

Greenhouse warming and the 21st Century hydroclimate of southwestern North America

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Climate models robustly predict that the climate of southwestern North America, defined as from the western Great Plains to the Pacific Ocean and from the Oregon border to southern Mexico, will dry throughout the current century as a consequence of rising greenhouse gases. This regional drying is part of a general drying of the subtropics and poleward expansion of the subtropical dry zones. It is shown that the drying is driven by a reduction of winter season precipitation associated with increased moisture divergence by the mean flow and reduced moisture convergence by transient eddies. Observations to date cannot confirm that this transition to a drier climate is already underway due to the presence of large amplitude decadal variations of presumed natural origin but it is anticipated that the anthropogenic drying will reach the amplitude of natural decadal variability by mid-century. In addition to this drop in total precipitation warming is already causing a decline in mountain snow mass and an advance of spring snow melt disrupting the natural water storage systems that are part of the regions water supply system. Uncertainties in how radiative forcing will impact the tropical Pacific climate system create uncertainties in the amplitude of drying in southwest North America with a La Niña-like response creating a worst case scenario of greater drying.

southwest drying | climate change | decadal variability | hydrological cycle

Abbreviations: ENSO, El Niño-Southern Oscillation; SWNA, Southwestern North America

The 24 climate models used as part of the Intergovernmental Panel on Climate Change Assessment Report Four (IPCC AR4) robustly predict that southwestern North America (SWNA), a region defined as stretching from the high Plains to the Pacific Ocean and from the latitude of the California-Oregon border to southern Mexico, will dry throughout the current century as a consequence of rising greenhouse gases (1,2). The drying is manifest as a drop in precipitation (P) minus evaporation (E), $P - E$, driven by a decline in P , or equivalently as a drop in surface and groundwater runoff. Figure 1 shows the 24 model median P , E and $P - E$ for SWNA and the 25th and 75th percentiles of the spread of $P - E$, for 1900-2100 using the simulations with historical forcings (greenhouse gases, aerosols, solar variability etc.) and the SRESA1B 'middle of the road' projections of future emissions. In the winter half year P drops beginning around 2000 and E increases, probably due to increased melting and evaporation or sublimation of snow mass associated with warming. Hence the drop in $P - E$ modestly exceeds the drop in P . In the summer half year both P and E drop and $P - E$ is relatively stable over time. These changes indicate that the drying of SWNA is driven by a reduction of winter season precipitation with the summer P and E drops probably caused by reduced soil moisture inherited from the prior season. If these changes in $P - E$ come to pass they will lead to reduced surface moisture and river flows and stress water resources in an already water scarce region with troublesome consequences for the states of the southwest U.S. as well as for Mexico.

Declining P is not the only one of SWNA's water woes. Rising temperatures are leading to a shorter snow season with later onset and earlier snowmelt and more winter precipitation falling as rain instead of snow (3,4,5). Many western states rely on winter snowpack as a natural means of water storage whose gradual melt can be captured in reservoirs in spring and summer. Warming-induced changes in snow

hydrology can therefore disrupt existing systems for water supply in the summer season of high use.

The likely considerable impact of changes to the hydroclimate of SWNA make it essential to determine if the model projections are correct and, if so, whether anthropogenic drying is already occurring. However it is also the case that SWNA is subject to large amplitude natural variability on interannual to multidecadal timescales and these will continue to impact SWNA whatever climate change may bring. It turns out that SWNA, during the decades of the 1980s and 1990s when the population of the southwest U.S. grew tremendously, benefited from a mostly wetter climate that was induced by the 1976/77 warm shift in the tropical Pacific Ocean (6). That warm phase of Pacific Decadal Variability (PDV) may have ended after the 1997/98 El Niño, after which more La Niña like conditions have prevailed along with a widespread shift to a drier SWNA. Hence, to predict the future hydroclimate of SWNA, we also need to know what natural decadal variability will bring and how this will compete with or augment anthropogenic drying.

In this paper we will examine the mechanisms that lead to SWNA drying in climate models and assess the extent to which we can determine if anthropogenic drying is already occurring. We will show how very different modeled responses of the tropical Pacific climate system to radiative forcing (in particular shifts towards stronger or weaker zonal SST gradients) lead to varying degrees of drying of SWNA. We will also briefly review the state of knowledge of local radiative forcing of the regional hydrological cycle and the potential for ecosystem responses to alter SWNA hydroclimate.

Causes of model-projected drying in southwestern North America

As shown by the maps in Figure 2, model-projected drying of SWNA is part of a planetary-scale change in the hydrological cycle with the deep tropics getting wetter, the subtropics getting drier and the higher latitudes also getting wetter. This 'dry getting drier and wet getting wetter' pattern has to first order been explained by Held and Soden (7). Their idea can be simplified as follows. Within the atmosphere, $P - E$ is balanced by the divergence of the time-averaged, column-integrated moisture flux F , viz.

