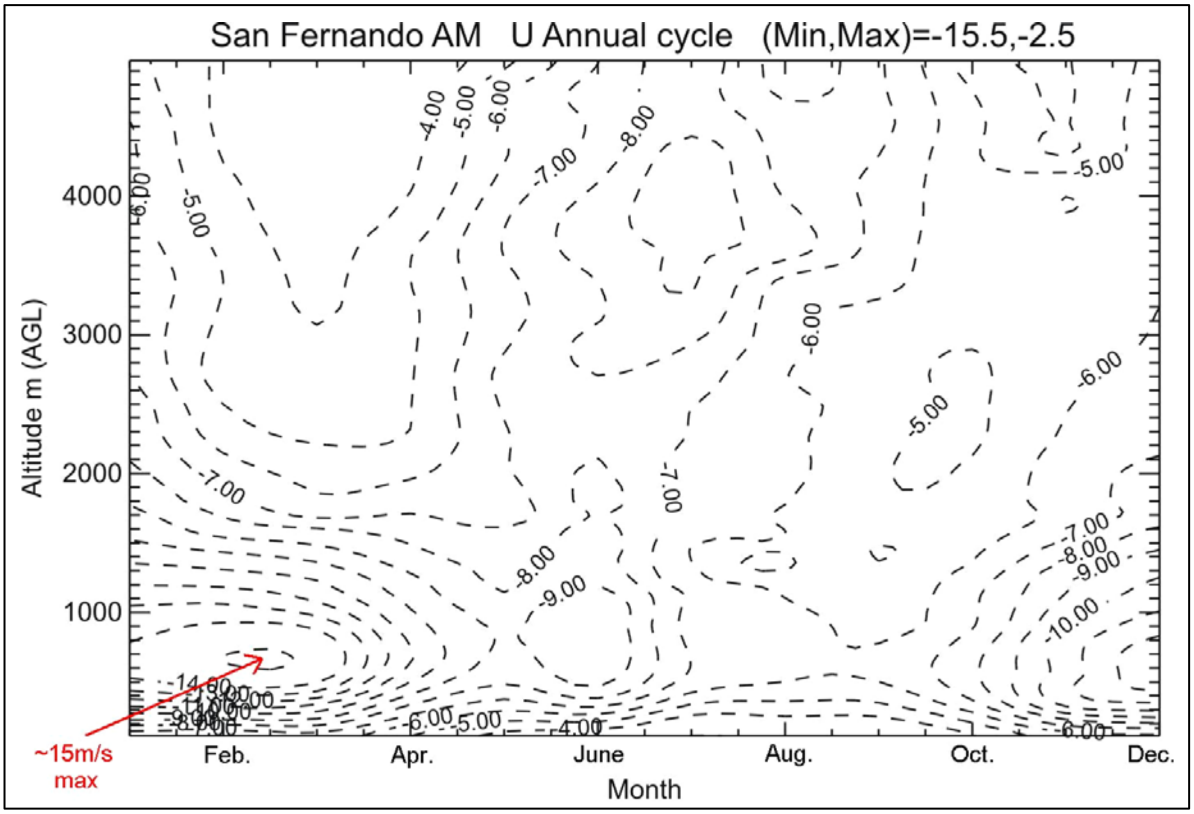
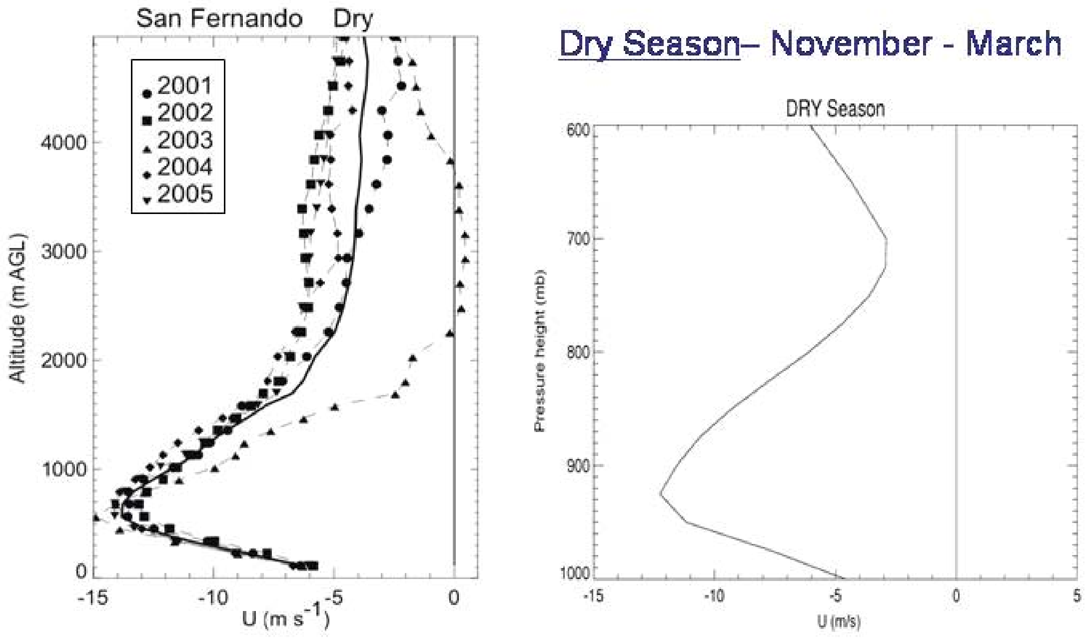


