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Moisture sources for Central America: Identification of moisture sources using a Lagrangian analysis technique

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[1] We herein present an analysis of the sources of atmospheric moisture for Central America using a Lagrangian technique. The results of backward and forward moisture tracking analysis using the FLEXPART model has enabled the identification of the main sources of moisture that reach Central America, as well as an evaluation of their spatial evolution during their passage toward the region of interest. Data from the European Center for Medium-Range Weather Forecasts (ECMWF) for a 5 year period (2000–2004) were used as input for the FLEXPART model. The applied method reproduces the variations in the location of the Intertropical Convergence Zone (ITCZ) over the study area very well. The primary source of moisture for Central America is identified over the Caribbean Sea, and a secondary source appears to exist near the equatorial Pacific region. The dominance of the Caribbean Sea region as a source of moisture for this region is clear, as is the importance of the Caribbean Low-Level Jet (CLLJ) as the principal transport mechanism. These characteristics are confirmed by inspection of the moisture transport patterns and their seasonal behavior.

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1. Introduction

[2] Tropical regions are characterized by strong convection patterns, both over the oceans and continents, with at least three different precipitation regimes being dominant in the diurnal cycle (oceanic, continental and coastal) [*Kikuchi and Wang*, 2008]. The identification of the physical mechanisms and sources of moisture responsible for the maintenance of these precipitation regimes is crucial for the understanding of the global hydrological cycle and for improving the predictive power of numerical models. Some regions, such as the IntraAmericas Sea (consisting of the Caribbean Sea, the Gulf of Mexico, the eastern tropical Pacific, Central America, and surrounding continental areas, hereafter IAS) are convectively very active, and precipitation is associated not only with surface heating due to incoming short-wave radiation, but also with upward motion triggered by topography or local features, traveling waves, tropical cyclones and the Intertropical Convergence Zone (ITCZ) perturbations [*Amador*, 2008]. As might be expected, the availability of moisture is one of the critical factors that determine the strength of the convection via the contribution of the moisture flux divergence term.

[3] Central America and southern North America are regions of particular meteorological interest within the IAS, where the thermal forcing that results from regional temperature gradients is a crucial element in the complex dynamic processes that occur and yield the wide variety of climatic regimes observed (e.g., the region is influenced by a semiarid climate, the convergence of the trade winds, and monsoon-like circulation patterns [*Wang*, 1994]). Under these conditions, regional climatic phenomena such as the Caribbean Low-Level Jet (hereafter CLLJ) can modulate the cyclogenetic activity and the regional weather, and the climate [*Amador*, 1998; *Amador et al.*, 2000; *Wang*, 2007; *Amador*, 2008]. The importance of the Caribbean Sea as a moisture supply for Central America, as well as its relationship with the local heat budget and its role in the hydrological cycle, have all been the subject of studies dating back to the late 1960s and 1970s [*Hastenrath*, 1966, 1967; *Portig*, 1965, 1976]. Nevertheless, the mechanisms that drive the transport of moisture have yet to be clearly determined. Recent studies of the CLLJ have pointed out the potential role of this low-level structure in moisture transport processes [*Wang et al.*, 2007], although some of the characteristics described were previously identified from a different perspective by *Hastenrath* [1966].

[4] The analysis of moisture transport for regions near Central America has previously been carried out using Eulerian approaches, and for southern Costa Rica and northern Panamá using isotope analysis [*Lachniet et al.*, 2007]. These methods can quantify flows of moisture to and from a region, but cannot identify the real sources and the associated physical processes. Within a Lagrangian framework, this characterization is described by trajectories of selected particles moving through space and time. The main characteristics of the different Lagrangian analysis methods that are used for moisture studies are described in

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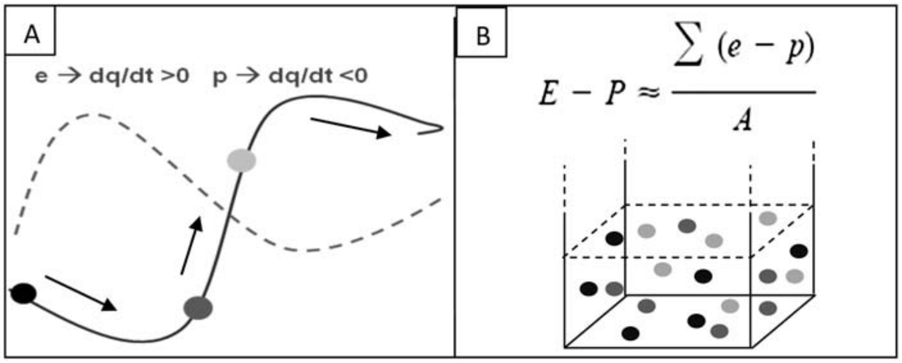

Figure 1. Schematic interpretation of the applied method in order to determine *e* and *p* as variations on specific moisture along the trajectories integrated over the vertical column for all the particles. Shading from light gray to black indicate that the specific moisture content of the particles vary along the trajectory. (a) Tracking method scheme; solid line and arrows indicate the trajectory, and gray dotted line indicates the variations on moisture content. (b) The vertical column containing a set of particles with different moisture content.

several studies, which also contain discussions of the advantages and disadvantages of both Eulerian and Lagrangian methods [see, e.g., *Nieto et al.*, 2007, and references therein].

[5] The general aim of the study described herein was to undertake a comprehensive analysis of the atmospheric moisture sources for Central America and southern North America using a Lagrangian approach, since few studies of moisture analysis have been carried out for Central America and most research in recent decades has focused on North and South America and complete studies on these regions can be found [see, e.g., *Mestas-Núñez et al.*, 2005, 2007; *Rasmusson*, 1968]. This paper presents an analysis of the moisture sources of the Caribbean and Central America using a Lagrangian approach, following the method developed by *Stohl and James* [2004, 2005] for the period 2000–2004, using data from the European Centre for Medium-Range Weather Forecasts (ECMWF). The main mechanisms involved in the moisture transport processes, the dynamic role of the CLLJ in transporting moisture from the Caribbean region to Central America, the energy budget, and the energy flux balances involved will be investigated in a future work.

[6] The data used in this paper, together with a general overview of the methods applied, are presented in section 2. The main features of the study region, including the topography, are described in section 3, together with a summary of the mean conditions in its vicinity over the period 2000–2004. The principal characteristics of the two most important transport mechanisms, the CLLJ and the Chorro del Occidente Colombiano (CHOCO) jet (a low-level jet located in the occidental region of Colombia [*Poveda and Mesa*, 2000]), are described in section 4. Section 5 contains the results obtained, which will then be discussed in section 6, together with a summary of the main conclusions presented in the study.

2. Data and Methods

[7] In order to undertake a detailed Lagrangian analysis of the moisture sources and their associated transport mechanisms in and around Central America and the Caribbean, we used the particle dispersion model FLEXPART [*Stohl et al.*, 2005]. The FLEXPART model is a Lagrangian particle dispersion model that has been applied in a wide variety of studies involving atmospheric transport. One of the advantages of the model is its flexibility to be feed by different data sets; ECMWF, GFS (Global Forecast System) as well as MM5 (National Center for Atmospheric Research Penn State University mesoescale model version 5). In general terms, the FLEXPART model is accurate to simulating long-range and mesoscale transport, diffusion and radioactive decay of tracers released from a source as well as dry and wet deposition.

[8] The objective analysis of the ECMWF (P. W. White (Ed.), IFS documentation, European Centre for Medium-Range Weather Forecasts, Reading, UK, 2002, http://www.ecmwf.int) for the period 2000–2004 was used with a 1° × 1° grid resolution as the FLEXPART input data. The period 2000–2004 was selected due to the absence of any extremely active El Niño–Southern Oscillation (ENSO) episodes (using a standard period at the global climate scale). An extended analysis of interannual variability will be examined in the next stage of the current research. The trajectories of 1,398,801 particles of equal mass were computed in order to track the moisture variations along the three-dimensional trajectories. The variations in moisture were represented by changes to the specific humidity (q). Six hourly data (4 times per day) were obtained from the ECMWF 60-level data set covering from the surface to the 10 hPa level (approximately 14 levels are below 1500 m) using the FLEXPART model output in order to reproduce the three-dimensional trajectories.