Reserved for Publication Footnotes

$$\rho_w g(P - E) = -\nabla \cdot F = - \int_0^{p_s} (\bar{\mathbf{u}} \cdot \nabla \bar{q} + \bar{q} \nabla \cdot \bar{\mathbf{u}}) dp - \int_0^{p_s} \nabla \cdot (\overline{\mathbf{u}'\mathbf{q}'}) dp. \quad [1]$$

Here \mathbf{u} is the vector wind and q is humidity, p is pressure, with p_s its surface value, g is the acceleration due to gravity and ρ_w is the density of water. Overbars indicate the time mean flow and primes departures from the time mean, that is, transient eddy quantities. Regions of moisture convergence have an excess of P over E and vice versa. It is expected that q will increase with temperature T as the atmosphere can hold more water vapor according to the Clausius-Clapeyron relation. Held and Soden then assume that F will also increase with T according to Clausius-Clapeyron scaling such that $\delta(P - E) \propto (P - E)\delta T$. That is, the existing pattern of $P - E$ will be enhanced with already wet (dry) areas getting wetter (drier). As Held and Soden show, this simple argument explains a remarkable amount of the model-projected global pattern of $P - E$ change, including widespread subtropical drying where the current mean $P - E$ is negative.

However $P - E$ is, in general, positive everywhere over land. This is because, unlike the ocean, the land surface is not a reservoir of water that can sustain whatever evaporation is needed to meet atmospheric demand. Instead $P - E$ is bounded by zero where P is very small and a dry surface sustains no evaporation, such as in the middle of deserts, and, elsewhere, positive $P - E$ for a catchment area is balanced, in equilibrium, by river flow to the oceans. Consequently the simple Held and Soden relation predicts an increase in $P - E$ over all land (see their Figure 7) and we must extend their argument to explain continental drying.

The complicated topography of the American Southwest makes it difficult to accurately determine the means by which the atmosphere supplies moisture to the region to sustain positive $P - E$. However, using the available data within the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis shows that positive $P - E$ in the winter season arises from a balance between transient eddies converging moisture (the third term in the final equality of Eq. 1) while the sum of the two mean flow terms (the first and second terms in the final equality of Eq. 1) diverge moisture. Negative $P - E$ in the summer season is driven by the mean flow moisture divergence. Because summer $P - E$ is negative, summer season P must be sustained by the evaporation of moisture stored in the ground from the previous season of positive $P - E$ (Anderson et al. (8) have arrived at a similar conclusion). The $\bar{q}\nabla \cdot \bar{\mathbf{u}}$ component of the mean flow moisture divergence will increase with global warming as atmospheric humidity increases even if there is no change in the mean flow and this could, potentially, promote more negative $P - E$. Figure 1 makes clear that $P - E$ is largely unchanged in summer as both P and E drop and hence it is the winter season drop in P that needs to be explained.

To calculate the change in modeled moisture budget requires daily data for winds, humidity and surface pressure at a minimal vertical resolution. Such data was only available for 12 of the 24 models within AR4¹. Figure 3 shows the mean for these models of the change in winter half year $P - E$, the two mean flow terms and the transient eddy moisture convergence. The mean flow moisture divergence term, $\bar{q}\nabla \cdot \bar{\mathbf{u}}$, strengthens in the 21st Century and contributes strongly to winter drying. This term is itself dominated by the contribution from rising humidity within a divergent mean flow and corresponds to the mechanism for subtropical drying proposed by Held and Soden, whose theory, with some modification can therefore apply over land as well as ocean.

The winter drying is assisted by a reduction in transient eddy moisture convergence. This is consistent with a poleward spreading and intensification of the Pacific storm track, part of a general poleward shift of the storm tracks under global warming (9). Strengthening is

consistent with the meridionally broad warming of the tropical and subtropical middle and upper troposphere which increases the vertically integrated meridional temperature gradient under global warming. The poleward broadening may be consistent with the way that changes in the meridional structure of static stability influence the refraction of transient eddies. The center of the storm track is roughly co-located with the maximum poleward moisture transport. Hence a stronger North Pacific storm track will increase the moisture transport, drying on its southern flank and moistening on its northern flank (Figure 3). The poleward shift will extend the region of drying poleward.

These results were for the 'middle-of-the-road' SResA1B emissions scenario but actual emissions in recent years have been exceeding IPCC's worst case scenario. Climate change in the coming years to a few decades is not too dependent on actual emissions trajectories because of system lags but continuation of current emissions will clearly lead to stronger drying in the latter half of the current century than illustrated here from A1B. Further, even if emissions were hypothetically reduced to zero in coming years a notable level of drying will still occur due to irreversible (on the timescale of centuries) aspects of the carbon cycle with the drying being worse the longer the move to zero emissions is postponed (10).

Is anthropogenic drying of the southwest already occurring?

Following the 1997/98 El Niño the southwest U.S. and Mexico experienced a multiyear drought as severe as any in the instrumental record (11). The drought reached its height in 2004, by which time Lakes Mead and Powell on the Colorado River were reduced to being half full, but despite amelioration, drought conditions have troubled some parts of SWNA ever since with, at the time of writing in September 2009, California and Texas in the most serious condition. Trends in climate are often computed over the post 1979 period because global satellite data, including for precipitation, begin at about that time. A post 1979 trend shows strong drying of SWNA. However, over that same period, the trend in SST shows, amidst widespread warming, a cooling of the eastern and central tropical Pacific Ocean. The tropical Pacific SST cooling is because the 1979 to 1997/98 period was a warm phase of Pacific Decadal Variability (12) and since the 1997/98 El Niño conditions have been more La Niña-like with no strong El Niño events.

