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On the origin of continental precipitation

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[1] About 9 out of 10 liters of water evaporated from the oceans every year precipitates back onto oceans. However, the remaining 10% that get transported to continents play an irreplaceable role feeding the land branch of the hydrological cycle. Here we use an objective 3-D Lagrangian model (FLEXPART) to detect major oceanic moisture source areas and the associated continental regions significantly influenced by each moisture source. Our results reveal a highly asymmetrical supply of oceanic moisture to the continents, with the Northern Atlantic subtropical ocean source impacting the continents considerably more than the large Southern Indian and North Pacific sources. Also, the small Mediterranean Sea and Red Sea basins are important moisture sources for relatively large land areas. The Indian subcontinent receives moisture from six different major oceanic source regions. Future changes in meteorological conditions over the oceanic moisture source regions may have an impact on water availability for many river basins.
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1. Introduction

[2] The global hydrological cycle is supplied annually with *circa* 500 000 km^3 of water evaporated from the Earth's surface, with the bulk of this volume evaporating from the oceanic surface (86%) and only 14% from continents [*Oki*, 2005]. The vast majority of the water evaporated from the oceans (90%) precipitates back onto oceans while the remaining 10% is transported to continents where it precipitates. About two thirds of the latter are recycled over the continents and only one-third runs off directly to the ocean. Ultimately, despite the continental recycling component, all water used by available to land ecosystems and human socio-economic activities has its origins in the oceans.

[3] In this context, the relentless upward trend in temperature observed in recent decades, that is expected to continue towards a warmer world, may pose an additional burden on the reliability of moisture sources in the future. Modeling studies suggest that the high sensitivity to temperature of saturation vapor pressure will result in increases of evaporation and precipitation leading to an exacerbation of the water cycle [*Held and Soden*, 2006]. The volume of water evaporating will depend largely on changes of sea and air temperatures and winds over major moisture source regions and these changes are bound to influence specific regions over continents.

[4] Thus, identification of regions particularly vulnerable to changes in the hydrological cycle requires locating all oceanic moisture sources and, additionally, to pin down where exactly water evaporating from these sources precipitates over land. While major oceanic source sectors have been relatively well identified recently [*Trenberth and Guillemot*, 1998], their contribution towards precipitation over continental land masses has not been equally well established.

[5] Here we used the 3-D Lagrangian transport model FLEXPART based on meteorological analysis data and a moisture tracking scheme to identify where continental regions are affected by precipitation originating from specific oceanic regions. Several such methods have recently been developed by *Stohl and James* [2004, 2005] (the one used in our study), *Sodemann et al.* [2008a, 2008b] and *Dirmeyer and Brubaker* [2007] to diagnose the net water vapor changes along a large number of back trajectories to infer the moisture sources for precipitation falling in a target region. Recently, these methods have been used by some of us to identify and quantify the moisture sources in different climatic regions such as the Sahel [*Nieto et al.*, 2006], Central Brazil and La Plata Basin [*Drumond et al.*, 2008], the Antarctic [*Sodemann and Stohl*, 2009] or the Iberian Peninsula [*Gimeno et al.*, 2010].

2. Methods

2.1. Method to Identify the Main Moisture Source Regions

[6] Moisture source regions are defined as maxima of vertically integrated moisture flux divergence (i.e., E-P) [*Trenberth and Guillemot*, 1998]. The vertically integrated moisture transport is defined as $1/g\int_0^{Ps} qvdp$, where g is the acceleration due to gravity, q is the specific humidity, P_s is the surface pressure, and v is the horizontal wind vector. ECMWF re-analysis (ERA-40) data on a 2.5° × 2.5° grid was used to compute flux divergences for the 44-year long period spanning from January 1958 to December 2001. Figure 1 shows the annual mean vertically integrated moisture flux divergence field, where values higher than 250 mm/yr are shown in gray scale, and the interval between the isolines is 250 mm/yr. The areas inside the red contour lines indicate the spatial extent of all major moisture source regions used in the forward integrations. These source regions were defined based on the threshold of 750 mm/yr for the oceanic sources (Figure 1, top) and 500 mm/yr for the land sources (Figure 1 (middle) and 1 (bottom)). As a supplement for Figure 1 we have included in the auxiliary material (Figures S1 and S2) global dis-