[9] Initially, the atmosphere was divided homogeneously into a number of "particles," which were then transported by the FLEXPART model via three-dimensional wind domain. Within this context, the simple physical concept of a particle was used, which consisted of a tiny portion of atmospheric matter with negligible internal motion and unique thermodynamic properties. Analyses every 6 h and 3 h forecasts at intermediate times were used in order to provide a better time resolution required for the accuracy of

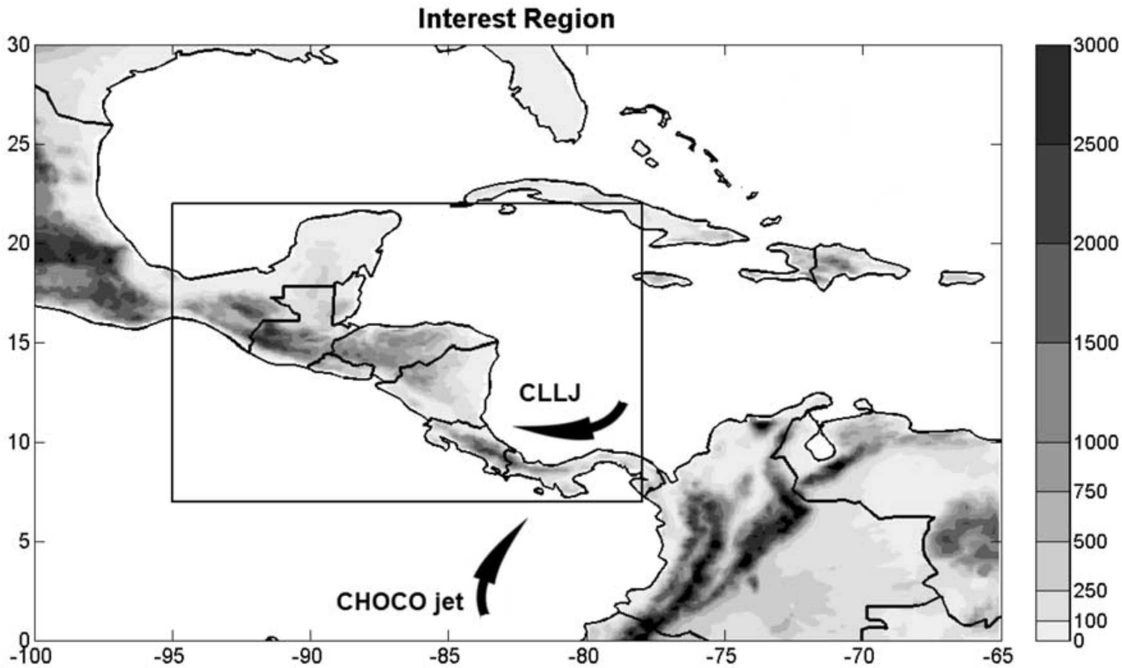

Figure 2. Map of the analysis region, black arrows represents the CLLJ and the CHOCO jets in its approximate location and winds direction.

the trajectories [*Stohl et al.*, 2005]. Particle positions and specific humidity information were recorded every 6 h. Following the computation of the trajectories, the moisture variations along the trajectories were calculated using the changes in specific humidity over time (dq/dt). For each particle, changes in moisture content are a function of evaporation (e) and precipitation (p), and may be described by the following relationship:

$$e - p = m\frac{dq}{dt}, \quad (1)$$

where m is the mass of the particle. As previously stated, the magnitude of $(e - p)$ represents the increase or decrease in the internal moisture of the particle along its trajectory. In this case, losses and gains can be understood in terms of positive ($e - p > 0$) or negative ($e - p < 0$) values of dq/dt, respectively. The sum of all the $(e - p)$ values for the complete set of particles residing in a specific atmospheric column is the final result $(E - P)$, and represents the surface freshwater flux,

$$E - P = \frac{\sum(e - p)}{A}, \quad (2)$$

where E is the evaporation, P is the precipitation per unit area, and A is the area. In order to determine the moisture sources for a particular region, this method was applied backward in time in order to obtain and track $(E - P)$ for a given region. The moisture sources thus detected were then evaluated using a similar process to track $(E - P)$ forward in time. The limit for the transport time was set at 10 days according to the average residence time of water vapor in the atmosphere [*Numaguti*, 1999]. Figure 1 presents a general scheme of the applied method.

[10] The seasonal, annual, and 5 year $(E - P)$ values were calculated as an average over each $1^\circ \times 1^\circ$ gridded area for the sources of moisture identified. $(E - P)$ back trajectory values for specific days are denoted by $(E - P)^{-n}$. Thus, $(E - P)^{-1}$ represents the total gain or loss of moisture on the previous day of the trajectory. Analysis of the $(E - P)$ values thus obtained indicates where and when the moisture for the analyzed areas was gained or lost. $(E - P)$ forward values are denoted by $(E - P)^{+n}$.

3. Mean Conditions in the Region During the Period of Analysis

[11] Central America is located between the two large water masses of the eastern tropical Pacific and Caribbean warm pools [*Wang and Enfield*, 2001, 2003]. The water masses near this region receive an annual mean surface incoming short-wave radiation flux in excess of approximately 220 W m^{-2}, with maxima to the west of Central America and to the north of South America of more than 250 W m^{-2} [*Amador et al.*, 2006]. The regions associated with these radiation peaks are characterized by strong evaporation and convection patterns, and the thermal contrast between the land and ocean induces the transport of local moisture.

[12] The region is also affected by the orientation of the mountainous range (SE to NW as shown in Figure 2), which account for the two main climatic influences from the Caribbean and the Pacific. The Central American mountain range system forms part of the continuum of the high topography found near the American Pacific coast, which

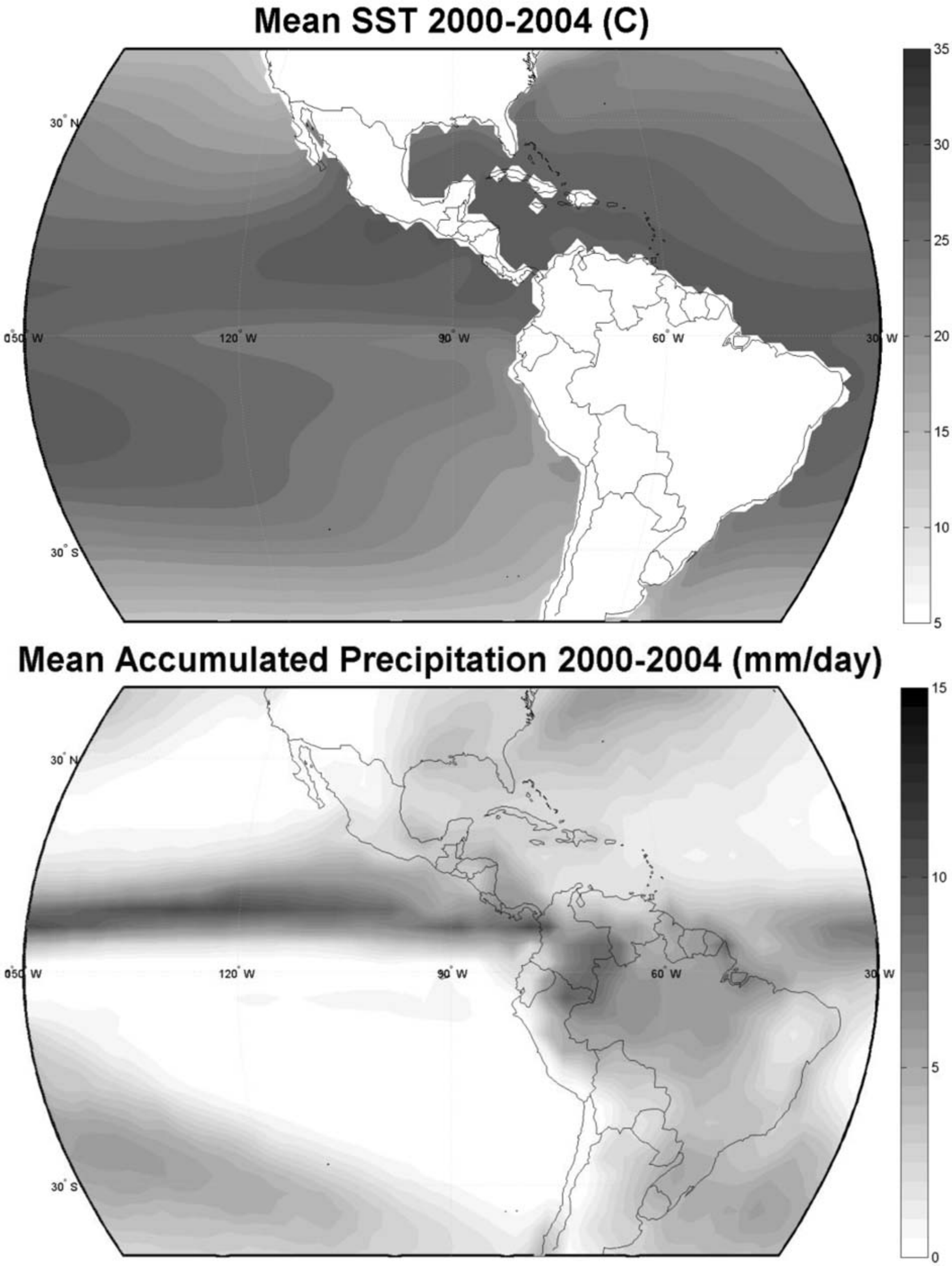

Figure 3. (top) Mean SST field for the period 2000–2004 data from ERA INTERIM and (bottom) mean accumulated precipitation for the period 2000–2004 data from the CPC Merged Analysis of precipitation.