Figure 4. Dry season pilot balloon soundings (pibal, left) and reanalysis zonal wind speeds for San Fernando. Note the numbers along the pilot balloon y-axis are in meters while the numbers along the reanalysis y-axis are in millibars.



Pibal
Zonal Wind Speed (m/s)

NARR
Zonal Wind Speed (m/s)

Figure 5. Same as Figure 4 but for the wet season.

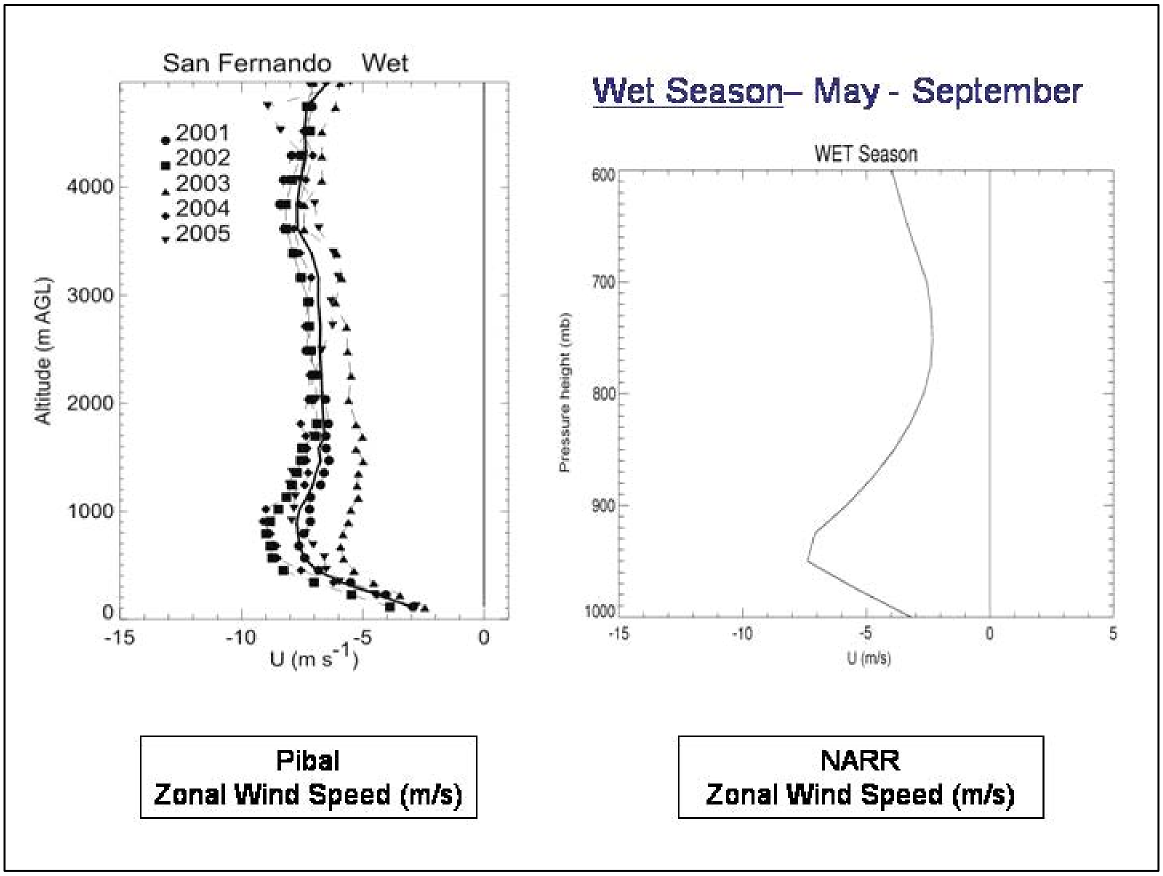


Figure 6. Dry season wind vectors at 1200 UTC at 925mb. Shaded contours represent wind speed in meters per second. Red areas over the Llanos and northwest of the Maracaibo Basin represent stronger wind speeds than do blue areas over the northeastern and northwestern branches of the Andes Mountains.

