Hydrodynamics of the Caribbean Low-Level Jet and Its Relationship to Precipitation

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ABSTRACT

The easterly Caribbean low-level jet (CLLJ) is a prominent climate feature over the Intra-America Seas, and it is associated with much of the water vapor transport from the tropical Atlantic into the Caribbean Basin. In this study, the North American Regional Reanalysis (NARR) is analyzed to improve the understanding of the dynamics of the CLLJ and its relationship to regional rainfall variations.

Horizontal momentum balances are examined to understand how jet variations on both diurnal and seasonal time scales are controlled. The jet is geostrophic to the first order. Its previously documented semidiurnal cycle (with minima at about 0400 and 1600 LT) is caused by semidiurnal cycling of the meridional geopotential height gradient in association with changes in the westward extension of the North Atlantic subtropical high (NASH). A diurnal cycle is superimposed, associated with a meridional land–sea breeze (solenoidal circulation) onto the north coast of South America, so that the weakest jet velocities occur at 1600 LT. The CLLJ is present throughout the year, and it is known to vary in strength semiannually. Peak magnitudes in July are related to the seasonal cycle of the NASH, and a second maximum in February is caused by heating over northern South America. From May through September, zonal geopotential gradients associated with summer heating over Central America and Mexico induce meridional flow. The CLLJ splits into two branches, including a southerly branch that connects with the Great Plains low-level jet (GPLLJ) bringing moisture into the central United States. During the rest of the year, the flow remains essentially zonal across the Caribbean Basin and into the Pacific.

A strong (weak) CLLJ is associated with reduced (enhanced) rainfall over the Caribbean Sea throughout the year in the NARR. The relationship with precipitation over land depends on the season. Despite the fact that the southerly branch of the CLLJ feeds into the meridional GPLLJ in May through September, variations in the CLLJ strength during these months do not impact U.S. precipitation, because the CLLJ strength is varying in response to regional-scale forcing and not to changes in the large-scale circulation. During the cool season, there are statistically significant correlations between the CLLJ index and rainfall over the United States. When the CLLJ is strong, there is anomalous northward moisture transport across the Gulf of Mexico into the central United States and pronounced rainfall increases over Louisiana and Texas. A weak jet is associated with anomalous westerly flow across the southern Caribbean region and significantly reduced rainfall over the south-central United States.

No connection between the intensity of the CLLJ and drought over the central United States is found. There are only three drought summers in the NARR period (1980, 1988, and 2006), and the CLLJ was extremely weak in 1988 but not in 1980 or 2006.

1. Introduction

The Caribbean low-level jet (CLLJ) is an easterly jet located over the Caribbean Sea between the northern coast of South America (Venezuela and Columbia) and the Greater Antilles (Cuba, Haiti, Dominican Republic, and Puerto Rico). It is present throughout the year and transports large amounts of moisture from the tropical Atlantic into the Caribbean Sea, into the Gulf of Mexico, across Central America, and into the Pacific basin.

In this paper, we build on results from previous work to further our understanding of the dynamics of the climatological CLLJ, including how the jet’s variations...

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are controlled on seasonal and diurnal time scales. In addition, the relationship between the CLLJ and rainfall is examined, with special attention to any connections between the jet and regional drought.

Current literature on the CLLJ is reviewed in the following section, illustrated with figures from the North American Regional Reanalysis (NARR; Mesinger et al. 2006), which also serve as reference figures for the results. The NARR is a reanalysis product, with output generated by assimilating observations of winds, temperature, pressure, moisture, and precipitation into numerical model integrations. Methods used for diagnosing the jet dynamics and its connections with rainfall are presented in section 3. Section 4 has two parts, one to discuss the diurnal and seasonal CLLJ dynamics and another to explore the relationship to rainfall. Section 5 contains the summary and conclusions.

2. Background

The existing literature on the CLLJ and its relationship to the larger-scale circulation and rainfall is reviewed here, illustrated with figures from the NARR. These figures, with a horizontal resolution of approximately 32 km, supplement previous descriptions of the jet in this and other reanalyses (e.g., Wang 2007; Whyte et al. 2008; Muñoz et al. 2008), help relate the current analysis with NARR-based studies centered over the United States (e.g., Weaver and Nigam 2008), and support the analysis presented in section 4. A more comprehensive review of our current understanding of the precipitation and circulation features of the Caribbean Basin, including the CLLJ, is provided by Gamble and Curtis (2008).

