ASSESSING CLIMATE MODE CONTROLS ON SOUTH AMERICAN HUMIDITY USING A NEW, HIGH-RESOLUTION DATASET

by

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STATEMENT BY THE AUTHOR

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As members of the Research Committee, we recommend that this thesis be accepted as fulfilling the research requirement for the degree of Master of Science.

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ABSTRACT

Between 1995 and 2009, the Brazilian coast and southern Andes were up to 25% more humid than the preceding 15 year period, while regions of central Brazil, northern Argentina, and the high central Andes were up to 25% more arid. Degreening accompanied aridification across the Brazilian and Argentine interior, and throughout the Andes, irrespective of humidity changes.

Using humidity data from newly released NCEP Climate Forecast System Reanalysis (CFSR), we examine aridity changes over South America as they relate to major climate modes and a postulated poleward shift in Hadley circulation. We find that over the last 30 years, the influence of the South American Summer Monsoon (SASM) weakened over most regions, whereas the influence of the Southern Annular Mode (SAM) increased in the austral fall and winter, at the expense of other seasons. However, we find no evidence of a poleward shift of Hadley circulation in our humidity data.
INTRODUCTION

Spanning almost 65 degrees of latitude, and host to one of the world’s highest mountain ranges, South America exhibits heterogeneous climate and weather patterns that include one of Earth’s wettest climates (the Amazon) and one of its driest (the Atacama). In the northern Andes, predominantly easterly winds from the Atlantic bring orographically focused precipitation to Andes’ eastern flanks, contributing to hyperarid conditions on the western side. By contrast, westerly winds prevail in the southern Andes, where most precipitation occurs near the coast. The Andes’ prominent topographic relief also gives rise to a summer monsoon that accounts for up to 50% of annular precipitation over parts of Brazil (Vera, 2006). Because of its meridional extent, South America feels the influence of climate modes that originate in the tropics, subtropics, and at the poles.

Numerous analyses invoke the El Niño Southern Oscillation (ENSO) as the primary source of interannual variability over South America (Garreaud and Vuille, 2009). ENSO is an aperiodic perturbation of the climate system that entails warming of the surface layers in the equatorial Pacific Ocean every 2-7 years. Typically, the oceanic thermocline in the equatorial Pacific and Indian Oceans is very steep, and the thermocline in the eastern equatorial Pacific near the South American coast is very shallow, due to upwelling of cool water from below. In El Niño years, the west Pacific thermocline shallows, and the eastern equatorial Pacific
experiences anomalously warm sea-surface temperatures (Rasmusson and Wallace, 1983). El Niño episodes are associated with aridity over the tropics, and wetter-than-normal conditions over the southeastern portion of the continent, and central Chile. During La Niña episodes, opposite conditions prevail (Wolter and Timlin 1998). Station records indicate flooding conditions in northern Peru and along the semi-arid coast of southern Ecuador during strong El Niño episodes (Garreaud, 2009).

The displacement of major rainfall-producing systems causes reorganization of climate regimes outside the tropics, and around the globe (Diaz and Markgraf, 2000). ENSO directly affects Peru, Ecuador and northern Chile, and indirectly affects northern Argentina, Uruguay and Brazil through atmospheric teleconnections (Webster, 1994; Wolter and Timlin 1998).

South America’s large tropical landmass also gives rise to a monsoonal system of rainfall. A combination of heating and moisture promote deep convection over the tropics, where a northwesterly jet, situated just east of the Andes, carries warm, moist air from the Amazon as far as 35oS (Grimm, 2007). The South American Southern Monsoon develops in the mid-latitudes each spring as this northwesterly jet and a southeasterly subpolar jet converge over the Amazon, creating a cyclone over southeastern Brazil (Zhou, 1998). Heavy rainfall occurs at the convergence. As the monsoon progresses, moisture moves south over Venezuela and southern Brazil, focusing heavy precipitation on the Altiplano and the Brazilian highlands (Zhou,
In late summer, when the jets once again separate, the monsoon dissipates (Zhou, 1998; Li, 2005).

The Southern Annular Mode (SAM) originates near the South Pole, and is caused by variations in sea-level pressure between the South Pole and southern mid-latitudes (40°-50°S) (Thompson and Wallace, 2000). The positive phase of the SAM is characterized by low surface pressure over Antarctica, and a poleward shift and strengthening of the Westerlies. In its negative phase, the Westerlies extend equatorward, and weaken. SAM variability directly affects the high-and mid-latitude portion of South America, where the Westerlies blow onshore.

