On the contribution of the Tropical Western Hemisphere Warm Pool source of moisture to the Northern Hemisphere precipitation through a Lagrangian approach

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[1] We herein investigate the role of the Tropical Western Hemisphere Warm Pool (WHWP) in providing moisture to the atmosphere throughout its annual cycle and identify those regions that could be affected by precipitation whose origin lies in this source. We use data from the Lagrangian FLEXPART model for the period 2000–2004 to identify the contributions of humidity from a region, by determining changes in specific humidity along the forward trajectories over a 10 day period. An analysis was performed for all the air parcels that lay in the region of the WHWP (defined according to the 28.5°C threshold applied in SST), and the monthly average conditions over the 5 year period were analyzed for May to October, inclusive. Our results show that this source provides a higher contribution of moisture to North America from June onward, when warmer waters may be observed over the Atlantic side of the warm pool and the transport of moisture may be increased by the Great Plains Low Level Jet. During the boreal summer, this contribution extends toward western Europe, probably as a result of the transport of moisture by the warm conveyor belts and the North Atlantic anticyclone. A qualitative similarity between the results of our Lagrangian analyses and the observed patterns of precipitation highlights the contribution of the source of moisture of the WHWP for the regimes of precipitation over eastern North America, the North Atlantic, and the Intertropical Convergence Zone.

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1. Introduction

[2] All the precipitation that falls in a region has one or more of three possible origins [*Brubaker et al.*, 1993], namely, (1) moisture that is already present in the atmosphere, (2) moisture transported into the region from remote sources by wind (advection), or (3) local evaporation from the Earth's surface (recycling). Over long periods, the major processes that are responsible for the observed atmospheric moisture are recycling and advection.

[3] A number of authors have attempted to identify the geographical distribution of sources of moisture in different regions using a range of methodologies [e.g., *Eltahir and Bras*, 1996; *Numaguti*, 1999; *Chen et al.*, 1994; *Crimp and Mason*, 1999], almost all of which apply Eulerian approaches. More sophisticated methods have recently been developed using fully kinematic trajectories calculated from different Lagrangian parcel models. For example, in the dispersion model developed by *Stohl and James* [2004, 2005], the net changes in the quantity of water are determined along a large number of backward or forward trajectories with low resolutions in space and time, enabling inferences to be made about the sources of moisture in a region. *Sodemann et al.* [2008] included the details of the losses of rainfall along the trajectories of the air parcels that precipitate in a target region.

[4] The Tropical Western Hemisphere Warm Pool (WHWP) may be considered to be the second largest tropical warm pool on Earth, after the Western Pacific Warm Pool [*Weisberg*, 1996]. According to *Wang and Enfield* [2001], the WHWP consists in a pool of water that has a temperature higher than 28.5°C, and that extends over the eastern North Pacific and west of Central America, the IntraAmericas Sea (i.e., the Gulf of Mexico and the Caribbean), as well as the western tropical North Atlantic. The threshold of 28.5°C reflects a temperature that has a significant impact on tropical convection [e.g., *Graham and Barnett*, 1987], and on the depth of the isotherm of this temperature, which is closest to the average depth of the mixed layer in the WHWP. The warm pool usually disappears at the start of the boreal winter, but surface heat fluxes warm the WHWP throughout the spring, thereby leading to a maximum sea surface temperature (SST), and a maximum extent of the WHWP, in late summer/early fall. Apart from the clear seasonal cycle, the interannual

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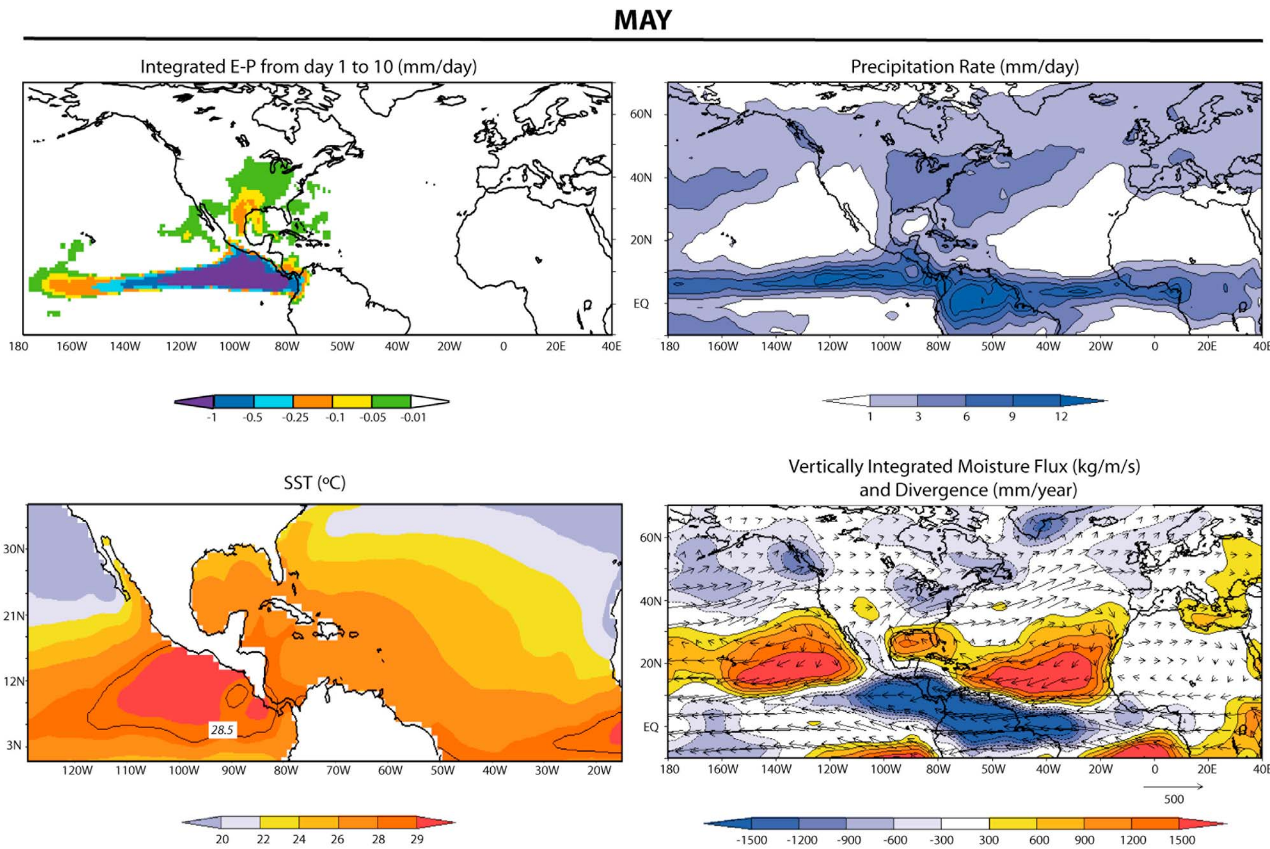