Figure 4 shows the observed trend in the blended satellite-gauge precipitation as reported by the Global Precipitation Climatology Project, the 24 model ensemble mean IPCC AR4 simulated (to 1999) and projected (2000 on) trend and the trend from a simulation with the National Center for Atmospheric Research Community Climate Model 3 forced by the observed SSTs in the tropical Pacific alone and which computes SSTs elsewhere using a simple mixed layer ocean model, all for the 1979 to 2007 period. Clearly the observed drying over SWNA is in excess of what the 24 models predict should have occurred as a consequence of changes in radiative forcing alone. In contrast, the model forced by observed tropical Pacific SST changes produces a drying closer to the magnitude of that observed. Consequently it is the observed trend towards La Niña conditions that is responsible for the post 1979 drying of SWNA which is consistent with a lot of recent work that shows that persistent La Niña-conditions promote drought in SWNA (11,13,14). The observed SST trend contrasts with the more spatially uniform SST trend in the ensemble mean of the AR4 models. These results suggest that the observed drying of SWNA

¹Our focus here is on near term climate change, defined as the coming years to a decade or two. However IPCC AR4 made daily model data only available for some years and hence Figure 3 uses 2046-2065 and 1981-2000, different periods from Figure 2. It should be noted that it is not possible to obtain a balance in the moisture budget because the data has been regridded from the original model grids, different numerical schemes are used in the budget calculation, and, most importantly over mountains, the models do not report humidity tendencies due to diffusion.

in recent decades is primarily a result of natural decadal variability of tropical Pacific SSTs. Indeed a similar 30 year trend of SWNA drying and central and eastern tropical Pacific cooling occurred across a presumed earlier shift point in Pacific decadal variability in the early to mid 1940s.

Predicting near-term future hydroclimate change in the

Southwest: natural variability and forced change

The broad agreement amongst the 24 models participating in AR4 that SWNA will dry in the current century arises from this being such a fundamental feature of a warming climate appearing even in idealized global atmosphere models with no surface inhomogeneities whatsoever when the opacity to longwave radiation is increased (15). However, post-1979 climate change makes clear that, while global warming will dry the SWNA, the future hydroclimate of SWNA will also depend, to an important extent, on the pattern of SST change. Over the coming years to decades tropical SST patterns will change due to the continuing evolution of natural modes of variability and because radiative forcing could induce non-uniform changes in SST.

Future evolution of natural variability. The 1976/77 shift to more El Niño-like conditions in the tropical Pacific heralded a wet two decades in SWNA, and an apparent opposite sign shift in the 1940s, suggest that these are part of Pacific decadal variability (PDV). It cannot be stated with confidence, but it is looking as if the 1997/98 shift to more La Niña like conditions is the latest in these decadal shifts (as was predicted by (16)). If so then it would be expected that SWNA will remain overall drier than in the 1980s and 1990s for reasons of purely natural atmosphere-ocean variability. However, as long as the causes of PDV remain unknown, and in the absence of predictions with realistic and comprehensive coupled models (as opposed to that used in (16)), it would be rash to claim this with any confidence. Similarly a warm tropical North Atlantic Ocean promotes drought in SWNA (17, 18). Atlantic SSTs have varied on multidecadal timescales over the last century (19,20) with a warm spell lasting from about 1930 to 1960 which model simulations indicate contributed to the 1930s and 1950s droughts (21). After a cooler spell the Atlantic basin has warmed again since about 1990 and, given the timescale of these SST anomalies, it is plausible that warm anomalies will persist for some time (22) contributing to dry conditions in SWNA.

The spatial pattern of the SST response to greenhouse gas forcing. It is striking that the great North American droughts of the 19th and 20th centuries were caused by very small SST anomalies, no more than a fraction of a degree Centigrade (13,14). Consequently, although global warming will change the mean temperature by a few deg C in the current century, small spatial asymmetries in the pattern of SST change could have large consequences for regional hydroclimate. This makes the issue of how the tropical Pacific climate system responds to radiative forcing potentially important. Theories have been advanced for why the Pacific should adopt a more La Niña-like state (23) or a more El Niño-like state (24) and exactly what nature has done over the past century, and what models project for the future, seems to be a result of multiple, coupled, processes in the tropical atmosphere and ocean (25,26,27).

Figure 5 shows the importance for global patterns of $P - E$ of how the equatorial Pacific east-west SST gradient changes. The 24 IPCC AR4 models were divided into two composites, one with an increase (in 2021-2040) in the gradient of more than 0.1 deg C (6 models) and one with a reduction of the gradient of more than 0.1 deg C (6 models). Both composites show subtropical drying including in the SWNA region (arising as a consequence of the overall global warming) but the more La Niña-like composite has considerably more drying than the more El Niño-like composite. This is presumably because the drying caused by overall warming has been added to by a

drying caused by a circulation change akin to that occurring during La Niña induced droughts. (With only one exception, the models within the composites retained these changes in SST gradient throughout the current century indicating that the gradient changes are a response to forcing as opposed to decadal variability.) This result is quite alarming because it makes clear that the near term future hydroclimate of SWNA will depend on tropical Pacific climate change but the current generation of climate models simulate the tropical Pacific very poorly (28) and our confidence in their widely varying projections is essentially non-existent.

Most models project that the North Atlantic Ocean should warm by less than other regions during the current century in part due to the influence of mean speed on the SST response to radiative forcing (29) and also to a weakening of the Atlantic meridional overturning circulation. Such a change in SST pattern would act akin to a cold phase of Atlantic decadal variability and offset to some degree global-warming induced drying in SWNA. Consequently, over the coming years to decades, SWNA hydroclimate on the interannual to multidecadal timescale will be impacted by 1) overall warming, 2) the specific spatial pattern of radiatively forced SST change, 3) Pacific decadal variability and 4) Atlantic decadal variability. For the coming years to decades these processes will be of roughly equivalent amplitude and the natural variability will ensure that the transition to increased aridity will not be as smooth as it appears in the IPCC model mean shown in Figure 1.