South American climate regimes are also largely governed by Hadley circulation. Air rises in the tropics, promoting convective clouds and precipitation. The air, wrung out of its moisture, descends to Earth in the subtropics, creating subtropical dry zones. Multiple studies have proposed that the descending limb of the Hadley circulation has migrated poleward during the past 30 years, by as much as 1.8 degrees. (Hu and Fu 2007; Johanson and Fu 2009). Because its landmass extends through the tropics and subtropics, a long-term reorganization of humid and arid regions would likely be felt in South America, if it occurred at all.

This study aims to examine changes in South American climate regimes over the last 30 years, with attention to the climate modes that govern them. We use new, high-resolution data to examine the strength of these many proposed correlations.
We will give particular attention to areas of high topographic complexity, which are not resolved with earlier climate data.
METHODS

Spatial Data

Monthly means of specific humidity at 2m above ground level were calculated from the NCEP CFSR (Climate Forecast Systems Reanalysis) dataset [http://rda.ucar.edu/pub/cfsr.html](http://rda.ucar.edu/pub/cfsr.html). Spatial resolution of this humidity data is 0.313° by 0.312°. CFSR data were obtained at 6 hour intervals (4/day) from December 1979 to December 2009.

Vegetation data are from the GIMMS (Global Inventory Modeling and Mapping Studies) dataset, a normalized difference vegetation index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17 (Tucker et. al, 2004; [http://glcf.umbc.edu/data/gimms/](http://glcf.umbc.edu/data/gimms/)). This is a NDVI dataset spanning 1981-2006 that has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change. Biweekly time slices were averaged to produce monthly means. Initially, NDVI data had very fine (8km) resolution, but was regridded to match the CFSR data for the purpose of comparison. Computational limitations prevented us from regridding the CFSR data down to NDVI size, although that would have eliminated the need to interpolate the values of multiple small grid boxes to one larger grid box.
We calculated anomalies with respect to the long-term monthly mean for each month, based on all data available for that month. We then divided both raw data and anomaly data into seasons, to filter out the seasonal cycle. Each month is considered separately, with no averaging or summing of the months within seasons.

**Timeseries Data**

Three Hadley indices were used in correlations: tropopause height, mean gradient, and streamfunction. Streamfunction (Ψ_{500}) is the equatorward-most latitude where mean meridional streamfunction shifts from negative to positive (Hu and Fu, 2007; Lu et al., 2007). Mean gradient (Mean–max δ_{TP} / δ_{ϕ}) is the latitude of the peak in the meridional gradient of tropopause height (Davis, 2012). Tropopause height (Δz_{TP}) is the equatorward-most latitude at which tropopause height descends to 1.5 km below the average for 15°S to 15°N (Davis, 2012). Hadley indices are calculated using global zonal averages, taken from NASA’s MERRA (Modern-Era Reanalysis for Research Applications) dataset.

Three climate modes were also considered: multivariate ENSO index (MEI), Southern Annular Mode (SAM) and the South American Summer Monsoon (SASM). The SASM index is derived from wind field intensity at 925 hPa within the South American monsoon domain (17.5° to 10°S, 62.5° to 50°W) (Li and Zeng, 2002, 2003, 2005). Only DJFM values exist for the SASM index. Several indices exist to characterize the SAM; here we use the leading EOF of the monthly mean 1000-hPa (700-hPa) height anomalies poleward of 20°S. (Marshall, 2003). The MEI comprises
six variables related to ENSO intensity: sea-level pressure, zonal and meridional components of the surface wind, sea-surface temperature, surface air temperature, and total cloudiness fraction of the sky (Wolter and Timlin 1998).

Anomalies were not calculated for the times-series, as they were with the spatial data; instead, raw values were used.

**Percent change**

Raw humidity and vegetation data, already divided into seasons, were then further divided into 15-year intervals to reveal humidity and land cover changes over time. Mean values were calculated for the interval 1979 to 1994 (\(x_{\text{early}}\)) and 1995 to 2009 (\(x_{\text{late}}\)), excluding missing data from the means. Since the study area encompasses one of the wettest places on Earth (the Amazon), as well as one of the driest (the Atacama), we view moisture changes as percent change. Percent change was calculated as \((x_{\text{late}} - x_{\text{early}})/x_{\text{early}}\).