Figure 1. (left) Values of ($E - P$) integrated over a 10 day period for the month of May for the period 2000–2004, calculated by forward tracking from the WHWP source of moisture, indicated by the black line in the field of SST. (top right) Precipitation rate and (bottom right) vertically integrated moisture flux (VIMF) and its divergence. Units of ($E - P$) and precipitation rate are mm d^{-1}, units of SST are °C, units of vectors of moisture flux are kg m^{-1} s^{-1}, and units of contours of divergence of moisture are mm yr^{-1}.

fluctuations of area and intensity are significant because the anomalies of the WHWP (in terms of SST and extent) occur at high temperatures at which small changes can have a pronounced effect on the tropical convection. The WHWP may be considered to be a monolithic source of heat to the atmosphere, which can be seen to migrate and change in size according to an annual cycle, and on which the narrow strip of land of Central America has little effect [*Wang*, 2002].

[5] Due to the fact that the Pacific side of the WHWP is close to the region of maximum variance of the El Niño–Southern Oscillation (ENSO), its behavior here is directly related to the variability of the ENSO [*Wang et al.*, 2006]. In view of this, a number of authors have focused their studies on the Atlantic side of the warm pool (hereafter the Atlantic Warm Pool, AWP), which may be considered as a potential source of predictability for summer rainfall in the U.S.A., including the large-scale meteorological conditions that relate to Atlantic hurricanes [*Wang et al.*, 2006].

[6] According to *Wang et al.* [2006] and the references contained therein, the AWP reaches an annual maximum in its extent during the summer, when it is correlated positively with rainfall in the Caribbean, and in Mexico, Central America, and the southeast Pacific. In particular, between August and October, the rainfall in the Caribbean, Central America, and eastern South America is related mainly to the size of the AWP. The variation in rainfall during the boreal summer in the Central part of the U.S.A. is due largely to the influence of the anomalous AWP on the southerly Great Plains low level jet (GPLLJ), and hence the transport of moisture in the region [*Ruiz-Barradas and Nigam*, 2005; *Wang et al.*, 2008]. According to *Wang et al.* [2006], AWP serves as a source of moisture for rainfall in North America. If more (less) moisture precipitates over the warm pool, less (more) is then available for transport into the Great Plains region, which is reflected in the negative correlation in rainfall between the Great Plains and the AWP region. From August to October, the atmospheric surface wind flows from AWP to the Great Plains, pointing to a transport of moisture from AWP that provides rainfall in this region. As AWP grows (shrinks) and the tropical North Atlantic becomes warmer (colder), the southerly wind from AWP to the Great Plains weakens (strengthens). This decreases (increases) the transport of moisture available for rainfall over the Great Plains and thereby results in lower (higher) rainfall there. These findings are in accordance with those of *Gimeno et al.*