Figure 1 displays the full NARR domain in a plot of the climatological (1979–2006) July zonal wind speed at 925 hPa (see also Fig. 1b in Muñoz et al. 2008). The CLLJ is prominent, with the highest wind speeds in the domain, exceeding 14 m s\(^{-1}\), between the northern coast of South America and the Greater Antilles. Because the CLLJ is located in the corner of the NARR domain, this reanalysis does not provide an optimal opportunity for investigating the relationship of the jet to tropical Atlantic or Pacific SSTs, which Muñoz et al. (2008) show is important for understanding the CLLJ’s interannual variability. However, the NARR does resolve the jet at high resolution and provides an opportunity for examining the “downstream” relationships, for example, with circulation and precipitation structures over Central America, southern Mexico, and the United States. Mo et al. (2005) provided a careful validation of the CLLJ in the NARR through comparisons with satellite scatterometer winds for 2000 and 2001, and Muñoz et al. (2008) compare three reanalysis products. They find that the representation of the jet in the reanalysis is accurate, with wind speeds only 1 m s\(^{-1}\) weaker than the scatterometer winds.

The CLLJ is present throughout the year. This is in contrast to the meridional Great Plains low-level jet (GPLLJ), which is a feature only of the boreal summer months. The CLLJ magnitude varies semiannually, as documented by Wang (2007), with peak easterly velocities in July. There is a secondary maximum in February and minima in May and October. Muñoz et al. (2008) relate this seasonality in the magnitude of the CLLJ to a similar semiannual cycling of the magnitude of meridional sea level pressure and temperature gradients, explaining that, to the first order, the CLLJ is geostrophic between 925 and 800 hPa. They suggest that heating over the approximately 1-km-high topography of northern South America intensifies these gradients, contributing to the strong meridional temperature gradients and thereby the zonal jet (Fig. 1).

Magaña et al. (1999) relate seasonal changes in the CLLJ to the occurrence of midsummer drought (MSD) along the Pacific coasts of Central America and southern Mexico. The MSD is a normal feature of that region’s precipitation climatology, defined by lower rainfall rates in July and August as compared with June and September–October. The low-level easterly flow intensifies at the beginning of the MSD period and weakens at the end. Magaña et al. (1999) propose that the driving of this seasonal variation originates in the eastern Pacific warm pool SSTs. The enhancement of the CLLJ during this period increases orographic rainfall along the Caribbean coast of Central America, depriving the Pacific coast of moisture to form the MSD intraseasonal variation. At the same time, the strengthening of the jet enhances moisture flux divergence to the east, which leads to a midsummer rainfall minimum over the Caribbean (Muñoz et al. 2008). On interannual time scales, the CLLJ strength and Caribbean rainfall rates are anticorrelated.

Although CLLJ wind speeds are similar in boreal summer and boreal winter, there is a distinct difference in the large-scale context of the jet in these seasons. One can divide the year into two parts for the CLLJ. During the months of October–April (ONDJFMA; Fig. 2a), the flow between northern South America and the Greater Antilles (i.e., between 12° and 20°N) continues westward over the Caribbean Sea, finally obtaining a southward component (presumably) in meeting the orography of Central America. The flow then enters the eastern Pacific basin. In contrast, during the months of May–September (MJIAS; Fig. 2b), the CLLJ splits into two branches over the central Caribbean Sea. One branch proceeds westward and enters the Pacific basin with an orographically induced southward component, and the northern branch flows into the Gulf of Mexico and connects with the GPLLJ.
There are also seasonal differences in the elevation and vertical structure of the CLLJ. Figures 3a–d display latitude–height cross sections of the zonal wind at 75°W and 925 hPa for July, February, May, and October, respectively, which are the two strongest and two weakest months of the CLLJ. For most of the year, the easterly wind speed maximum is located close to 925 hPa. Beginning in late July (Fig. 3a) and extending into August, September, and October (Fig. 3d), the jet core moves farther from the surface. In September and October, for example, the easterly wind maximum is located near 800 hPa. Comparing Figs. 3a,b indicates that, although the strong jets of the summer and winter have almost the same core wind speed, the summer jet is considerably deeper. Comparing Figs. 3c,d, one can see that the spring and fall jets have similar magnitudes; however, in the fall, the jet core is located higher in the atmosphere.

The diurnal cycle of the zonal wind in the CLLJ region for February, May, July, and October is plotted in Fig. 4a (see also Muñoz et al. 2008). The diurnal cycle is more subdued than the seasonal cycle, and it is similar throughout the year. The daytime jet is weaker (up to 2 m s$^{-1}$) than the nighttime jet. The semidiurnal variations produce the weakest jet at 1600 LT, with a secondary minimum at 0400 LT. Maximum jet speeds occur at 0700 LT. Note that this is very different from the diurnal cycle of the (climatological) GPLLJ, which is composed of a series of distinct, nocturnal low-level jet events.

The diurnal cycle of the meridional wind in the CLLJ region, shown in Fig. 4b, is very different from that of the zonal wind, and the meridional wind changes sign with season. In February (solid line), the meridional wind averaged over the day is southward, except in midmorning, with strongest speeds maintained through the night. In the other months displayed in Fig. 4b, the daily-mean meridional wind is northward in the CLLJ region, with strongest speeds in the day.

