

# Moisture flux convergence in regional and global climate models: Implications for droughts in the southwestern United States under climate change

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[1] The water cycle of the southwestern United States (SW) is dominated by winter storms that maintain a positive annual net precipitation. Analysis of the control and future climate from four pairs of regional and global climate models (RCMs and GCMs) shows that the RCMs simulate a higher fraction of transient eddy moisture fluxes because the hydrodynamic instabilities associated with flow over complex terrain are better resolved. Under global warming, this enables the RCMs to capture the response of transient eddies to increased atmospheric stability that allows more moisture to converge on the windward side of the mountains by blocking. As a result, RCMs simulate enhanced transient eddy moisture convergence in the SW compared to GCMs, although both robustly simulate drying due to enhanced moisture divergence by the divergent mean flow in a warmer climate. This enhanced convergence leads to reduced susceptibility to hydrological change in the RCMs compared to GCMs. **Citation:** Gao, Y., L. R. Leung, E. P. Salathé Jr., F. Dominguez, B. Nijssen, and D. P. Lettenmaier (2012), Moisture flux convergence in regional and global climate models: Implications for droughts in the southwestern United States under climate change, *Geophys. Res. Lett.*, 39, L09711, doi:10.1029/2012GL051560.

## 1. Introduction

[2] The southwestern United States (SW) has experienced a severe multiyear drought over the last 10 years that is unprecedented in the observed hydroclimatic record [e.g., Cook *et al.*, 2004]. Many Global Climate Models (GCMs) predict that the SW will continue to become drier throughout this century as a consequence of climate change [Seager

*et al.*, 2007]. In GCMs, the drying is manifested as a drop in net precipitation (precipitation (P) minus evapotranspiration (E), P-E) equivalent in the long-term mean to a decline in runoff [Seager *et al.*, 2007]. However, streamflow projections for the Colorado, the main river in the SW [e.g., Christensen and Lettenmaier, 2007], differ markedly in their magnitude and these discrepancies have caused considerable concern for water managers. The implications of the inferred changes go well beyond scientific interest [e.g., Gertner, 2007] and there is some urgency in resolving the source of the differences in the projections.

[3] While GCMs are internally consistent with respect to their representation of the water cycle in the land-atmosphere-ocean system, they suffer from coarse spatial resolution. This is especially problematic in topographically complex areas like the western U.S. For instance, within the Colorado River Basin, high elevation headwater areas are disproportionately important to the hydrology of the basin [Gao *et al.*, 2011]. GCMs, which typically use spatial resolutions of several degrees latitude by longitude, smooth the topography and do not capture the high elevations that are associated with these headwater areas. Therefore, GCMs only crudely represent the Continental Divide, a major topographic barrier that forms the eastern boundary of the basin. The climate change simulations by Christensen and Lettenmaier [2007] account for terrain effects because the downscaling method uses bias correction and spatial disaggregation steps that are based on observations. This method has the disadvantage that it implicitly assumes that future climate patterns and mechanisms will be similar to those observed in the past.

[4] One approach to resolving these problems is to use higher resolution Regional Climate Models (RCMs) driven by GCMs at their lateral boundaries [e.g., Leung *et al.*, 2004]. Gao *et al.* [2011] analyzed output from RCM simulations performed by the North American Regional Climate Change Assessment Program (NARCCAP) [Mearns *et al.*, 2009] and found that runoff in the Colorado River Basin is less susceptible to a warming climate in RCMs than in GCMs, primarily because of the inability of GCMs to represent snow accumulation and ablation processes at high elevations. In this paper, we argue, through analysis of the atmospheric moisture budget, that the coarse spatial resolution of GCMs and their resulting inability to represent the effects of topographic blocking is an additional reason for the differences between GCM and RCM simulations for the southwestern United States. Changes in atmospheric moisture convergence are equivalent to changes in P-E, or runoff,

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so our results have direct implications for runoff and drought projections for the southwestern U.S. under climate change.

