Poleward expansion only dries subtropical land in certain, specific regions and seasons

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The climatology of precipitation on Earth is broadly characterized by a wet tropical belt associated with the rising branch of the Hadley cell, wet mid-latitude belts associated with the northern and southern baroclinic storm tracks, and the dry subtropical belts between that are associated with the descending branches of the Hadley cell.

About a decade ago, researchers noticed that according to multiple zonal-mean metrics, the general circulation seemed to be expanding poleward in subtropical to mid-latitudes (e.g., Seidel et al. 2008 and references therein) and that climate models robustly project this expansion to continue in response to global warming (e.g., Yin 2005; Lu et al. 2007). Critically, this literature expressed concern that reductions in water supplies on the poleward margins of the subtropics would result, as mid-latitude wetness would be replaced by subtropical dryness. More recent observational studies using modern reanalyses and objective metrics (e.g., Birner 2010; Rikus 2015; Davis and Birner 2017) have broadly confirmed these zonal-mean results, though with reduced magnitude and/or lower confidence, particularly in the Northern Hemisphere.

Yet, no one lives in the zonal mean: the full 2D structure of climatological precipitation is actually quite complicated due to monsoons, topography, and the oceanic subtropical gyres (e.g., Hartmann 2016). This is particularly true in the summer, when several large and strong wet belts diagonally bridge the subtropics, linking the tropical and mid-latitude wet zones together (e.g., Scheff and Frierson 2012a). Also, the projected wintertime storm-track changes are very zonally asymmetric. Thus, it is unclear exactly which places would expect to see precipitation declines from the zonal-mean poleward expansion of the subtropics.

In particular, precipitation decline over *land* is much more consequential for society than precipitation decline over the ocean, because only land-based precipitation creates freshwater resources for human use and because only land-dwelling plants need to be watered. Yet land makes up only a minority of the subtropical surface. Studies such as Seager et al. (2010), Scheff and Frierson (2012a,b), and He and Soden (2016) confirmed that precipitation and precipitation-minus-evaporation are projected to decline across broad regions of the subtropical-to-mid-latitude transition in 2D (not just in the zonal mean), and that these declines are indeed caused by circulation change. However, they did not specifically focus on land, leading them to conclusions that mainly hold over the ocean and are, thus, largely irrelevant to society.

In fact, He and Soden (2016) found that the ocean- and land-based drying are caused by fundamentally different mechanisms. Ocean-based drying is largely a direct consequence of the rise in CO_2 itself, via "fast" ocean-to-land zonal circulation responses. Only the land-based drying (which is quite spatially confined) is significantly caused by planetary warming and the attendant meridional circulation expansion. Thus, we would not expect them to be similar.

Indeed, Schmidt and Grise (2017) showed that in year-to-year variability, land precipitation is only sensitive to the zonal-mean Hadley cell edge latitude in certain specific subtropical regions. That is, most of Earth's subtropical land precipitation is not at all sensitive to Hadley cell width variations as usually measured. So we might expect that the projected expansion of the subtropical dry zones and Hadley cells with global warming will only cause land precipitation to decline in certain, specific regions.

Here, I examine the Scheff and Frierson (2012b) results on robust CMIP5-projected subtropical precipitation declines but with an explicit focus on land precipitation. The broad conclusions of that study about Hadley-driven poleward expansion of subtropical dryness are much less relevant over most of the land than over the ocean. The projections of land-based drying are far less widespread and far less uniformly poleward-expansion driven than implied by that largely ocean-based study.

Interpretation of CMIP5 projections of drying over land

Figure 1 is a reproduction from Scheff and Frierson (2012b). The four maps correspond to the four meteorological seasons (December-February, March-May, June-August, and September-November). On each map, the continents are outlined in cyan. The black curves are contours of climatological seasonal-mean precipitation as simulated by the CMIP5 36-model average. The lightest contour (1 mm/day) encircles the hearts of the subtropical dry zones, the intermediate contour (2 mm/day) broadly separates the dry and wet zones, and the boldest contour (5 mm/day) encircles the tropical wet belt and the wettest parts of the mid-latitude wet belts.