3. Analysis methods

The dynamical analysis first centers on understanding the $u$- and $v$-momentum balances in the region of zonal flow acceleration immediately east of the CLLJ maximum winds, from 12° to 15°N and from 60° to 75°W. Then, a larger-scale view is used to understand how the regional momentum balance is related to the large-scale circulation. Jet dynamics on both diurnal and seasonal time scales is investigated.

A Lagrangian perspective is used to explain why parcels of air traveling westward with the large-scale tropical Atlantic circulation are accelerated upon approaching the CLLJ region. The momentum equations in the form

$$\frac{du}{dt} = +f v - \frac{\partial \Phi}{\partial x} + F_x$$

and

$$\frac{dv}{dt} = -f u - \frac{\partial \Phi}{\partial y} + F_y$$

provide an understanding of the diurnal and seasonal cycles of the jet, including ageostrophic components.

Fig. 1. The 925-hPa zonal wind (m s$^{-1}$) from the NARR 1979–2007 climatology for July. Contour interval is every 2 m s$^{-1}$. Negative values denote easterly flow.
Muñoz et al. (2008) show that the CLLJ is basically geostrophic. Here, we extend their analysis to understand what regional force imbalances cause the jet to accelerate and decelerate on diurnal time scales (Fig. 4) and how and why the momentum balances vary with season (Figs. 2, 3). Ageostrophic components of the flow are of special interest, because these may be convergent or divergent and therefore related more directly to the

Fig. 2. The 1979–2007 climatological 925-hPa geopotential height (m) and winds (m s\(^{-1}\)) for (a) ONDJFMA and (b) MJJAS. White shading indicates regions outside of the NARR domain and regions in which the topography rises above 925 hPa.
precipitation field. Of particular interest also is the generation of the northward component of the flow over the western Caribbean and Gulf of Mexico in the summer months, when one branch of the CLLJ and the (climatological) GPLLJ are coupled.

Connections with rainfall are explored using two approaches. In one, we examine rainfall anomalies associated with extremely strong and weak CLLJs. In the other, we ask if prominent drought periods over the central United States can be associated with CLLJ anomalies. NARR rainfall values are used, because they are assimilated in the reanalysis and known to be relatively accurate where there is a reasonable spatial density of precipitation gauge observations, such as over the United States and Mexico, though some weaknesses such as poor rainfall estimates over Canada, for hurricanes, and spurious grid-scale precipitation events have been reported (e.g., Mo et al. 2005; Mesinger et al. 2006; West et al. 2007). Overall, using the rainfall from NARR provides the advantage of having the circulation and precipitation coupled within the blended model–observation system of the reanalysis.

4. Dynamics of the CLLJ

a. Diurnal variations of the CLLJ

Each term in the $u$-momentum equation [Eq. (1)] is displayed in Fig. 5a for July, when the jet is strong and the diurnal cycle amounts to a difference of about 2 m s$^{-1}$ (~20%) between day and night, but the results apply to all months (not shown). The terms are averaged from 12° to 15°N and from 60° to 75°W, just east of the CLLJ maximum (see Fig. 1), to capture the region in which the easterly flow experiences acceleration.

The (Lagrangian) zonal acceleration (solid bold line) $\frac{du}{dt}$ is negative for most of the day, strengthening the easterly flow; however, for about 4 h in the middle of the day (~0800–1300 LT), it is positive. The semidiurnal cycling of the zonal acceleration (and of the CLLJ speed)
is due to the semidiurnal cycling of the zonal geopotential height gradient (dashed line). An examination of regional maps on the 3-hourly resolution of the NARR (not shown) indicates that changes in the westward position–extension of the North Atlantic subtropical high (NASH) is the primary cause of the semidiurnal signal in the CLLJ acceleration region. Analysis on a large domain, with finer temporal resolution, may be needed to identify the cause of these changes, or these changes may be associated with a semidiurnal cycle of precipitation over the mountainous islands of the Greater Antilles that is not represented well in the NARR.

The hours of positive zonal acceleration that begin at about 0800 LT cause the afternoon minimum of the CLLJ, and the cause is related to the diurnal cycle of the Coriolis term (long–short dashed line). Coriolis accelerations are relatively large and positive ($f\nu > 0$) in late morning and are associated with the afternoon deceleration of the zonal flow. To understand this diurnal variation of the meridional wind, consider the meridional momentum equation [Eq. (2)]. Each term is plotted as a function of the time of day for July in Fig. 5b. To the first order, as discussed by Muñoz et al. (2008), the meridional momentum balance is geostrophic. Friction and the nonlinear terms are small, and imbalances between the meridional geopotential height gradient and Coriolis forces accelerate the meridional wind on diurnal time scales. In particular, $d\nu/dt > 0$ during the night, which leads to the northward velocity maximum at 1000 LT, the maximum in $f\nu$, positive $d\nu/dt$ values, and the weakening of the CLLJ to its afternoon minimum.

