GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 1–8, doi:10.1002/grl.50338, 2013

Influence of the intensification of the major oceanic moisture sources on continental precipitation

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Received 28 January 2013; revised 7 March 2013; accepted 7 March 2013.

[1] In this study, we address two key issues in the hydrological cycle that have remained elusive: 1) to what extent can we expect climate change to affect the transport of moisture? and, in particular, 2) how will the changes in the sources' intensity (that is, more evaporation) affect the distribution of continental precipitation? This was achieved using a multimodel ensemble that allowed delimiting those oceanic areas where climate change will likely lead to an increase in evaporation (E) minus precipitation (P). Finally, a sophisticated Lagrangian model was used to identify which continental regions will be affected by changes in precipitation ($E-P<0$) originating in each oceanic moisture source. We find that in boreal winter, wide sectors of Europe, Asia, Middle East, South America, and southern Africa are affected, but North America emerges as the most affected continental region. In austral winter, the largest changes are confined to northern and Central America.
Citation: Gimeno, L., R. Nieto, A. Drumond, R. Castillo, and R. Trigo (2013), Influence of the intensification of the major oceanic moisture sources on continental precipitation, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50338.

1. Introduction

[2] One of the greatest threats posed by climate change stems from major changes in the hydrological cycle, including the location and strength of the most important oceanic moisture sources [*Gimeno et al.*, 2012]. Global warming driven by increasing concentrations of greenhouse gases is expected to cause increased global mean precipitation and evaporation [*Wentz et al.*, 2007; *Intergovernmental Panel on Climate Change (IPCC)*, 2007]. Furthermore, according to the Clausius-Clapeyron equation, the high sensitivity of saturated vapor pressure to temperature will result in increased atmospheric water vapor and, hence, water vapor transport that amplifies the water cycle [*Allen and Ingram*, 2002; *Held and Soden*, 2006]. This effect will in turn accentuate the pattern of evaporation minus precipitation ($E-P$); put simply, wet (dry) regions get wetter (drier).

[3] An indirect way of predicting trends in oceanic evaporation, and their relationship with precipitation, is through salinity time series. Various authors have consistently shown an increase in the salinity of the upper subtropical oceans in all oceanic basins in recent decades [e.g., *Curry et al.*, 2003], which indicates an increase in ($E-P$). Observational studies of atmospheric moisture content and precipitation are consistent with these expectations [*Durack et al.*, 2012]. According to the satellite-based Special Sensor Microwave Imager [*Santer et al.*, 2007], since 1988, there has been an increase of 0.041 kg/m^2/yr in the total atmospheric moisture content over the oceans and an increase in global mean precipitation over land by about 2% over the period 1900–1998 [*Dai et al.*, 1997]. Regional changes in precipitation also illustrate how wet (dry) regions get wetter (drier): for example, an increase in precipitation in the extratropical latitudes (about 7%–12% in zonally averaged precipitation between 30°N and 85°N), more intense rainfall associated with the Asian and Indian summer monsoons, and substantially less precipitation in dry regions, including the Sahel, the Mediterranean, southern Africa, and parts of southern Asia [*Folland et al.*, 2001; *IPCC*, 2007].

[4] Climate models do indeed indicate a general increase of precipitation associated with several tropical monsoon systems (particularly the Asian and South American ones), and also at high latitudes (due to intensification of the global hydrological cycle), accompanied by a decrease in the subtropical latitudinal band [*Curry et al.*, 2003]. Models also predict that subtropical dry zones will expand poleward [*Seager et al.*, 2010].

[5] Moisture transport from oceanic sources to the continents links oceanic evaporation and continental precipitation, and analyzing this transport can provide a better understanding of observed changes and an improved physical understanding of future climate projections [*Gimeno et al.*, 2012]. Recent studies have considered the moisture transported both between latitudes [*Knippertz and Wernli*, 2010] and on a global scale [*Gimeno et al.*, 2010, hereafter G10]. We previously used a 3-D Lagrangian approach to identify the continental regions affected by precipitation that originated from specific oceanic source regions [*Gimeno et al.*, 2010]. We found that the supply of oceanic moisture to the continents is highly asymmetrical and specific to each oceanic basin and season. However, this analysis was restricted to 5 years of data, which does not allow the generation of a climatology of moisture transport from the oceanic sources to the continents, or the study of interannual variability or possible trends. Moreover, we used a lower precision approach where the total number of particles followed was relatively low. Here the analysis has been extended to