According to the triangular legend at the top, locations where most of the 36 models project precipitation to *significantly decline* with strong global warming (RCP8.5 scenario) are colored in bold red, locations where most models project precipitation to significantly increase are colored in bold blue, and locations where most models project insignificant precipitation changes are colored in white or very light colors. Intermediate intensity and/or purple hues correspond to regions of inter-model disagreement, which are extensive.

In each season, the continents can be carefully examined for regions of robustly projected significant drying (bold red color), which can then be compared to the black climatology contours to assess whether they are likely to be related to poleward expansion of the dry zones.

In December-February (northern winter/southern summer, Figure 1a), land drying is clearly projected in coastal portions of North Africa, the Middle East, and southern Europe in the Mediterranean Basin. This is right on the edge between the Saharan dry zone and the European storm track, so it clearly represents classic subtropical expansion drying. Similarly in Chile, the region between the central drylands and the southern temperate rainforest, where the subtropical flank of the Pacific storm track reaches the continent around 40°S, is projected to dry.

However, these are the only such regions on the planet: no other land areas in the entire Southern Hemisphere are colored bold red in December-February. The other robust southern drying regions, highlighted in Scheff and Frierson (2012b), are simply too far south to affect Australia or Africa. In the Northern Hemisphere, the north coast of South America is projected to dry, but this is located on the equatorward edge of the subtropical dry zone, so it could not be associated with poleward expansion of the circulation.

A region from Mexico into the far southwestern US is also projected to dry in December-February, but this coincides with a spurious feature of the multi-model precipitation climatology that is not present in reality: a wet belt extending meridionally from the East Pacific