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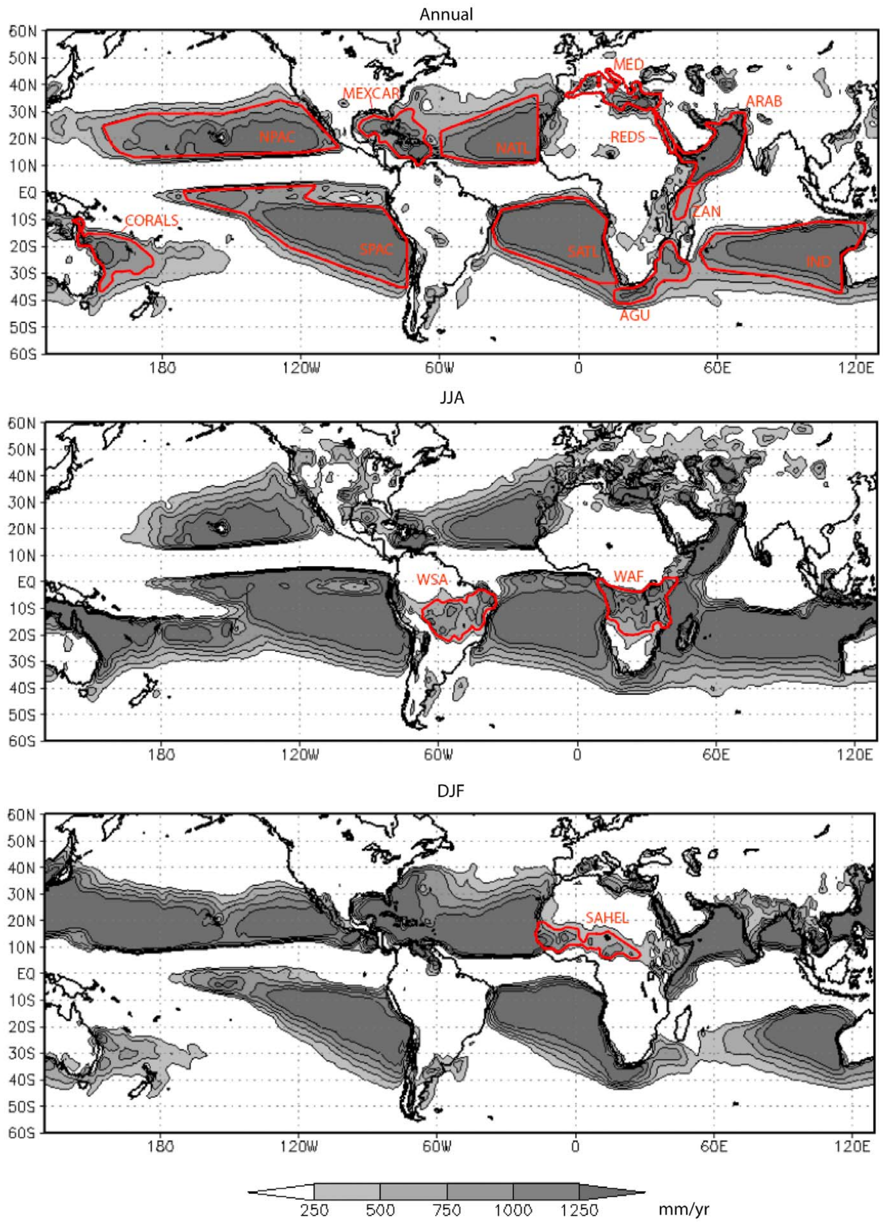

Figure 1. Climatological (top) annual, (middle) JJA and (bottom) DJF vertically integrated moisture flux divergence (mm/yr). Values higher than 250 mm/yr are in gray scale, with an interval between isolines of 250 mm/yr. Areas inside the red contour lines indicate the regions considered as moisture sources in the forward integrations. The areas were defined based on the threshold of 750 mm/yr for the oceanic sources (CORALS, Coral Sea; NPAC, North Pacific; SPAC, South Pacific; MEXCAR, Mexico Caribbean; NATL, North Atlantic; SATL, South Atlantic; ARAB, Arabian Sea; ZAN, Zanzibar Current; AGU, Agulhas Current; IND, Indian Ocean) and 500 mm/yr for the land sources (WAF, Winter Africa; WSA, Winter South America; SAHEL, Sahel). Two boxes were also defined using the physical boundaries of oceanic basins (MED, REDS). Data: ERA40 (1958–2001).