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0094-8276/13/10.1002/grl.50338

two decades (1980–2000) of the ERA-40 reanalysis and using the Lagrangian model tuned to higher precision, allowing a reevaluation of the previous results. By considering composites of extreme years of high and low values of $E-P$, we performed an assessment of how increased evaporation in the source regions affects continental precipitation, as well as the identification of possible regions where precipitation is affected more by changes in moisture transport as the climate warms. This restriction of the analysis to data since 1979 reflects the impossibility to work meaningfully with high-resolution upper-level data prior to the incorporation of satellite data in the reanalysis.

2. Methods

[6] Identification of the main oceanic moisture source regions are based on the maxima of the annual climatological vertically integrated moisture flux divergence using the available European Centre for Medium-Range Weather Forecasts reanalysis ERA-40 data [*Uppala et al.*, 2005] on a $1^\circ \times 1^\circ$ grid between January 1980 and December 2000. Ten oceanic moisture source regions were identified based on a threshold of 750 mm/yr for the integrated moisture flux divergence (Figure 1, top). The work is based on the approach [*Stohl and James*, 2004] which uses the FLEXPART three-dimensional (3-D) Lagrangian particle dispersion model [*Stohl et al.*, 2005] to diagnose specific humidity changes along a large number of trajectories linking moisture source to moisture sink regions. The model was initialized in forward mode to track atmospheric moisture for the entire atmosphere using the ERA-40 reanalysis 24 data set, with a 1° horizontal resolution and a vertical resolution in 61 vertical levels. This was done for a 21 year period, from 1980 to 2000, and considering that the atmosphere is divided homogenously into 1.9 million particles which are advected using the ERA-40 3-D wind input data. The FLEXPART model requires consistent high-quality data of wind and humidity at all these 61 vertical levels, thus hampering the application to older reanalysis data (~1979), i.e., prior to the significant decrease of the errors of these variables (namely, over the oceans) due to the inclusion of satellite data [*Bengtsson et al.*, 2004; *Uppala et al.*, 2005]. Records were made at 6 h intervals (00, 06, 12, and 18 UTC) of the position and specific humidity values q of every particle along its trajectory over a 10 day period, which is the average time that water vapor resides in the atmosphere [*Numaguti*, 1999]. A data base was constructed that identified all trajectories originating from oceanic moisture sources. The ($E-P<0$) values, integrated over the 10 days of transport, indicate the most important sinks of moisture for precipitation originating in each oceanic moisture source. It should be noted that there are several differences between the methods and data sets used in G10 that preclude a completely objective comparison between results. Thus, in G10, the Lagrangian model was used in a low precision mode, with much less particles being considered in each box. Here the methodology is applied in a higher precision mode, allowing particles located between latitude degree lines to be selected. Integration of contribution of a much higher number of particles may provide a higher magnitude of $E-P$ values.

[7] The composite differences between the average of the five highest intensity episodes and the average of the five lowest intensity events identified for that source (High − Low) were obtained for JJA and DJF. A bootstrap method [*Wei et al.*, 2012] was used to test the statistical significance of composite differences.

[8] The identification of oceanic regions with higher evaporation rate in a future climate change scenario was based on data generated by 15 of the GCM models included in the Coupled Model Intercomparison Project phase 3 [*Meehl, et al.*, 2007] used for IPCC AR4. Here we performed moisture budget calculations for a future period of climate change between 2046 and 2065 and computed a multimodel ensemble mean [*Seager et al.*, 2010]. The criteria for using only 15 of the 24 models and the corresponding list can be found in the work by *Seager et al.* [2010, Table 1]. To identify regions of higher changes, a comparison was made against the period 1961–2000 for the semiannual periods of October–March and April–September. These regions were defined based on the threshold of 0.3 mm/yr. These regions were used with the FLEXPART model in forward mode to identify which continental regions would be affected by changes in precipitation ($E-P<0$) originating in each oceanic moisture source.

[9] Full methods and any associated references are available in Method section in the auxiliary material.