Impacts of rising temperatures on snowpack and runoff

Winter snowpack is a major means of natural water storage across the western United States and spring and summer melt releases water at times when economic, recreational and environmental demand is high (3,4). The timing and magnitude of snowmelt can also influence the frequency and intensity of forest fires (30). Over recent decades western snowpack has declined and the spring snowmelt has become earlier which has been attributed to increases in surface temperature (3,4,5,30). The resolution of global coupled climate models used in the IPCC AR4 is insufficient to project the details of snow accumulation changes in the complex orography of the SWNA. However, details aside, the robust projections of reduced wintertime precipitation in SWNA and warming surface temperatures in response to greenhouse gas increases provides a strong basis from which to project a long-term further reduction of total snowpack and still earlier release of spring and summer meltwater to rivers during this century. A further complication is that the rate and timing of snowmelt can also be influenced by the rate of deposition of desert dust on snow which reduces its albedo. The arid regions of SWNA are a major source of dust to the Rockies, and the projected drying could lead to increased dust deposition that will exacerbate the snowpack reduction driven by temperature increases (31).

Potential impacts on runoff of vegetation feedbacks

The IPCC AR4 projections did not consider the possible impacts on land surface hydrology of changes in vegetation whether induced by climate change, land use change, or rising CO_2 . However changes in vegetation could be important by impacting evapotranspiration and runoff rates, as well as the rate of desert dust erosion. Increasing atmospheric CO_2 can cause partial closure of plant stomata and reduce the rate of evapotranspiration (32). However increasing CO_2 could also lead to an increase in foliage area and, therefore, an increase in evapotranspiration (33). The relative strength of these competing impacts on how precipitation is balanced by runoff and evapotranspiration are uncertain but one recent study suggests vegetation dynamics dominate leaf processes and that rising CO_2 is causing a reduction in runoff (33). The impact of these factors will be mediated to a large degree by the overall changes to vegetation cover, rooting depth etc. (34). Increases in surface temperature and reductions in water avail-

ability will stress the native plants of SWNA (35) which will be potentially offset to an uncertain degree by CO_2 fertilization (e.g. (36)). The vegetation change will then subsequently impact the precipitation but model studies that explore this interaction yield conflicting results (36–38). Nonetheless the amplitude of the modeled changes in precipitation caused by vegetation feedbacks in these studies are substantially smaller than the climate-driven reductions in precipitation. Further there is little basis to hope that vegetation response to rising CO_2 will allow runoff to be maintained as GHG-induced reductions in precipitation progress.

Conclusions

Models project that SWNA will dry in the current century with the drying reaching the amplitude of past multiyear droughts by mid-century. The drying is driven by a winter decrease in precipitation associated with increased moisture divergence by the mean flow, largely a consequence of rising humidity in a divergent flow, and reduced moisture convergence by transient eddies. The latter is associated with a strengthening and poleward spread of the winter Pacific storm track. These changes arise as a consequence of overall global warming its impact on storm track location and intensity. However SWNA hydroclimate is strongly influenced by natural decadal variability in the Pacific and Atlantic Oceans. Our best estimates, which are quite uncertain, are that modes of Pacific and Atlantic decadal variability are currently in phases that promote drought in SWNA and these oceanic conditions can be expected to last for years to come. Given that, in addition, anthropogenic drying will strengthen as the years go by, this combination of natural variability and forced change make it unlikely that SWNA will ever return to the moist climate of the two decades immediately before the 1997/8 El Niño. What is more, there is a worst case scenario in which a forced La Niña-like response to increased radiative forcing intensifies drying in SWNA. Models are about equally spread between projecting this scenario and a scenario in which more El Niño-like conditions become established and SWNA drying is less dramatic. It is worrying that the future hydroclimate of SWNA will depend in part on the response to radiative forcing of a part of the climate system that is so poorly modeled, where gains in realism seem so hard to come by, and where fundamental gaps in our understanding of climate physics seem to blame.

Despite ample uncertainties in model projections one thing is sure: SWNA will drier in the current century than in that just past. Skillful prediction of the magnitude and timing of this drying will require prediction of the rate of anthropogenic change and prediction of the evolving natural variability for which currently there is scant evidence of any predictability beyond the interannual timescale. Another likely outcome is a continuing decline in winter snowpack and earlier onset of snow melt that will add to the stress on regional water resources. The implications of these hydroclimate changes will vary across the region. For Mexico, though winter precipitation is expected to decline, the future of the North American monsoon, important for water resources and agriculture, will be critical and remains uncertain. Reservoirs in the California Sierra Nevada fall squarely in the region of projected drying. On the other hand the Colorado River gains most of its flow from small regions of high topography around its headwaters which are on the northern boundary of the region of projected P-E decline and predicting how its flow will decline, as it surely will, will require high resolution atmosphere models that can represent the mountains and their ability to harvest snow from winter storm systems.

