Dynamical causes of the 2010/11 Texas-northern Mexico drought

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ABSTRACT

The causes of the Texas-northern Mexico drought during 2010-11 are examined using observations, reanalyses and model simulations. The drought began in fall 2010 and winter 2010/11 as a La Niña event developed in the tropical Pacific Ocean. Climate models forced by observed sea surface temperatures (SSTs) produced dry conditions in fall 2010 through spring 2011 strongly influenced by transient eddy moisture flux divergence related to a northward shift of the Pacific-North America storm track, typical of La Niña events. In contrast the observed drought was not associated with such a clear shift of the transient eddy fields and instead was significantly influenced by internal atmospheric variability including the negative North Atlantic Oscillation of winter 2010/11 which created mean flow moisture divergence and drying over the southern Plains and southeast. The models suggest that drought continuation into summer 2011 was not strongly SST-forced. Mean flow circulation and moisture divergence anomalies were responsible for the summer 2011 drought, arising from either internal atmospheric variability or a response to dry summer soils not captured by the models. Summer of 2011 was one of the two driest and hottest summers over recent decades but does not represent a clear outlier to the strong inverse relation between summer precipitation and temperature in the region. Seasonal forecasts at 3.5 month lead time did predict onset of the drought in fall and winter 2010/11 but not continuation into summer 2011 demonstrating the current, and likely inherent, inability to predict important aspects of North American droughts.

1. Introduction

In the fall of 2010 the U.S. Drought Monitor showed no areas of the U.S. in drought, a situation essentially unique since the Drought Monitor was initiated in 1999 as an easy-to-understand means of tracking drought status. By fall 2010 the southwest drought that began after the 1997/98 El Niño had finally ended and the southeast drought of 2007/8 was long and gone. However, even as the Drought Monitor was showing unusually moist conditions across the country, seasonal-to-interannual forecasts were predicting a return to dry conditions across the southern U.S. and northern Mexico in the winter ahead. Those forecasts were based on forecasts of a developing La Niña in the tropical Pacific Ocean. Historically La Niña events have led to drier than normal conditions in the southwest U.S. northern Mexico, the southern Plains and southeast U.S and wetter than normal conditions in the Pacific northwest (Ropelewski and Halpert 1986; Mason and Goddard 2001; Seager et al. 2005a). This turned out to be a good forecast for much of the southern U.S. in winter 2010/11 which experienced drier than normal conditions except in southern California.

The interior southwestern states of the U.S. receive most of their precipitation in the winter and, hence, this was sufficient to move those states back towards abnormal dryness or drought. In Texas, precipitation is more evenly distributed throughout the year, and the dry winter was followed by a dry spring and a dry summer which, in sum, were sufficient to cause one of the most catastrophic short-term droughts in U.S. history. As is usually the case, dry conditions in the southern Plains went along with higher than normal temperatures and Texas and surrounding regions in summer 2011 broke records for the warmest summer on record. The costs in terms of U.S. agricultural losses were staggering. The National Climatic Data Center estimated it at $12 billion (http://www.ncdc.noaa.gov/billions/events.pdf). The Texas drought, combined with the spring 2011 tornado season, floods in the Mississippi basin and Hurricane Irene, made 2011 the costliest ever in terms of weather and climate related disasters. The vulnerability of the U.S. to extreme weather and climate events has never been so clear. Meanwhile in Mexico in November 2011 the Secretary for Social Development reported that drought had left 2.5 million Mexicans with insufficient drinking water (http://www.radioformula.com.mx/notas.asp?Idn=210675) and shortages of basic foodstuffs led to a large increase in imports from the U.S. (http://www.mnoticias.com.mx/note.cgi?id=403006). Mexico has been suffering a drought since the mid 1990s (Seager et al. 2009; Stahle et al. 2009) so the severity of the 2011 drought further revealed the climatic vulnerability of Mexico.

This paper focuses on the Texas-northern Mexico (hereafter TexMex) drought and addresses the question of what caused it? This is an important question in that it has been argued that anthropogenic global warming should lead to aridification of the subtropics and a poleward expansion of subtropical dry zones and also a shift to more extreme precipitation events. Was the TexMex drought a case of such anthropogenically induced climate change? It would certainly be rash to draw such a conclusion given that past droughts in the southwest and Plains have been reliably attributed to forcing of atmospheric circulation anomalies by naturally occurring cool tropical Pacific and, to a lesser extent, warm tropical North Atlantic sea surface temperature (SST) anomalies (Schubert et al. 2004b,a; Seager et al. 2005b; Herweijer et al. 2006; Seager 2007). This most recent drought also coincided with a La Niña event. Indeed a recent study (Hoerling et al. 2013) has concluded that the summer of 2011 Texas drought and heatwave was within the range of natural variability of the atmosphere-ocean-land surface system, made much more likely by the La Niña of 2010/11 and, only to a lesser extent, by anthropogenic climate change.

While the 2010/11 drought and heat wave were decidedly severe this event is, by the standards of recent history, so far quite brief. The records that were broken during the event were often set in the 1930s and 1950s during two devastating multiyear droughts created by some mix of tropical Pacific and Atlantic SST variations and internal atmospheric variability and, for the 1930s Dust Bowl drought, dust aerosol forcing (Schubert et al. 2004b,a; Seager et al. 2005b, 2008; Cook et al. 2008, 2009, 2010; Hoerling et al. 2009). By the standards of those droughts, or some 19^{th} Century droughts (Stahle and Cleaveland 1988; Herweijer et al. 2006), the 2010/11 drought was intense but brief. However, after a relatively wet winter in 2011/12, especially in eastern Texas, at the time of writing (September 2012) the Drought Monitor shows extreme to exceptional drought in the central Plains and dry conditions to severe drought extending across most of Texas, the southwest, the Rockies and the midwest so this event is not yet over.

In this paper we focus on the dynamical causes of the 2010/11 TexMex drought in terms of circulation anomalies and variations of surface evaporation and transports and convergence of moisture within the atmosphere and examine its evolution from fall of 2010 to its most extreme state in summer and fall of 2011. Our goal is to determine the ocean-atmosphere dynamics of this event and, by reference to prior work, assess how similar or different it was to other droughts in the region and the typical seasonal-to-interannual variability of hydroclimate in the region forced by the tropical oceans. As part of this effort we will examine how well the drought can be reproduced in atmosphere models forced by the observed SSTs and, hence, the potential predictability of the event. In addition we will examine how well the event was actually forecast in advance which depended on the ability to forecast the SSTs and the atmospheric response to them and any atmospheric response to prior land surface conditions.

A comprehensive analysis and understanding of the 2010/11 TexMex drought, and its predictability, will inform decision making and disaster planning by allowing assessment of its likelihood, advance warning signs and ability to predict ahead of time, or lack thereof. This will also inform attempts to assess whether this event arose from natural variability, and akin to prior events, or bore an imprint of anthropogenic climate change which, in turn, influences likelihood of similar events in the future.