What causes the day–night differences in the meridional acceleration (solid bold line in Fig. 5b)? The meridional acceleration is southward during the day and northward at night, and the diurnal variation is primarily due to diurnal variations in the meridional height gradient (dashed line in Fig. 5b). The gradient strengthens from 0400 to 1600 LT and weakens from 1600 to 0400 LT. Figures 6a,b display close-up views of the 925-hPa geopotential heights in the CLLJ region at 0400 and 1600 LT, respectively. These figures show that the diurnal cycle of the meridional height gradient is caused by the diurnal cycle of heating over northern South America. The contour lines crossing the islands of the Greater Antilles are the same at 0400 and 1600 LT, but geopotentials rise and fall in a diurnal cycle over northern South America.
America. The center of the daytime heating, represented by low geopotential heights in the late afternoon (Fig. 6b), is over the northern Andes, presumably associated with solar heating of the elevated surface. So, the meridional wind variation is a land–sea breeze, with anomalous southward acceleration during the day and anomalous northward flow at night. In July, the maximum northward velocity occurs at 1000 LT; however, after that the flow is accelerated southward as the land surface heats up for the day. The northward flow begins to weaken and even becomes southward by 1600 LT (Fig. 4b), changing the sign of the \( u \)-equation Coriolis force (i.e., \( f\nu \)) and the zonal acceleration (Fig. 5a), and intensifying the CLLJ after its 1600 LT minimum.

### b. Seasonal cycle of the CLLJ

As is well documented in the literature (e.g., Wang 2007; Muñoz et al. 2008), the CLLJ has a semiannual seasonal cycle. It is strongest in July and has a secondary maximum in February. It is weak in May and very weak and vertically displaced (Fig. 3d) in October. The \( v \)-momentum balance is approximately the same throughout the year (as shown in Fig. 5b for July), with the primary balance being geostrophic. So, a first-order understanding of the CLLJ seasonality comes from understanding seasonal changes in the meridional geopotential height gradient.

Figures 7a–d display the 925-hPa climatological geopotential heights for July, February, May, and October, respectively. Comparing July and February, when the jet is strong, one can see that strong meridional height gradients are in place, concentrated in the CLLJ region. These gradients are stronger in July, consistent with the higher zonal wind speeds of that month compared with February. Examining the geopotential height patterns in Figs. 7a,b on larger space scales, it is clear that the cause of these enhanced gradients (e.g., compared with the annual mean; not shown) is different in the two months. In July, the westward extension of the NASH into the Caribbean north of the CLLJ region tightens the gradients. In contrast, the strong meridional height gradients in February are more closely related to heating over northern South America, in the northernmost edge of the South American monsoon system, and the NASH is weaker and positioned farther east.

In May (Fig. 7c), low geopotential heights persist over northern South America as in February, but the NASH is located farther north and east. In October, the NASH has retreated from the Caribbean, but heating over northern South America is not yet strong. However, this is not the whole story behind the weak October CLLJ, because the jet has also vertically moved from 925 to 800 hPa (Fig. 3d). This is the month with warmest Caribbean SSTs (not shown) and a well-developed atmospheric boundary layer that mixes heat vertically and weakens the 925-hPa meridional height gradients.

In addition to understanding the seasonal changes in the magnitude of the CLLJ, there is a change in wind direction that is important in connecting the jet with rainfall patterns and variability downstream. As seen in Fig. 2, during ONDJFMA the jet is largely zonal across the Caribbean; however, in MJJAS, the addition of a northward component connects the CLLJ with moisture transport into the Gulf of Mexico. Figure 8 displays differences in the flow and height fields between these two states, showing clearly that the difference amounts to a northerly wind component that is related to the positive
zonal height gradients between the summer thermal low over Central–North America and the NASH. Because the meridional wind in ONDJFMA in the CLLJ region has a small southward component and it has a pronounced northward component in summer, the Coriolis force in the \( u \)-momentum equation changes sign seasonally. Figure 9 shows the terms in the \( u \)-momentum equation for February, representing the fall and winter jet, for comparison with the July values in Fig. 5a. The Coriolis force \((fv)\) is negative in February for most of the diurnal cycle, whereas it was mostly positive in July (Fig. 5a) and it is the same sign as the pressure gradient force. Thus, the ONDJFMA \( u \)-momentum balance is not at all geostrophic, with friction playing a strong role.