Much work is ongoing in improving model realism but it will be years before the persistent biases in the tropical Pacific have been corrected and models have accurate and detailed simulations of the North American monsoon and winter snowfall correctly coupled into the global climate system. Despite the limitations of state-of-the-art projections our current understanding of hydroclimate change in SWNA suggests it would be unwise to delay exploring the likely consequences of, and adaptation strategies for, a drying SWNA, particularly as guiding principles of water management become no longer applicable (39). Developing such an adaptation strategy will be complicated by the uncertainties inherent in projections of regional hydroclimate and by the need to weigh the various social, economic and political needs in the region. Delay amid drying could cause potentially severe disruptions to, in the southwest U.S., a hydraulic society that has taken a century to build and, in Mexico, recently developed export-oriented agriculture and industries in the north and water quality and availability across the country.

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Filtered IPCC 24 Model P-E, P and E 1900-2099

P-E Median (red), P-E 25 to 75th (pink), P 50th (blue), E 50th (green)

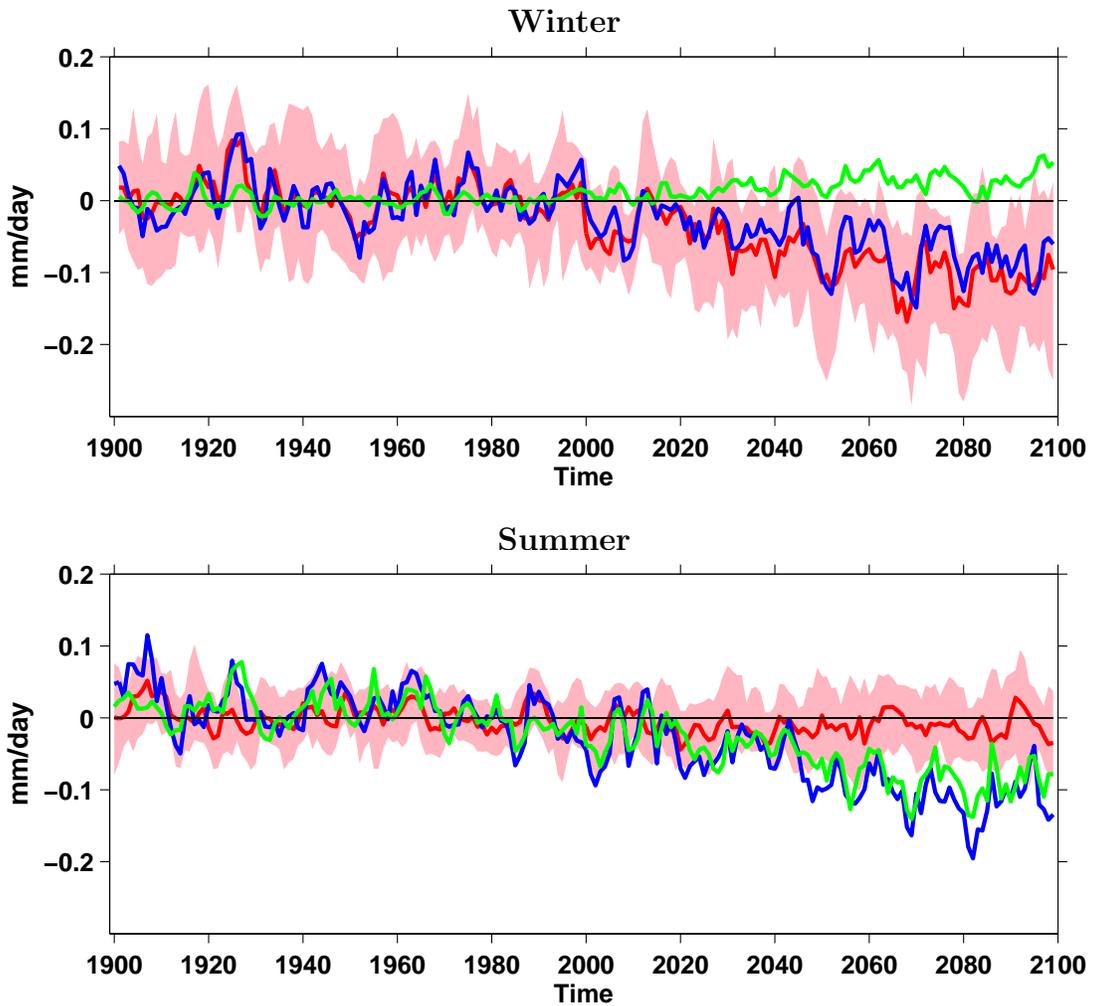


Fig. 1. Time series for 1900-2099 of the median of 24 IPCC AR4 models' simulated and projected change in $P - E$ (red), with 25th and 75th percentiles of the distribution (shading), P (blue) and E (green) for the winter (Oct-Mar, top) and summer (Apr-Sep) half years and averaged across the SWNA land region, relative to 1950-1999 climatologies. Units are mm/day