## 2. Material and Methods

[5] We used four sets of RCM simulations for which sufficient model output was archived to allow calculations of the mean and transient moisture flux convergence (MFC). Mean refers to averaging over time, and transient refers to the deviation from the time mean. All RCM simulations were performed using the Weather Research & Forecasting (WRF) model [Skamarock *et al.*, 2005]. WRF was driven by lateral boundary conditions from four global coupled atmosphere-ocean GCMs: CCSM3 [Collins *et al.*, 2006], CGCM3 [Flato *et al.*, 2000], ECHAM5 [Roesch and Roeckner, 2006], and HadCM3 [Gordon *et al.*, 2000] (W\_CCSM3, W\_CGCM3, W\_ECHAM5 and W\_HadCM3 in short, respectively). The W\_CCSM3 and W\_CGCM3 runs were generated for a North American domain at 50 km grid resolution and archived by NARCCAP [Mearns *et al.*, 2007, 2009]. The W\_ECHAM5 and W\_HadCM3 runs were produced by Salathé *et al.* [2010] and Wi *et al.* [2012] at 36 km and 35 km grid resolution, respectively. Interior nudging was applied to W\_ECHAM5 and W\_HadCM3 to keep the large-scale circulation in the regional simulations close to that of the GCMs providing the boundary conditions. At spatial resolutions between 35 and 50 km, terrain features that influence moisture convergence at the regional or river basin scale are well captured by the RCMs. We analyzed two common time slices of 30 years (1970–1999 and 2040–2069) from each of the four WRF simulations. Although the W\_ECHAM5 and W\_HadCM3 simulations are longer, we used only the periods that were common to all of the model runs. Details about the RCM and GCM simulations used in this study are summarized in Table S1 of the auxiliary material.<sup>1</sup> Readers are referred to the papers cited above and Gao *et al.* [2011] for detailed evaluations of the RCM simulations.

[6] Vertically integrated MFC is equivalent in the long-term mean to net precipitation (P-E), and in turn to river runoff [Seager *et al.*, 2007]. MFC can be partitioned into two components: the MFC associated with the mean flow and the transient eddies. Monthly mean and transient MFC were estimated from the vertically-integrated moisture fluxes, which were calculated based on the 6-hourly winds and humidity at all vertical levels, and surface pressure. We used the same method as Seager and Vecchi [2010] and Seager *et al.* [2010] to calculate MFC, except that we used 6-hourly rather than daily data for the analyses of both GCMs and RCMs. Comparisons of 6-hourly and daily computations for one of the GCMs (ECHAM5) used both by Seager and us confirmed that the results were similar.

[7] To prevent mass conservation problems introduced in the post-processing stage of the analysis [Trenberth, 1991], we adopted the approach of Berbery and Rasmusson [1999] and performed our analyses in the archived model coordinate system at full horizontal resolution and standard pressure levels. The MFC calculations still yielded non-negligible residuals (i.e., imbalance between MFC and P-E), especially for ECHAM5 and CCSM3, but the MFC changes are mostly

not correlated with or affected by the residuals (not shown). Despite the residual between MFC and P-E, we argue that the MFC is nonetheless usable to estimate water cycle changes over land. For presentation and comparison purposes, we regridded the final MFC values to a common grid with a spatial resolution of 2.5-degrees.