**Correlations**

In an effort to explain the physical basis for humidity variability over South America, we invoked the aforementioned climate modes and Hadley indices. We cropped the data to an area of interest (AOI) encompassing 40° to 10°S and 80° to 60°W. This area was chosen for its complexity: it includes both high and low terrain, and is positioned to receive moisture from the southern trade winds, or the northern trade winds.
For each mode and index, correlation maps were generated for the AOI by calculating the correlation between that mode or index, and the humidity anomalies at each grid point. In this bivariate case, the correlation coefficient is identical to the r value of a linear regression between the two timeseries (index or mode, and humidity anomalies at any given gridpoint). Thus, for the (x,y) pair (humidity, mode or index value) at each time slice, we calculated a line of best fit through those points. The regression coefficient of that line, a value between -1 and 1, is the correlation coefficient. Each correlation incorporates 90 data pairs (3 months * 30 years).

Neither the humidity data nor the timeseries data are statistically independent from month to month; both data show some degree of autocorrelation. Accordingly, statistical significance must be calculated based on the effective sample size of data, which is smaller than the full complement of pairs at each point.

Lag-1 autocorrelation was calculated for each timeseries, and at each gridpoint, yielding effective sample sizes of about 60 to 90% of the actual sample size. Because the effective sample sizes were still large, areas of statistical significance were, in general, only slightly smaller than when calculated with the actual sample size.

**Principle components**

Principle components analysis (PCA) is a mathematical procedure for decomposing spatiotemporal data into the leading patterns of space and time that
account for its variability. In the case of data, PCA can be used to isolate the individual influences that combine to give climate its complexity. The leading mode of variability (PC1) accounts for most of the variability in that system, PC2 explains less, and so on.

We conducted PCA over the AOI, as well as the whole of South America, to extract the primary modes of humidity variability over each region. We then calculated the correlation between the first 10 modes of variability, and each climate mode and index, to see if any of the primary modes of variability could be attributed to one of the modes or indices.

In an effort to isolate the influence of climate modes and indices over certain regions, the AOI was also divided into equal-sized quadrants—northwest, southwest, northeast, southeast—for analysis (Figure 1). Thus, we calculated modes of variability individually for the continental, AOI, and quadrant scales.
RESULTS

Percent change

Our analysis reveals that the most dramatic moisture changes over the last 30 years have occurred along the crest of the Andes, where the northern and southern ends have become wetter, and the Altiplano (between 15-25°S) has become drier, in all four seasons (Figure 2). Drying has also occurred in eastern interior Brazil, and over the Mendoza region of central Argentina. Between those two drying regions, there is an area (25 to 20°S, 60°W) that shows a weaker, but still significant wetting trend. The north coast of Brazil has gotten significantly wetter, although the percent change is small (<10%). White contours in all figures encircle areas of correlation that are statistically significance at the 95%CI.

In general, these observations are borne out by the vegetation data. The vegetation maps show greening of the southern and northern Andes, and vegetation loss over the central Andes, over the same time interval (Figure 3). In the summer (DJF) and fall (MAM) seasons, we see greening of eastern Brazil and diminished vegetation over Mendoza, although we do not see the dry-wet-dry pattern along that is evident between Mendoza and Brazil in Figures 2a and 2d. The winter (JJA) and spring (SON) seasons show a marked decrease in vegetation continent-wide.

The humidity data show a clear anti-phase relationship between Mendoza and the north coast of Brazil, where drying in the former corresponds to wetting of the
latter (Figures 2a, 2b, 2d). The same pattern is discernible, although weaker, in the vegetation data. Most noticeable in the vegetation data is a slightly different anti-phase relationship: during the summer and fall, the continent between 15-35°S has become less green, whereas the rest of the continent has become predominately greener. In the winter and spring, de-greening has occurred nearly continent-wide.

**Correlations**

**South America**

Summer humidity over South America is dominated by the monsoon, with SAM as an additional influence. Again, we observe antiphase relationships between eastern and southern Brazil, and northern Brazil and Mendoza: SASM is positively correlated with northern and southern Brazil, and negatively correlated with eastern Brazil and Mendoza (Figure 4). The northern Brazil/Mendoza anti-phase is also visible in the SAM correlation, where a positive SAM index correlates to aridity in northern Brazil, and humidity in Mendoza (Figure 5).