5. Relationship of the CLLJ to rainfall and drought

The relationship between the intensity of the CLLJ and rainfall is investigated by correlating the CLLJ strength with precipitation anomalies. A CLLJ index is defined as the magnitude of the monthly-mean 925-hPa zonal wind in an area bounded by 70°–75°W and 12°–15°N, which captures the jet core, and standard deviations from the 1979–2007 monthly-mean zonal wind are calculated. These values are listed in Table 1. Although the goal is to connect variations in the CLLJ to drought (i.e., precipitation anomalies on seasonal and longer time scales), examining connections with rainfall on monthly time scales provides a better connection with physical processes to start.

Figure 10 shows the monthly correlations between the CLLJ index defined in Table 1 and the rainfall anomalies over the NARR temporal period. Correlations significant at the 95% confidence level are shaded in the figure with positive (negative) values lightly (darkly) shaded. White contour lines enclose regions at the 99% confidence level for both positive and negative correlation values.

A prominent and coherent region of strong negative correlation (strong jet with weak precipitation and vice versa) forms over the eastern Caribbean Sea, northern South America (northern Venezuela and Columbia, in the NARR domain), and the islands of the Lesser Antilles in May (Fig. 10e). The region expands westward into the Gulf of Mexico, Central America, and southern Mexico as the summer progresses, then retreats eastward after September (Fig. 10i). During October and November, the region of negative correlation is restricted to the eastern Caribbean. This is consistent with the results of Wang (2007) and Muñoz et al. (2008), who associate a strong CLLJ with enhanced divergence and reduced rainfall over the Caribbean Sea during the course of the annual cycle.

A generally coherent but less spatially robust area of negative correlations forms along the Pacific side of Central America, beginning in May over Costa Rica, Nicaragua, and Panama; migrating northwestward off the Guatemalan coast by August; and retreating equatorward back over El Salvador, southern Honduras, Nicaragua, Cost Rica, and Panama by September. This signal relates the CLLJ and the MSD, though the negative correlation is only significant at the 95% level over western Nicaragua, western Honduras, El Salvador, and Guatemala during July. Furthermore, the area of significant negative correlation is located off the southwestern
Mexican coast in August, north of the most prominent MSD signal (see Fig. 4 in Magaña et al. 1999).

Absent from the boreal summer correlations (i.e., May–September) is evidence of a significant positive correlation along the Caribbean coast of Central America south of 20°N. Magaña et al. (1999) and Magaña and Caetano (2005) suggest that the strong, low-level easterly flow associated with the CLLJ impinges on the orography of Central America, producing an enhancement in the summertime convective activity on the upslope side of the terrain. Closer inspection of the monthly correlation fields does reveal weak positive correlations ranging between +0.15 and +0.30 during the boreal summer along the Caribbean side of Central America from eastern Honduras to Panama, but these magnitudes fall below the 95% level of significance of +0.361. This discrepancy may be at least partially associated with the absence of surface observations along the eastern coast of Panama, Nicaragua, and Honduras to constrain the NARR precipitation assimilation. In the absence of assimilation data, NARR rainfall is based on estimates from the Climate Prediction Center Merged Analysis of Precipitation (CMAP); at a resolution of 2.5°, it is likely too coarse to capture this regional-scale climate feature.

Significant positive correlations between CLLJ strength and rainfall occur in a band stretching along the eastern seaboard and the Gulf Coast of the United States and into central Mexico in November (Fig. 10k). These positive correlations persist along the Gulf Coast until February, gradually moving northward over the southeastern and south-central United States. Positive correlations persist into late spring–early summer (i.e.,

Fig. 7. The 1979–2007 monthly climatological 925-hPa geopotential heights (m) for (a) July, (b) February, (c) May, and (d) October. Contour interval is every 5 m. White shading indicates regions outside of the NARR domain and regions in which the topography rises above 925 hPa.
May and June) over the southeastern United States, but the strength of the CLLJ and rainfall are uncorrelated over the United States during July and August.

To explore the dynamics of the connections between the strength of the CLLJ and regional rainfall, months with especially strong and weak jets were selected for compositing. Strong (weak) CLLJ months are identified when the standard deviation of the CLLJ index is less than (greater than) or equal to $2.1$. The dark (light) shading denotes strong (weak) jet months during the 1979–2007 period in Table 1. Of the 348 months (29 yr) analyzed, 16% (58 months) are identified as strong CLLJ months and 14% (52 months) are identified as weak CLLJ months.

Because the number of strong or weak CLLJ jet events is small for any given month in the 29-yr analysis period, composites were formed for the months during which the mean CLLJ has a pronounced northward component (i.e., MJJAS; Fig. 2b) and months during which the CLLJ does not connect strongly with the flow into the Gulf of Mexico (i.e., ONDJFMA; Fig. 2a). This yields 24 (34) events in the strong CLLJ category and 25 (27) events in the weak CLLJ category for the MJJAS (ONDJFMA) composite.