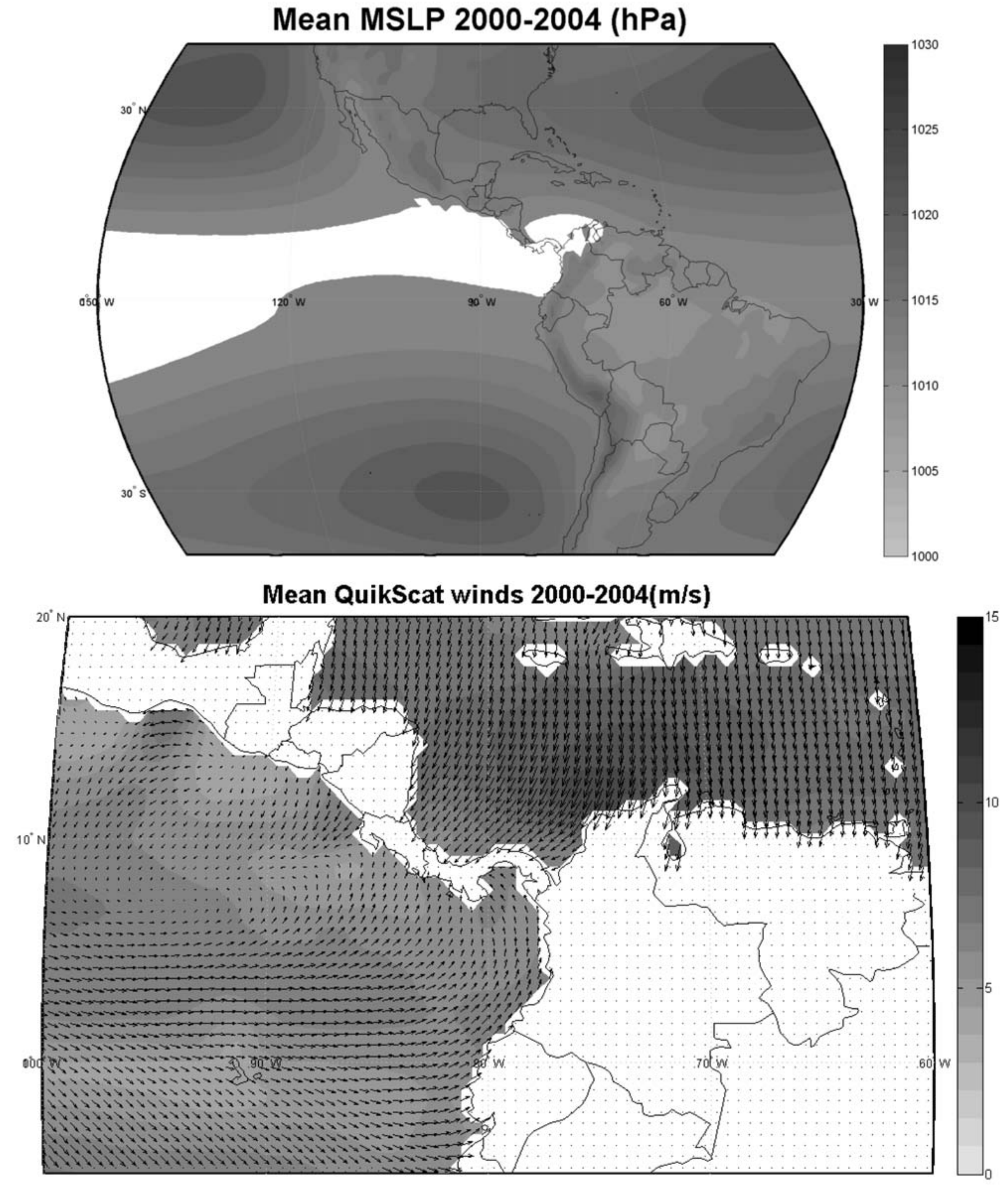

Figure 4. (top) Mean SLP field for the period 2000–2004 data from ERA INTERIM and (bottom) mean wind magnitude and vectors data from QuikScat (http://www.ifremer.fr).

extends from the Rocky Mountains in the north to the Andes in the south.

[13] The local topography is an important element in weather and climate modulation, and the presence of topographic passes in some regions (e.g., Chivelas, Tehuantepec, Papagayo and Panama) favors the funneling of wind through the region [*Amador et al.*, 2006]. On the Pacific side, a reduction in precipitation is generally observed in July and August commonly denoted as the Mid Summer Drought (MSD, or locally 'veranillo' [*Magaña et al.*, 1999]); June, September, and October are usually the rainiest months. The Caribbean slope is characterized by

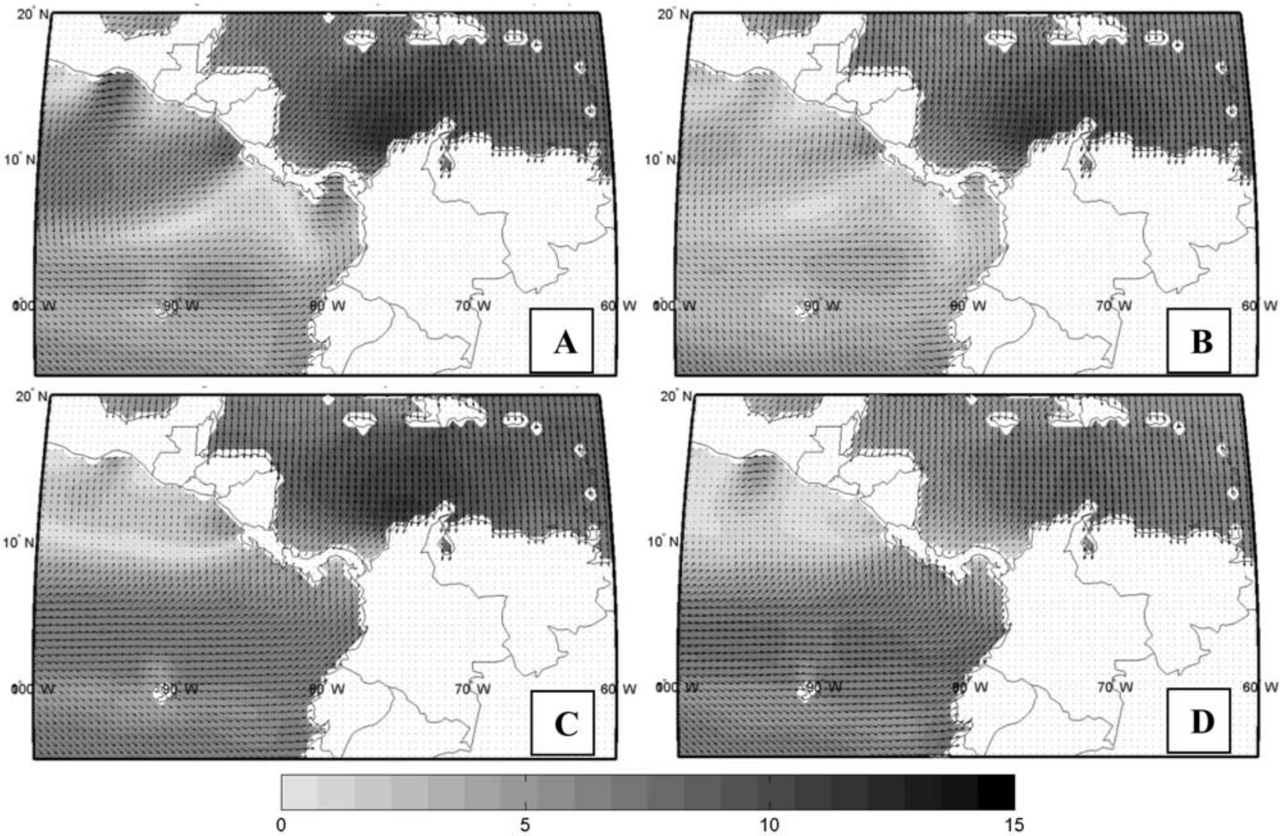

Figure 5. Mean seasonal (a) winter, (b) spring, (c) summer, and (d) autumn wind magnitude and vectors for the 2000–2004 period in m/s. Data from QuikScat (http://www.ifremer.fr).

the occurrence of precipitation throughout the year (see Figure 3). The study region is greatly influenced by the seasonal migration of the ITCZ [*Waliser and Gautier*, 1993] and by the increase of the trade winds during boreal summer and winter [*Waylen et al.*, 1996; *Hastenrath*, 1991; *Amador et al.*, 2006]. The local climate is also influenced by regional structures such as the warm pools [*Wang and Enfield*, 2001, 2003], the North Atlantic Subtropical High, low-level jet structures [*Amador*, 1998; *Poveda and Mesa*, 2000] and by atmospheric oscillations at different time scales, such as ENSO [*Amador*, 2008].