3. Results

[10] The first step in quantifying atmospheric water vapor transport is to locate moisture source regions where evaporation exceeds precipitation on average; these are sources in the sense that, in these regions, there is net moisture transport into the atmosphere. These regions can be identified through diagnosis of the divergence of the vertically integrated moisture flux [*Trenberth and Guillemot*, 1998] (see Method section in the auxiliary material). The main net moisture sources are shown in Figure 1 (top left) for both boreal summer (JJA) and winter (DJF). The highest values of $E-P$ are found in the subtropical oceans (Indian, North and South Pacific, and North and South Atlantic), in smaller semienclosed seas such as the Caribbean, Mediterranean and Red Seas, and South Africa (Agulhas Current region). We acknowledge that not all the precipitation falling over the continents was originated within these major oceanic source areas, and a fraction may have its origins in negative $E-P$ regions observed over the extratropical Oceans and in local recycling [*Gimeno et al.*, 2012]. In order to evaluate the role played by the nonsource areas, we computed the moisture contribution evaporated from all the oceanic areas that were not considered in the analysis (white oceanic areas in Figure 1, top right) and concluded that their contribution is restricted to a narrow tropical strip and two large high latitudinal bands, being moderately relevant in boreal winter over northern Europe and the patches of the North American continents (see Figure S1 in the auxiliary material).

[11] The second step uses a Lagrangian approach [*Stohl and James*, 2004] to diagnose specific humidity changes along a large number of trajectories (see Methods section), hence linking moisture source to moisture sink regions. The main oceanic source areas and their associated continental sink regions are shown for both winter and summer: at the global scale in Figure 1 (top right) and for individual sources in Figure S2. Overall, the pattern is similar to that identified by the initial study based on the lower density of particles approach and the shorter 5 year (2000–2005) period [*Gimeno et al.*, 2010]. In terms of influence on