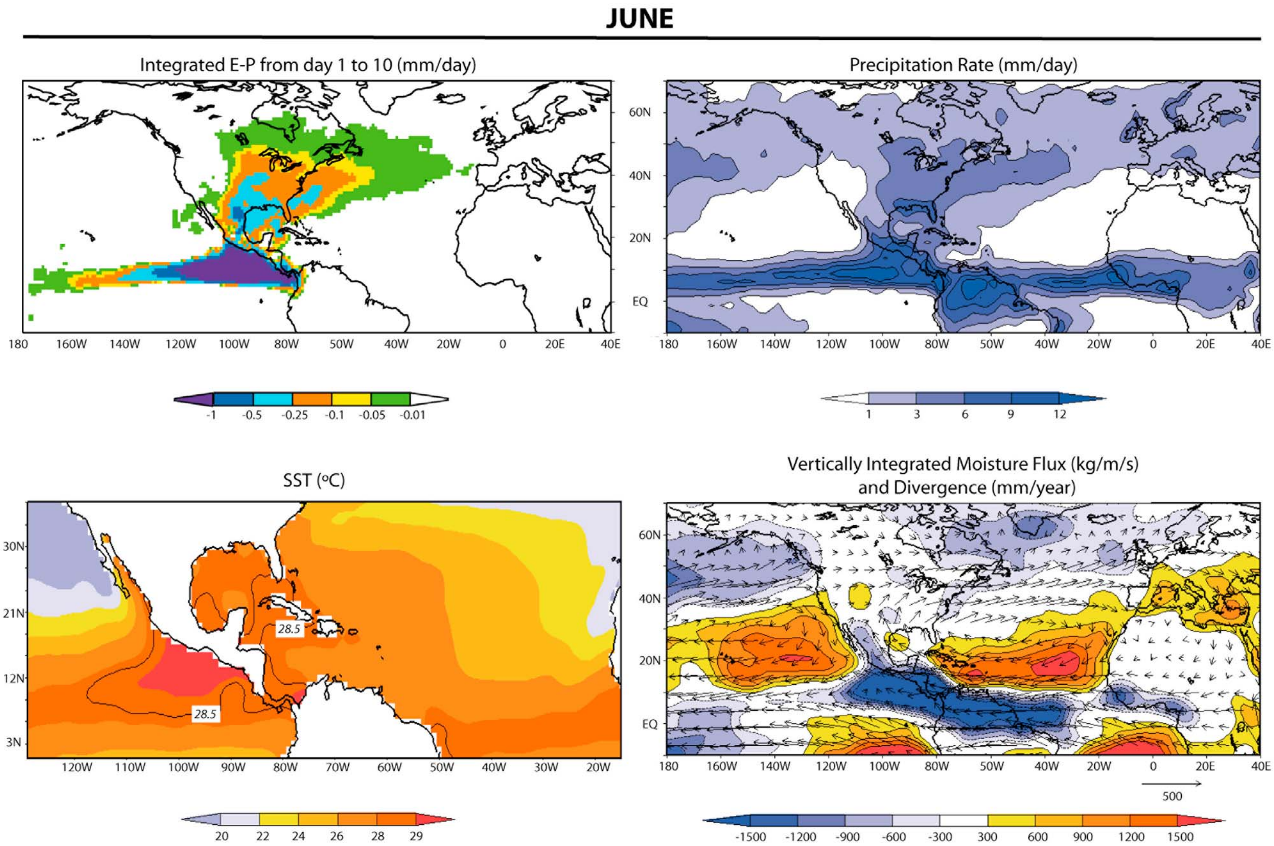

Figure 2. Same as Figure 1 but for June.

[2010a], who showed the importance of the Mexico-Caribbean region in providing moisture to Eastern North America and Central America for precipitation throughout the year.

[7] The aim of the study described herein was to determine the role of the WHWP as a mechanism for providing moisture to the atmosphere in the Northern Hemisphere. We used the Lagrangian diagnostic model FLEXPART, developed by *Stohl and James* [2004, 2005]. FLEXPART allowed us to identify those regions that are affected by precipitation that originates in the WHWP. A monthly analysis was performed for the period May to October for the years 2000–2004, using results obtained from the model that were based on meteorological analysis and a scheme for tracking moisture. All the air parcels identified in the source region were tracked forward in time. The robustness of the method has been well documented, and it is worth noting that the methodology proposed herein has previously been applied successfully in climatological studies of sources of moisture in other regions, including the Sahel [*Nieto et al.*, 2006], Iceland [*Nieto et al.*, 2007], the Orinoco River basin [*Nieto et al.*, 2008], the South American Monsoon System [*Drumond et al.*, 2008], Northeastern Brazil [*Drumond et al.*, 2010], Central America [*Durán-Quesada et al.*, 2010], and the Mediterranean region [*Nieto et al.*, 2010]. Recently, *Gimeno et al.* [2010a] carried out a seasonal analysis of the contribution of the principal global sources of moisture to precipitation in continental regions.

[8] The remainder of the paper is organized as follows. In section 2, we describe the data and model, and present the methodology. In section 3, we describe the results of the trajectory analyses. In section 4, we discuss the results and present implications for further work.

2. Data and Methodology

[9] Our study was based on the method developed by *Stohl and James* [2004, 2005] to determine the contribution of the WHWP to precipitation. Our model made use of data obtained from the meteorological operational analysis carried out by the European Centre for Medium-Range Weather Forecasts (ECMWF) to track different meteorological parameters for the entire atmosphere along individual trajectories. Because we are particularly interested in atmospheric moisture, we used the equivalent humidity interpolated to the positions in the trajectories at given times.