2. Observational and model data

The observed precipitation data is from the National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction (NCEP) Climate Prediction Center (Chen et al. 2002) available from the Data Library of the International Research Institute for Climate and Society (http://iridl.ldeo.columbia.edu) and which cover 1948 to present. For the analyses of observed SST, atmospheric circulation and surface air temperature we use data from the NCEP/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis covering 1949 to present (Kalnay et al. 1996; Kistler et al. 2001).

The first model used is the NCAR Community Climate Model 3 (CCM3, which has been used extensively by us for North American drought research (e.g. Seager et al. (2005b)).

NCAR has released many atmosphere models since CCM3 and all have been experimented with at Lamont Doherty Earth Observatory but none found to be as skillful at reproducing the observed history of U.S. southwest and Plains precipitation as CCM3. Hence, despite its vintage, we use CCM3 here. The model is forced by observed SSTs which are from the Kaplan et al. (1998) data in the tropical Pacific Ocean and the Hadley Centre data (Rayner et al. 2003) elsewhere. 16 ensemble members were generated with different initial conditions and results are primarily shown for the ensemble mean, which averages over uncorrelated weather in the members and closely isolates the common SST-forced component. The simulations begin on January 1 1856. Unlike in Seager et al. (2005b), the simulations here also have the observed increases in CO_2 and CH_4 imposed allowing land surfaces to warm and the atmospheric circulation to adjust to the changes in radiative properties. The other model is the European Centre-Hamburg 4.5 (ECHAM4.5, Roeckner et al. (1996) and we use a 24 member ensemble from 1950 on available in the International Research Institute for Climate and Society Data Library (http://iridl.ldeo.columbia.edu/docfind/databrief/cat-sim.html).

We also use the NCEP-NCAR reanalysis and the European Centers for Medium Range Weather Forecasts (ECMWF) Reanalysis-Interim (ERA-I, Dee et al. (2011)) data sets to evaluate the components of the moisture budget that caused precipitation anomalies during the drought. For both reanalyses we evaluate anomalies of the convergence or divergence of the vertically integrated moisture transports by (i) the mean flow and (ii) the transient flow. The former is evaluated using monthly mean values of winds and specific humidity and the latter using co-variances of departures of the daily values from the monthly means. The vertical integrals extend to the monthly mean surface pressure. It should be noted that evaluating the moisture budget in this way diagnostically from Reanalysis data leads to significant errors compared to the actual moisture budget calculation in the models that produce the Reanalyses due to differences in the numerical methods used and the time resolution of the calculation. This is the topic of another paper (Seager and Henderson 2013) where it is shown that, if care is taken to adopt the best computational methods, as is the case here, diagnostic evaluation of moisture budget components can produce useful results.

Anomalies shown here are computed relative to the period that is common to all the models and observations, January 1950 to November 2011. The only exception is for the ERA-I which begins in 1979 and for which we assess anomalies relative to a 1979 to 2011 climatology.

3. Typical La Niña associated precipitation and circulation anomalies in the Pacific-North America

Since the 2010/11 drought was associated with full and then waning La Niña conditions we first of all review the typical precipitation and circulation anomalies in the Pacific-North America region associated with La Niñas for later comparison with what happened during the 2010/11 event. This was done based on the NINO3 index (SST anomalies averaged over $5°S - 5°N, 130° - 90°W$) which was formed into DJF, MAM, JJA and SON seasonal anomalies. The years when the anomaly values were less than one standard deviation were then identifed. Values of observed SST, and observed and modeled precipitation and 200mb height, were then composited for these years to provide seasonal values of typical La Niña conditions[1].

a. Observed canonical La Niña conditions

SST anomalies are well developed in SON and go along with a high anomaly over the mid-latitude west Pacific and North America and dry anomalies across the U.S. and Mexico from southern California to the Atlantic (Figure 1). The classic ENSO pattern is clear in DJF with a cyclonic anomaly immediately north of the cold tropical Pacific SST anomaly, a well developed North Pacific high anomaly that merges with a zonal band of high pressure over North America and the mid-latitude Atlantic Ocean. Dry conditions extend across

[1]The years and seasons identified as La Niñas were 1950 (MAM, JJA, SON), 1955 (SON), 1956 (JJA), 1964 (JJA, SON), 1970 (JJA, SON), 1971 (MAM, JJA, DJF), 1973 (JJA, SON), 1974 (MAM, JJA, DJF), 1975 (MAM, JJA, SON), 1976 (MAM, DJF), 1985 (DJF), 1988 (JJA, SON), 1989 (MAM, DJF), 1999 (all seasons), 2000 (MAM, DJF), 2007 (SON), 2008 (MAM, DJF), 2010 (JJA, SON), 2011 (MAM, DJF) where DJF 2011 indicates DJF 2010/11 for example. The two models used different SST data sets and, in particular, have some additional La Niña seasons in 1954, 1955 and 1956.

Mexico and the southern portions of the U.S. with a maximum at the Gulf coast. La Niña SST anomalies are typically weaker in MAM and so are the circulation and precipitation anomalies. Even though the SST anomalies remain in JJA, the circulation anomalies are weak, consistent with our understanding of the seasonal cycle of tropical to mid-latitude teleconnections.

b. Modeled canonical La Niña conditions

The models use different SST data sets to that used for the SST anomalies shown in Figure 1 but the differences are very small. CCM3 shows a typical La Niña height response from SON through MAM with a ridge extending from the North Pacific to the mid-latitude Atlantic with a localized high somewhere over North America in each season (Figure 2). This is also the case for ECHAM4.5 (Figure 3) but with the SON anomalies weaker, and the DJF anomalies stronger, than in CCM3. The SON La Niña precipitation anomalies in both models show wet in the Pacific northwest and dry across most of the rest of the continent as observed (Figure 1). The observed north-south wet-dry La Niña dipole in DJF is best modeled by ECHAM4.5 while CCM3 continues with the wet Pacific northwest and dry everywhere else pattern seen in SON. CCM3 produces widespread dry anomalies in MAM and JJA of La Niñas in contrast to the more spatially variable observed La Niña precipitation anomalies in these seasons. ECHAM4.5 produces MAM precipitation anomalies that are far too strong but have some of the observed pattern with dry conditions in the southwest. ECHAM4.5 also produces far too extensive dry conditions over the U.S. and Canada in La Niña JJAs but does capture the wet conditions in Mexico and Central America.