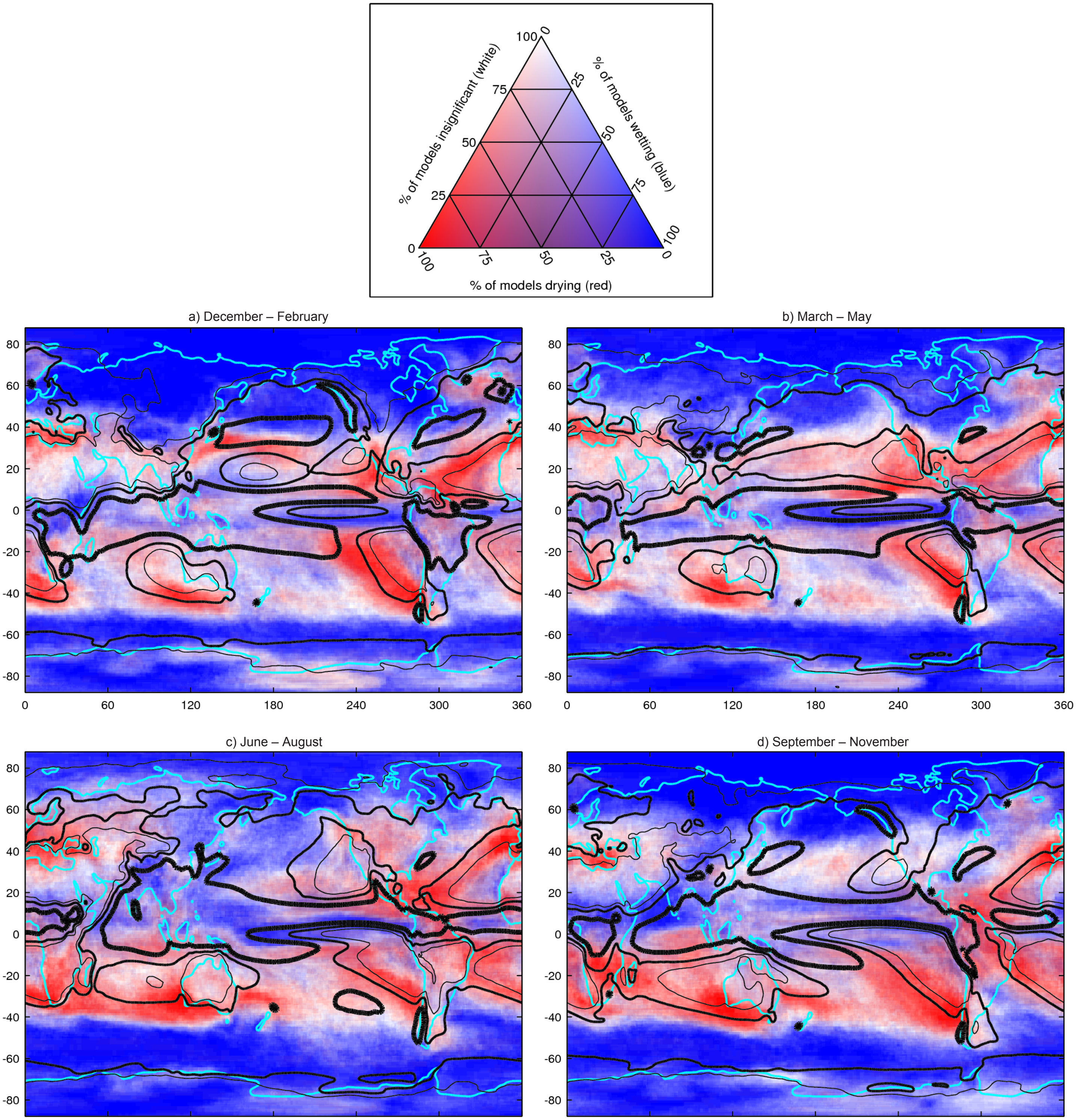

Figure 1. In each season, black contours are the 1980–1999 CMIP5 multi-model climatological precipitation (1, 2, 5 mm/day, going from lightest to boldest). At each point, the colored shading shows the proportion of CMIP5 models for which the RCP8.5 1980–2099 seasonal precipitation trend in the native model gridbox containing that point is negative and significant (red), positive and significant (blue), or insignificant (white), according to the legend. Significance level is 5%.

Intertropical Convergence Zone (ITCZ) across much of Mexico to the beginning of the Atlantic storm track over the northern Gulf of Mexico coast. In actuality, this region receives extremely little precipitation in winter (generally less than 0.3 mm per day, as opposed to the substantial >2 mm per day simulated by the models). So the models are projecting the drying of a feature that does not really exist. In contrast, there is no robust drying projected at the poleward edges of the two nearby subtropical dry zones in California and Central America.

In March-May (northern spring/southern autumn; Figure 1b), the Mediterranean and Chilean poleward-expansion drying regions are still very apparent, and both are shifted somewhat north relative to December-February. Another small but clear poleward-expansion land drying region appears in parts of the western US and far northwest Mexico (well to the northwest of the spurious December-February drying), at the northern apex of the Pacific subtropical dry zone, or southern flank of the western US storm track. However, those are the only substantial robust land-based drying regions on Earth projected for March-May. The vast majority of subtropical land is not robustly projected to dry in this season, by any mechanism. There is a hint that robust drying may extend to the extreme southwest tips of Africa and Australia in this season, but it is not clear.

In June-August (northern summer/southern winter, Figure 1c), there are more regions of projected land drying. The Mediterranean poleward-expansion drying now encompasses much of the European continent, as southern European summer dryness replaces northern European wetness. The Chilean poleward-expansion drying is also still strong. The western North American drying is no longer present, but the South Atlantic and South Indian Ocean poleward-expansion drying belts now finally intersect southwestern Africa (the Cape region) and southwestern Australia in a substantial way.

Drying is also robustly projected well into the interior of southern Africa, but again this region receives essentially no winter rainfall (in the models or in reality), so it is inconsequential. Drying is projected across much of Central America and (less robustly) in the far-western Sahel and northeastern South America, but these are again located on the equatorward edges of the dry zones rather than the poleward edges, so could not be caused by poleward circulation expansion.

Finally, in September-November (northern autumn/ southern spring; Figure 1d), a couple of interesting new projected land-drying regions emerge. The classic Mediterranean, Chilean, far south/southwest Australian, and Cape African poleward-expansion-driven areas are still apparent. However, there is also very robust drying projected in the interior of southern Africa around 10-25°S (which now receives substantial rain, unlike in winter) and somewhat robust drying projected in tropical northeast Brazil.