[10] In order to identify the trajectory of each parcel, at the beginning of the model run we divided the atmosphere equally into a large number of parcels all of which had the same mass. The parcels were then advected using the three-dimensional ECMWF winds. The locations of the air parcels, together with their specific humidity values (q), were interpolated temporally from the input data, which were recorded at 6-hourly intervals. The increases (e) and decreases (p) in moisture along the trajectory may be calculated from the

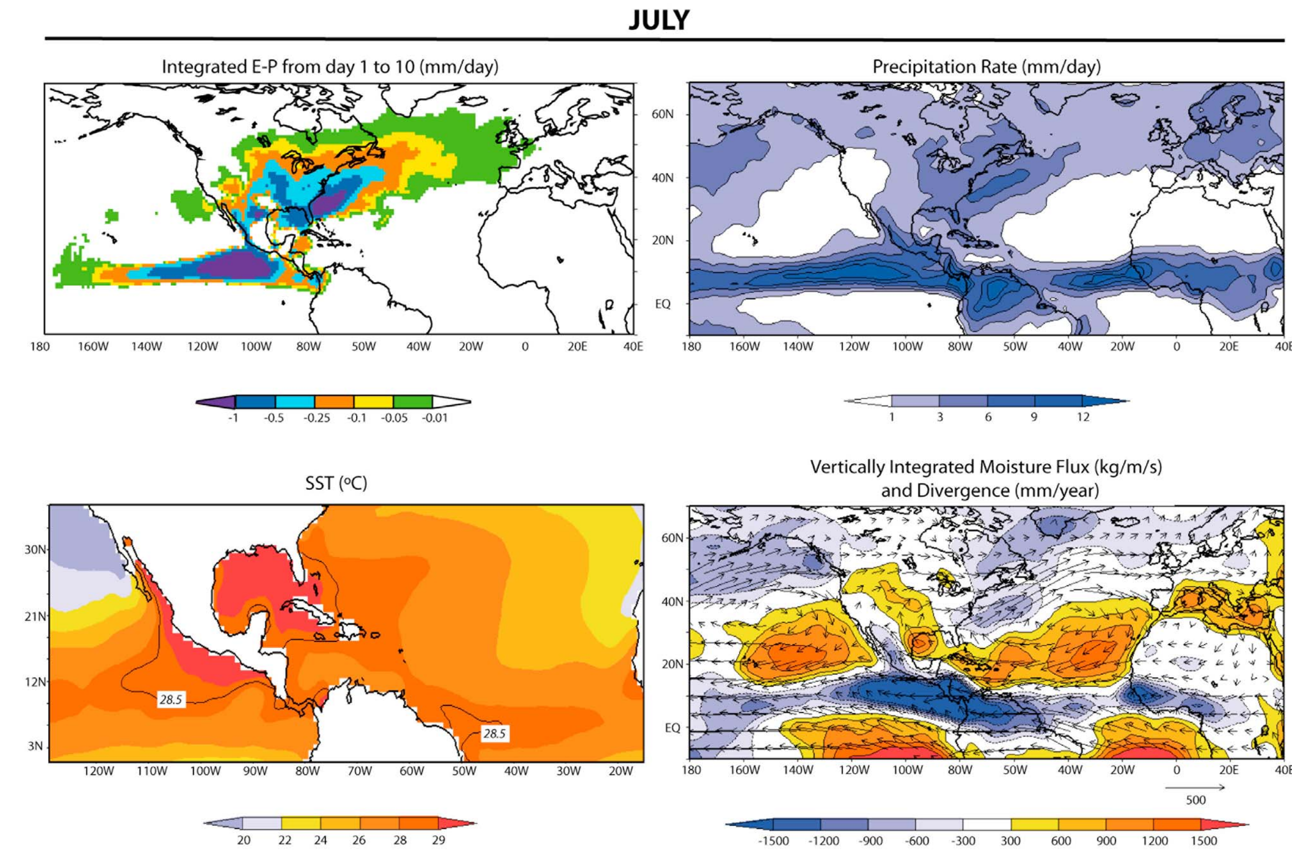

Figure 3. Same as Figure 1 but for July.

changes in (q) with time ($e - p = m\ dq/dt$), where m is the mass of the parcel. By summing all the values of ($e - p$) for the parcels selected in a given atmospheric column over an area, it is possible to obtain ($E - P$), where (E) is the evaporation and (P) is the rate of precipitation per unit area. The method may also be used to track ($E - P$) from any specific region backward in time along the trajectories by selecting those parcels that reach the target region at the time of interest. We herein traced the transport of water vapor for 10 days, forward in time, this being the average time that water vapor resides in the atmosphere [*Numaguti*, 1999], and a period over which the trajectories can be considered to be relatively accurate [*Stohl*, 1998]. According to *Stohl and James* [2004], the limitations of the method are related mainly to the fact that fluctuations in q also occur along individual trajectories for numerical reasons (e.g., as a result of interpolation or errors in the trajectory). In part, such errors cancel each other out given the large number of parcels in a given atmospheric column. Full details of the method have been provided by *Stohl and James* [2004, 2005].

[11] A global simulation of the transport of 1.4 million parcels was carried out for a 5 year period (2000–2004). The computed data were derived from the 6-hourly operational analyses of the ECMWF using a 1° × 1° grid on each of 60 vertical levels. Forward trajectory analysis of ($E - P$) was performed for all the air parcels that lay over the WHWP during the months of May to October. The monthly variability in the spatial extension of the WHWP was taken into account in the areal definition of the source of moisture using the threshold of 28.5°C in the 5 year monthly averages of SST [*Wang and Enfield*, 2001].

[12] We used data from the monthly Global Precipitation Climatology Project (GPCP, version 2.1) [*Adler et al.*, 2003], with a horizontal resolution of 2.5°, as well as the NOAA Optimum Interpolation SST V2 data [*Reynolds et al.*, 2002], for each month at a horizontal resolution of 1°. Both data sets were provided by the NOAA/OAR/ESRL PSD via their website (http://www.esrl.noaa.gov/psd/). The monthly data on the vertically integrated moisture flux (VIMF) was a product derived from the NCEP/NCAR Reanalysis and provided via David Stepaniak's webpage (http://www.cgd.ucar.edu/cas/catalog/newbudgets/index.html#Sec11).