Figure 11a shows the NARR MJJAS precipitation climatology (shading) along with vectors representing vertically integrated water vapor transport. The largest rainfall rates, greater than 6 mm day$^{-1}$, occur mainly...
over the eastern Pacific and along the Central American coast. Therefore, the eastern United States, rainfall rates range between 3 and 5 mm day\(^{-1}\). Note that there are some falsely low rainfall rates produced in the NARR (e.g., over Cuba, over Hispaniola, and along the Texas-Mexico border) apparently related to a lack of reported rainfall observations and/or the transition from the dense observing network over the United States.

The composite of MJAS strong CLLJ events is shown in Fig. 11b. Only moisture transport vectors that are significantly different from the climatology at the 90% level are plotted. Shading indicates regions in which differences in precipitation are significant. In the climatology, these are the months during which the CLLJ and GPLLJ seem to be connected to form the southwest quadrant of the anticyclonic flow about the NASH (Fig. 11a); however, during strong CLLJ events (Fig. 11b), the GPLLJ (and moisture transport northward across the Gulf of Mexico) is not enhanced. Instead, strong wind speeds in the core region of the CLLJ are associated with enhanced moisture transport across the Caribbean and reduced rainfall rates throughout the Caribbean in association with stronger moisture flux divergence over the eastern Caribbean Sea [consistent with Mestas-Nuñez et al. (2007) and Muñoz et al. (2008)].

The lack of correlation between the northward branch of the CLLJ and the GPLLJ in MJAS is consistent with the dynamical analysis in the previous section. The northward branch of the CLLJ, as well as the northward flow across the western Caribbean in general, occurs in association with the positive zonal geopotential height gradients between the summertime thermal low over the land (Central America and Mexico) and the NASH. So, the lack of correlation between the northward branch of the CLLJ and the intensity of the CLLJ in the averaging area just north of South America indicates that the large-scale zonal gradient across the western Caribbean is not related to the meridional geopotential gradient in the averaging region. This makes sense, because one would not necessarily expect a correlation between these two gradients (e.g., between a western and a southward displacement of the NASH).
FIG. 10. Correlation between monthly rainfall anomalies and the monthly zonal wind anomaly for the 12°-15°N and 70°-75°W Caribbean low-level jet averaging region for (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December. Light (dark) shading indicates positive (negative) correlations significant at the 95% level, whereas the contouring within each shading region shows the 99% significance level.
FIG. 10. (Continued)
FIG. 11. (a) MJJAS climatological mean precipitation (mm day$^{-1}$) and vertically integrated water vapor transport ($\times10^5$ kg m$^{-1}$), and MJJAS anomalous precipitation and vertically integrated water vapor transport for the (b) strong and (c) weak CLLJ jet composites. (d)–(f) As in (a)–(c), but for ONDJFMA. Vectors and precipitation anomalies shown in (b),(c),(e),(f) are statistically significant at the 90% level. Contours interval is 5 gpm, and the vector scale is shown.
Rainfall rates are enhanced off the east and west coasts of Panama and Costa Rica and reduced over land in the strong CLLJ composite. It is unclear whether this signal is associated with variability of the MSD over Central America. Interpretation of results from Magaña et al. (1999) and Magaña and Caetano (2005) suggests that a strong CLLJ is associated with high orographic rainfall in eastern Panama and Costa Rica and drying to the west because of a rain-shadow effect. We examined the response as in Fig. 11b at high resolution, taking advantage of the NARR 32-km grid spacing, and such a pattern is not evident. However, the Magaña et al. (1999) study is probably more accurate at these space scales, because it is based on station data, and the rainfall assimilated by the NARR in this region is the lower-resolution product from CMAP.

Anomalous rainfall and vertically integrated moisture transport for the MJJAS weak CLLJ composite are shown in Fig. 11c. The westerly flow anomaly extends into the Pacific, just as the easterly flow anomaly did in the strong CLLJ composite (Fig. 11b), suggesting that there is some forcing from or relationship with the Pacific Ocean sector. This is consistent with other studies (e.g., Waylen et al. 1996; Higgins et al. 1999; Englehart and Douglas 2002, 2003; Schubert and Gutzler 2008), but further investigation of this connection is not possible with the NARR (Fig. 1). As in the strong CLLJ case for the warm season (MJJAS), there is no perturbation of the moisture transport into the United States associated with a weak CLLJ. There is a weak anomalous cyclonic circulation centered over the Gulf of Mexico, but the anomalous moisture transport vectors parallel the Gulf Coast.