[14] Wind field presents a particular seasonal behavior in which trade winds and the position of the region near the equator play a major role in determining the direction of local winds. The general picture of the wind field as shown by Figure 4 reveals the presence of two jet-like structures in both Caribbean and Pacific sides; Figure 5 presents the seasonal variations of the wind field. These structures are dominant features of the regional wind fields and relevant for local moisture transport, as will be later properly discussed. These structures are specifically known as the CLLJ [*Amador*, 1998] and CHOCO [*Poveda and Mesa*, 2000] jets for the Caribbean and Pacific, respectively.

4. Local Low-Level Jet Structures

4.1. CLLJ

[15] Recent renewed interest in the presence of a low-level jet structure near the Caribbean Sea has come as a result of its importance for weather and climate forecasting in the region [*Amador*, 1998; *Amador and Magaña*, 1999; *Amador et al.*, 2000, 2003, 2006; *Wang*, 2007; *Wang and Lee*, 2007; *Wang et al.*, 2007; *Whyte et al.*, 2008; *Muñoz et al.*, 2008; *Amador*, 2008]. The importance of the CLLJ is related to its possible link with the Great Plains Low-Level Jet (GPLLJ) and to the South America Low-Level Jet (SALLJ). The presence of a low-level jet structure in the vicinity of the Caribbean Sea was first described by *Amador* [1998] using zonal wind, potential vorticity, and vertical velocity analysis techniques. A jet-like structure was identified in the lower troposphere (925 hPa) with a jet core near 75°W, 15°N, where the mean flow has been shown to be barotropically unstable. It has also been conjectured that this low-level jet is a mechanism that links the SST anomalies found in the Caribbean Sea with those found in the eastern tropical Pacific [*Amador*, 1998]. A variety of analyses of the presence of a low-level jet over the Caribbean Sea has recently been published [*Wang*, 2007; *Wang and Lee*, 2007; *Wang et al.*, 2007; *Whyte et al.*, 2008; *Muñoz et al.*, 2008; *Amador*, 2008]. These studies focused on the interaction of this low-level jet with the warm pools, variations in (sea level pressure) SLP gradients via interaction between the Atlantic Warm Pool (AWP) and the North Atlantic Subtropical High (NASH) [*Wang*, 2007] and also the weakening of the GPLLJ northward moisture transport [*Wang et al.*, 2007]. All the mentioned studies agree in the seasonal behavior with primary and secondary maxima (boreal summer and winter, respectively). Figure 5 gives a

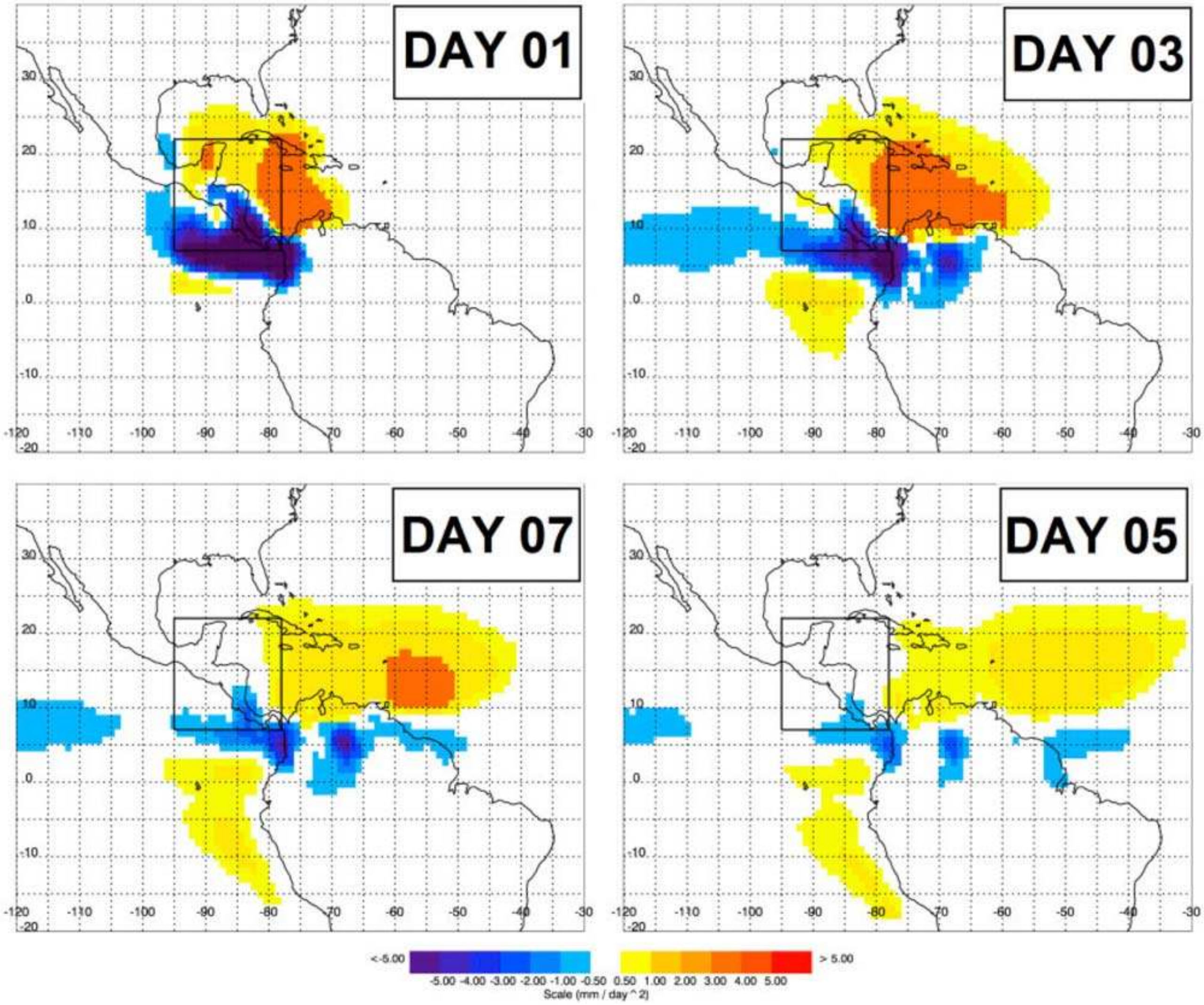

Figure 6. Mean ($E - P$) for the period 2000–2004 for days 1, 3, 5, and 7 before the particles reach Central America using backward mode.

clear representation of the mentioned seasonal behavior. The role of the CLLJ as a moisture transport mechanism for the Central America region has not been directly mentioned and properly explained as is the case of the GPLLJ for the regions of the Gulf of Mexico and the North American Great Plains [*Bosilovich and Schubert*, 2002].

4.2. CHOCO Jet

[16] The CHOCO jet is a low-level westerly jet that is characterized by a core near 5°N, 80°W at approximately 925 hPa, peaks during the months of October and November, and has a minima during February and March, and that is linked with the contrast in temperature between the land and ocean.. The CHOCO jet has been associated with the genesis and development of deep convection, related to the presence of a topographic gap known as the Mistrató Pass [*Poveda and Mesa*, 2000] and to the rotation of the southerly wind flow by the Coriolis effect (see Figure 5). Although the CHOCO jet has some characteristics in common with the CLLJ, they do not have precisely the same type of structure; the CHOCO jet is not barotropically unstable and its intensity is normally about half of that of the CLLJ. Furthermore, the CLLJ is not associated with any of the topographic features of Central America, unlike the CHOCO jet, which is associated with the Andes. Both low-level jet structures show opposite response to the phases ENSO [*Amador et al.*, 2006]. The most important effect of both these low-level jet structures is their role in inland low-level moisture advection.