24 Model Mean IPCC P-E (2021 to 2040) - (1950 to 1999)

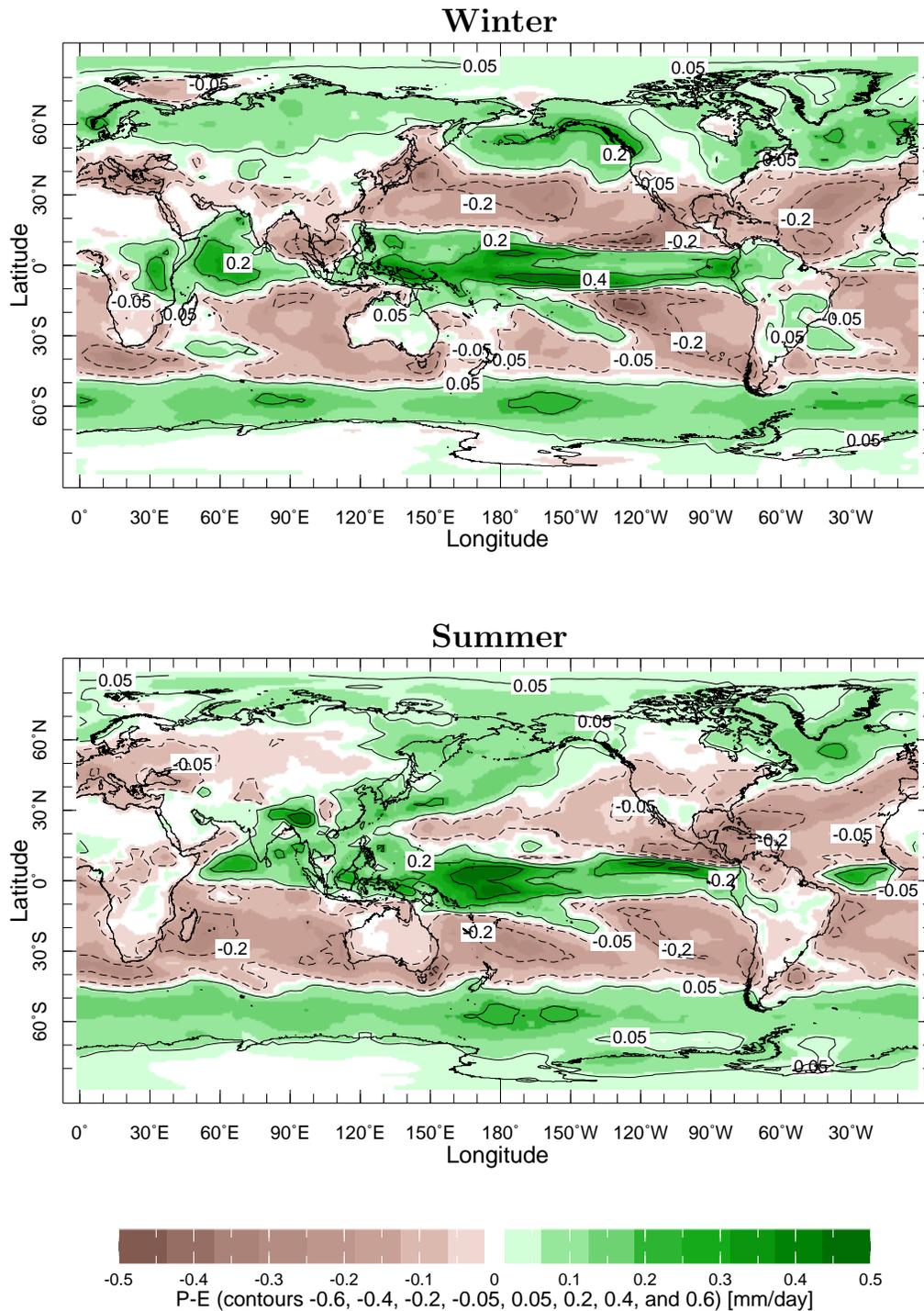


Fig. 2. The 24 model mean change in $P - E$, 2021 to 2040 minus 1950 to 1999, for winter and summer half years. Units are mm/day