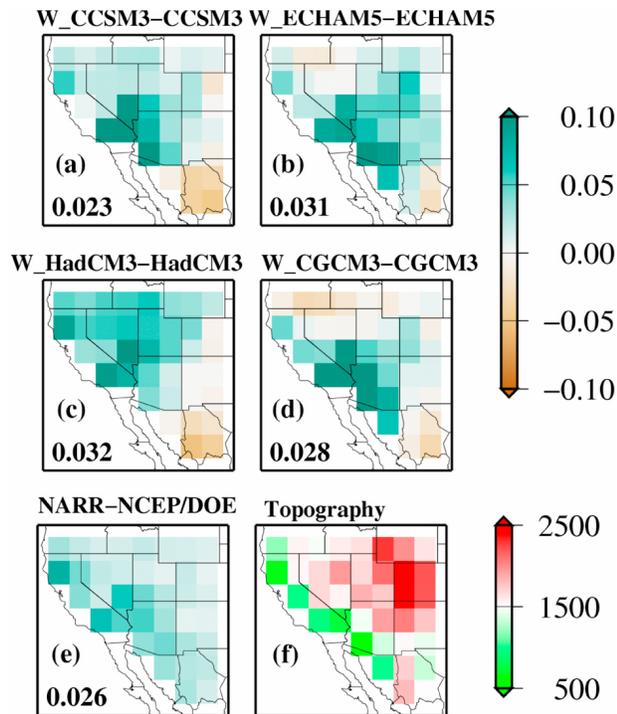
## 3. Results

[8] As discussed by Seager and Vecchi [2010] and also supported by our analysis, the future drying in the SW is driven primarily by reductions in P-E during winter, because P-E is largely unchanged in the summer as the multi-model ensemble means of both P and E are reduced in the future. To understand possible differences in the drying projected by GCMs and RCMs, we compare the GCM and RCM simulated P-E during the winter season. In general, the mean and transient eddy MFC contribute differently to the climatology of annual P-E over the SW. In all of the RCMs and GCMs, positive annual P-E (hence runoff) arises from a balance between the transient eddies corresponding to Pacific storms which converge moisture, and the mean flow which diverges moisture due to the influence of the subtropical high pressure system. This is especially clear during winter. Stated otherwise, the storm tracks keep the climatology of P-E positive in winter, which maintains a positive P-E year round. This is consistent with the NCEP/NCAR reanalysis, which is a plausible surrogate for historical moisture fluxes over the region [Anderson *et al.*, 2004].

[9] Given the importance of transient eddy MFC on the moisture budget of the SW and the coarse resolution of GCMs, it is imperative to ask whether transient eddy MFC can be realistically simulated in the SW where topography provides a dominant mechanism for vertical uplift and converging atmospheric moisture. Figures 1a–1d show the difference in westerly transient moisture flux fraction between RCMs and their host GCMs for the period 1970–1999. The RCM results are plotted at a resolution comparable to that of the GCMs to highlight the impacts of RCM resolutions on MFC at the scales of the GCMs. For all RCM-GCM pairs, the RCMs simulated higher ratios of westerly transient moisture flux to the total (mean plus transient) moisture flux than their GCM counterparts. Figure 1e shows that similar differences exist in the westerly moisture flux in the North American Regional Reanalysis (NARR) [Mesinger *et al.*, 2006] with 32-km resolution relative to the National Centers for Environmental Prediction/Department of Energy reanalysis (NCEP/DOE) [Kanamitsu *et al.*, 2002] with 2.5-degrees resolution. All the high resolution models show an enhanced westerly transient moisture flux, which is most apparent west of topographic barriers such as the Sierra Nevada and the Rocky Mountains. These topographic barriers interact with the large scale flow to generate more hydrodynamic instabilities and transient variability, which produce mesoscale transient features that can be better resolved at higher spatial resolution.

[10] Figure 2 shows the winter-time changes in the mean and transient eddy moisture flux convergence as well as their sum (total) as simulated by RCMs and GCMs for 2040–2069 compared to 1970–1999. Changes in the column integrated moisture and total and transient moisture flux are included in the auxiliary material as a reference. Figure 2 shows that for all four of the host GCMs used in our analysis, the mean moisture flux divergence is intensified in

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2012GL051560.



**Figure 1.** (a–e) Distribution of the wintertime differences in the westerly transient moisture flux fraction (transient moisture flux / (mean + transient moisture fluxes)) between RCM and GCM simulations and (f) topography (units: m) over the SW. Blue indicates more transient moisture fluxes in the RCM output compared to GCM output. Numbers in the left-bottom corner of Figures 1a–1e are the domain average differences in the westerly transient moisture flux fraction.