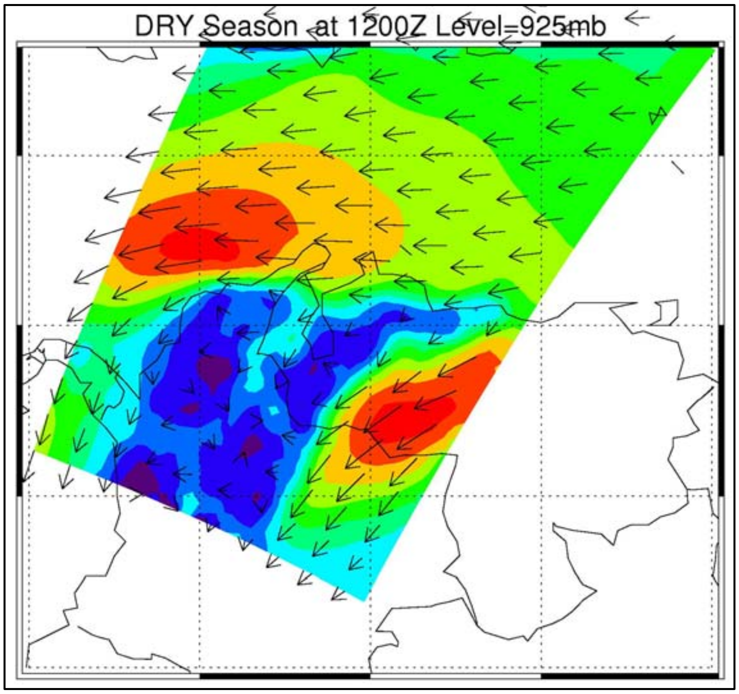


Figure 7. Same as Figure 6 but for wet season wind vectors. Yellow and green areas over the Llanos and northwest of the Maracaibo Basin represent stronger wind speeds than do blue and purple areas over the northeastern and northwestern branches of the Andes Mountains, and represent weaker wind speeds than do red areas in the dry season map (Figure 6).

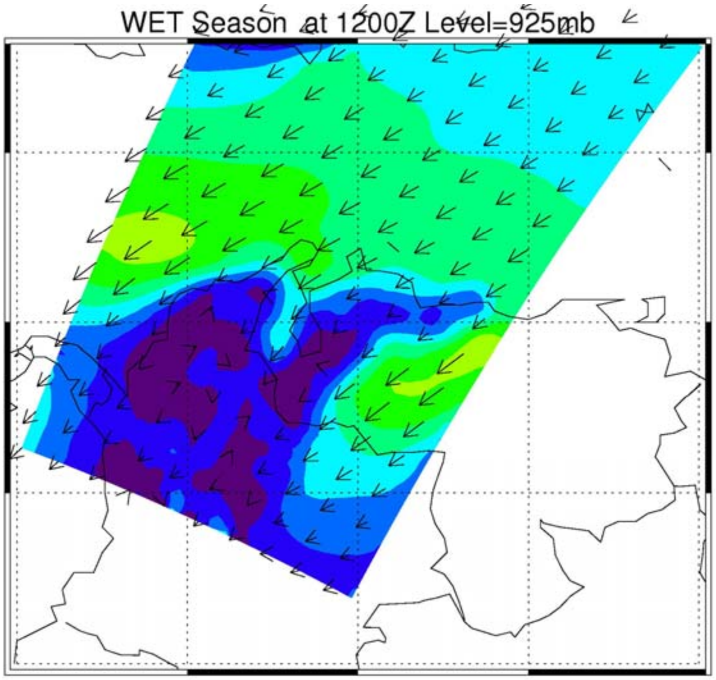


Figure 8. Average frequency composites for strong and weak LLJ events during dry and wet seasons from April 2002 to February 2004. The frequency represents the percentage of cloud tops with temperatures colder than or equal to -38ºC.