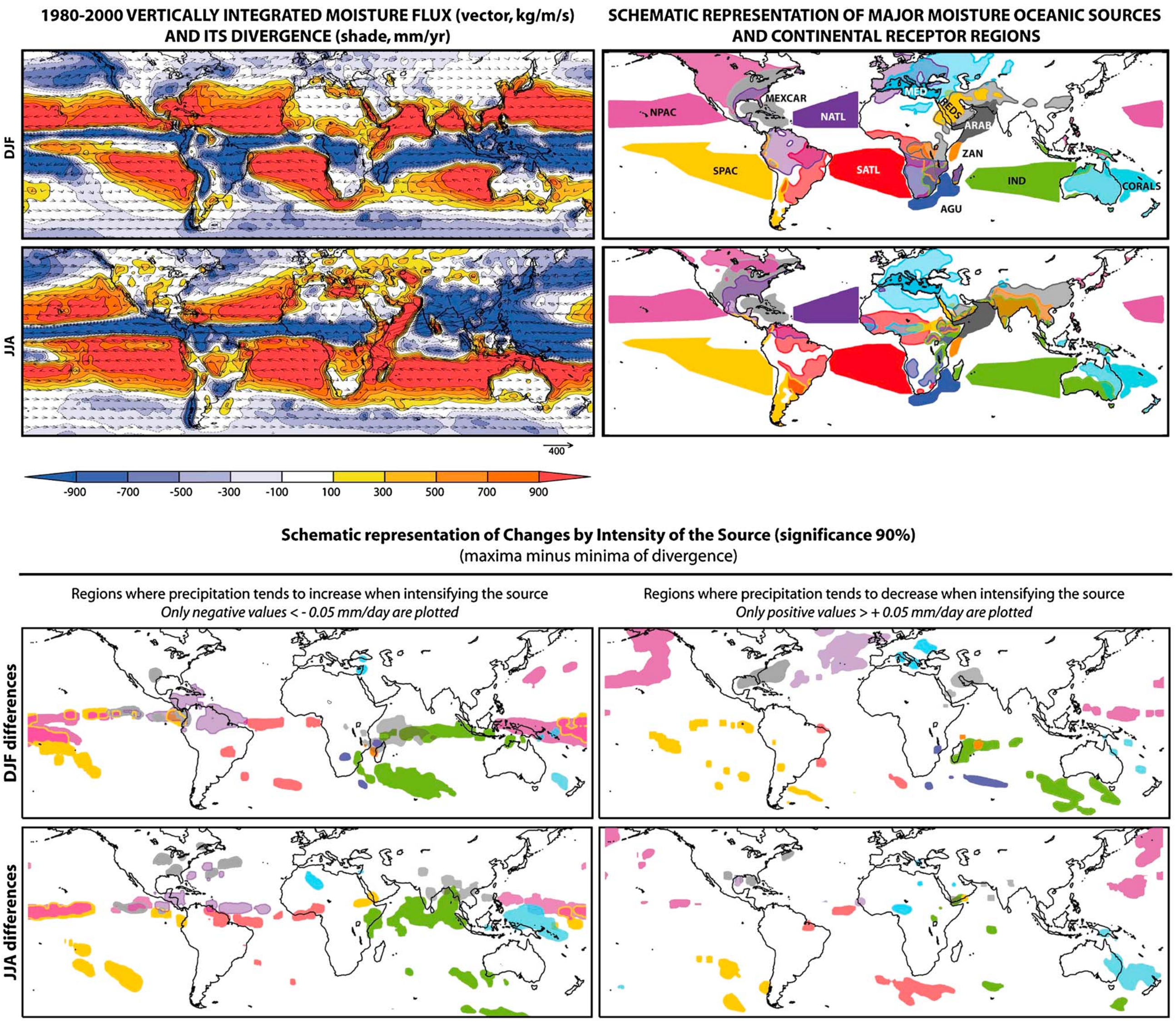

Figure 1. Main oceanic moisture sources associated with continental sink regions of the evaporated moisture and changes associated with the intensity of the source. (top left) Vertically integrated moisture flux for the period 1980–2000, shown as vectors (measured in kg/m/s), and its divergence, shown as warm and cool colors (measured in mm/yr) for summer (JJA) and winter (DJF). Data are from ERA-40. (top right) Schematic representation of oceanic moisture source regions and continental sink regions, for the period 1980–2000, for JJA and DJF. The sources of moisture are the same as in *Gimeno et al*. [2010, Figure 1]: NPAC, North Pacific; SPAC, South Pacific; NATL, North Atlantic; SATL, South Atlantic; MEXCAR, Mexico Caribbean; MED, Mediterranean Sea; REDS, Red Sea; ARAB, Arabian Sea; ZAN, Zanzibar Current; AGU, Agulhas Current; IND, Indian Ocean; CORALS, Coral Sea. Six of these source regions were defined based on the threshold of 750 mm/yr of the annual vertically integrated moisture flux calculated for the period 1980–2000 using data from ERA-40 for the oceanic sources. The Mediterranean and Red Seas were defined using their physical boundaries. $E-P$ fields are calculated by forward tracking from the defined moisture sources. Continental regions with an $E-P$ value less than -0.05 mm/d are shown using the same colors as the oceanic source region that contributes their moisture. Overlapping continental regions are plotted with a shaded mask comprising the relevant colors. (bottom) The composite differences in $E-P$ generated by each moisture source (identified using the same color scheme as the upper plot) between the average of the five highest intensity of source episodes and the average of the five lowest intensity seasons, during (left) December–February and (right) June–August. The black contour lines indicate areas where the absolute values of differences greater than 0.01 mm/d are significant at the 90% confidence level, according to a bootstrap test permuting the original time series 1000 times.