Both of these latter responses might also possibly be caused by poleward expansion of the circulation: the southern African drying is located at a "saddle" in the precipitation field where mid-latitude precipitation reaches equatorward, and the northeast Brazilian drying is located on the poleward/westward side of the South Atlantic dry zone, where it grades into the wet South Atlantic Convergence Zone. However, they are both located in tropical latitudes and substantially affect tropical rather than mid-latitude precipitation, so it is not clear whether poleward expansion of the Hadley cell edge could physically cause them.

Synthesis and discussion

Robustly projected reductions in *land* precipitation that are likely caused by the *poleward expansion of the atmosphere's general circulation* are confined to very specific regions (and often very specific seasons). These consist of the Mediterranean/European area and Chile all-year round (further poleward in the local warm season and further equatorward in the local cool season); a modest portion of interior western North America in local spring only; extreme southwestern Africa (the Cape region) and extreme southwestern/southern Australia in local winter, spring, and possibly fall; and possibly interior southern Africa and northeast Brazil in local spring. Many (but not all) of these are located in Mediterranean, winter-rain climate zones, as one might expect. Many also correspond to the specific regions highlighted by Schmidt and Grise (2017) where the zonal-mean Hadley cell's edge latitude is strongly correlated with local land precipitation in year-to-year variability and to the specific regions found by He and Soden (2016) where subtropical drying is caused by warming, rather than by direct CO_2 effects.

Other regions/seasons of robustly projected subtropical land drying are clearly unrelated to poleward expansion (e.g., Central America in local summer) and/or are likely spurious (e.g., Mexico and vicinity in local winter). In fact, Figure 1 shows that the vast majority of subtropical land is *not* robustly projected to be affected by poleward-expansion related drying: the North American subtropics outside of the specific area mentioned above, the South American subtropics east of the Andes, the vast African and Australian subtropical belts outside of the small coastal zones highlighted above (with the possible exception of interior southern Africa in spring), and the entire Asian subtropics. This was noted to some degree in Scheff and Frierson (2012b) but not explicitly. This also parallels the conclusion from Schmidt and Grise (2017) that precipitation over most subtropical land gridpoints is not at all correlated with the zonal-mean Hadley cell edge latitude. Over land, projections for precipitation-minus-evaporation are broadly similar to precipitation projections but weaker and much less robust (Scheff et al. 2017), so using precipitation-minus-evaporation instead of precipitation would not be likely to yield additional robust drying areas.

Why does the poleward expansion of the circulation with warming fail to broadly and robustly dry subtropical land in CMIP5 projections? The most basic reason may be that the fully 2D subtropical dry zones are preferentially located over the oceans (black contours in Figure 1), so that their poleward expansion disproportionately affects precipitation over oceans. Indeed, most of the land poleward-expansion drying regions listed above are simply downstream (eastward) continuations of much larger poleward-expansion drying regions over the ocean.

However, Figure 1 also shows that there are still vast regions over land that are clearly in the transition belts between subtropical dry zones and mid-latitude wet zones yet are not robustly projected to become drier with global warming. These include (among other regions) the American West in seasons other than springtime, most of southern Australia, much of subtropical South America, and almost all of Central Asia. Many of the subtropical-to-mid-latitude transition belts over the ocean do not robustly dry with warming either, such as in the North Pacific for most of the year. Thus, the lack of poleward-expansion drying over much of land is also simply because a zonal-mean subtropical expansion or zonal-mean storm-track shift does not imply that these features move poleward at *every* longitude but just at some. In addition, He and Soden (2016) found that the direct effect of CO_2 increase is to reduce precipitation over parts of the subtropical oceans but *increase* precipitation over parts of the subtropical land, offsetting part of the poleward-expansion induced drying that might otherwise be expected on land.

In conclusion, despite earlier studies tacitly implying that the poleward expansion of the general circulation would cause a broad reduction in water supplies on the poleward edges of the subtropical dry zones, such projections are actually quite spatially and seasonally confined in multi-model CMIP5 output over land. This discrepancy arises from key climatological and climate-response differences between the land (where precipitation matters to society) and the ocean (where most of the earlier 2D studies were effectively focused), as well as from the basic fact that a zonal-mean response does not imply a similar response at each longitude or even at most longitudes. Future work should seek to better understand this zonal asymmetry by uncovering the key dynamical mechanisms for tropical expansion and the ways that those mechanisms are expressed in latitude-longitude space, neither of which is well understood today.

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