The lack of a summertime connection between the CLLJ intensity and U.S. rainfall holds even for years of drought. Averaged over the warm season, the weakest CLLJ jet of the 29-yr NARR period analyzed occurred during 1988 (Table 1), which was exceptionally dry across the central United States. However, during the drought summer of 1980 the CLLJ was only slightly weaker than usual, and during the dry 2006 summer it was anomalously strong (with a sample size of only 3 drought years in the central United States during the analysis period, one would need to see extremely high consistency among the cases to be convinced of a connection). However, the fact that 1988 was so dry and the jet was so weak suggests that a case study for this particular year may be useful. Also, because there is only one year in the NARR record identified with drought in Central America and Mexico, a case study approach would be needed here as well.

Figure 11d shows vectors of the vertically integrated water vapor transport climatology along with shaded contours of precipitation from the NARR for ONDJFMA. In the climatology (Fig. 2a), there is no obvious relationship between the CLLJ and the transport of moisture into the central United States during ONDJFMA. However, when strong CLLJ events are composited for this period (Fig. 11c), it is apparent that, when the CLLJ is strong, northward moisture transport across the Gulf of Mexico into the central United States occurs and rainfall rates increase over Louisiana and Texas. Even though the GPLLJ does not exist during these months in the climatology (Fig. 2a), it forms temporarily and creates a connection between the CLLJ and central U.S. rainfall in the ONDJFMA composite. Westward moisture transport is also stronger over the southern Caribbean Sea, with rainfall reduced throughout much of the Caribbean.

The weak CLLJ composite for ONDJFMA (Fig. 11f) exhibits anomalous westerly flow across the southern Caribbean region, similar to the weak CLLJ composite for MJJAS (Fig. 11c). Rainfall is reduced by 0.5–1 mm day$^{-1}$ over a large region of the eastern United States, extending to the southern Texas coast. The drying is associated with southerly moisture transport anomalies in the western Gulf of Mexico. This is the only case in which precipitation changes over the Caribbean are not significant at the 90% level.

Figures 12a,b show 925-hPa geopotential heights and winds during MJJAS for the strong and weak CLLJ composites, respectively, for comparison with the climatology shown in Fig. 2b. Only wind vectors significantly different from the climatology are shown, and shading indicates regions of significantly different geopotential heights. Although the extension of the NASH over the Gulf of Mexico and western North Atlantic is stronger (weaker) in the MJJAS strong (weak) CLLJ composite in Fig. 12a (Fig. 12b), the low-level zonal geopotential gradient over the Caribbean is similar in the two cases. As a result, the meridional low-level flow over the western Gulf of Mexico is not strongly influenced, which is consistent with the lack of a connection between the CLLJ strength and U.S. rainfall in MJJAS (Fig. 11). The differences in the jet strength are primarily the result of geopotential height variations over northern South America. In the strong (weak) CLLJ case, geopotential heights are approximately 10 gpm lower (8 gpm higher) in the strong (weak) CLLJ case compared to the climatology.

During the rest of the year (ONDJFMA), the strength of the CLLJ is more strongly related to variations in the NASH rather than variations in geopotential heights over northern South America. Figures 12c,d show ONDJFMA 925-hPa geopotential heights and winds for the strong and weak CLLJ composites, respectively. There is not a large difference in heights over northern South America, but the 925-hPa heights of the NASH are approximately
15 gpm higher (lower) in the strong (weak) CLLJ composite. The low-level zonal height gradient over the Gulf of Mexico intensifies (weakens) when the NASH is strong (weak), producing enhanced (reduced) southerly flow from the Caribbean Sea and Gulf of Mexico and an increase (decrease) in rainfall over the central United States and along the western Gulf Coast (Fig. 10).

6. Conclusions

The CLLJ is low-level easterly wind maximum present throughout the year over the ocean in the region between the northern tip of South America and the islands of the Greater Antilles, extending into the western Caribbean Basin (Amador 1998; Wang 2007; Whyte et al. 2008). It is a prominent climate feature of the Intra-America Seas (Amador 2009), and it plays a major role in the transport of moisture throughout the region (Mo et al. 2005; Mestas-Núñez et al. 2007). Monthly-mean maximum wind speeds of 10–14 m s$^{-1}$ in the monthly-mean climatology distinguish the jet from the background tropical easterly flow of 2–4 m s$^{-1}$. Here, the North American Regional Reanalysis (NARR) is analyzed to improve our physical understanding of the dynamics of the CLLJ and its relationship to rainfall variations, including drought, over Central America, the Caribbean, and the United States.