Change in P-E and moisture transport [2046-2065] - [1961-2000], Oct-Mar

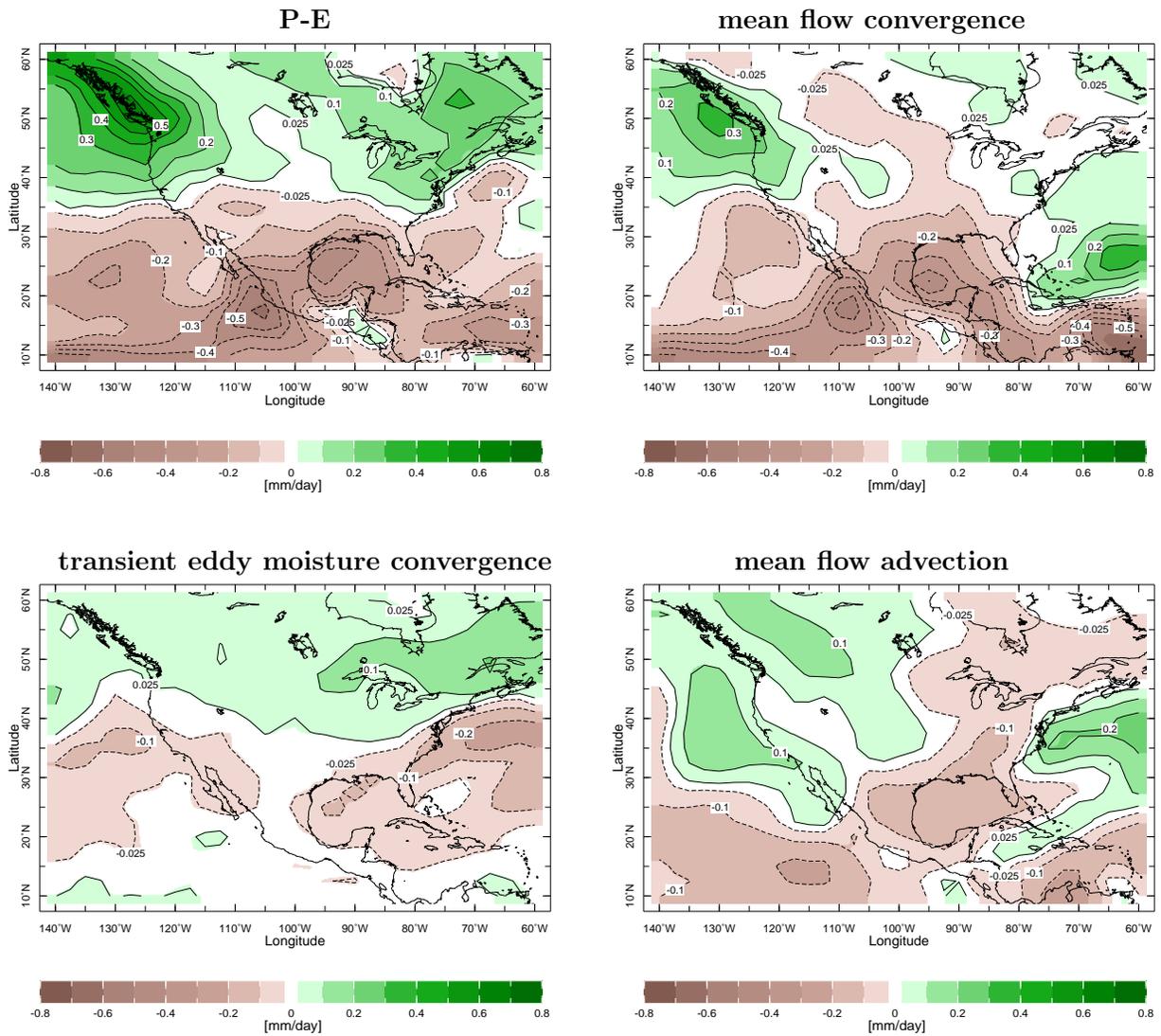
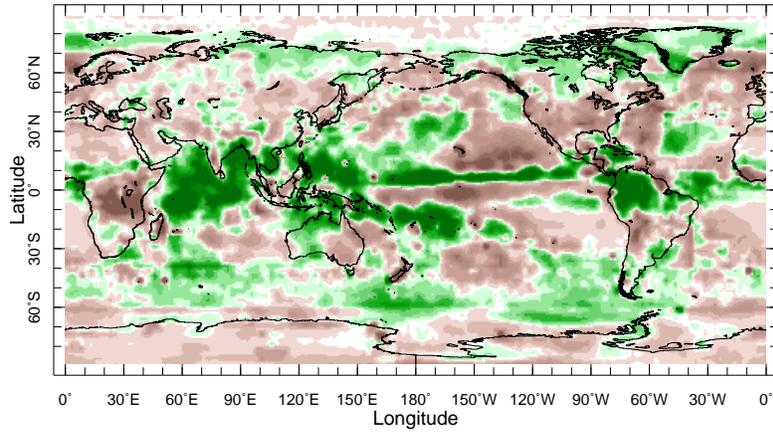


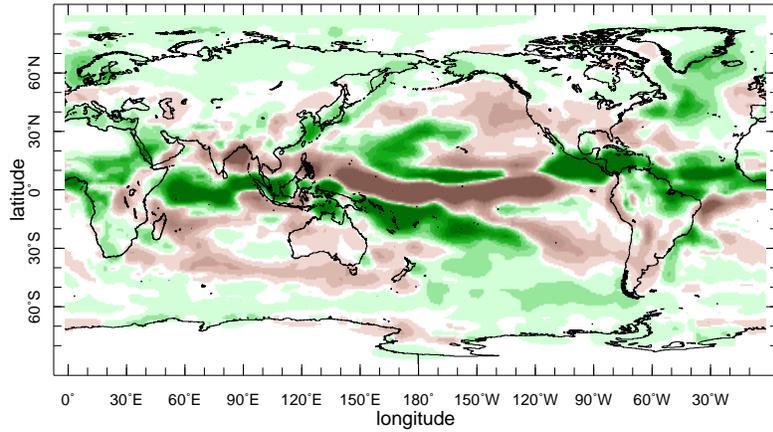
Fig. 3. The 12 model mean climatology change (2046-2065 minus 1961-2000) in October to march half year $P - E$ (top left) and terms in the vertically integrated moisture budget due to the mean flow divergence term ($\bar{q}\nabla \cdot \bar{\mathbf{u}}$, top right), the mean flow advection term ($\bar{\mathbf{u}} \cdot \nabla \bar{q}$, bottom right) and the transient eddy convergence ($\nabla \cdot \bar{\mathbf{u}}' \bar{q}'$, bottom left). All units are mm/day.