3. Results

[13] The results for each month are shown in Figures 1–6, and cover the period from May to October. For each month, Figures 1–6 show the 10 day integrated values of ($E - P$), as well as the SST, the rate of precipitation and the vertically integrated moisture flux (VIMF), together with the monthly averages of its divergence for 2000–2004. Despite the relative complexity of the method of forward tracking, these fields provide a reasonable picture of the sinks of moisture from parcels in transit from the area of study. Only the negative values of $E - P$ are shown ($E - P < 0$), indicating

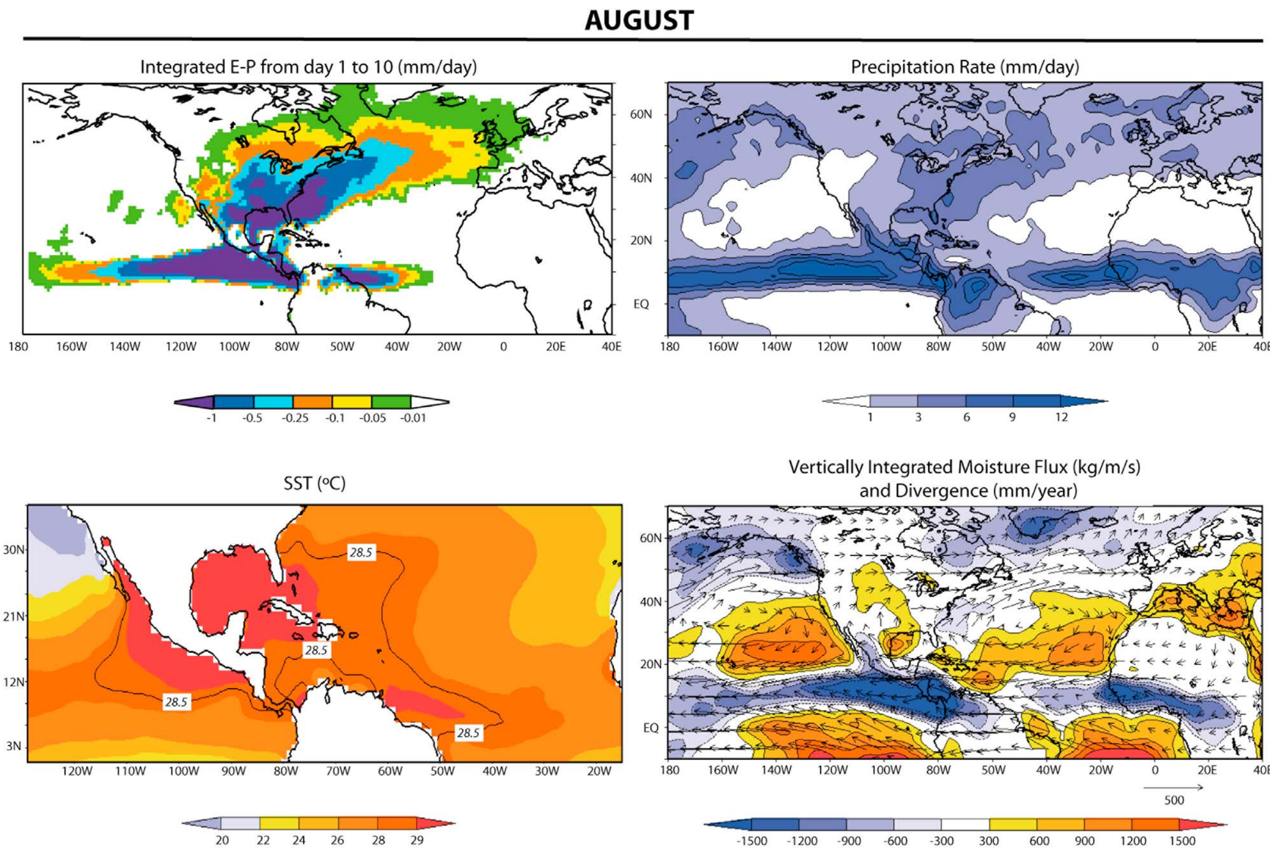

Figure 4. Same as Figure 1 but for August.

those regions where precipitation exceeds evaporation for the air masses that travel from the WHWP, or those areas with a net loss of moisture for the parcels concerned. It is important to mention that a net loss of moisture may not occur when all the parcels existing in the same atmospheric column are considered together. The contribution of moisture from a source for precipitation may be dynamically supported if the losses associated with the parcels are observed together with a convergence of the moisture flux in an Eulerian analysis of the VIMF. In this way, a qualitative comparison between ($E - P$) and precipitation allows the identification of those regions where the precipitation can be supplemented by moisture from the air masses that leave the WHWP.