Previous studies show that the CLLJ exhibits semi-diurnal cycling, with an amplitude of about 2 m s$^{-1}$ (Muñoz et al. 2008). Maximum easterly velocities occur

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**Fig. 12.** The 925-hPa geopotential heights (gpm) and winds (m s$^{-1}$) for the MJJAS (a) strong and (b) weak CLLJ composites and for the ONDJFMA (c) strong CLLJ and (d) weak CLLJ composites. Only wind vectors locally significant at the 90% level are shown; shading denotes geopotential heights locally significant at the 90% level.
near 2200 and 0700 LT in the NARR climatology, and the day’s weakest jet velocities occur at 1600 LT, with a secondary minimum at 0400 LT. The semidiurnal signal is related to semidiurnal variations in the meridional height gradient associated with changes in the westward extension of the NASH. The daily minimum in the jet speed is a secondary effect of a meridional land–sea breeze (solenoidal circulation) onto the north coast of South America, with anomalous southward (northward) acceleration during the day (night). This change in the meridional flow modulates the zonal flow of the CLLJ through Coriolis accelerations.

The CLLJ has a semiannual seasonal cycle (Wang and Lee 2007; Muñoz et al. 2008). Wind speeds are greatest (>14 m s\(^{-1}\)) at 925 hPa in July and February and weakest in May and October (<8 m s\(^{-1}\)). Maximum wind speeds occur near 925 hPa for most of the year, except in boreal fall, when the jet maximum moves up to 800 hPa in association with the year’s warmest SSTs.

To the first order, the jet is geostrophic, so the seasonal cycle is largely explained by seasonal variations in meridional geopotential height gradients (Muñoz et al. 2008). Two factors control this gradient over the Caribbean: namely, the strength and position of the NASH and heating over northern South America. During boreal summer, the westward expansion of the NASH tightens the meridional geopotential gradient over the Caribbean to produce the July wind speed maximum. During boreal winter, the meridional gradient is primarily strengthened by heating over South America, in the northernmost part of the South America monsoon system. Muñoz et al. (2008), using a lower-resolution reanalysis product [the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40)], also find that heating over the topography of northern South America intensifies the CLLJ; however, unlike this study, they suggest that the influence is important for intensifying the easterly flow in both boreal summer and winter.

Another facet of the CLLJ’s seasonality is its structure and connections with the large-scale circulation. During October–April (ONDJFMA), the CLLJ flows westward into the Pacific basin with a slight southward component resulting from the Central American topography. In sharp contrast, the CLLJ is split into two branches over the Caribbean Sea in May–September (MJJAS; see also Wang 2007). One branch flows to the west as in ONDJFMA, and a southerly branch flows into the Gulf of Mexico and connects with the GPLLJ.

A CLLJ index is used to characterize the strength of the jet and is correlated with rainfall anomalies. Whenever the CLLJ is strong (at any time of the year) rainfall is reduced across the Caribbean Basin, in agreement with previous studies (e.g., Wang 2007; Muñoz et al. 2008). During the warm season months of May through September, the moisture is lost to the Caribbean Basin when the zonal flow carries it into Central America and the Pacific. During the months of October through April, the moisture is transported northward out of the Caribbean Basin across the Gulf of Mexico.

Connections between the CLLJ strength and regional rainfall are investigated by forming strong and weak CLLJ composites for the MJJAS and ONDJFMA periods. The composite of MJJAS strong CLLJ events reveals that moisture transport into the south-central United States is not enhanced when the CLLJ is strong, despite the fact that the CLLJ and GPLLJ flows are continuous in the climatology during these months. This disconnect is related to the basic dynamics of the jet. The southerly branch of the CLLJ, as well as the southerly flow across the western Caribbean in general, occurs in association with the positive zonal geopotential height gradients between the summertime thermal low over the land (Central America and Mexico) and the NASH. This zonal gradient is controlled by different factors than the meridional gradient in the jet-averaging region, according to the dynamical analysis discussed. A correlation between the factors causing a western displacement of the NASH and those that cause a southward displacement of the NASH would be needed to generate a correlation between the CLLJ strength and the southerly flow across the Gulf Coast. For similar reasons, there is also no perturbation of the moisture transport into the United States associated with a weak CLLJ in the warm season.

In contrast, during the cool season, there are statistically significant correlations between the CLLJ index and rainfall over the United States. In the strong CLLJ event composite for ONDJFMA, there is anomalous northward moisture transport across the Gulf of Mexico into the central United States and pronounced rainfall increases over Louisiana and Texas.

The weak CLLJ composite for ONDJFMA reveals anomalous southwesterly flow across the southern Caribbean region, extending into the Pacific basin. Reduced rainfall over the central United States results.

We found no connection between the intensity of the CLLJ and drought over the central United States. Although the CLLJ was anomalously weak during the summer of 1988, an extremely dry summer in the Great Plains, it was only a little weak in another dry year (1980) and it was strong in the dry summer of 2006. With only three dry years in the United States in the NARR record, these results cannot be seen as definitive, because there are quite probably several means of inducing drought in the region. One of them may be related to the CLLJ, so a case study for 1988 would be worth pursuing.
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