Annual Precipitation Trend 1979-2006

GPCP



CCM3 POGA-ML



IPCC Mean

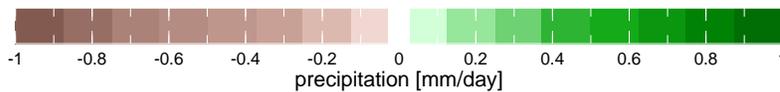
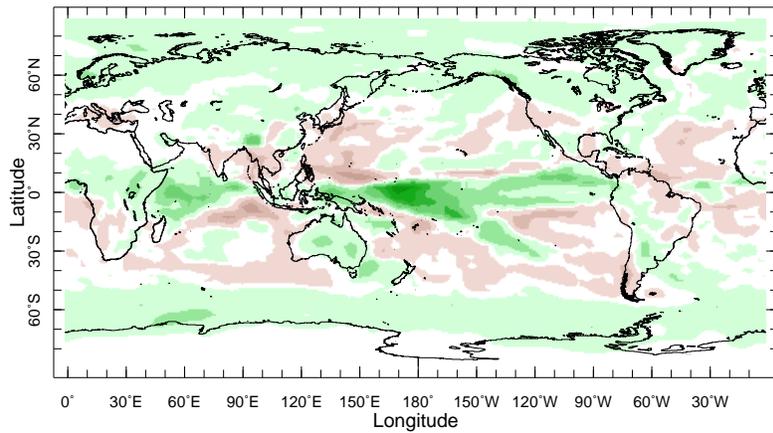


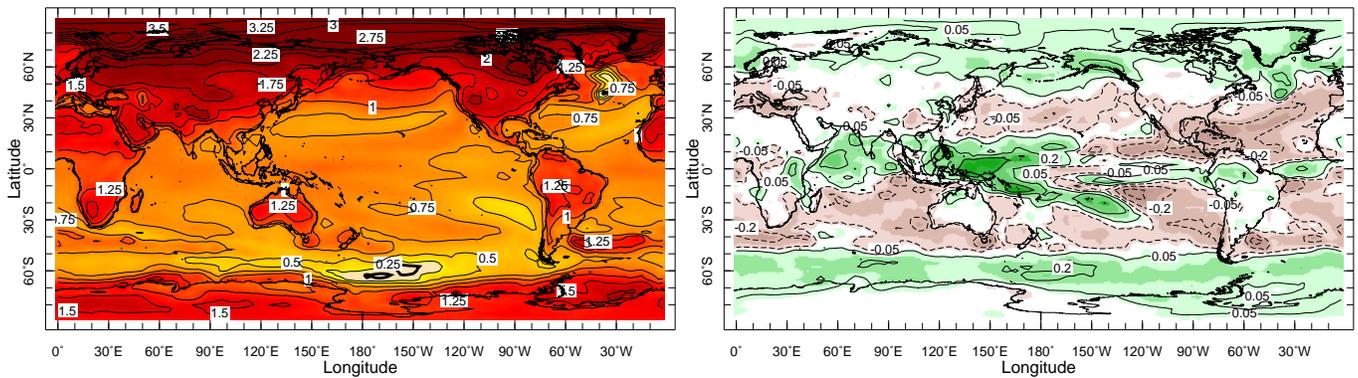
Fig. 4. The observed (top, from combined satellite-gauge GPCP data), simulated with an atmosphere GCM forced by observed SSTs in the tropical Pacific ocean (middle) and IPCC 24 model mean simulated and projected (middle) trend in precipitation for 1979 to 2006. Units are mm/day.

IPCC (2021 to 2040) - (1950 to 1999)

Temperature

Precipitation - Evaporation

Positive Temperature Gradient Composite



Negative Temperature Gradient Composite

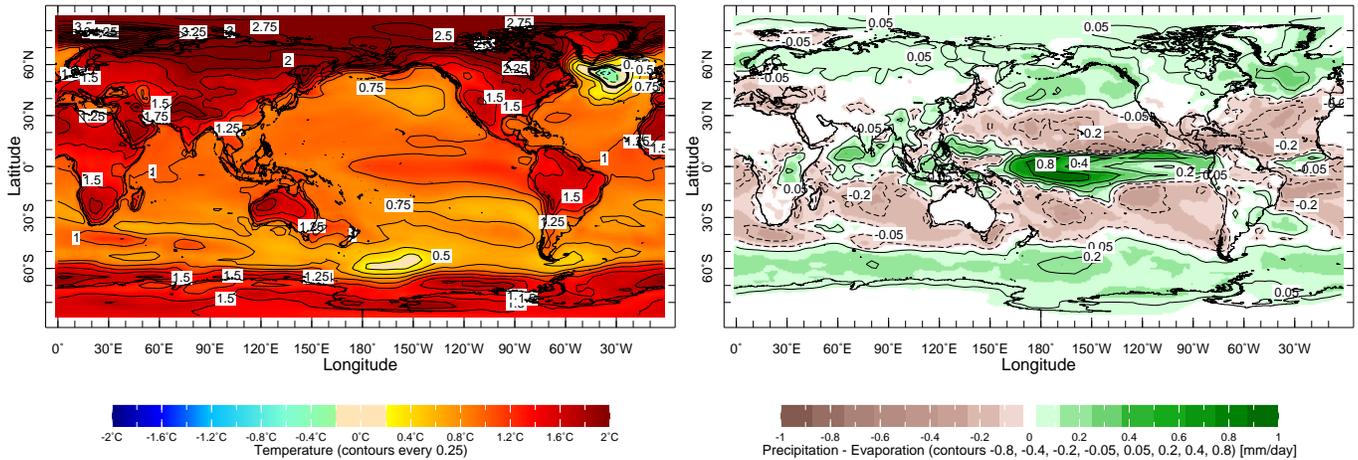


Fig. 5. The change in surface temperature (left) and $P - E$ (right) for 2021 to 2040 minus 1950 to 1999 for models that have a strengthening equatorial Pacific SST gradient (top, 6 models) and a weakening gradient (bottom, 6 models). Units are deg C and mm/day.