[14] In May (Figure 1), the warm pool (shown by the isotherm of 28.5°C in the SST) extends over the eastern North Pacific region, a phenomenon that characterizes the onset of the WHWP [*Wang and Enfield*, 2001]. The values of ($E - P$) indicate that the WHWP contributes locally to moisture in the Intertropical Convergence Zone (ITCZ) in the Pacific, and that some moisture is transported toward North America in an anticyclonic flow centered over the Gulf of Mexico. A qualitative comparison between ($E - P$) and patterns of precipitation rate can help to assess the contribution from the WHWP to the observed precipitation over the Pacific ITCZ (both ($E - P$) and precipitation rate are shown using the same units and the 1mm/d isoline is included in Figures 1–6, but we stress that they cannot be compared directly because ($E - P$) only represents the 10 day integrated net loss of moisture of the parcels in question). These results are associated dynamically with the convergence of the VIMF over the Pacific ITCZ, as well as with the transport of moisture from the WHWP toward North America, possibly via the GPLLJ. It is particularly noteworthy that in western Mexico, the net loss of moisture from parcels that originate from the WHWP, which is characterized by negative values of ($E - P$), is not reflected in the observed precipitation, probably due to the proximity of a large area of divergence in the VIMF, which does not favor the generation of rain.

[15] Following the temporal evolution of the WHWP, the spatial extension of the warm pool in the eastern North Pacific reduces during the month of June, while some warming of the SST and reduction in divergence of the VIMF are observed over the Atlantic side (Figure 2). The values of ($E - P$) show a similar pattern, in terms of the reduction in moisture provided by the air masses that leave this source and move toward the Pacific ITCZ, while a large contribution of moisture is made by the air masses that cross eastern North America toward the North Atlantic, which might be associated with the transport of moisture by the GPLLJ, [*Wang et al.*, 2006]. It is worth noting that the pattern of ($E - P$) is qualitatively similar to that of the precipitation observed in the Pacific ITCZ, North America and the North Atlantic, which points to the importance of the WHWP in providing a source of moisture for precipitation in these

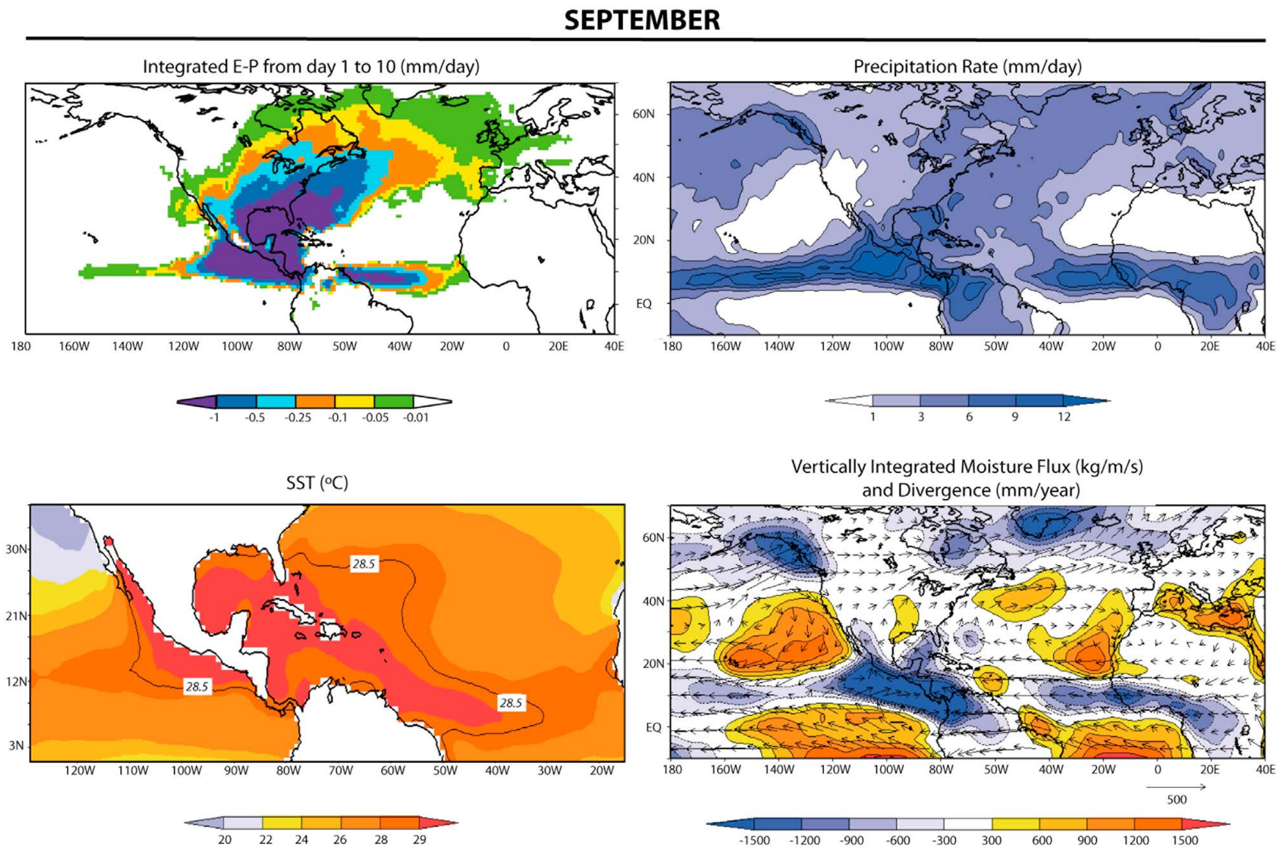

Figure 5. Same as Figure 1 but for September.