continental precipitation, the northern Atlantic subtropical ocean is the dominant source providing moisture for precipitation over vast areas, especially during DJF when its influence extends from Mexico to parts of Eurasia and from the Eurasian Arctic to the Amazon. This Atlantic influence on the Central and South American continent owes to the very efficient low-level jet systems associated, namely, the Caribbean low-level jet [*Amador*, 2009], the South American low-level jet [*Marengo et al*., 2004], and the Choco jet [*Poveda and Mesa*, 2000] that controls precipitation (mainly in DJF) over central America, tropical and Subtropical South America east of the Andes, and tropical Pacific coast of South

America, respectively. However, its influence on Europe during the summer vanishes. Major oceanic sources do not contribute directly to precipitation over vast continental areas (including most arid inland regions), though they can contribute through subsequent local moisture recycling. By contrast, a few small oceanic sources provide disproportionate amounts of moisture relative to their size. For instance, the Mediterranean is a dominant source for Europe and northern Africa during JJA, and the Red Sea provides large quantities of moisture that precipitate between the Gulf of Guinea and Indochina during JJA and between the African Great Lakes and Asia during DJF. There is also significant interhemispheric transport, with implications for continental precipitation, from the North Atlantic source during DJF and from western Indian sources during JJA. While vast areas, including Europe, South America, and Australia, receive moisture mainly from a single source, the monsoonal regimes in India, tropical Africa, and the quasi-monsoonal regime of North American Great Plains are fed by moisture from multiple source regions.