4. SSTs during the 2010/11 TexMex drought

Returning to the specific case of 2010/11, Figure 4 shows the history of sea surface temperature and surface air temperature over land during the drought. In fall (September to November, SON) of 2010 a strong La Niña had already developed with anomalies of around $-2°C$ while the tropical Atlantic Ocean was warmer than normal. The La Niña was still strong in winter (December to February, DJF) 2010/11 and the SST anomalies in both oceans then weakened through spring (March to May, MAM) and summer (June to August, JJA) of 2011. By summer of 2011 the La Niña was essentially gone and the tropical Atlantic SST anomalies were also weak. The La Niña began to reform in fall of 2011 (and developed into another La Niña for winter 2011/12, not shown). Temperatures over North America were actually colder than normal in winter 2010/11, especially in the eastern U.S. Anomalous heat developed in Mexico, the southern and central Plains and the southeast in spring 2011 and maximized in the summer with a bulls eye centered on the central Plains and extending over northern Mexico and the entire eastern U.S. The fall 2010 and winter 2010/11 SST pattern would be expected to force dry conditions across the southern U.S. both as a response to the cold tropical Pacific SSTs and the warm tropical North Atlantic SSTs, an ideal configuration for forcing North American drought (Schubert et al. 2009). However the continuation and intensity of the drought in summer and fall 2011 is hard to reconcile with contemporaneous SST forcing since the SST anomalies are weak by that season. This suggests a role for ether land surface feedback that can extend the drought forward in time after being initiated by prior SST forcing or a role for random internal atmospheric variability. Tropical Pacific SST anomalies are known to be quite predictable on the seasonal-to-interannual timescale (e.g. Jin et al. (2008)) so it would also be expected that the component of the drought forced from the tropical Pacific could be predicted several months ahead of time.

5. Comparison of observed and model-simulated precipitation anomalies during the TexMex drought

Figure 5 shows for 3 months seasons beginning in September to November 2010 and ending in September to November 2011 the observed precipitation anomalies and those modeled by the CCM3 and ECHAM4.5 models when forced by the observed SSTs. The actual precipitation anomaly was consistently negative across Texas and Mexico and much of the surrounding states throughout this entire 15 month period. Dry anomalies were modest in fall 2010 but were in full force in DJF 2010/11 and centered in the southeast, strong and centered in Mexico and the south-central U.S. in MAM 2011 and then intensified and spread into JJA 2011 and persisted into SON 2011. In JJA and SON 2011 the drought was very centered on Texas and northern Mexico although, in fall, most of the west and central U.S. was also dry while the midwest and northeast were very wet. From SON 2010 to MAM 2011 the observed precipitation anomalies have some similarity with those typical for La Niña conditions during those seasons (Figure 2) but the strong summer drying is not typical.

The models simulate widespread dry conditions across most of the U.S. and Mexico in fall 2010 and the southern U.S. and Mexico in winter 2010/11. These model patterns are quite similar to those observed except over California where the models simulated dry conditions as a typical model La Niña response (Figures 3 and 4) but, in fact, atypically a wet fall 2010 and winter 2010/11 actually occurred. In MAM 2011 the models simulate dry conditions across most (CCM3) or all (ECHAM4.5) of Mexico and almost all of the U.S. and fail to reproduce the north-south wet-dry dipole actually observed, although ECHAM4.5 does simulate the wet midwest and northeast observed. The model precipitation anomalies in MAM 2011 are similar to their canonical La Niña responses. After spring, as the La Niña faded away, the models generally fail to reproduce the focused and strong northern Mexico-Texas drought in summer and fall 2011 although ECHAM4.5 does produce widespread but modest drying across the U.S. and northern Mexico. Hoerling et al. (2013) show results for June through August for SST forcing of the atmosphere model component of the National Atmospheric and Oceanic Administration's Climate Forecast System version 2. That model also produces drying that is only half as strong as that observed and also not focused in the TexMex area. The results from these models indicate that the beginning of the drought in fall 2010 and winter 2010/11 was related to the development of SST anomalies but that the intensity of the drought in summer and fall 2011 was not uniquely a response to SST anomalies and hence must have had other causes.

Table 1 lists the area-weighted anomaly correlation coefficients between observed and modeled precipitation anomalies for land areas between $20°N$ and $50°N$ providing a quantitative measure to go with the description above. ECHAM4.5 performs better than CCM3, especially in MAM and JJA 2001, the models are very similar in the DJF 2010/11 precipitation patterns and both have similarity to the observed pattern (all reflecting similar patterns of response to SST forcing) and the models fail to reproduce the observed pattern in SON 2011.

6. Causes of the 2010/11 TexMex drought: modeled and reanalyzed moisture budget anomalies

a. Modeled moisture budget anomalies

The two atmosphere models used here, together with the two Reanalyses, provide some indication of the causes of the drought and hence we analyze the variations in the atmospheric branch of the hydrological cycle within the models to determine how changes in evaporation and moisture convergence by the mean and transient flow combined to generate lower than normal precipitation. Figures 6 through 10 show anomalies in modeled precipitation, evaporation and convergence of vertically integrated moisture transport by the mean flow and by transient eddies for the seasons from fall 2010 through fall 2011.

In SON 2010 (Figure 6) the reduction of precipitation simulated by both the CCM3 and ECHAM4.5 models is sustained by a spatially varying mix of a reduction of evaporation, mean flow moisture convergence and transient eddy moisture convergence. Both models agree that the transient eddy moisture convergence anomaly at this time is not very organized. Also, both models agree that the mean flow moisture convergence anomaly moistens the Pacific coast states of the U.S. and Baja California and provides broad areas of drying over the central and eastern U.S. and parts of Mexico.

In DJF 2010/11 (Figure 7) the models agree that the negative precipitation anomaly focuses across the southern U.S. and all of Mexico with negative evaporation anomalies in roughly the same area. Most impressive is that the models agree that there is a strong region of anomalous transient eddy moisture *divergence* stretching from northern Mexico and Texas across the entire eastern U.S. while the mean flow produces a moisture convergence anomaly in roughly the same area but dries western Texas and the interior southwest U.S.

The same drying of northern Mexico, Texas and the eastern U.S. by anomalous transient eddy moisture flux divergence occurs in both models in MAM 2011 while anomalous mean flow moisture divergence causes widespread drying across the central and northern Plains, Rocky Mountains and Great Lakes region (Figure 8).