areas. The role of the source in the southwestern North Atlantic has been reported in several studies of regions in western Europe [e.g., *Nieto et al.*, 2007; *Sodemann et al.*, 2008; *Gimeno et al.*, 2010b], and it reflects one of the main physical mechanisms at play in the transport of moisture from the Tropical North Atlantic toward higher latitudes, otherwise known as the North Atlantic warm conveyor belt [*Eckhardt et al.*, 2004]. According to *Eckhardt et al.* [2004] and the references contained therein, the warm conveyor belt consists in an airflow that originates in the warm sector of the extratropical cyclone, and it is responsible for most of the cyclone's meridional transport of energy, in terms of both the latent and the sensible heat. The North Atlantic warm conveyor belt can be identified to be the Atlantic "tropospheric river" [*Zhu and Newell*, 1998], an atmospheric band that contains particularly large horizontal fluxes of water vapor, and can also be related to the extratropical cyclones that are responsible for most of the precipitation that occurs in extratropical latitudes [*Ralph et al.*, 2004; *Bao et al.*, 2006]. The North Atlantic anticyclonic circulation may also enhance the transport of moisture from the WHWP toward northern latitudes, where a convergence in the VIMF may be seen.

[16] A reduction in the size of the warm pool in the eastern North Pacific follows during July, while its expansion continues on the Atlantic side toward the Gulf of Mexico (Figure 3). As observed in June, these changes in SST are reflected in the values of $(E - P)$. While the contribution of moisture to the Pacific ITCZ reduces, its expansion over eastern North America toward Europe is particularly associated with the transport of moisture by the North Atlantic warm conveyor belt. Here again, a qualitative comparison with the temporal evolution of the observed patterns of precipitation helps to explain the similarities between the two fields over Eastern North America and the North Atlantic, and particularly for the eastward expansion of the maximum precipitation nucleus over the eastern part of the continent of North America. In terms of the atmospheric circulation, it appears that a dipolar structure of divergence/convergence of the VIMF over central/eastern North America is associated with the eastward displacement of the precipitation, and an eastward flux of moisture probably associated with the North Atlantic Anticyclone flows toward Western Europe.

[17] In August, the warmer SST field expands again, as shown by the position of the 29°C isotherm over the eastern North Pacific, as well as by the eastward and southward expansion of the boundaries of the AWP to northern South America (Figure 4). The rise in SST over the Pacific may be a particular characteristic of the period we have chosen (2000–2004). In any case, this southward expansion of the WHWP may be associated with the negative values of $(E - P)$ at around 10°N, which suggest that the WHWP contributes moisture locally to the ITCZ. In the North Atlantic, the