5. Results and Discussion

[17] The whole column of air mass over Central America (defined by the region 7°N–22°N and 78°W–95°W; see Figure 2) backward in time was tracked. In order to determine the moisture sources for the Central American region for the 10 day backward trajectories, the quantity ($E - P$) was calculated every 6 h. For the first time step, all the target particles remained over Central America and ($E - P$) represented the region-integrated net freshwater flux. For subsequent trajectory time steps, ($E - P$) represented the net freshwater flux into the air mass moving into

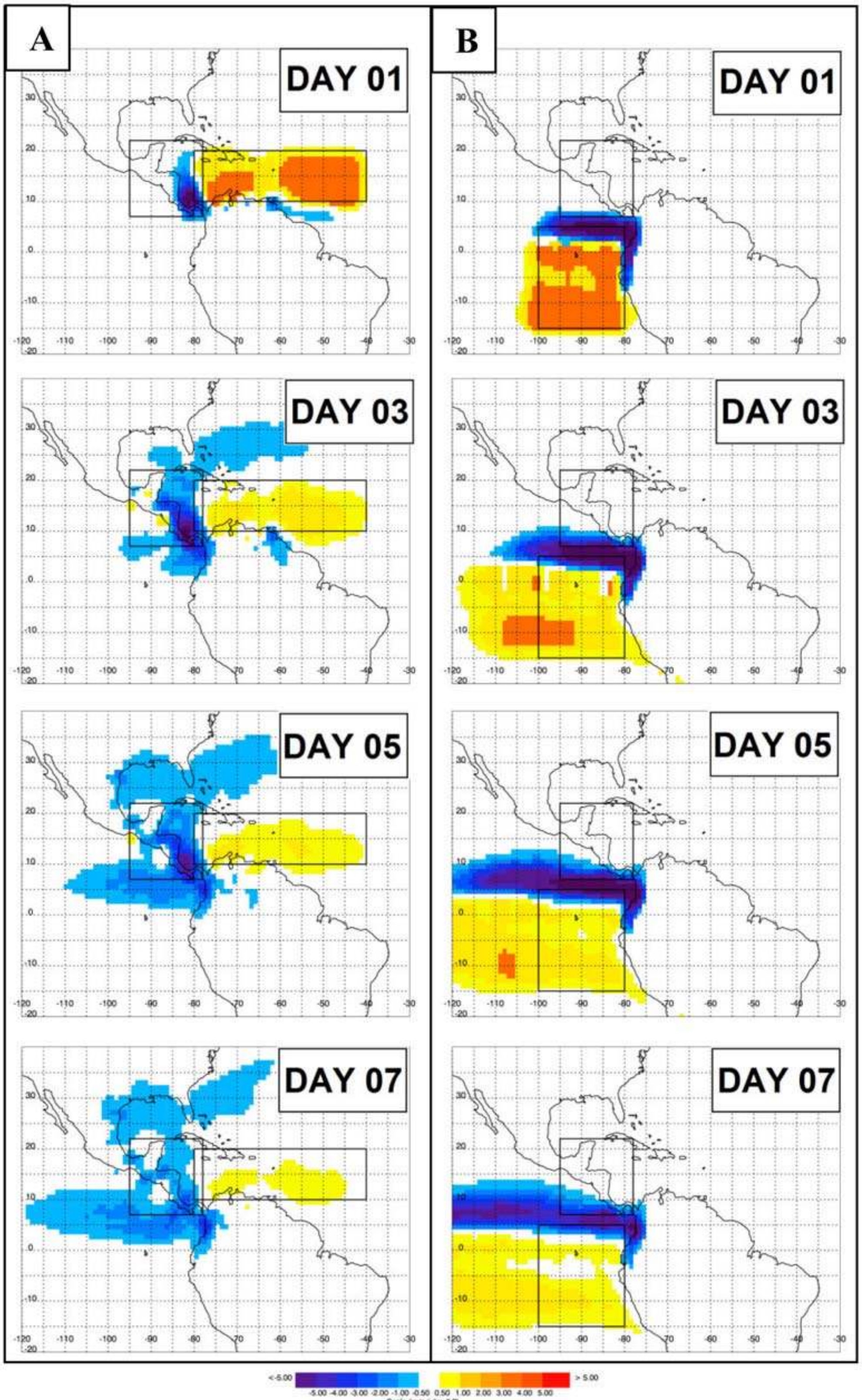

Figure 7. Mean ($E - P$) for the period 2000–2004 for days 1, 3, 5, and 7 using a forward tracking method (a) after the particles leave the CS source and (b) after the particles leave the PS source.

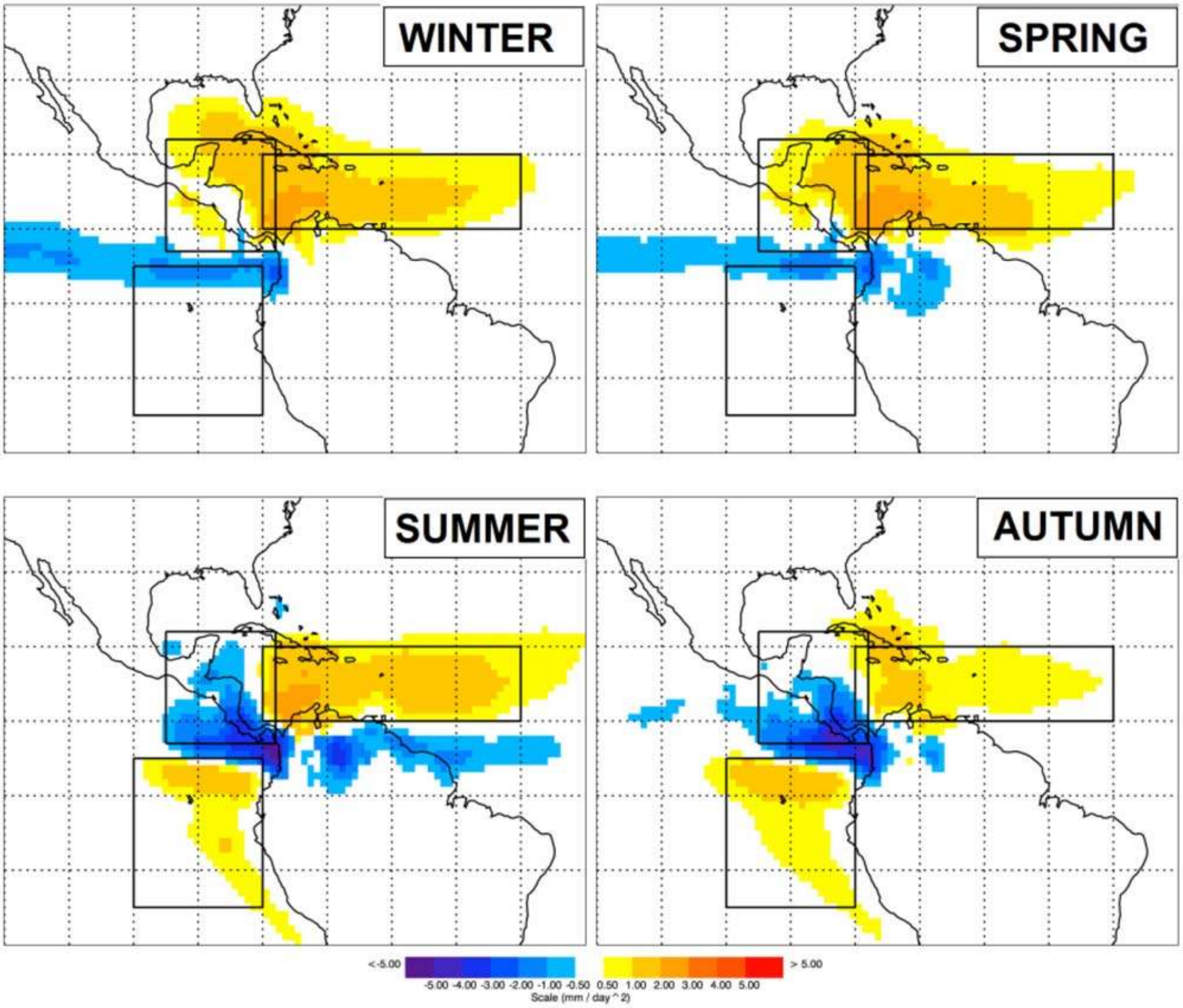

Figure 8. Integrated seasonal (winter, December–January–February; spring, March–April–May; summer, June–July–August; autumn, September–October–November) $(E - P)$ for the period 2000–2004 obtained using particle backward mode.

the Central American region. $(E - P)$ was estimated on a $1^\circ \times 1^\circ$ grid and averaged over seasonal and 5 year periods. Analysis of the $(E - P)$ values thus obtained determines where and when the moisture over Central America was gained or lost.