tributions of continental precipitation (Chen et al., 2002) for annual and seasonal basis.[1]

2.2. Lagrangian Approach to Quantify the Contribution of Each Moisture Source Region to the Continental Precipitation

[7] We make use of the method developed by *Stohl and James* [2004, 2005], which relies on the Lagrangian particle dispersion model FLEXPART [*Stohl et al.*, 2005]. Using this model, the atmosphere is divided homogeneously into a large number of virtual particles which have a constant mass and then these particles are advected by the model using three-dimensional (3-D) operational ECMWF [*White*, 2002] winds as well as superimposed stochastic turbulent and convective motions. The particle positions and specific humidity (q) are recorded every 6 hours. The increases (evaporation, e) and decreases (precipitation, p) in moisture along the trajectory can be calculated from changes in (q) with time $e - p = m\frac{dq}{dt}$, where m is the mass of each particle.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL043712.

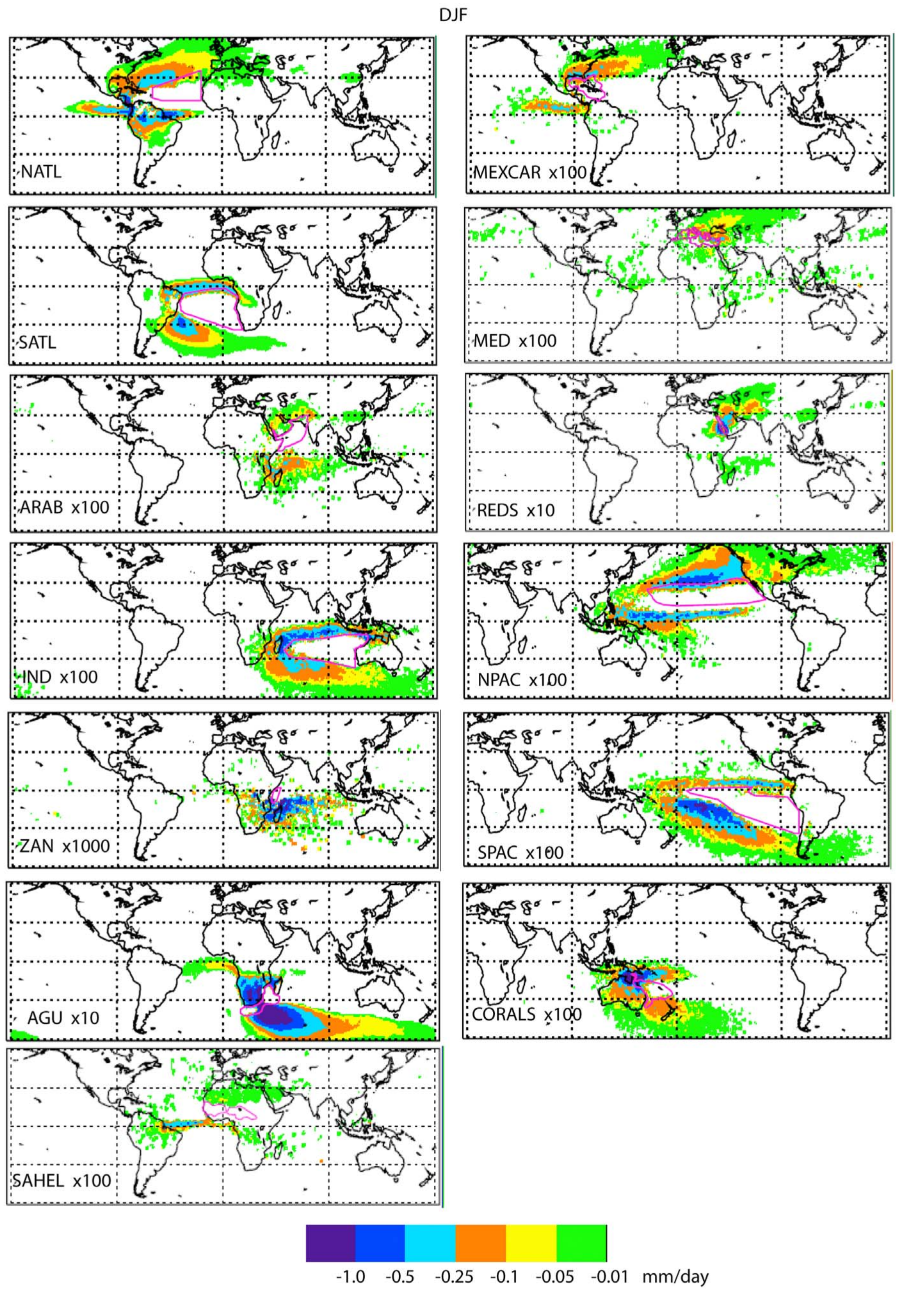

Figure 2. DJF fields of (E-P) integrated over 10 days for the period 2000–2004 calculated by forward tracking from the moisture sources indicated by the pink lines and identified on the left bottom of each plot. Only negative values are plotted and they were scaled by the different factors indicated in each plot in order to use the same colour bar.

When adding $(e - p)$ for all the particles in the atmospheric column over an area, we can obtain (E-P), where the surface freshwater flux (E) is the evaporation and (P) is the precipitation rate per unit area. The method can also track (E-P) from any specific region backwards or forwards in time along the trajectories, allowing to diagnose the relationships between net moisture source and net moisture sink regions. Full details of the method and its limitations are described by *Stohl and James* [2004, 2005].

[8] In the work reported here we used the tracks of 1.3 million particles over a 5-year period (2000–2004), computed using ECMWF operational analyses available every 6 hours (00, 06, 12 and 18 UTC) plus short-term forecasts available at intermediate times (3, 9, 15, 21 UTC) at a 1° × 1° resolution in latitude and longitude on 60 vertical levels.

[9] A database of trajectories (position and q interpolated from ECMWF data) emanating from each source region identified in Figure 1 was constructed. We traced (E-P) forwards from each source region limiting the transport time to 10 days, which is the average time that water vapour resides in the atmosphere [*Numaguti*, 1999], assessing the location of the most important sinks of moisture associated to each