In JJA 2011 (Figure 9) only ECHAM4.5 has a strong negative precipitation anomaly across the U.S. and Mexico. In this season the transient eddy moisture flux anomalies are weak and, in ECHAM4.5, the mean flow moisture convergence creates a dry anomaly across northwestern Mexico, the southwest, the Pacific coast states and the Rockies. Both models have widespread negative evaporation anomalies indicative of dried soils. In SON 2011 (Figure 10) the precipitation anomalies are amorphous in CCM3 but remain widespread and negative in ECHAM4.5 and are coincident with reduced evaporation. Both models agree on a renewed drying tendency by transient eddy moisture flux divergence in the central U.S. including Texas while ECHAM4.5 still has a mean flow moisture divergence anomaly creating a drying tendency in northern Mexico, the southwest and Rocky Mountains.

b. Moisture budget anomalies in the NCEP-NCAR and ERA-I reanalyses

By virtue of ensemble averaging, the variations in moisture convergence or divergence in the models are caused by changes in the mean and transient atmospheric circulation that are forced by the imposed SSTs. These variations can be contrasted with those that actually occurred, as realized in Reanalyses, to assess the realism of the SST-forced variations and their importance relative to variations associated with internal atmospheric variability not associated with particular ocean conditions. In Figure 11 we show the history of variations in the convergence and divergence of vertically integrated moisture transport by the mean flow and the transient circulation as diagnosed from the NCEP-NCAR Reanalysis. In the first two seasons of the drought (SON 2010 and DJF 2010/11) the NCEP-NCAR Reanalysis indicates that it is anomalous moisture divergence by transient eddies that contributes a drying trend across the southern U.S. in fall and the central U.S. in winter. In MAM 2011 the NCEP-NCAR moisture budget has only a transient eddy moisture divergence anomaly causing drying over southern, mid-Atlantic and northeastern states. In JJA and SON 2011 mean flow moisture divergence anomalies do cause extensive drying in the drought region.

The NCEP-NCAR moisture divergence anomalies bear some resemblance to the observed precipitation anomalies (Figure 5, the drying tendency in the Plains and wetting tendency in the northeast in SON 2011 particularly closely matches the observed precipitation pattern). However the differences are also sufficiently large that it makes sense to examine the ERA-I Reanalysis as well (Figure 12). The ERA-I Reanalysis reports the divergence of the vertically integrated moisture transport as a diagnostic quantity which is presumably evaluated on the model grid and at the model time step and, hence, is close to that actually evaluated during the model analysis cycle. This is plotted along with the mean and transient flow components as computed by us. With the partial exception of MAM and JJA 2011, the actual ERA-I Reanalysis moisture divergence or convergence anomaly quite closely matches the observed precipitation anomaly. Since the sum of the two components quite closely matches the actual divergence or convergence (not shown) the partition can be considered valid and useful.

Comparing Figures 11 and 12, it is seen that there is notable agreement between the two Reanalyses in the patterns of moisture divergence and convergence by the mean and transient flow. ERA-I suggests a mean flow drying of Texas and the Plains in SON 2011 in addition to the transient flow drying of much of southern North America which NCEP-NCAR and ERA-I agree upon. In DJF 2011 ERA-I also suggests a mean flow moisture divergence anomaly drying Texas, northeast Mexico and the southeast adding to a more general transient component drying that again agrees with NCEP-NCAR. In MAM 2011 ERA-I agrees with NCEP-NCAR with a transient component drying from northeast Mexico to the northeast that is opposed by a mean flow moistening. In JJA 2011, at the height of the 2010/11 drought, ERA-I indicates that anomalous mean flow moisture divergence was widespread across North America, largely confirming the results from NCEP-NCAR. Widespread, but weaker, mean flow moisture convergence anomalies persisted into SON 2011, again confirming the NCEP-NCAR results.

In summary, both Reanalyses suggest that the drought was caused by a combination of mean and transient flow moisture divergence anomalies in fall 2010 and winter 2010/11 but that by spring, summer and fall 2011 the mean flow divergence anomalies were dominant. The next step is to relate these anomalies in the moisture budget to the anomalies in the mean and transient atmospheric circulation.

7. Causes of the 2010/11 TexMex drought

a. Mean atmospheric circulation anomalies

In relating the moisture convergence and divergence anomalies to circulation anomalies we make use of the simple concept that increased moisture convergence and precipitation are associated with rising motion and vice versa, as shown for El Niño and La Niña in prior work (Seager et al. 2005a). Then we expect, on large scales, rising motion anomalies to be found where the mean flow is poleward, and descending motion where the mean flow is equatorward, according to a simple vorticity balance between advection of planetary voracity and vortex stretching and thermal balance between meridional advection and adiabatic cooling or warming due to vertical motion and expansion or compression. Of course the vorticity and thermal budgets controlling the location of vertical motion anomalies are in reality more complex than this but this reasoning will be applied below to guide the linking of circulation and moisture budget anomalies.

In Figure 13 we show the Reanalysis 200mb height anomalies by season from SON 2010 through SON 2011 together with the ensemble mean of the CCM3 and ECHAM4.5 simulations. In SON 2010 the observations show mid-latitude high pressure over Asia and the western North Pacific, a low over the Pacific northwest, a high over the central North America and a low over the eastern seaboard and western North Atlantic. This is quite similar to the typical fall La Niña height anomaly pattern (Figure 5). This height pattern is consistent with increased precipitation in the northwest U.S. and western Canada and dry anomalies further south as observed (Figure 5) with mean flow moisture convergence and divergence anomalies being responsible (Figure 11 and 12). Low height anomalies over the tropical Pacific are forced by the cold La Niña SST anomalies. Consistent with that, the two models also show negative height anomalies over the tropical Pacific with the characteristic off-equatorial cyclones. The models also have widespread subtropical to mid-latitude ridges characteristic of La Niña (Seager et al. 2003) with high anomalies over the North Pacific and southern North America, again typical of the response to La Niña forcing (e.g. Strauss and Shukla (2002)). The two models' height anomalies are very similar to each other and provide evidence that the subtropical to mid-latitude highs over Asia, the North Pacific and North America were largely a forced response to the emerging 2010/11 La Niña. The low anomaly west of Canada and the anomalies over the North Atlantic are not reproduced in the SST-forced models but are in the observed SON La Niña composites suggesting that the models are not capable of simulating these features faithfully (as seen in Figures 1 to 3).

In DJF 2010/11 the reanalysis shows the development of a strong high over the North Pacific that extends into western North America. This is a typical La Niña-forced pattern (Figure 1) but similarity is not seen over eastern North America and the Atlantic where a strong negative North Atlantic Oscillation (NAO) event developed. The reanalysis observations also show strong low height anomalies over the tropical Pacific Ocean consistent with forcing from the underlying cold La Niña SST anomalies. Both SST-forced models show the low heights over the tropical Pacific, though weaker than those observed. ECHAM4.5 also develops a strong high over the North Pacific, albeit east of the observed one while, oddly, the CCM3 has only weak and poorly defined high anomalies over the North Pacific. The models, not surprisingly, fail to produce the negative NAO event and the ECHAM4.5 simulation is, instead, quite reminiscent of a typical La Niña pattern. The observed height anomalies, including the contribution of the NAO in generating strong northerly flow over the central and eastern U.S., are consistent with negative precipitation anomalies in the southwest U.S. and across the central and eastern southern U.S. as observed (Figure 5) with anomalous mean flow moisture divergence responsible (Figures 8 and 9). In contrast, the ECHAM4.5 height anomalies would be expected to cause reduced precipitation over the west coast of North America due to anomalous mean flow moisture divergence. The modeled high off the U.S. southeast is consistent with modeled anomalous mean flow moisture divergence to its east (over the Atlantic) and anomalous mean flow moisture convergence to its west over the eastern U.S. (Figure 7) which is distinct from the observed NAO-induced drying in the region.