A strong negative correlation exists between streamfunction (psi500s) and humidity over northern Brazil during the summer months (Figure 7). The other Hadley indices (mean gradient and tropopause height) have no significant correlation with humidity during the summer, nor does MEI (Figures 6, 8, 9).

The pattern of humidity correlations in the autumn (MAM) is similar to DJF, but the strength of the signal weakens in the northern half of the continent while
becoming stronger in the south. A well-developed anti-phase relationship is still visible in the SAM and SASM correlations.

Winter and spring correlation maps show that the northern/eastern Brazil anti-phase is well developed in relation to mean gradient and tropopause height, especially in spring (Figures 8 and 9). SASM continues to correlate well with humidity over southernmost South America and the Southern Ocean (Figure 4). The three Hadley indices show similar patterns of correlation in the winter and spring, which is not clearly seen in DJF or MAM.

**1979-1994 vs. 1995-2009 subplots**

The SASM appears weaker, and the SAM stronger, in the more recent (1995-2009) DJF interval (Figures 4 and 5). Correlation with streamfunction becomes stronger, as does tropopause height in the southern half of the continent.

SASM shows a strong negative correlation with humidity over much of the map for the earlier DJF interval (Figure 4). That influence appears delayed in the more recent interval, where monsoon influence is strongest during MAM. DJF and MAM show a greater MEI influence in the more recent interval (Figure 6).

For MAM, the earlier interval shows a positive correlation between humidity and the Hadley indices in the northern half of the continent, which becomes negative in the later interval (Figures 7, 8 and 9). The more recent interval shows a very strong negative correlation between humidity and SASM, but because there is no monsoon
index for April or May, that relationship is based only on 15 March datapoints for each interval, and is not statistically significant.

The Hadley index correlations—positive and extensive in the earlier JJA interval—become negative or nonexistent in the interval 1995-2009 (Figures 7, 8 and 9). In particular, tropopause height—which is positively correlated with much of the map in 1979-1994—shows virtually no correlation with humidity in recent times. Meanwhile, the influence of the SAM is much more pronounced and extensive in the later interval (Figure 5).

In SON, the Hadley index correlations, which are positive to nonexistent during 1979-1994, become more pronounced in the later interval, reflecting the northern/eastern Brazil anti-phasing (Figure 7, 8 and 9). The SAM, which has a strong positive correlation over the southern South America during the earlier interval, shows a less extensive, less positive correlation with humidity in the more recent interval, and a negative correlation over the eastern part of the map. The 1979-1994 SON map resembles the 1995-2009 JJA map more closely (Figure 5). This lagged relationship can be seen for all four seasons, with 1979-1994 JJA resembling 1995-2009 MAM, and so on.

**AOI subplots**

Elevation influences which parts of the continent are most affected by climate modes and indices. Subplots of the AOI reveal that, at elevations greater than
2000m, climate modes and indices have very little effect on humidity in any of the four seasons (Figure 10). During the austral summer, there is a negative correlation between humidity and stream function, and humidity and SAM (Figure 7). Additionally, there is a positive correlation with tropopause height, that penetrates the high Andes during austral winter (Figure 9). However, the correlations are patchy and weak (< ± 0.3).

During all four seasons, climate modes and indices exert most of their influence on the lowlands (<2000m elevation) east of the Andes. A lesser, but still significant correlation exists between the Hadley indices and the lowlands west of the Andes during austral winter (Figures 7, 8 and 9).

At the quadrant scale, we observed that the low-relief eastern quadrants correlated more strongly with climate modes and indices than did the high-relief western quadrants, although in general, except for the monsoon, correlations were weak or insignificant (Figure 10).

**Principal components**

Principal components analysis of humidity over South America for the entire 30-year time period reveals that this system has no single, dominant mode of variability eclipsing other influences. PC1 explains, on average, only 17.6% of variability in the system, and PC2, 14.6% (Table 1). That said, SASM (in DJF/MAM) and Hadley
indices (in SON) are each well correlated with PC1. Hadley indices are well correlated with PC2 during DJF.