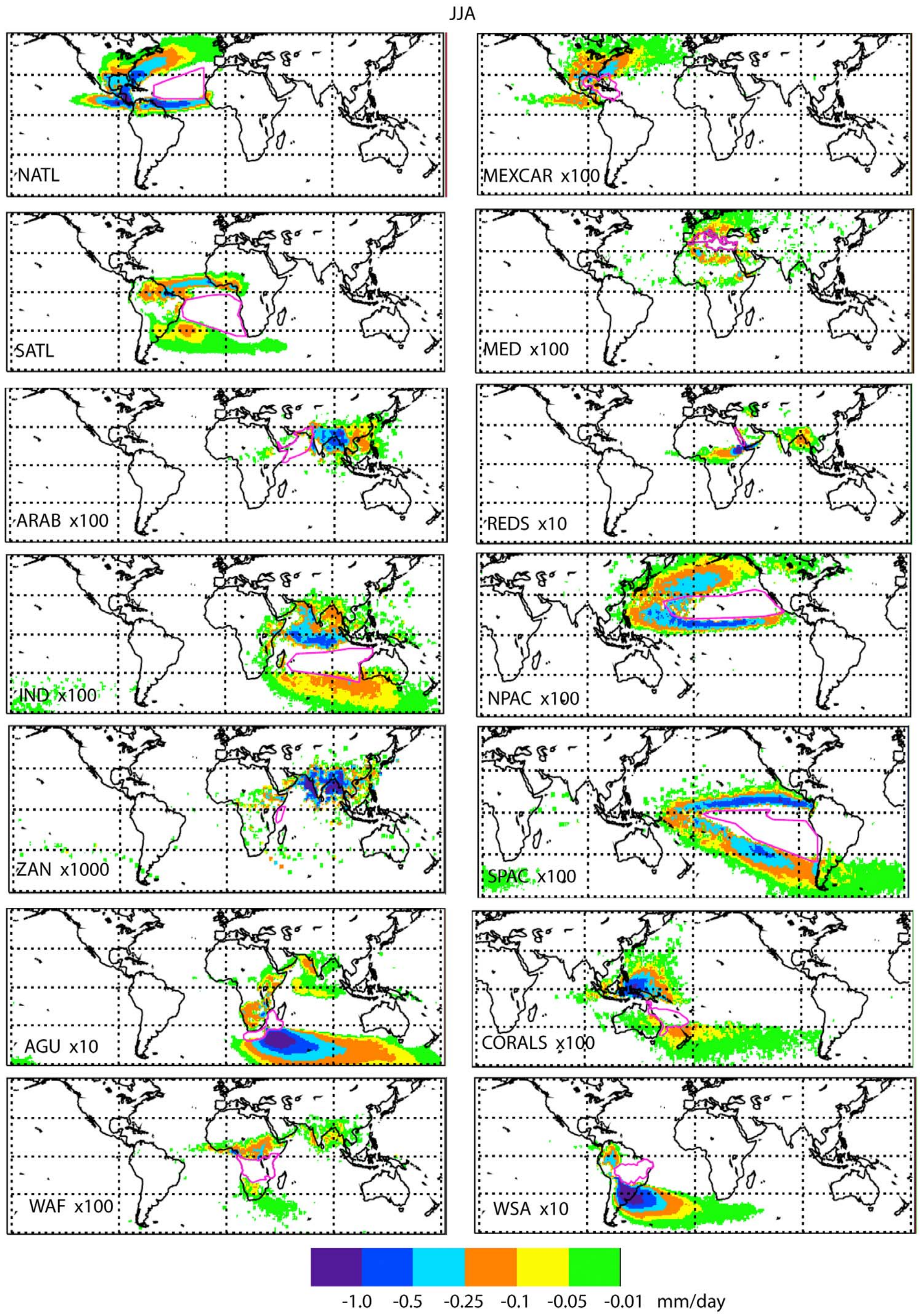

Figure 3. The same as Figure 2, but for JJA.

source. Results were analyzed for the full annual period as well as split into the four seasons defined as DJF, MAM, JJA and SON.

3. Results

[10] Major sources of moisture can be identified as large regions characterized with high values of vertically integrated moisture flux divergence [*Trenberth and Guillemot*, 1998], which is equivalent to net evaporation (E) minus precipitation (P). We tracked more than one million virtual particles from the identified source regions to the landmasses where most of that water precipitates in the 10 days following evaporation. Results are shown in Figures 2 and 3 for DJF and JJA respectively, while results for transition seasons are shown in Figures S3 and S4. At a global scale most of the evaporated water has its origin in tropical and subtropical oceanic areas (Figure 1). Seasonally, tropical continental areas over America and Africa contribute, too. It could be that the continental sources (mainly the Sahel moisture source) are coming at least partially from analysis increments in soil moisture. It should be stressed that most water evaporating from the oceanic source regions precipitates back onto oceans and only a minor, but vital, fraction precipitates over land. To help readers to visualize the role of the atmospheric circulation in the transport of moisture we have added maps of