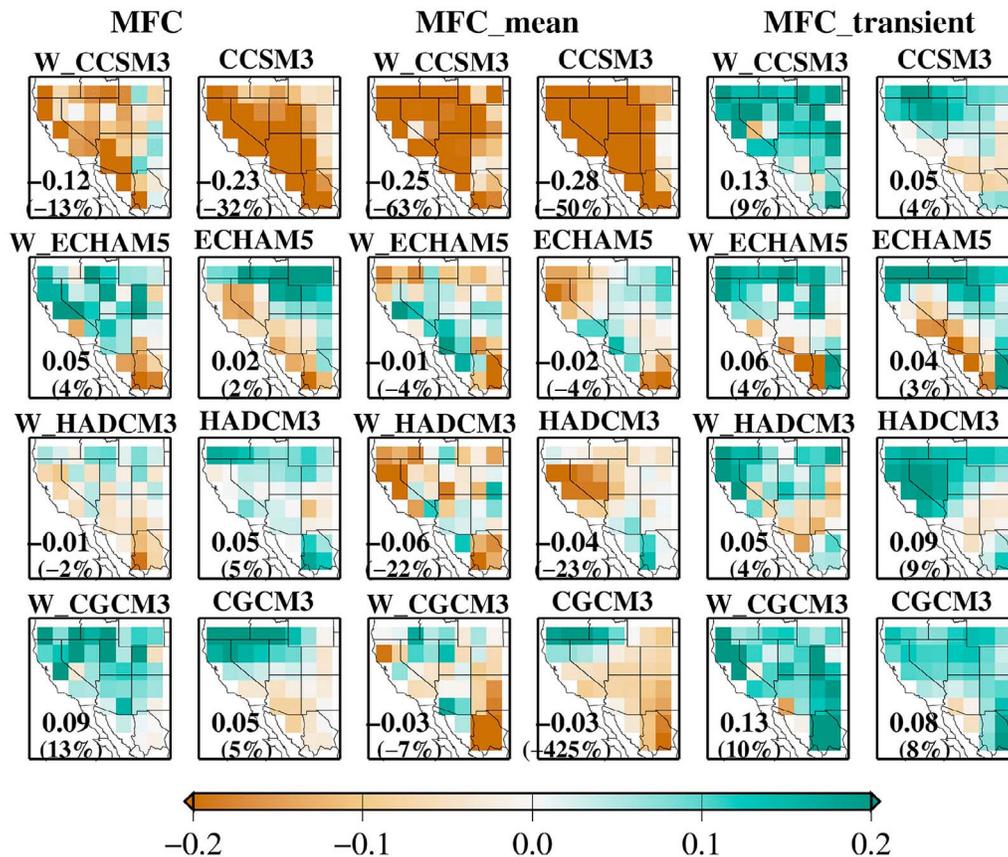
winter under warming due to strengthening or poleward expansion of the subtropical high that diverges atmospheric moisture in the American Southwest. This is consistent with the mean moisture flux divergence over the SW from 15 GCMs used by *Seager et al.* [2010] and *Seager and Vecchi* [2010]. Differences in the reduction of mean MFC are quite large among the four GCMs. Changes in the mean MFC from the RCMs track the changes simulated by the GCMs, but with variations. For instance, whereas W\_CGCM3 predicts about the same decrease as CGCM3, W\_CCSM3 and W\_ECHAM5 predict smaller reductions compared to their forcing GCMs when averaged over the SW. W\_HADCM3 predicts a larger decrease in the mean moisture flux convergence than HADCM3 across the entire SW. Although there are slight differences between RCMs and GCMs in terms of mean MFC change, all RCMs and GCMs project decreases in the mean MFC (third and fourth columns of Figure 2). The decrease in the mean MFC over the SW for the RCMs and GCMs is reflective of the robustness of the Clausius-Clapeyron scaling. Even without any change in atmospheric circulation, the increase in water vapor content due to warming leads to drying in regions with divergent mean flow.

[11] *Seager and Vecchi* [2010] and *Seager et al.* [2010] found that P-E reductions in a warmer climate are augmented

in the winter by a reduction in transient eddy MFC related to a shift of storm tracks to the north. However, Figure 2 shows that in all four of the GCMs we used in our analysis, the transient eddy MFC in winter is intensified. W\_CCSM3, W\_ECHAM5 and W\_CGCM3 predict more intensification in transient moisture flux convergence than do their host GCMs. W\_HadCM3, on the other hand, predicts less intensification compared to its host GCM. The general reductions in the transient eddy MFC at the southern edge and intensifications at the northern edge in all GCMs and RCMs are consistent with the poleward shift and intensification of the storm tracks at the northern edge of the subtropics under global warming [*Seager and Vecchi*, 2010; *Yin*, 2005]. However, three of the four RCMs show a larger intensification (west of the Sierra Nevada) or less reduction (southwest of the Rocky Mountains) in transient moisture convergence on the windward side than do the host GCMs. Further decomposition of the transient moisture convergence into zonal and meridional components (not shown) revealed that the zonal moisture flux convergence due primarily to synoptic storm systems propagating from the Pacific Ocean to the Southwest increases or reduces less in three of the four RCMs compared to their GCM counterparts under climate change. The zonal transient eddy MFC change in the RCMs offsets part of the drying due to the mean moisture divergence and the change in meridional transient moisture divergence. This ultimately causes less drying in the RCMs than in the GCM projections.