In MAM 2011 the models retain the same character of a La Niña forced height anomaly pattern both in the tropics and extratropics as they showed in the previous season consistent with the continued, but weakening, cool tropical Pacific SSTs. In the reanalysis observations the low anomalies over the tropical Pacific are also present but there was a band of low pressure stretching from Korea to western Canada with similarly zonally oriented high anomalies sandwiched between here and the tropical low anomalies. This has some similarity to the observed MAM La Niña composite (Figure 1) and, as for SON 2010, the observations seem to combine a forced response to the waning La Niña with a substantial component of internal atmospheric variability. The observed height anomalies drive westerly anomalies into the Pacific Northwest consistent with a wet Pacific Northwest and drier conditions to the south as observed (Figure 5) with mean flow moisture convergence/divergence anomalies the cause. The model precipitation anomalies, with dry anomalies extending further north than observed (Figure 5), and drying by a combination of mean flow moisture divergence (to the north) and transient eddy moisture divergence (to the south) (Figure 8), are different to observations but consistent with their more canonical La Niña height anomalies.

In JJA 2011, as the La Niña continued to wane, the models provide no evidence of a strong extratropical circulation response with only weak positive height anomalies over North America. The reanalysis observations however show a localized upper level high anomaly, and low level low (not shown), over the North American continent (quite unlike the very weak composite JJA La Niña pattern in Figure 1). The JJA 2011 patterns are consistent with the precipitation anomalies: the observations show a strong dry anomaly under the high anomaly and the models have much weaker and more amorphous dry anomalies. The suggestion is that the JJA 2011 dry anomaly was a result of either internal atmospheric variability, rather than ocean forcing, or a forced response to dry soils that was not captured by the models. In SON 2011 the La Niña regained strength, and this time the CCM3 model responded with a canonical height anomaly while ECHAM4.5 did not. The observed height anomaly appears dominated by internal atmospheric variability and has a high over northeast Canada and a low over the southern U.S and western Canada. This favored dry conditions over much of the southern U.S. and wet conditions over the northeast U.S. via mean flow moisture divergence/convergence anomalies (Figure 5, 11 and 12). The models notably fail to simulate that precipitation pattern consistent with it not being forced by SSTs.

In summary, the evolution of the height anomalies in the observations and SST-forced models suggest that the 2010/11 La Niña played an important role in causing the development of the TexMex drought from fall 2010 to spring 2011 but that even within that season, and entirely for summer and fall of 2011, internal atmospheric variability unrelated to ocean conditions, played a critical role in determining the severity and persistence of the drought.

b. *Transient atmospheric circulation anomalies*

The previous section attempted to draw connections between changes in precipitation during the 2010/11 TexMex drought and changes in the mean flow, but it was clear from Section 3 that the drought was also caused in some seasons by reduced moisture convergence, or enhanced divergence, by transient eddies. Here we examine the changes in the reanalysis observed and modeled transient eddy fields to attempt to link them to the changes in eddy moisture convergence. As shown in Figure 14, in SON 2010, amidst considerable differences, the reanalysis observations and models agree on a band of increased upper tropospheric eddy meridional velocity variance, $\overline{v'^2}$, that extends across central North America at about $40-50°N$. The models have a band of reduced variance south of this suggestive of a poleward shift of the storm track as is typical of La Niña events (see (Seager et al. 2010)). If such bands co-locate with bands of increased and decreased poleward eddy moisture transport this would be expected to contribute a transient eddy drying tendency to most of the U.S. in rough agreement with the computed model transient eddy moisture flux convergence anomalies in Figure 6 and the Reanalysis ones in Figures 11 and 12.

In DJF 2010/11 the reanalysis observations and models agree on increases in $\overline{v'^2}$ over the North Pacific north of $30-40°N$ and over the Pacific coast of North America. There is little agreement between models and observations further east over North America with the observations showing indistinct features over Mexico and the U.S. and the models showing reduced $\overline{v'^2}$ over Mexico and the southern U.S. and, in ECHAM4.5, increased $\overline{v'^2}$ over the central U.S. In the models the transient eddy anomalies are consistent with a transient eddy moisture divergence (convergence) anomaly over the south and southeastern U.S. (Gulf of Mexico and subtropical Atlantic) and translating into a drying tendency over the land as seen in Figure 7. The disagreement with the observed $\overline{v'^2}$ anomalies suggests that the actual

P reduction in this region was not sustained in this way and it could instead have been caused by mean flow moisture divergence associated with the negative NAO event (Figure 13).

In MAM 2012 the models again agree on strengthening of $\overline{v'^2}$ across the North Pacific and North America on the poleward flanks of the upper tropospheric high anomalies seen in Figure 13 and, once more, this is consistent with a drying tendency due to a transient eddy divergence anomaly to the south (Figure 8). The reanalysis observations have quite different patterns of $\overline{v'^2}$ over the North Pacific but have some similarity to the models with increased $\overline{v'^2}$ over central North America but with the addition of a strong and widespread reduction over Canada. The observed and modeled patterns are consistent with anomalous transient eddy moisture divergence and drying over south central and southeast North America. The transient eddy anomalies are weak in JJA 2011 and, in SON 2011, the observations have increased $\overline{v'^2}$ over North America. Only CCM3 of the two models is roughly consistent with the SON 2011 $\overline{v'^2}$ pattern and has transient eddy drying over the southern U.S (Figure 10) although the reanalyses do not support this (Figures 11 and 12). ECHAM4.5 has a pattern of $\overline{v'^2}$ over the North Pacific and west coast of North America that is similar to that of CCM3 but the patterns are quite different over central and eastern North America.

In summary, while the reanalysis observed transient eddy anomaly field and transient eddy moisture transports provide some evidence for involvement in generating the drought, especially transient eddy drying over the southern U.S. in MAM 2011, the evidence for SST-forcing of these anomalies, in the sense of agreement between observed and SST-forced ensemble mean patterns, is limited. This probably reflects the mix in observations at the seasonal timescale and for an individual event of a modest SST-forced component with a much larger component of internal atmospheric variability.