[12] Moisture source regions are not stationary, varying in intensity from year to year and expected to change in the future. The longer data set employed here allows us to perform a sensitivity analysis on the influence of source intensity (periods with enhanced or reduced $E-P$) on the transport of moisture from the net evaporating oceanic regions to the net precipitating continental ones (an analysis impossible to perform in G10). Differences in $E-P$ between the average of the five highest and lowest intensity episodes/seasons were obtained for each source during DJF (Figure 1, upper panels in the bottom plot) and JJA (Figure 1, lower panels in the bottom plot): see Method section and Figure S3 in the auxiliary material for further details. Using the same color scheme as employed previously for each source region, the figures indicate that precipitation tends to increase along the tropical band (and for both seasons) when the source is intensified. The subtropical oceanic sources contribute more to increases in precipitation in the central and western parts of the corresponding basin, while the intensification observed in the eastern tropical Pacific is due to moisture transported from the Caribbean source. The increase in precipitation associated with more intense monsoon circulations is evident during DJF for the South American monsoon (from the North Atlantic source), confirming the role of cross-equatorial moisture transport during intense monsoon events over the Amazon basin [*Carvalho et al*., 2010]. The role of the enhanced transport of moisture from the Arabian Sea in the intensification of the rainfall associated with the Asian and Indian summer monsoons is apparent, confirming previous results [*Meehl and Arblaster*, 2003; *Misra et al*., 2012]. Likewise, stronger than usual North America monsoon systems during JJA also rely on enhanced moisture availability from the Caribbean source [*Hu and Feng*, 2002]. According to our results, there is no significant displacement of the continental sink regions receiving precipitation from oceanic sources during periods of high intensity. Thus, the enhanced precipitation in tropical areas and monsoon regions projected by climate models might be related to enhanced moisture transport from the same moisture sources as before. Furthermore, there is no evidence of a general intensification of precipitation over the continents associated with strengthening of the moisture source in midlatitudes, being mostly restricted to the North Pacific and North Atlantic oceanic areas. Finally, most areas affected by a decreasing trend during periods of high intensity tend to be also restricted to the oceanic areas with the few exceptions of southeastern U.S. and Mediterranean areas in DJF and eastern Australia in JJA (Figure 1, lower panels in the bottom plot). This insensitivity of precipitation at higher latitudinal bands (particularly over the continents) to changes in moisture source intensity suggests that the main process responsible for the expected intensification of precipitation at these latitudes is dynamical.

[13] A complementary approach to identifying continental regions most vulnerable to increased intensity of oceanic moisture sources focuses on sources that will experience the highest increase in $E-P$ in the next few decades according to a large ensemble of global climate models (GCMs), which are able to reproduce very consistently the current main moisture sources pattern [see *Seager et al*., 2010, Figure 1]. It should then be possible to identify where moisture coming from these sources contributes to precipitation currently. We show as hot spot source regions (hssr's) those areas with modeled $E-P$ increases greater than 0.3 mm/d for the periods 2046–2065 compared with 1961–2000, as predicted by 15 GCMs used in the AR4 assessment, for boreal winter (Figure 2, top) and boreal summer (Figure 3, top) half years [*Seager and Vecchi*, 2010]. Ideally, we should use the same Lagrangian method directly to climate change scenario fields obtained with GCMs, in order to detect changes in the continental areas affected by these hssr's. However, the vast majority of GCMs available have neither the same spatial resolution as the ERA-40 data sets nor sufficient vertical levels of data to apply the FLEXPART model efficiently [*Stohl et al*., 2005]. Instead, we applied the same Lagrangian approach as for current climate data (1980–2000) to identify those potentially vulnerable continental regions that receive moisture from these hssr areas in boreal winter (Figure 2, bottom) and boreal summer (Figure 3, bottom) (see also Method section in the auxiliary material).

[14] In boreal winter (Figure 2, top), large sectors of Europe, Asia, Middle East, North and South America, and southern Africa are affected. Two hssr's have the widest influence: one in the central North Atlantic that influences precipitation over Europe and South America, and the other in the subtropical western North Pacific that influences precipitation over North America and the Southeast Asian continent. It is worth mentioning the potential or an amplified role of the North Atlantic and North Pacific sources to increase the frequency of atmospheric river events (confined areas of lower troposphere that transport vast amounts of moisture from the subtropics). It has been widely reported in the last decade that a large fraction of intense precipitation and flood events in North American west coast and also over the UK and the Mediterranean are related with the occurrence of these extreme episodes [see *Gimeno et al*., 2012].