When principal components are calculated for the two time periods independently, it appears that the correlation between Hadley index and SON developed in the last 15 years, as the correlation between Hadley index and PC2 is nonexistent for the first 15 year period (Table 2a, 2b). Similarly, SASM influence appears to have increased. SASM correlated best with PC5 and PC7 during the earlier interval, each of which explains only 4 to 7% of the variance. In the more recent interval (1995-2009), SASM correlates well with PC5 (in DJF) and PC1 (in MAM), which explain 7.7 and 21.1% of the variance, respectively. MEI, on the other hand, which correlated with PC1 of MAM during the 1979-1994 time interval, has no strong correlations with modes of variability in 1995-2009 (Table 2a, 2b).

**Principal components: AOI**

Principal components analysis of humidity over the AOI for the 30-year time period reveals a much less complex series of modes. PC1 explains, on average, 91.8% of variability in the system, and PC2, 2.7%. with subsequent modes explaining even less of the variance (Table 3).

Principal components analysis at the quadrant scale also shows less complex modes of variability. SAM and SASM are strongly correlated with PC1 of the eastern
quadrants, in both intervals. All other correlations between principal components and climate modes are weak, or unsustained through the two intervals (Table 4).
DISCUSSION.

Percent change

We observe an antiphasing of humidity between northeast Brazil and much of the rest of tropical South America, both on seasonal and decadal timescales over the period 1979-2009. Over the past 30 years, northeastern and coastal Brazil has become wetter, while interior tropical South America has become more arid (Figure 2). In the mid-latitudes, the southern tip of Brazil has become more humid, anti-phased with neighboring Argentina.

In the mountains, most of the Altiplano in the central Andes has become significantly more arid, whereas the southern high Andes have become significantly wetter. Garreaud and Vuille (2007) observed that the climatic conditions on the Altiplano are closely related to the upper-air circulation, with easterly zonal flow favoring wet conditions and westerly flow favoring dry conditions. They propose that monthly variation is related to the location of the Bolivian High, whereas interannual variability reflects changes in SST and SLP gradient between the tropics and sub-tropics, which affects zonal flow over the continent. Our data may indicate a more westerly zonal flow in the upper atmosphere over mid-latitude South America since 1994.
**ENSO**

Our data indicate that the northwestern, and subtropical portions of the continent (Peru, Colombia, Venezuela, northern Argentina) respond similarly to ENSO forcing, with eastern Brazil being anti-phased (Figure 3). This supports previous findings that positive MEI years bring tropical aridity and subtropical moisture. The strength of the ENSO correlations, and anti-phasing, over the continent appear marginally stronger since 1994, than between 1979 and 1994 (Figure 6).

Yet our data also show weaker-than-expected ENSO/humidity correlations over South America overall, considering the supposed prominence of ENSO in governing South American climate (Figure 6). We find no significant correlation between MEI and any of the leading modes of variability. We propose that the new CFSR data reveals heterogeneities in ENSO forcing over complex terrain that were not available to previous continent-scale analyses. Vuille and Keimig (2004) showed that, over the central Andes, there exists an intraseasonal antiphasing of wet and dry conditions between the northern and southern part of their study area. We propose that similar small-scale phenomenon corrupt the spatially coherent ENSO forcing posited by coarser resolution studies.

**South American Monsoon**

A strong positive correlation exists between SASM and humidity over the eastern Amazon, whereas a marked negative correlation prevails over the
surrounding areas (Figure 4). Our data reflect the dynamics observed by Zhou and Lau (1997) and others, in which the summer convergence of two jets creates a vortex over southeastern Brazil, leading to heavy rainfall in that area. The marked antiphasing of Venezuela, Paraguay and northern Argentina may reflect the deflection of normal circulation—which would typically exit the continent south, over Argentina—into the vortex over southeastern Brazil, carrying any moisture with it (Figure 11; Grimm et. al., 2007). The stronger the monsoon, the more deflection, and the less humidity transported south from the Amazon. Principal components analysis indicates a significant increase in correlation with the PC1s of DJF and MAM humidity during the more recent time interval, perhaps indicating that the monsoon’s influence is extending later into the austral fall. However, because the SASM index includes values only for March, the monsoon correlations observed in Figures 4b and 5b are not statistically significant.