8. How unusual was the 2010/11 TexMex drought?

Droughts and heat waves are recurring features of the climate of Texas and Mexico so the question arises as to whether the 2010/11 event was in any way unusual? In the summer of 2011 many high temperature records were broken across the region so we focus on the June through August (JJA) season. Figure 15 shows a scatter plot of observed and modeled JJA surface air temperature and precipitation anomalies for the 1950 to 2011 period averaged over land areas between $22°N$ and $40°N$ and $105°W$ and $90°W$. The observations show a striking inverse and linear relationship between summer temperature and precipitation with dry conditions going along with high temperatures. This is a simple result of reduced moisture availability at the surface necessitating incoming solar radiation be balanced less by evapotranspiration and more by sensible heat flux and long wave radiative cooling which requires higher surface temperatures. JJA 2011 is marked and stands out as both the driest and hottest JJA since 1950 in this region. However JJA 2011 does not appear as an outlier in that, given the precipitation reduction, the temperature is what would be expected and it is accompanied by a close analog (which is JJA 1980).

The values plotted for the two models are from the individual ensemble members and hence, like the observations, contain the effects of both SST-forcing and internal atmospheric variability. The models also produce an inverse relation between temperature and precipitation variability comparable in strength to that observed. The individual ensemble member simulations of JJA 2011 are plotted as green crosses and are clearly biased warm for the associated precipitation anomaly. Note that the circles in Figure 15 are color coded according to year and that for the models the later years are typically warmer than the earlier years. This, and the 2011 values, indicate the effect of global warming which is included in both models via the imposed SST history and additionally in CCM3 via imposed changes in CO_2 and CH_4. No warming tendency appears in the observations where precipitation is instead the dominant control on JJA temperature. The JJA 2011 precipitation anomalies in CCM3 were scattered around zero (see Figure 5) but were biased dry for ECHAM4.5, some extremely so. Two ensemble members (one from each model) achieved a JJA 2011 drying and warming that essentially matches that observed with the modeled warming clearly aided by greenhouse-induced warming. In a similar analysis for Texas alone (which is a subset of our larger domain) Hoerling et al. (2013) found that 2011 was a true outlier with temperatures well above the temperature-precipitation line and concluded that background global warming likely was responsible for the warming above what would be expected given the precipitation reduction. This is not so striking for the larger region considered here but nonetheless appears to also be the case.

Another way of looking at the observed precipitation and temperature history is seen in Figure 16 which shows the time history of JJA average observed temperature and precipitation for 1950 to 2011 averaged over the TexMex region. Since temperature tends to rise when precipitation goes down we have inverted the temperature scale here. The inverse relation between the two quantities is also abundantly clear here with 2011 standing out as as having the driest JJA and, hence, the warmest one too. The hot and dry summer of 1980 is also clear here but as an isolated one year event. The string of hot dry summers in the 1950s is also clear as well as the cooler and wetter extended period from the mid 1960s through the mid 1990s. Amidst considerable seasonal to decadal variability, neither temperature nor precipitation in the TexMex region have a clear trend. However the TexMex region is expected to get drier as a consequence of greenhouse gas-driven global warming, according to climate models (Seager et al. 2007; Seager and Vecchi 2010) but it is quite likely that that trend is currently masked by the presence of large amplitude natural variability on interannual to multidecadal timescales (Hoerling et al. 2013).

9. How well was the 2010/11 drought forecast by operational seasonal-to-interannual prediction systems?

Understanding the dynamical causes of droughts is important but more important from the point of view of planning ahead for, and possibly preventing, damaging impacts is development of an ability to predict droughts. Of course this will not always be possible. Indeed the analysis so far of the causes of the 2010/11 TexMex drought would suggest that it would not have been well predicted ahead of time. After all, prediction of drought on the seasonal-to-interannual timescale will depend on the ability to predict slowly evolving boundary conditions that, by forcing the atmospheric circulation, can create tendencies towards drought-inducing patterns of sufficient amplitude that they can emerge amidst the internal atmospheric variability. SSTs and soil moisture anomalies are the boundary conditions to be predicted, with the former the one that has been best shown to provide predictability.

However, our analysis has shown that the 2010/11 drought was at best only loosely linked to SST anomalies so we would not expect a very skillful prediction.

The International Research Institute for Climate and Society (IRI) produces each month seasonal forecasts of precipitation based on predictions of the evolving ocean state and the atmospheric response to it. The realtime forecasts issued by the IRI (i.e. the 'Net Assessments') over the United States are taken from the operational forecasts from the Climate Prediction Center (CPC) of the National Weather Service in which the multi-model ensemble product from the IRI (Barnston et al. 2010)[2] is one input. Here we just present the IRI multi-model ensemble results for the global SST and North American precipitation forecasts but adopt the same plotting conventions as for the publicly issued Net Assessment forecasts, i.e. probabilities of precipitation amounts falling within terciles of the distributions, as opposed to actual amounts, and limit ourselves to a qualitative comparison with what actually occurred. In Figures 17 and 18 we show the 3.5 month lead time forecasts of seasonal means from SON 2010 through SON 2011. Looking at the SST forecasts first, which can be compared to the observed SST anomalies in Figure 4, it is clear the the La Niña conditions in the Pacific Ocean during winter 2010/11 were quite well forecast with a 3.5 month lead. The warmth of the Atlantic Ocean was, however, not well forecast. The forecast then had the La Niña persist at strength into MAM 2011 whereas in nature the event was already significantly decayed by then. The forecast did not have the La Niña decay until SON 2011 but by then, in nature, the weakened La Niña had already begun to strengthen again.

Turning now to the precipitation forecasts, which can be compared against observed precipitation anomalies shown in Figure 5, there was considerable skill from SON 2010 through MAM 2011. The 3.5 month forecast for DJF 2010/11 confidently predicted a 40 to 50 % chance of drier than normal conditions (lowest tercile) across the southern U.S. and northern Mexico clearly matching the observed anomaly. The forecast also successfully predicted continued dry conditions in MAM 2011. These precipitation forecasts were driven by the largely successful prediction of La Niña conditions from SON 2010 through MAM

[2]The IRI two-tier forecast system uses a product based on the combination of 3 different SST predictions (from both dynamical and statistical methods and persistence) to force a variety of atmosphere GCMs to create a multi-scenario, multimodel ensemble which is used to generate the precipitation forecasts.

2011. However, as noted in Section 6, the observed precipitation reductions in the southeast U.S. seem to have been associated with the negative NAO event and, hence, it seems the forecast skill in that region is partly luck. For JJA 2011, despite the forecast of continued La Niña conditions, the precipitation forecast for North America was for climatological amounts. This is consistent with teleconnections between tropical Pacific SST anomalies and North American precipitation in the summer season being insufficiently robust to provide predictive skill. As such, the forecasts failed to predict the serious near pan-continental drought of summer 2011. As the La Niña redeveloped in SON 2011, and the forecast also predicted weak La Niña conditions, the seasonal reestablishment of teleconnections transferred this into forecasts of modest likelihood of drier than normal conditions which was in line with what occurred.