[18] The corresponding analyses of the mean $(E - P)^{-n}$ fields for backward trajectories over Central America are shown in Figure 6. Only those results from days 1, 3, 5, and 7 days of transport prior to the time of analysis are presented. Thus, each map indicates those regions where the air masses gain $(E - P > 0)$ or lose $(E - P < 0)$ moisture prior to their arrival in Central America. The spatial patterns show two areas where air masses gain moisture (reddish colors). $(E - P)^{-n}$ patterns show significant positive values at the eastern boundary, and from $(E - P)^{-5}$ and $(E - P)^{-7}$ a relatively low intensity source (compared to the Caribbean) was detected reaching the southern boundary of Central America from the eastern tropical Pacific. For the case of the Caribbean Source for $(E - P)^{-5}$ and $(E - P)^{-7}$ the patterns are similar to $(E - P)^{-1}$ and $(E - P)^{-3}$ with some variation in the spatial extent; this source pattern being elongated eastward because of the dominant easterly wind direction. From the second source over the Pacific ocean not all the moisture reaches the Central Caribbean region, as is shown by the negative $(E - P)^{-n}$ values between the source and the target area. It is also important to note that the positive $(E - P)^{-n}$ values that occur during the days before the particles reach the region indicate the importance of local evaporation. The differences observed between $(E - P)^{-1}$, $(E - P)^{-3}$, $(E - P)^{-5}$ and $(E - P)^{-7}$ show the importance of the loss of moisture prior to the air mass reaching the study region. So, two main moisture sources for the Central American region may be clearly identified, the most important one being over the Caribbean Sea between 10°N and 20°N and 40°W–80°W (hereafter CS) and a minor one, but still important, source is observed near the tropical South American Pacific Coast between 15°S–5°N and 80°W–100°W (hereafter PS).

[19] In order to better understand the nature of the source-receptor relationship, the forward trajectories were

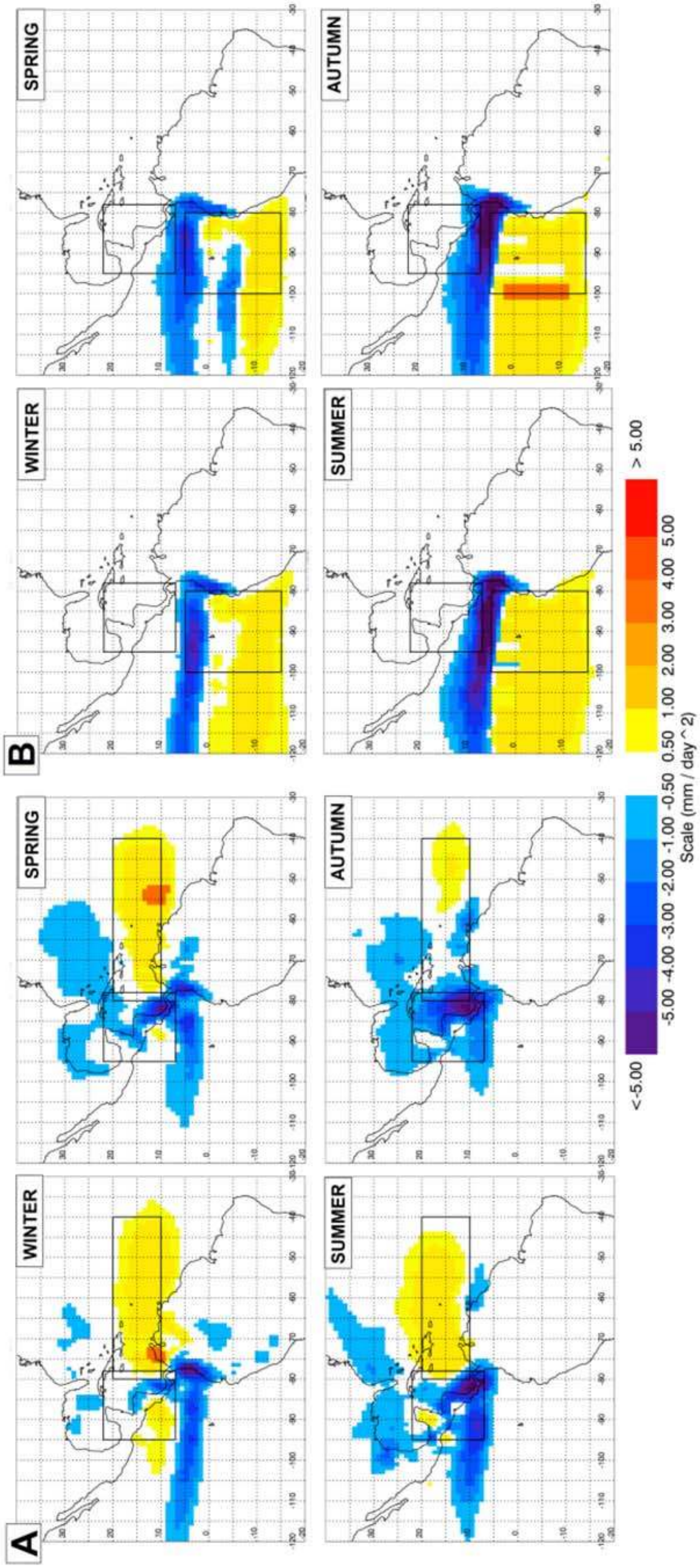

Figure 9. Integrated seasonal $(E - P)$ for the period 2000–2004 using a forward tracking method undertaken for (a) CS and (b) PS.

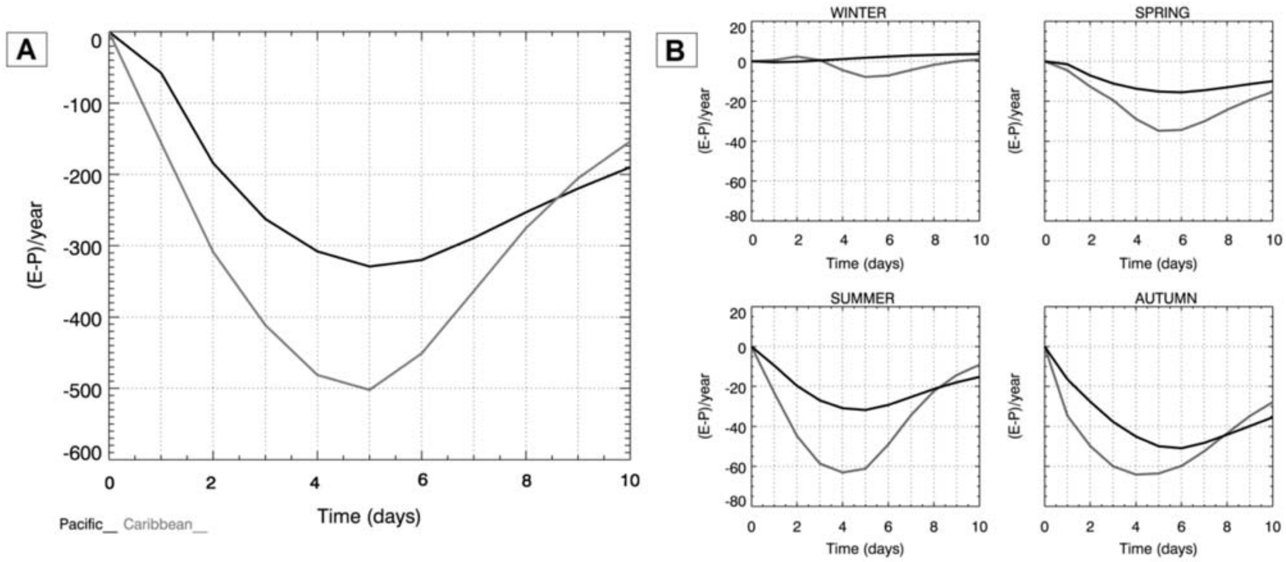

Figure 10. (a) Ten day integrated transported $(E - P)$ from the indicated source to Central America. (b) Seasonal mean 10 day integrated transported $(E - P)$ from the indicated source to Central America. Solid black lines represent PS, and solid gray lines represent CS.

computed for particles departing from the CS and PS source regions. Calculation of $(E - P)$ from the sources to the target region allows an accurate quantification of the source-receptor relationship. Figure 7 shows the $(E - P)^{+n}$ results for the forward analyses which indicate that after the particles leave the sources, moisture is lost along their trajectories and only part of the moisture reaches Central America. The main observed difference between the moisture sources is the receptor region associated with each source. As well as the particles from the CS reach the analysis region, particles from the Pacific source (Figure 7b) only reach the southernmost part of Central America, specifically southern Costa Rica, and do not represent an important moisture source for northern Central America.