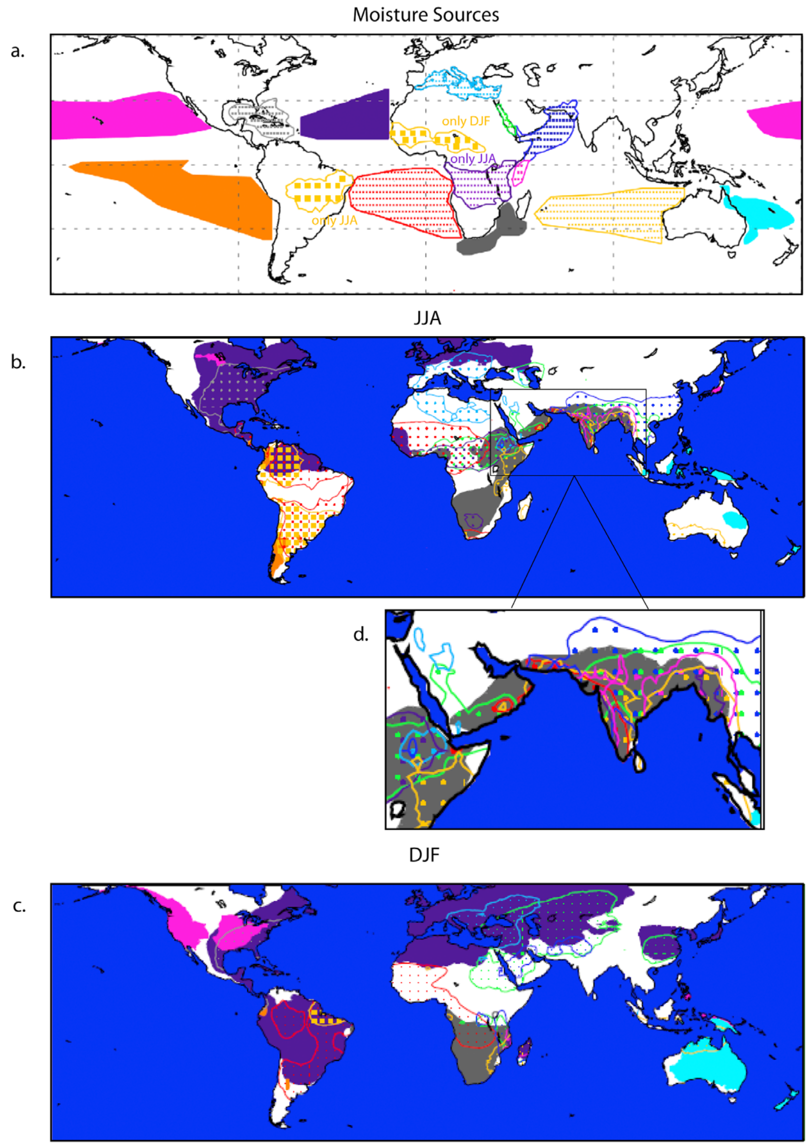

Figure 4. (a) Moisture source regions identified as maxima of vertically integrated moisture flux divergence in the period 1958–2001. The regions were defined based on the threshold of 750 mm/yr (500 mm/yr) for the oceanic (land) sources. (b) (E-P) contour of -0.05×10^{-2} mm/day during JJA and (c) (E-P) contour of -0.05×10^{-2} mm/day during DJF. (d) As Figure 4c but expanded for Indian region. Contour colors in Figure 4b–4d correspond to the color scheme used in Figure 4a.

surface wind for annual and seasonal basis in the electronic online material (Figures S5 and S6).

[11] The North Atlantic source (NATL) is the area providing the most moisture for precipitation over continents among the regions defined in Figure 1. It provides moisture for precipitation in Eastern North America, Central America and Northern South America during JJA but it extends its influence during DJF providing moisture also to Europe, Northern Africa and central South America. These results reflect the main physical mechanisms transporting moisture to Europe during winter, the warm conveyor belt [*Eckhardt et al.*, 2004] and the systems of low level jets in America: Great Plains low level jet [*Song et al.*, 2005], Caribbean low level jet [*Amador*, 2008] and South America low level jet [*Marengo et al.*, 2004]. The importance of this source has been well documented in previous analysis for Central America [*Durán-Quesada et al.*, 2010] Central South America [*Drumond et al.*, 2008] and Europe [*Gimeno et al.*, 2010]. The other source over the North Atlantic, the Mexico-Caribbean one (MEXCAR) does not provide moisture to the South American low level jet and plays a relatively minor role for the European continental moisture during winter since most of the moisture falls over the North Atlantic, so its influence is limited to Eastern North America and Central America. The South Atlantic source (SATL) is the second largest source of moisture for precipitation over continents in the world, being the main source region for precipitation in Eastern South America with the exception of NE Brazil where flux diffluence associated to the transition of the ITCZ complicates the moisture fluxes (A. Drumond et al., Lagrangian identification of the main sources of moisture affecting northeastern Brazil during its pre-rainy and rainy seasons, submitted to *PLoS ONE*, 2010). The latitudinal seasonal propagation of the ITCZ is clearly apparent in the

extension to the North during JJA of the pattern of E-P over Northern South America and in the influence of this source during JJA for the precipitation over the Sahel [*Nieto et al.*, 2006].