Despite the inability to predict the severe dry anomalies of summer 2011, consistent with the limited influence of SSTs on North American hydroclimate in the summer, the 3.5 month forecasts nonetheless warned of an impending and developing drought. If we recall that in summer 2010 the U.S. was essentially free of drought according to the Drought Monitor, the forecast from spring and summer 2010 that the southern U.S. and Mexico would immediately move back into drier than normal conditions was prescient and provided useful information, with seasonal forewarning, for any efforts in drought planning.

10. Conclusions

We have attempted to determine the causes of the 2010-11 severe drought in North America which was centered on the regions of Texas and northeastern Mexico and which had severe social consequences. Our conclusions are as follows:

- The drought began in fall of 2010 just as a La Niña developed in the tropical Pacific Ocean and was concurrent with La Niña conditions through to fall of 2011 when our analysis ends. Historically, severe and extended droughts in the southwest U.S, Plains and northern Mexico have coincided with La Niña conditions and, in that sense, the recent drought appears the latest such event.

- Climate models forced by observed SSTs, produce drought conditions across the southern U.S. and northern Mexico from fall 2010 to spring 2011 which coincides with the seasons when tropical Pacific SSTs are most effective in exciting a teleconnected atmospheric circulation response over North America. In summer 2011 the models produce much weaker precipitation reductions than those observed which, while consistent with low teleconnectivity to the tropical Pacific in summer, and an important role for internal atmospheric variability in the observations, could also indicate weak local land-atmosphere interactions in the models.

- Despite the model support for tropical Pacific SSTs as the cause of the onset and continuation of the drought, detailed analysis of precipitation and mean and transient atmospheric circulation fields provides evidence that the actual drought was also strongly influenced by internal atmospheric variability that caused departures of these patterns from those typically associated with La Niña conditions. For example during winter 2010/11 a very strong negative NAO event caused northerly and descending flow over the southern Plains and southeast U.S. inducing drying.

- The decomposed moisture budgets in the models and Reanalyses provide better indication of the mechanisms involved in the drought. In the models during winter 2010/11 the drought intensifies over much of the southern U.S. due to anomalous moisture divergence by transient eddies which is related to the canonical northward shift of the Pacific-North America storm track expected during La Niña events. In the Reanalyses drying by transient eddies is much more spatially diffuse. However, the ERA-Interim does show strong drying over Texas, the south central and southeastern U.S. due to mean flow moisture divergence associated with the negative NAO event. The Reanalyses agree that mean flow moisture divergence anomalies sustain the drought in the summer of 2011 but this is not captured by the SST-forced models.

- The inability of the models to reproduce the observed precipitation and circulation anomalies as a consequence of SST-forcing alone could be in part a result of model error but also suggests that random internal atmospheric variability played a significant role in the character, timing and evolution of this particular drought. This limits predictability of the drought, even in the winter season when North America is most influenced by tropical Pacific SST anomalies and even when, as in winter 2010/11 the SST anomalies were strong. Continuation of the drought into summer 2011 appears unpredictable in terms of the weakening La Niña SST anomalies and could have arisen also from random internal atmospheric variability. However, the role of soil moisture-atmosphere interactions should also be examined and whether these are adequately captured in climate models.

- Realtime predictions performed by the IRI did successfully predict drought over the southern U.S. and northern Mexico to develop in SON 2010 and to intensify and persist through MAM 2011 which was based on successful forecasts of La Niña conditions. However, given the role of the NAO in the observed winter 2010/11 drought, the mechanisms of the forecast drought probably differed in details from the actual drought. The SST forecasts continued the La Niña into summer 2011 but this did not translate into a drought forecast and the actual drought in summer was not predicted.

- The high (and record-breaking) surface air temperatures during summer 2011 in the TexMex region are consistent with the very dry conditions and the general and clear inverse relation between precipitation and temperature in the region over past decades. Summer 2011 appears as extreme in terms of its dryness and warmth but not necessarily outside the range expected from this relation alone.

The 2010/11 drought has extended into fall of 2012 with another summer of record breaking heat and drought as well as the extension of the drought into both the southwest and the midwest. La Niña conditions also persisted from 2011 to 2012 before fading in summer of 2012. Follow up work will be needed to assess the cause of the 2011/12 drought but, as for the prior year, a combination of SST-forced and internally generated atmospheric circulation and moisture budget anomalies are likely the cause. The possibility that temperature records have been broken because background global warming is adding on to the high temperatures caused by dry conditions also needs to be addressed (Hoerling et al. 2013). In terms of seasonal-to-interannual prediction, successful prediction of tropical Pacific SSTs can enable a prediction of emerging or continuing dry conditions during the northern hemisphere fall, winter and spring seasons. However extremes are rarely, if ever, predicted as a most-likely outcome. Nonetheless, the summer drought conditions appeared essentially unpredictable with current prediction systems. It should be remembered that in some cases atmospheric variability will offset the impacts of SST-forced anomalies; in other cases they will enhance the SST-forced anomalies. However, in the case of 2010/11, the combination of La Niña conditions and internal atmospheric variability led to a drought that was severe, much worse in terms of dryness and heat than that forecast ahead of time and at the very edge of the observed natural variability of climate.

Acknowledgments.

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Table 1. Anomaly correlation coefficients between observed and modeled precipitation anomalies for the $20°N$ to $50°N$ region, land areas only, accounting for area weighting.

	SON 2010	DJF 2010/11	MAM 2011	JJA 2011	SON 2011
Obs-CCM3	0.05	0.45	0.33	0.03	-0.30
Obs-ECHAM	0.43	0.41	0.63	0.32	-0.03
CCM3-ECHAM	0.34	0.56	0.69	0.60	0.15