[20] These patterns represent, from a general point of view, the way in which the air masses can be dried or moistened along their trajectory, and are affected by local transport as a function of local winds and temperature conditions. It may be deduced from Figure 7 that air masses originating in the Caribbean Sea region tend to lose moisture over Central America and the Gulf of Mexico, the maximum amount of moisture being lost over southern Central America and the Caribbean side of Costa Rica, in a similar manner to moisture that originates in the PS region. Only a small proportion of this moisture reaches the continental region of southern Central America and most is lost over the ocean. Another important result obtained is that the CS is an important source of moisture for the Pacific ITCZ.

[21] The intensity and extent of the moisture sources varies throughout the year. Figure 8 shows the seasonal average values (winter, DJF; spring, MAM; summer, JJA; autumn, SON) obtained for the 10 previous days $(E - P)^{-10}$. In general, the mean position of the CS source does not vary significantly, apart from a slight displacement toward the Gulf of Mexico during winter. In contrast, the location of the PS source shows significant variation throughout the year, and disappears as a source during winter and spring mainly due to the influence of the ITCZ, which seems to affect the amount of moisture loss over southern Central America during its seasonal migration.

[22] As for the annual case, analyses of the forward trajectories were also conducted in order to determine whether there were seasonal variations in the destination of the moisture departing from both sources. Seasonal means of total $(E - P)^{+10}$ (integrated forward over the following 10 day period), were calculated for each moisture source (Figure 9). The seasonal patterns obtained confirms that the moisture that departs from the CS region contributes to precipitation over Central America, while the moisture that departs from the PS region is not able to reach the entire Central American region, contributing only to precipitation in its southernmost portion, specifically in Costa Rica. In summary, the moisture from the CS region is lost over the whole of Central America, whereas the moisture from the PS region is lost only over Southern Central America. Additional evidence of the observed differences in each source's contribution to the moisture may be seen in Figure 9. Negative $(E - P)^{+n}$ values indicate contributions to precipitation, because $(P - E)$ is actually equivalent to the runoff term. Figure 10 presents the 10 day integrated transport from both the identified sources to Central America (calculated from and to the same boxes shown in Figure 8), Figure 10a indicates that effectively transport from the CS to Central America exceeds significantly the transport from the PS to the same target region. The seasonal results shown in Figure 10b are consistent with the patterns of precipitation, boreal winter being the driest season. It can be also be seen how the transport from each source follows a similar pattern as the known precipitation distribution for each basin (Caribbean and Pacific).

[23] The results obtained using this Lagrangian approach are reinforced by the analysis of the seasonal moisture divergence (Figure 11). Data from the "vertically integrated mass, moisture, heat, and energy budget products derived from the NCEP/NCAR reanalysis" by David Stepaniak

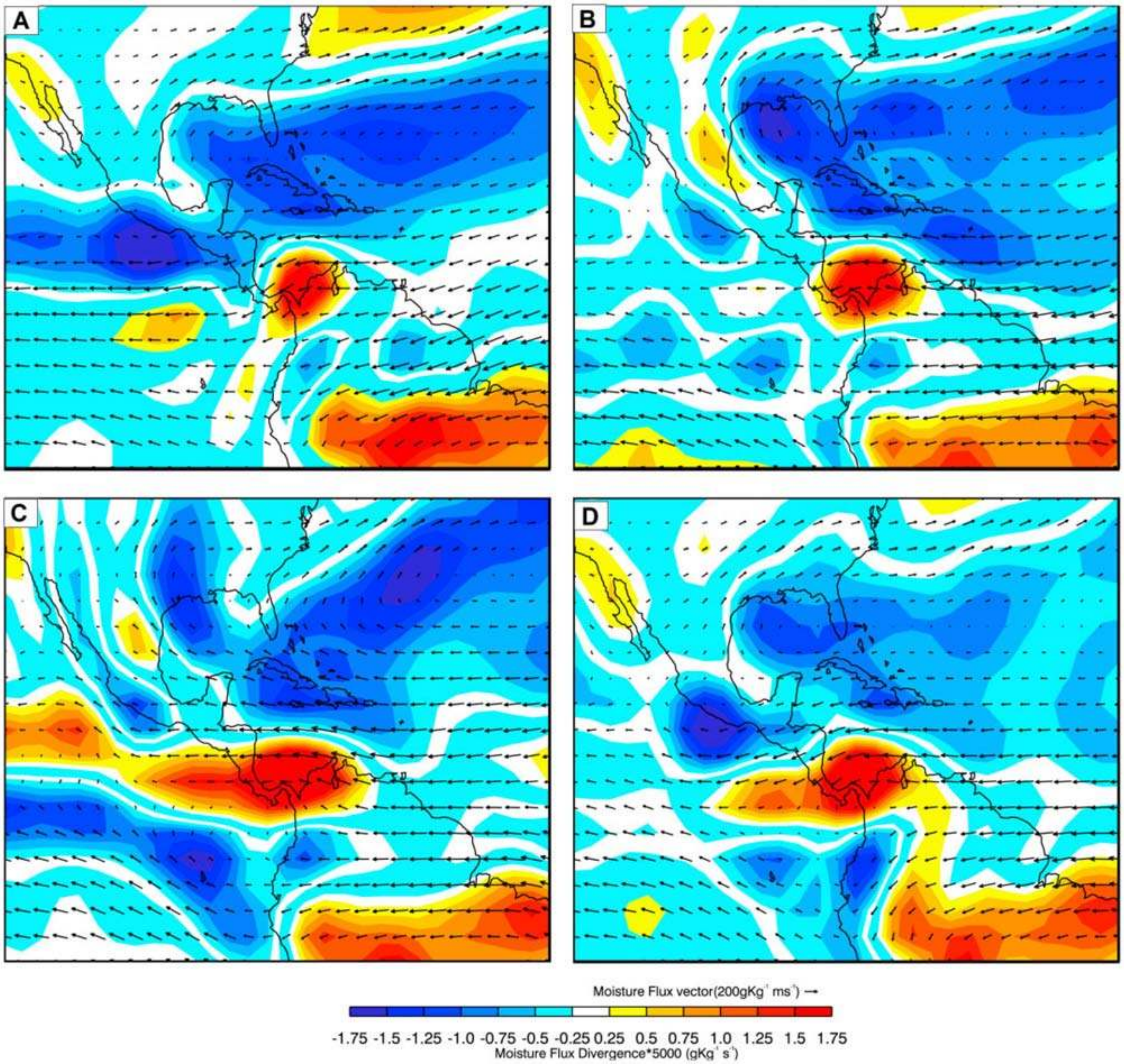

Figure 11. Vertically integrated moisture flux vectors and moisture divergence contours for the 2000–2004 period for boreal (a) winter mean, (b) spring mean, (c) summer mean, and (d) autumn mean.

(http://www.cgd.ucar.edu/cas/catalog/newbudgets/) were used at a grid size of $1^\circ \times 1^\circ$ in order to compute fluxes and flux divergences for the period 2000–2004. Moisture convergence in Central America during winter is clearly less important than during spring and autumn, when the moisture flux over the continental area of Central America becomes more relevant. It is important to mention that the presence of convergence of moisture during summer should not be understood as a contribution to precipitation since the pattern is a direct result of the intense local wind, not necessarily related to local precipitation. The effect of moisture sources on precipitation is of central importance. In order to evaluate this relationship, the monthly variability of the runoff term from both sources (CS and PS) together with the monthly mean precipitation over Central America were plotted. The monthly runoff term was computed as precipitation minus evaporation ($P - E$) using the sum of $(E - P)^{+10}$ for the two sources defined. The monthly mean precipitation was computed using data from the CPC Merged Analysis of Precipitation (CMAP) data set [*Xie and Arkin*, 1997].