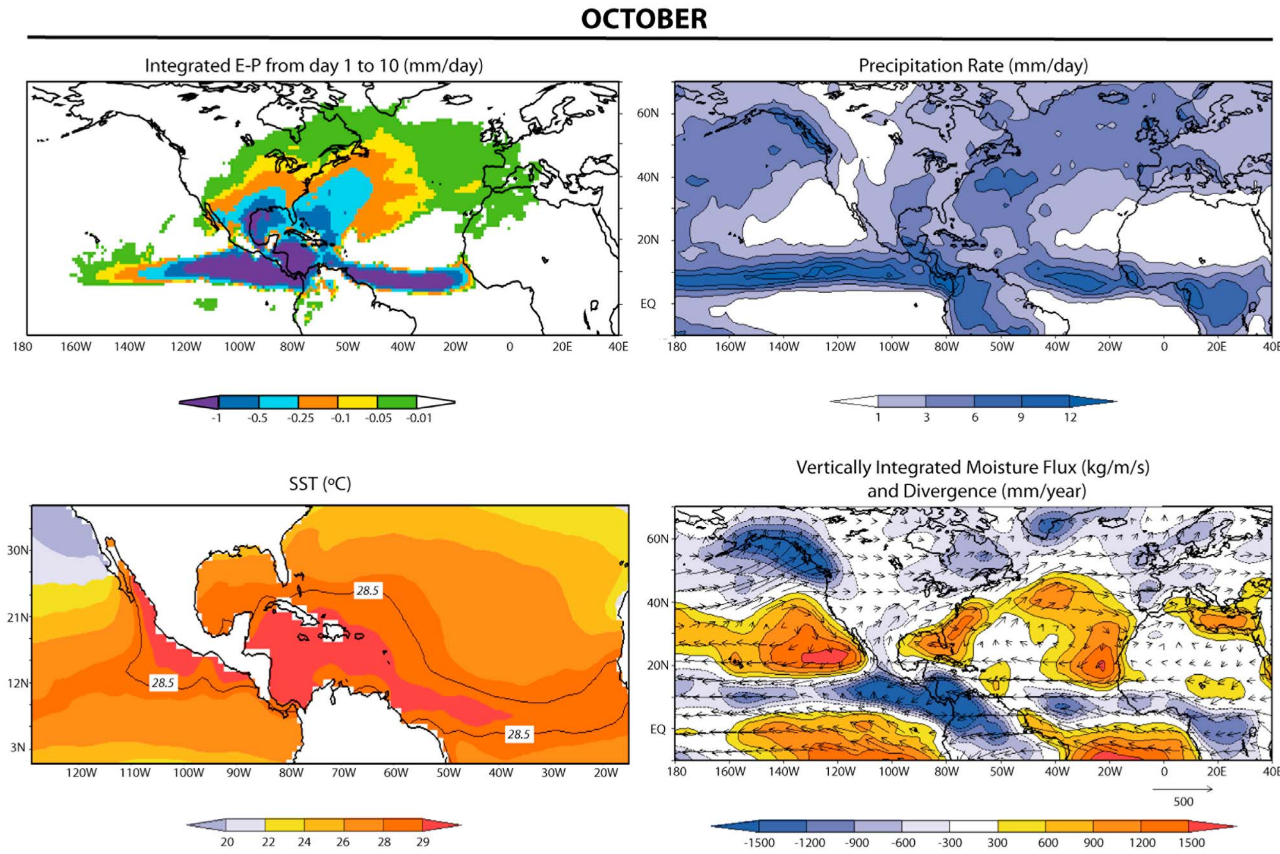

Figure 6. Same as Figure 1 but for October.

moisture provided by the air masses that leave the WHWP and cross North America and the ocean increases considerably. However, this increase is not reflected in the observed precipitation over the continent, probably due to the predominance of the divergence of the flux of moisture over central North America, which inhibits precipitation in the region. It is noteworthy that the contribution of moisture from the selected air masses from the WHWP reaches western Europe, a phenomenon that is probably associated with the transport of moisture by the North Atlantic warm conveyor belt [*Eckhardt et al.*, 2004].

[18] In September, although the size of warm pool in the eastern North Pacific is reduced, the spatial expansion of the 28.5°C isotherm over the IntraAmerica Seas is at a maximum, in agreement with the findings of *Wang and Enfield* [2001]. The values of ($E - P$) indicate a rather lower contribution of moisture to the precipitation in the Pacific ITCZ and a higher contribution to the Atlantic ITCZ, which is probably associated with the spatial expansion of the warm pool toward the equatorial Atlantic. A higher contribution of moisture to the Gulf of Mexico and southeastern North America is also observed in the precipitation, and is associated with the convergence of the VIMF over the area. The air masses that leave the WHWP and are destined for western Europe provide a greater contribution of moisture to the Iberian Peninsula than they do in August. The contribution of the Gulf of Mexico and the Subtropical-Tropical North Atlantic as a source of moisture for the Iberian Peninsula throughout the year, and particularly in winter, was verified by *Gimeno et al.* [2010b].

[19] In October (Figure 6), the cooling of the AWP associated with the displacement of the 28.5°C isotherm toward the Equatorial Atlantic is in agreement with the findings of *Wang et al.* [2006]. The contribution of moisture to the Atlantic ITCZ increases, but it decreases to North America and the western Atlantic, although some moisture continues to reach the Iberian Peninsula via the warm conveyor belt. A qualitative comparison between ($E - P$) and the patterns of precipitation shows the coincidence of the nuclei of two maxima located over the Gulf of Mexico and eastern North America, which suggests the persistence of the WHWP in providing moisture for precipitation in those areas.

4. Conclusions

[20] The aim of our work was to investigate the role of the Tropical Western Hemisphere Warm Pool (WHWP) in providing moisture to the atmosphere throughout its annual cycle, and to identify those regions that are affected by the moisture transported by the air masses that originate in this source. Using data obtained from the FLEXPART model for the period 2000–2004 and carrying out the analysis from a Lagrangian perspective, it has been possible to improve our understanding of the contribution of moisture from the warm pool that we originally obtained using Eulerian

techniques. The approach described herein has allowed us to identify the air masses that originated in the WHWP and to track the variability of the moisture content along the trajectories in detail.

[21] Analysis of the forward trajectories of $(E - P)$ was carried out for all the air parcels that lay over the WHWP (defined according to the threshold of 28.5°C applied to the monthly average SSTs for the period 2000–2004). We limited the time of transport to 10 days in all cases, and the monthly average conditions were analyzed for the 5 year period for the months of May to October.

[22] Analysis of the temporal evolution of the WHWP shows a greater contribution of moisture from this source to North America from June onward, when warmer waters may be observed over the Atlantic side of the warm pool and the transport of moisture may be increased by the Great Plains Low Level Jet. During the Boreal Summer, this contribution expands toward western Europe, possibly as a result of the transport of moisture by the North Atlantic anticyclone and the warm conveyor belts. The qualitative similarity between $(E - P)$ and the patterns of precipitation over eastern North America and the North Atlantic highlight the importance of the WHWP as a source of moisture that modulates the regimes of precipitation in these regions. The Intertropical Convergence Zone (ITCZ) over the eastern Pacific is another system of precipitation that is modulated by this source, which also provides some moisture to the Atlantic ITCZ as the warmer waters of the Atlantic warm pool expand southward.

[23] The results discussed herein relate only to 5 years and to the whole of the WHWP, thereby providing a short 'climatological' overview of this source of moisture. This relatively short time frame can nevertheless be considered to be a standard period of time at the scale of the global climate, because of the lack of clear extremes in the major modes of climate variability, such as ENSO or NAO. During the period of analysis, one negative NAO event was observed, as well as one instance of La Niña and two of El Niño, all of which were weak or moderate in intensity. Nevertheless, we are currently exploring an extension to the FLEXPART data set as far back as 1979, allowing us to explore the interannual variability of the source of moisture, and the role of the main modes of climate variability such as ENSO. Moreover, the separate study of the Pacific and Atlantic sides of the warm pool may offer more specific information on the role of these subregions.

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