[12] Given our analysis demonstrating the role of spatial resolution and mountains in enhancing transient eddies (Figure 1), it is important to understand how mountains may modulate changes in transient MFC simulated by RCMs and GCMs. *Frierson* [2006] found robust increases in midlatitude static stability in simulations of global warming by GCMs used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4) [*Intergovernmental Panel on Climate Change*, 2007]. He attributed the increased static stability to increases in moisture content as well as increases in meridional gradient of equivalent potential temperature under global warming. Based on simple arguments using the Froude number, mountain blocking should generally increase in a more stable atmosphere [e.g., *Leung and Ghan*, 1998], resulting in more moisture converging on the windward side of mountains. The general increase in transient MFC in the RCMs compared to GCMs (Figure 2) can thus be explained by the increased atmospheric stability under global warming and the ability of the RCMs to better simulate transient eddies and resolve the mountains to simulate the MFC response to increased mountain blocking.

[13] P-E changes in the seasonal cycle in RCM projections track those in the host GCMs (not shown). Consistent with the smaller reduction or larger increase in total MFC (Figure 2) in the RCMs compared to the GCMs during winter, the RCMs predict smaller P-E changes on an annual basis than their host GCMs, except W\_HadCM3/HadCM3, because winter changes in MFC dominate annual P-E changes in the SW. Taken over all RCM/GCM pairs, projected changes in P-E from the RCMs indicate that the SW may be less susceptible to enhanced drought under a warming climate than is indicated by the GCMs. Furthermore, winter season P-E changes, which are reflective of



**Figure 2.** Distribution of wintertime changes in the vertical-integrated MFC, the mean MFC (MFC\_mean) and the transient eddy MFC (MFC\_transient) for 2040–2069 as compared to 1970–1999. Numbers in the left-bottom corner are the domain average winter changes for annual with RCMs changes in black and GCMs in red (units:  $\text{mm d}^{-1}$  (%)).

large scale storm track changes, generally show smaller changes for the RCMs than for the GCMs.

#### 4. Conclusions

[14] We calculated monthly P-E estimates from the vertically-integrated atmosphere moisture flux convergence from four pairs of WRF simulations and the GCMs that forced them at their boundaries. We evaluated changes in P-E for mid 21st century relative to late 20th century for the four model pairs over the SW. We further investigated causes of P-E changes in the winter season through partitioning of the column-integrated moisture flux transport into mean and transient components. Our key findings are:

[15] 1. The transient eddy flow convergence keeps the climatology of net precipitation positive over the SW. Because of the ability to resolve processes such as orographic uplift and hydrodynamic instability, RCMs simulate a higher fraction of transient moisture flux compared to GCMs. Comparison between regional and global reanalyses, in which spatial resolution is a primary difference, supports our interpretation. As a result, potential changes in transient moisture flux will play a more significant role in assessing SW droughts projected by RCMs than GCMs.

[16] 2. The mean moisture flux divergence intensifies from the late 20th century to the mid 21st century in both RCM and GCM results. However, while the GCMs project

reductions or slight increases in the transient flux convergence, three out of the four RCMs used in this study project larger increases that counter the drying caused by the enhanced mean moisture flux divergence. The larger increase in transient moisture flux convergence is likely related to the increase in static stability projected robustly by the AR4 GCMs [Frierson, 2006], which increases mountain blocking and moisture convergence on the windward side of mountains. The ability of RCMs to better resolve transient eddies and their interactions with mountains allows RCMs to capture the response of transient flux convergence to changes in stability. This leads to reduced susceptibility to hydrological change in the RCMs compared to predictions by GCMs.

[17] In summary, this study suggests that limitations in how GCMs represent terrain and its effects on moisture convergence have important implications for their ability to project future drying in the SW where mountains play an important role in the regional water cycle. To further test the robustness of the RCM/GCM differences, more RCM-GCM pairs will become available from NARCCAP, which can offer additional insights since NARCCAP includes RCMs with different dynamical formulations and physics parameterizations. Comparison of coarse and high resolution GCMs should also be useful for assessing the effects of model resolution on transient moisture fluxes and their changes under global warming.

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