[24] In Figure 12, the mean annual cycle is represented twice consecutively for the period 2000–2004 in order to better identify the two dry seasons of Central America. Using a single cycle on Figure 12, it may be observed no significant time delay between moisture supply and precipitation, because the moisture contributions to Central America from the identified sources exhibit the same annual cycle as the local estimated precipitation (two maxima between June and September and a minimum in February). The time delay observed between the precipitation and the contribution of the runoff term from the PS to Central America is on

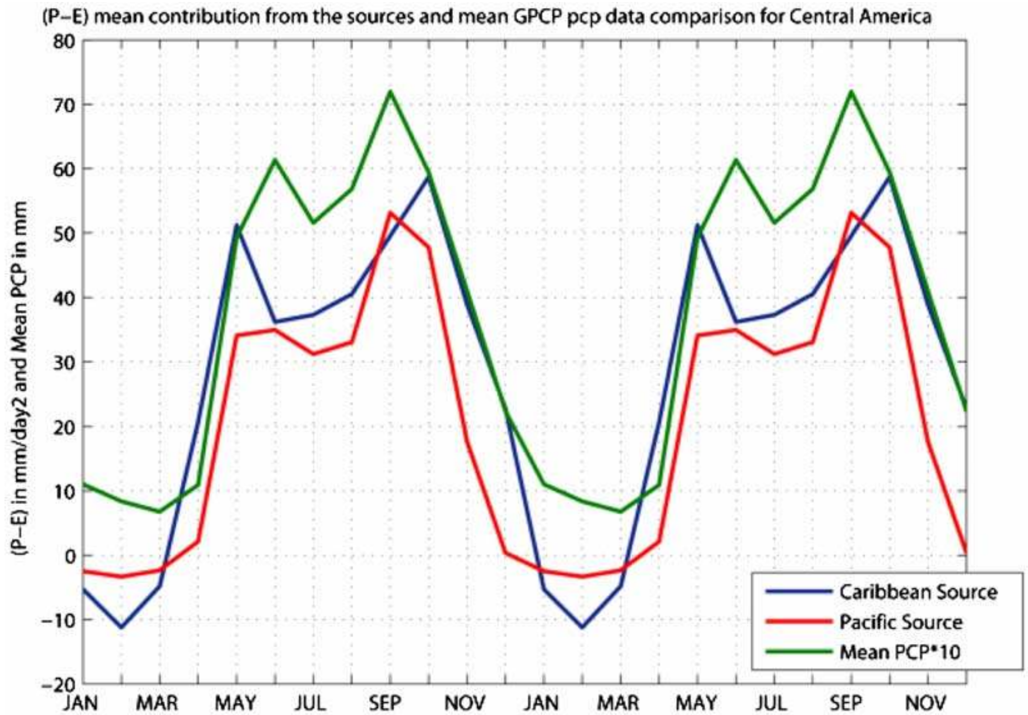

Figure 12. Monthly mean values (2000–2004) of the runoff term $(P - E)^{10}$ (in mm d^{-1}) for the Caribbean source (blue line) and the Pacific Source (red line) and precipitation (in mm × 10, green line) computed for Central America.

the order of a month, similar to the delay for the case of the CS. The reason for the presence of these time lags may be a response to the transport mechanisms, a complete detail of this point will be cleared out in a further study of the moisture transport mechanisms.

6. Conclusions and General Remarks

[25] The Lagrangian analysis method applied in the study described herein allowed not only the identification of the main sources of moisture for Central America, but also the quantification of moisture transport from them. It thus provided significant details of the way moisture evolves from its source to the target region and vice versa. The method also described with good accuracy the presence of known structures, such as the presence and seasonal migration of the ITCZ and the moisture dynamics near the Gulf of Mexico where moisture from the CS is also spread apart Central America (not discussed in this paper).

[26] Two main sources of moisture for Central America have been identified; one located near the eastern equatorial Pacific (PS) and other over the Caribbean Sea (CS), with the CS as the more important in terms of its effective transport to the Central American region as a whole. The PS source seems to be significant only for southern Central America, because transport is not favored for three reasons, namely (1) the large amount of divergence in the wind crossing southern Central America, (2) the low wind intensity close to the Pacific region, and (3) the presence of mountain systems within the track. These factors result in a significant loss of moisture content via precipitation mechanisms that are linked dynamically to the ITCZ and geographically to the presence of mountain systems. The identified moisture sources are in good agreement with the results of isotope analysis presented by *Lachniet et al.* [2007] based on δ^{18}O data collected in Costa Rica and Panamá, which provide information on the contribution of the Pacific Ocean to the moisture content over the region and on the predominance of the Caribbean Sea as a moisture source for the Isthmus. *Lachniet et al.* [2007] emphasize the importance of the Caribbean Sea for its contribution to the moisture over Costa Rica and Panamá. The authors also refer to the presence of another moisture source that has its origin on the Pacific side, whose intensity is minor compared to the Caribbean source, as reported in this paper using Lagrangian analysis.

[27] In general terms, good agreement has been obtained between the amounts of moisture gained by Central America that originate in the CS region, and the amount of Caribbean Sea moisture that is lost over Central America. The contribution of Caribbean Sea moisture to southern Central America is quantitatively more important than that over northern Central America. The dominance of the CS over the PS moisture source may be easily seen throughout the 10 day transport period. Both moisture sources are well defined in seasonal terms, with the PS disappearing for the other periods and Caribbean source varying significantly in its extent throughout the year. For northern Central America, CS is the main source of moisture, although during winter and autumn the source seems to be displaced toward the Gulf of Mexico. Southern Central America (mainly Costa Rican territory) receives moisture that originates from the PS region during summer and autumn.

[28] The transport of moisture to the analysis region by winds associated with the CLLJ is the same mechanism by which moisture transport in the North American Great

Plains is controlled via the GPLLJ. Applying an Eulerian analysis method, *Bosilovich and Schubert* [2002] demonstrated the importance of the Caribbean Sea via the GPLLJ as a moisture source for the Gulf of Mexico and the southern United States while describing the role of the CLLJ in moisture transport. The CLLJ acts not only as a moisture belt, but also as a humidity collector that is capable of modulating surface evaporation as a result of its moisture content [*Wang et al.*, 2007] as shown here by computations of moisture flux divergence for the analyzed period and area. The results obtained from Lagrangian analysis show a noticeable correspondence between the $(E - P)$ variations throughout the year and the seasonal variations in the CLLJ. The core of CLLJ wind jet is consistent with the maximum nucleus of moisture gain over the Caribbean Sea found in this paper using Lagrangian analysis, which also confirms previous results derived from Eulerian approaches [*Wang et al.*, 2007; *Wang and Lee*, 2007; *Wang*, 2007]. The 10 day mean contribution to precipitation in Central America from the identified sources (see Figure 6) shows the seasonal differences observed in precipitation for Central America, as well as the contribution from each source to the analysis region. The major contribution occurs during boreal summer, and for the case of the CS region this is in good agreement with the maximum observed winds in the core of the CLLJ. However, the second maximum of the CLLJ in boreal winter is not associated with any important transport, mainly due to the incidence of the dry season, which is characterized by less intense winds than in summer and a minimal amount of precipitable water, as shown in previous analyses [*Wang et al.*, 2007].

[29] The contribution of moisture to Central America that originates in the PS region is partly determined by the presence of the CHOCO jet, which in turn allows the development of deep convection in the region. This contribution is more noticeable over northern Colombia (outside the study region) when it appears to be combined with the effect of orographic lifting as described by *Poveda and Mesa* [2000]. The importance of the PS region is greatest during those parts of the boreal summer and autumn that coincide with the maximum velocities within the core of the CHOCO jet (whose intensity is almost half of the CLLJ intensity). A significant part of the moisture transported by the CHOCO jet is unable to reach Central America completely, mainly as a result of the loss of moisture in the ITCZ and the presence of a mountain range in Costa Rica. The important difference in wind intensity between the CLLJ and the CHOCO jets and the influence of the easterly flow are just part of the explanation of the relatively major significance of the CS region compared with the PS. More details on the transport process are required in order to understand these differences.

[30] The seasonal migration of the ITCZ is an important element, its northernmost location during boreal summer extends over Central America and its relative absence over Central America during boreal winter could help to explain the observed seasonal differences in the contribution of the moisture sources to Central America. For example, for the PS region, the ITCZ is a determining factor in the low contribution of the PS to Central America. The northward movement of the ITCZ implies that losses occur before the moisture from the Pacific reaches the target region, which confirms how most of the moisture that leaves the PS region is lost over the ocean; for this reason the contribution to Central America is less compared with that of the CS during spring and summer.

[31] The interannual variability of these processes of moisture transport should be also assessed in order to understand their influence at different time scales. In order to undertake these research tasks, a longer period of data will be analyzed and the results of this will form part of a further work.

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