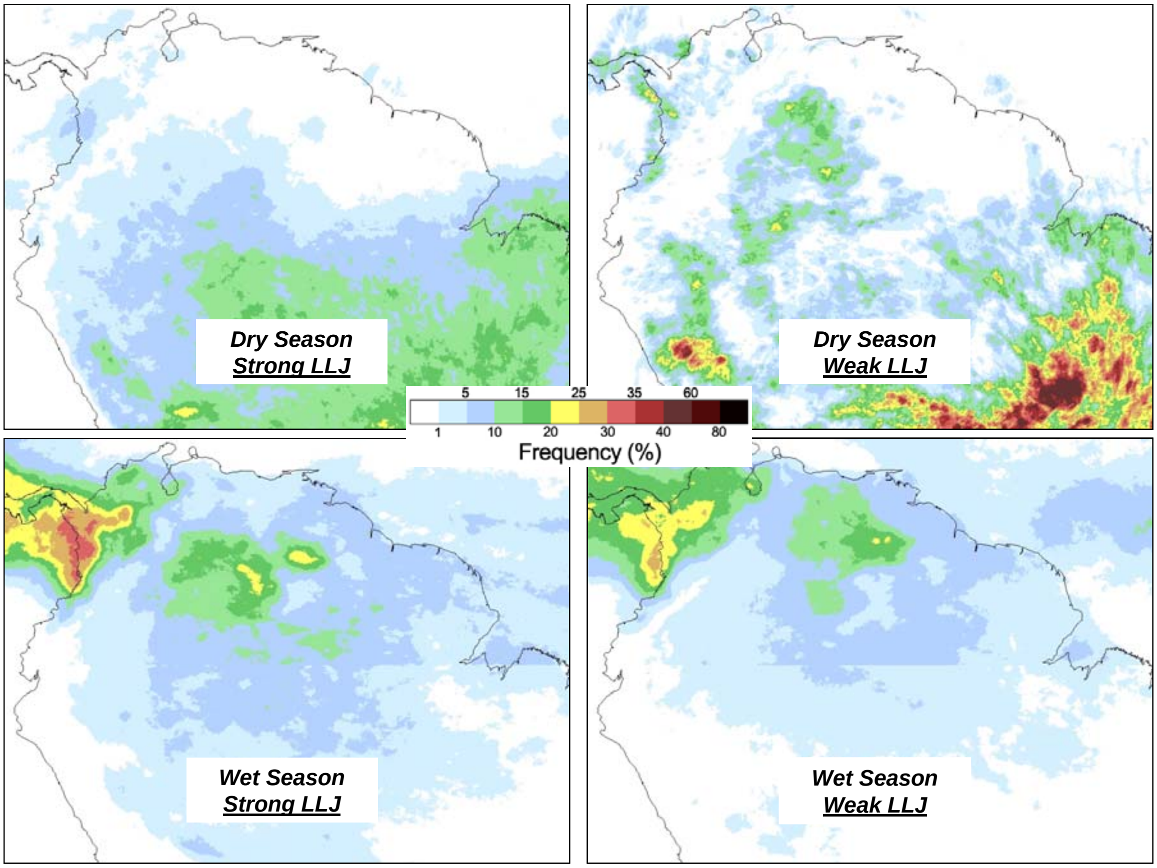


Figure 9. Dry season (November through March) convective anomaly composite (weak LLJ – strong LLJ). Blues represent positive areas that correspond to convection occurring within a weak jet, while pinks represent negative areas that correspond to convection occurring within a strong jet.

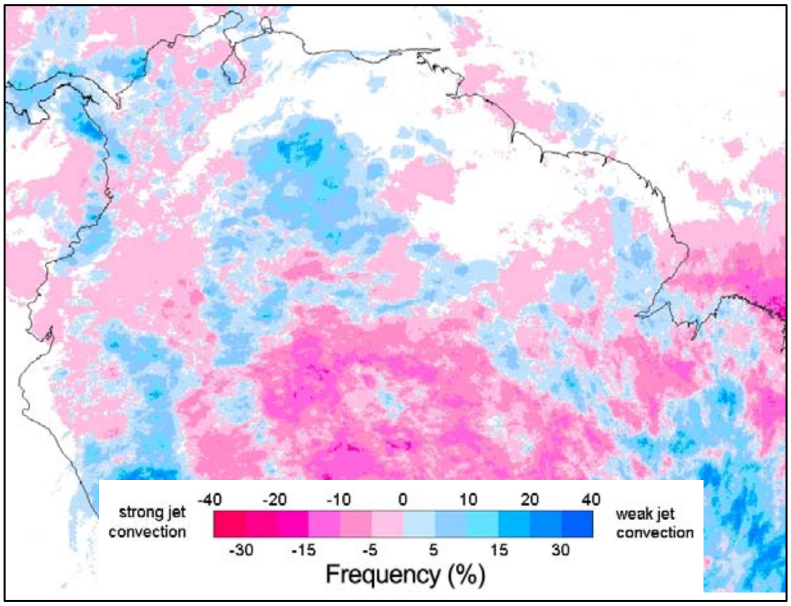


Figure 10. Same as Figure 9 but for a wet season (May through September) convective anomaly composite (weak LLJ – strong LLJ).