[15] The small Mediterranean hssr has a strong influence on European precipitation; nevertheless, this influence can soften the expected combined impact of climate change in southern Europe, i.e., more frequent droughts and summer heat waves, which is so consistent among different GCMs [*IPCC*, 2007]. On the whole, North America is the most affected continental region, being directly influenced by four different hssr's: in the Caribbean, the tropical Mexican coastal Pacific, the subtropical western North Pacific, and the central North Atlantic.

[16] In austral winter (Figure 3, top), the two regions most likely to be influenced by future extreme changes in $E-P$

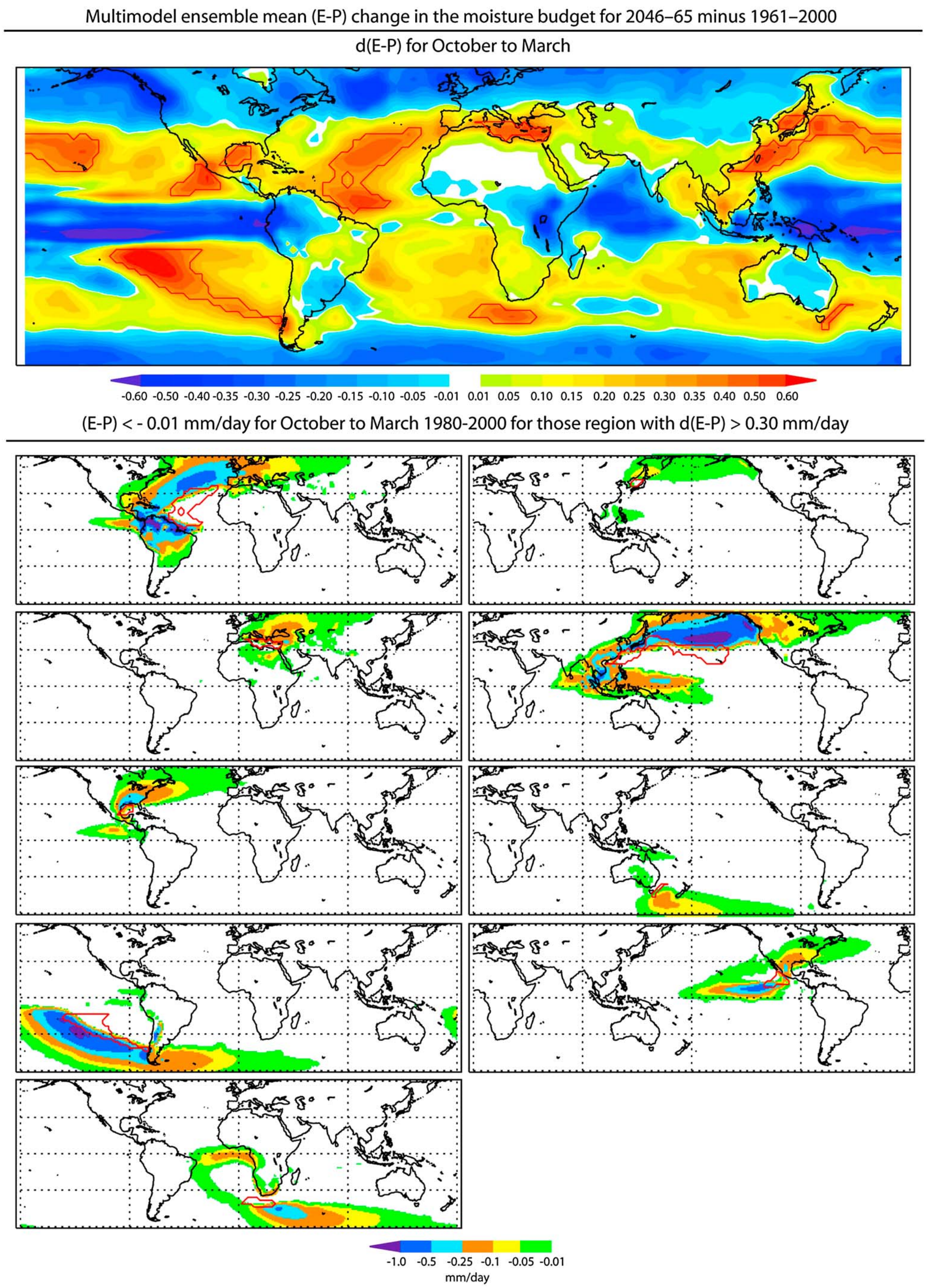

Figure 2. Oceanic moisture sources with the highest predicted change of intensity associated with continental sink regions of the evaporated moisture (for October–March). (top) Multimodel ensemble mean ($E - P$) change in moisture budget for 2046–1965 minus 1961–2000 for October–March, based on the data generated using 15 GCMs run as part of the Coupled Model Intercomparison Project phase 3 [*Meehl et al*., 2007] and used for the Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC AR4). Data provided by Richard Seager [*Seager et al*., 2010]. (bottom) Each of these plots is associated with a single moisture source. ($E - P$) values integrated over 10 days for October–March for the period 1980–2000, calculated by forward tracking the FLEXPART model from the moisture source (indicated by the closed red line) and identified according to the largest values of the multimodel ensemble mean change in ($E - P$) which exceeded a threshold of 0.3 mm/d. Only negative values less than -0.01 mm/d are plotted.

are in the northern and Central America, which receive moisture for precipitation from the Atlantic warm pool hssr [*Drumond et al*., 2011], and the Sahel [*Nieto et al*., 2006], which is affected by moisture from the nearby Gulf of Guinea hssr. These two areas are particularly prone to prolonged drought events, and therefore, the possibility of having an intensified supply of precipitation from their main oceanic source corresponds to good news, particularly for Mexico and southwestern, where GCMs predict increase of evaporation and less precipitation and soil moisture [*IPCC*,