[12] Among the three Pacific sources, two of them, the North Pacific source (NPAC) and the South Pacific source (SPAC) provide moisture for precipitation over the latitudinal extremes of the American continent, with a stronger influence in the respective hemispheric winter. As commented for Europe in respect to NATL the physical mechanism responsible for this transport is the feeding of moisture to extra-tropical cyclones by the Warm Conveyor Belt systems [*Koster*, 1986]. During the Northern Hemisphere winter the Eastern coast of North America receives moisture for precipitation from the Atlantic (NATL and MEXCAR) and the Pacific (NPAC), however the amount of moisture received from the former is about 100 times higher than the moisture received from the latter. The other Pacific source (CORALS) is located in the Southern Hemisphere along the eastern coast of Australia and it is the major source over Oceania continent along the year.

[13] The structure of Indian Ocean sources is much more complex. During DJF the four sources, (IND, embracing most of the oceanic areas between Australia and south Africa; AGU, located over the Agulhas current; ZAN, situated over the Zanzibar Current and ARAB, placed on the Arabian Sea) provide moisture for surrounding continental areas of the African continent and the Arabian Peninsula; however during the Southern Hemisphere winter (JJA) the monsoon circulations transforms the four areas into sources of moisture for precipitation falling over the Indian Peninsula [*Annamalai et al.*, 1999]. This unique situation implicates that the Indian subcontinent receives moisture from 6 different major source regions during the Southern Hemisphere winter, including the four Indic ones plus the Red Sea (REDS) and a continental source over tropical Southern Africa (WAF).

[14] Despite their relatively small size the two inner Seas, i.e., the Mediterranean (MED) and the Red Seas (REDS) play an important role at a much larger scale. During the Northern Hemisphere winter (DJF), both sources supply moisture for precipitation on continental areas placed to their Northeast. During JJA the Mediterranean provides moisture to its surroundings extending to Northern Europe while the Red Sea provides moisture to the remote area over the Indian Peninsula as commented before.

[15] Although in a secondary way (after precipitation plus further evaporation) there are two other important moisture regions during the Southern Hemisphere winter (JJA), one placed in the tropical South Africa (WAF) and the other over the Amazon (WSA) and one during the Northern Hemisphere winter (DJF) over the Sahel (SAHEL). Their evaporation is so high that they could be considered as continental Seas [*Dirmeyer and Brubaker*, 2007]. They provide moisture for most of the precipitation over important areas of the world such as the Parana, Orinoco or Congo river basins.

4. Summary and Discussion

[16] In this study we use an objective 3-D Lagrangian model (FLEXPART) to detect major oceanic moisture source areas and to identify the associated continental regions significantly influenced by each moisture source. To summarize our results, Figure 4 illustrates the source regions (Figure 4a) and compares their relative importance on the origin of precipitation on continental landmasses by showing a single contour line (E-P = -0.05×10^{-2} mm/day) for JJA (Figure 4b) and DJF (Figure 4c).

[17] Our results illustrate the highly asymmetrical role of major oceanic moisture sources over continents. The Northern Atlantic subtropical ocean source provides moisture for precipitation over vast geographical areas in winter (from Mexico to large parts of Eurasia), whereas the influence of other large oceanic sources is confined to much smaller continental areas (e.g., Southern Indian and the North Pacific oceans). The small enclosed Red Sea source provides vast amounts of moisture that precipitate between the Gulf of Guinea and Indochina (JJA) and the African great lakes and Asia (DJF). Likewise vast continental areas lack appreciable direct water transport from any major source regions, usually corresponding to some of the most arid inland regions (e.g., inner Asian continent).

[18] Our analysis further emphasizes that some land masses obtain moisture from only one or two sources located in the same hemisphere (e.g., Northern Europe or Eastern North America), while others receive moisture from both hemispheres with large seasonal variations (e.g., Northern South America). Finally, the continental areas characterized by monsoon regimes (India, tropical Africa and the great lakes region) benefit from a large number of source regions (Figure 4d) which indicates the complex nature of precipitation.

[19] Although further study on changes in water source due to climate change is necessary it is obvious that changes in the atmospheric circulation in a changing climate will result in changes in circulation between source and sink redirecting moisture in a different way. Those continental regions receiving moisture from only one or two source region(s) may be exposed more strongly to changes in the water cycle due to a changing climate than regions that draw on multiple moisture sources.

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