**Southern Annular Mode**

In general, SAM-positive indices have prevailed from 1994-2009. This corresponds to stronger, more poleward, Westerlies during that time (Garreaud, 2007). Our data reflect that trend: correlations are generally stronger in the 1994-2009 interval, and more focused on latitudes south of the Andes (Figure 5). By comparison, SAM correlations between 1979 and 1994 are more diffuse. We also note that the SON correlation map from 1979-1994 resembles JJA from 1995-2009; JJA from 1979-1994 resembles MAM 1995-2009, et cetera; in other words, the
timing has been offset by almost a full season. This may indicate a difference in not just the spatial extent, but the timing of the SAM’s South American influence, when in its positive phase.

We also observe an antiphasing of humidity patterns, between southern South America, and southeastern Brazil /Uruguay and the Altiplano, especially during MAM/JJA (Figure 5). Strong Westerlies bring moisture to southern South America during positive phases of SAM, while the Altiplano and Uruguay region remain dry. Moreover, the arid region has shifted from west to east during the two time intervals considered. Silvestri and Vera (2009) document changes in the organization of the SAM between the 1960s–70s and 1980s–90s, observing that, in the 1960s-70s, the SAM positive phase was associated with an anticyclone that developed in the subtropical Atlantic and increased precipitation over southeastern South America. Since 1980, the anticyclone has tended to develop farther west, over the continent, where it interrupts convergence patterns and decreases precipitation over southeastern South America. This may explain the antiphasing, and the eastward shift of the MAM negative correlation zone, between the two intervals of study.

**Hadley Circulation**

Hadley indices--which once showed strong, and mostly positive correlations with humidity over Brazil/Argentina-- show weak, and mostly negative correlations between 1995-2009 (Figures 7, 8 and 9). Eastern Brazil stands out as its own
province, usually anti-phased from much of the rest of the continent. Only in Figure 4b do any of the Hadley plots show a distinct horizontal band around 30°S that could represent the descending limb of the Hadley cell, and this could just as easily represent the northwesterly jet that comes off the Andes and is involved in the monsoon. As such, it is impossible to tell from these data whether any migration of the cell has occurred over the last 30 years.
CONCLUSIONS.
Several modes of variability govern humidity over South America in any season, and no one mode of variability is seen to dominate. Local and regional atmospheric phenomena—like localized cyclones and jets—add considerable complexity to South American climate regimes, creating a patchwork of opposing responses to climate forcing. Traces of these antiphase relationships are reflected in the dramatic aridity changes of the last 30 years, but none is sufficient to explain them.

Over the mountains, where aridity changes are observed to be the starkest, our analysis shows that the major climate modes are nearly irrelevant to aridity changes. In our case study of a small mountainous region of the central Andes, we found less than 10% of humidity variability could be explained by climate modes. The primary mode of variability, which accounts for 90% of the variance, appears unrelated to any mode or index that we tested. At least over the high Andes, therefore, the explanation for recent humidity changes remains so far elusive.
TABLES
Table 1. Principal Components, Percent Variance Explained, and their Correlation to the Suite of Climate Modes and Indices—South America, 30 years. Numbers in bold correspond to the percent of variability explained by each PC. Color coding highlights PCs for which a strong correlation (positive or negative) exists with one of the climate modes or indices. Psi = streamfunction, Mean= mean gradient, tp=tropopause height, mon=SASM, mei=MEI, san=SAM
<table>
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<th>PC</th>
<th>1979-1994</th>
<th>EARLY</th>
<th>South America Comparison, 1979-1994 vs. 1995-2009. Numbers in bold correspond to the percent of variability explained by each PC. Color coding highlights PCs for which a strong correlation (positive or negative) exists with one of the climate modes or indices. Psi = streamfunction, Mean = mean gradient, tp = tropopause height, mon = SAM, mei = MEI, san = SAM</th>
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<th>SAMJJA</th>
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Table 2a. Principal Components, Percent Variance Explained, and their Correlation to the Suite of Climate Modes and Indices.
Table 2b. Principal Components, Percent Variance Explained, and their Correlation to the Suite of Climate Modes and Indices. South America Comparison, 1995-2009. Numbers in bold correspond to the percent of variability explained by each PC. Color coding highlights PCs for which a strong correlation (positive or negative) exists with one of the climate modes or indices. Psi = streamfunction, Mean= mean gradient, tp=tropopause height, mon=SASM, mei=MEI, san=SAM
Table 3. Principal Components, Percent Variance Explained, and their Correlation to the Suite of Climate Modes and Indices--AOI, 30 years. Table shows the first 10 principal components of variability for the AOI, in each of four seasons. Numbers in bold correspond to the percent of variability explained by each PC. Color coding highlights PCs for which a strong correlation (positive or negative) exists with one of the climate modes or indices. Psi = streamfunction, Mean = mean gradient, tp = tropopause height, mon = SAM, mei = MEI, san = SAM.
Table 4a-b. Principal Components and their Correlation to the Suite of Climate Modes–AOI quadrants, 1979-1994 and 1995-2009. Table shows the first 3 principal components of variability for each quadrant (northeast, northwest, southeast, southwest), in each of four seasons. Color coding highlights PCs for which a strong correlation (positive or negative) exists with one of the climate modes or indices.