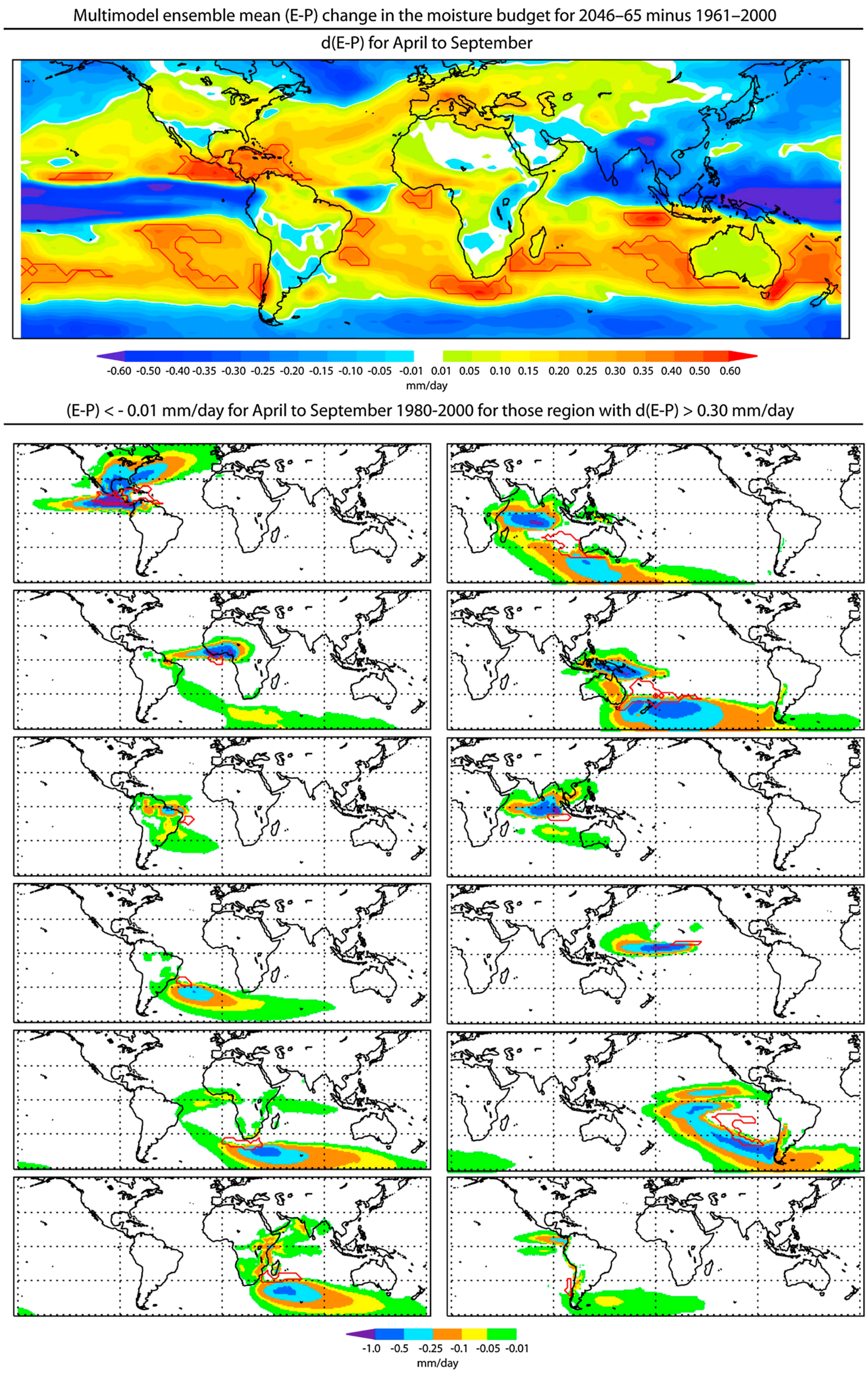

Figure 3. Potential oceanic moisture sources with higher predicted change of intensity associated with continental sink regions of the evaporated moisture (for April–September). Same as Figure 2 but for the months April–September.

2007]. The two hssr's located in the Indian Ocean have a moderate effect on surrounding continental areas: the hssr to the south of the Bay of Bengal influences the Malaysian Peninsula, while the hssr close to the Agulhas Current provides moisture for the East African coast and the Indian subcontinent. This is consistent with the results obtained showing that the increase in the monsoon rainfall in the future is mainly related with the intensification of the atmospheric moisture transport into the Indian region related to rather strong increases in evaporation over the Arabian Sea (May 2011). Finally, the Pacific hssr located to the east of Australia affects the eastern half of the continent.

4. Concluding remarks

[17] Observational and modeling studies suggest that the strong dependence of saturated vapor pressure on temperature will result in increases of evaporation and, hence, precipitation, leading to an exacerbation of the water cycle. Robust identification of those regions particularly vulnerable to changes in the hydrological cycle requires the location of all major oceanic moisture sources and the tracking of the water that evaporates from those sources to where it precipitates over land [*Gimeno et al*., 2010]. In this study, we first provide a more robust identification of all major oceanic moisture sources and assess their recent changes in amplitude. In particular, we address two key issues in the atmospheric branch of the hydrological cycle that have remained elusive: (1) to what extent can we expect climate change to affect the transport of moisture? and, in particular, 2) how will the changes in the sources' intensity (that is, more evaporation) affect the distribution of continental precipitation? We have confidence in the overall representativeness of these results, because the underlying assumptions are relatively robust: (i) the use of FLEXPART for climatological assessment of oceanic and continental moisture source areas has been shown to be consistent at the regional and global scales [*Gimeno et al*., 2012]; (ii) the identification of areas prone to significant changes in $E-P$ was derived using a large ensemble of GCMs and agrees well for those regions receiving precipitation from the hssr's; and (iii) our results stand despite the moisture contribution evaporated from all the oceanic areas that were not considered in the analysis, as their overall contribution to the precipitation over midlatitude continents is only relevant in boreal winter over northern Europe and a few patches of the North American continents (Figure S1). Finally, we must stress that areas affected by these highly sensitive hssr regions are often spread over the oceans (Figures 2 and 3). However, we have identified those hssr's that do have an impact over specific continents, including highly populated areas (e.g., Central and North America, Europe, and Gulf of Guinea) that are under water stress [*Vörösmarty et al*., 2010] and could become less prone to disruption of their water resources under climate change.

[18] **Acknowledgments.** This work was supported by the Spanish Government and FEDER through the projects MSM and TRAMO. The authors thank Richard Seager and two anonymous reviewers for theirs critical comments. Ricardo Trigo was partially supported by the FCT (Fundação para a Ciência e a Tecnologia, Portugal) through project STORMEx FCOMP-01-0124-FEDER-019524 (PTDC/AAC-CLI/121339/2010) cofunded by FEDER through COMPETE program.

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