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FIGURES
Figure 1. South America. Location map, including regions of interest.
Figure 2. Percent change in mean specific humidity, 1979-1994 and 1994-2009. 
Blue represents an increase in humidity; red, a decrease in humidity between the two intervals. 
[(mean 1995-2004)–(mean 1979-1994)]/(mean 1979-1994). White circles enclose areas of change that are statistically significant at 95%.
Figure 3. Percent change in NDVI vegetation index, 1979-1994 and 1994-2009. Blue represents an increase in vegetative "greenness"; red, a decrease in greenness between the two intervals. ([mean 1995-2004]-[mean 1979-1994])/[mean 1979-1994]. White circles enclose areas of change that are statistically significant at 95%.
Figure 4. Humidity anomalies correlated against South American Summer Monsoon Index (SASM) index by season. The top row of each plot shows correlations between seasonal humidity anomalies and mean gradient over the entire study interval (1979-2009). Subsequent rows show correlations for the earlier (1979-1994) and later (1995-2009) intervals. SASM index after Li and Zeng (2002, 2003, 2005).
Figure 5. Humidity anomalies correlated against Southern Annular Mode (SAM) index by season. The top row of each plot shows correlations between seasonal humidity anomalies and mean gradient over the entire study interval (1979-2009). Subsequent rows show correlations for the earlier (1979-1994) and later (1995-2009) intervals. Several indices exist to characterize the SAM; here the leading EOF of the monthly mean 1000-hPa (700-hPa) height anomalies poleward of 20° S is used. (Marshall, 2003)
Figure 6. Humidity anomalies correlated against Multivariate ENSO Index (MEI) by season. The top row of each plot shows correlations between seasonal humidity anomalies and mean gradient over the entire study interval (1979-2009). Subsequent rows show correlations for the earlier (1979-1994) and later (1995-2009) intervals.
Figure 7. Humidity anomalies correlated against streamfunction, by season. The top row of each plot shows correlations between seasonal humidity anomalies and mean gradient over the entire study interval (1979-2009). Subsequent rows show correlations for the earlier (1979-1994) and later (1995-2009) intervals. Streamfunction (Ψ500) is the equatorward-most latitude where mean meridional streamfunction shifts from negative to positive (Hu and Fu, 2007; Lu et al., 2007).
Figure 8. Humidity anomalies correlated against mean gradient, by season. The top row of each plot shows correlations between seasonal humidity anomalies and mean gradient over the entire study interval (1979-2009). Subsequent rows show correlations for the earlier (1979-1994) and later (1995-2009) intervals. Mean gradient (Mean-max $\delta$TP / $\delta$P) is the latitude of the peak in the meridional gradient of tropopause height (Davis, 2012).
Figure 8. Humidity anomalies correlated against mean gradient, by season. The top row of each plot shows correlations between seasonal humidity anomalies and mean gradient over the entire study interval (1979-2009). Subsequent rows show correlations for the earlier (1979-1994) and later (1995-2009) intervals. Mean gradient (Mean–max δTP / δφ) is the latitude of the peak in the meridional gradient of tropopause height (Davis, 2012).
Figure 10. Humidity anomalies in Area of Interest (AOI), correlated against modes and indices, 1979-2009. Upper-left panel shows quadrants used for local principal components analysis. AOI was chosen for its heterogeneous terrain: upper-left quadrant is mostly mountainous, right quadrants are mostly low-relief, lower-left quadrant is mixed terrain. Correlation for MAM only reflects March (index is not calculated for April or May).
Figure 11. Schematic evolution from (a) spring dry conditions to (b) peak monsoon conditions in southeastern Brazil, showing jet convergence convergence, and cyclone formation. Note the deflection of the northwestward jet into the cyclone. (from Grimm, 2007)
REFERENCES