List of Figures

Observed La Niña Composite 1950-2011

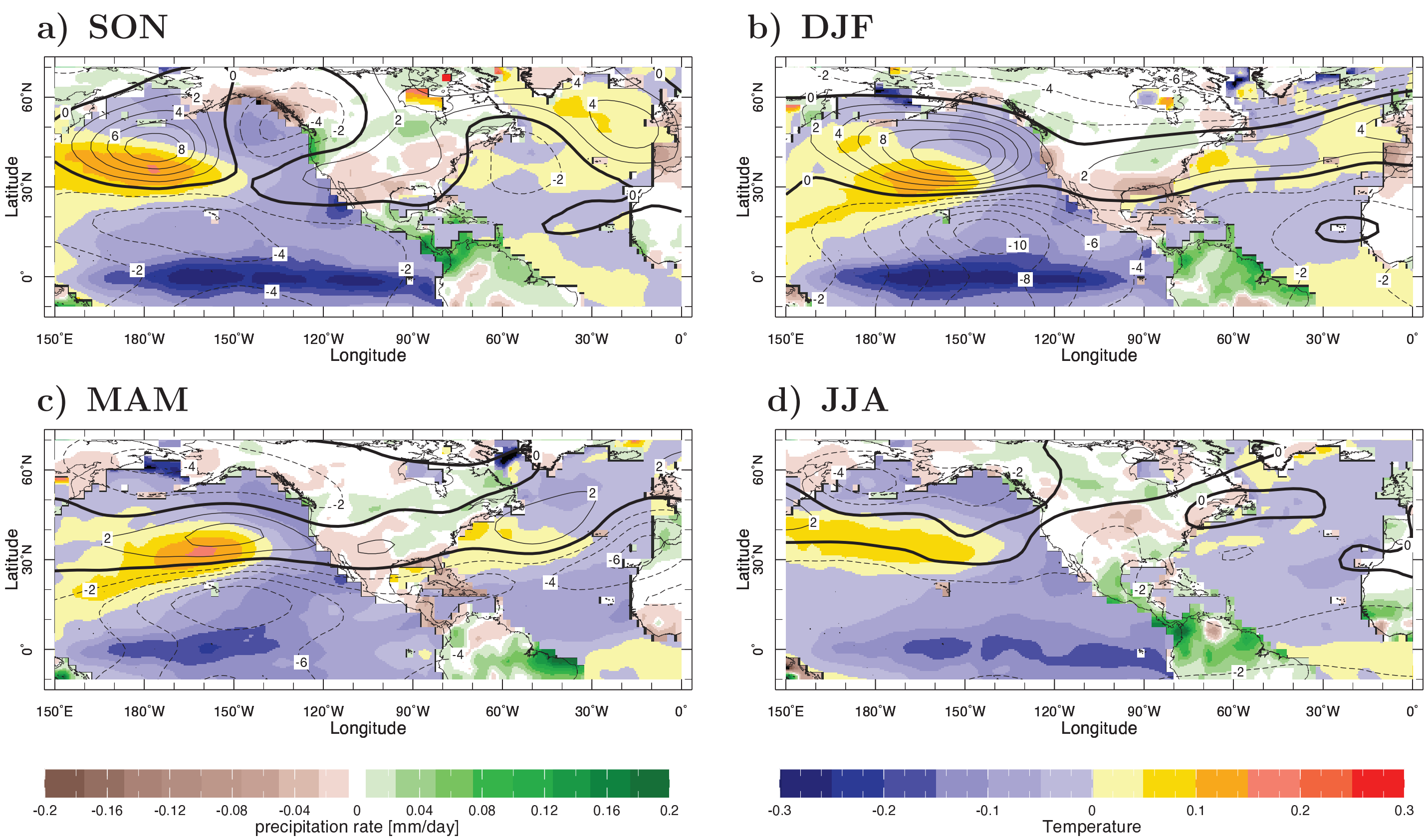

FIG. 1. The observed SST, precipitation (over land only) and 200mb heights composited over La Niña events by season. Units are Kelvin, mm/month and geopotential meters.

CCM3 La Niña Composite 1950-2011

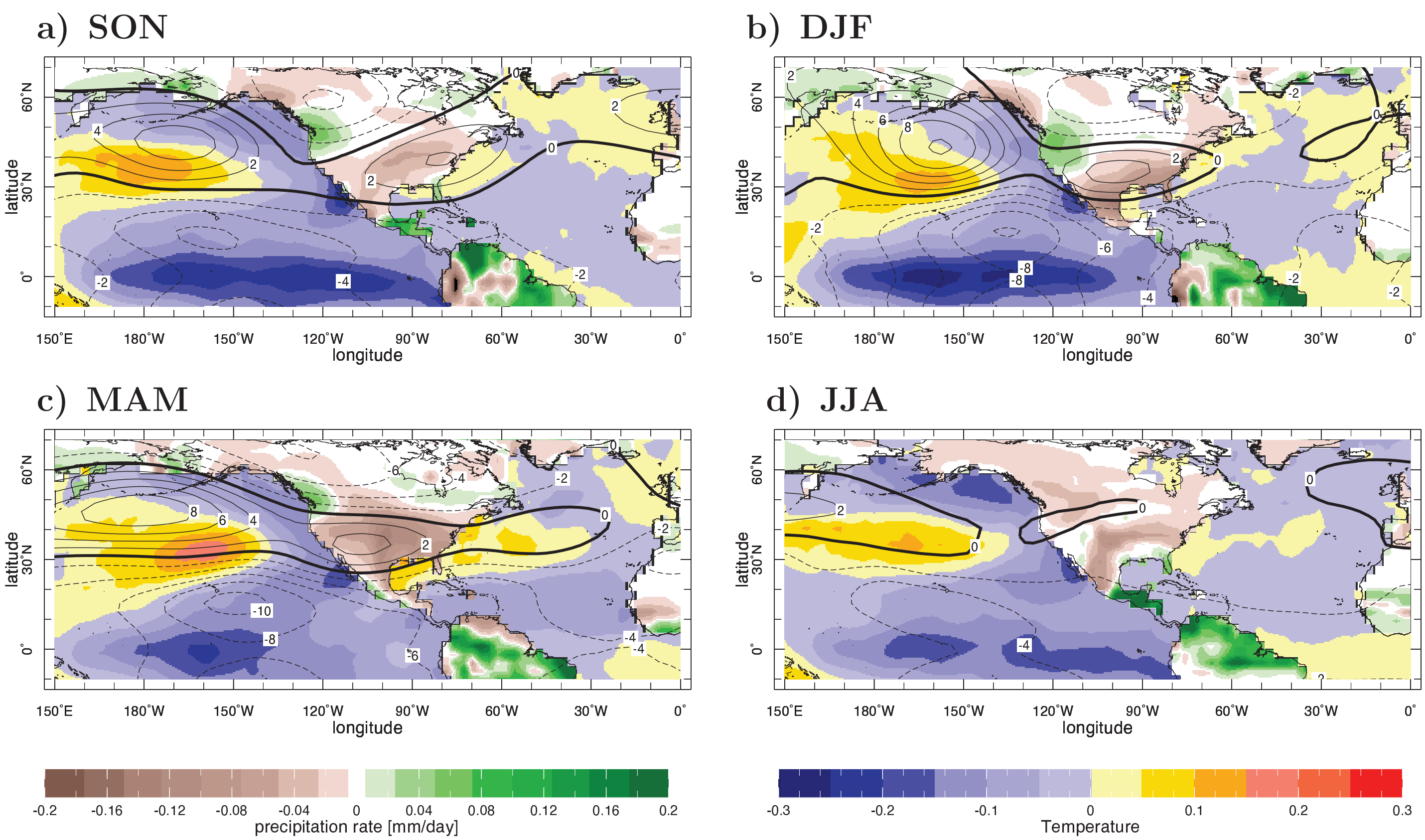

FIG. 2. As for Figure 1 but for the CCM3 model simulations

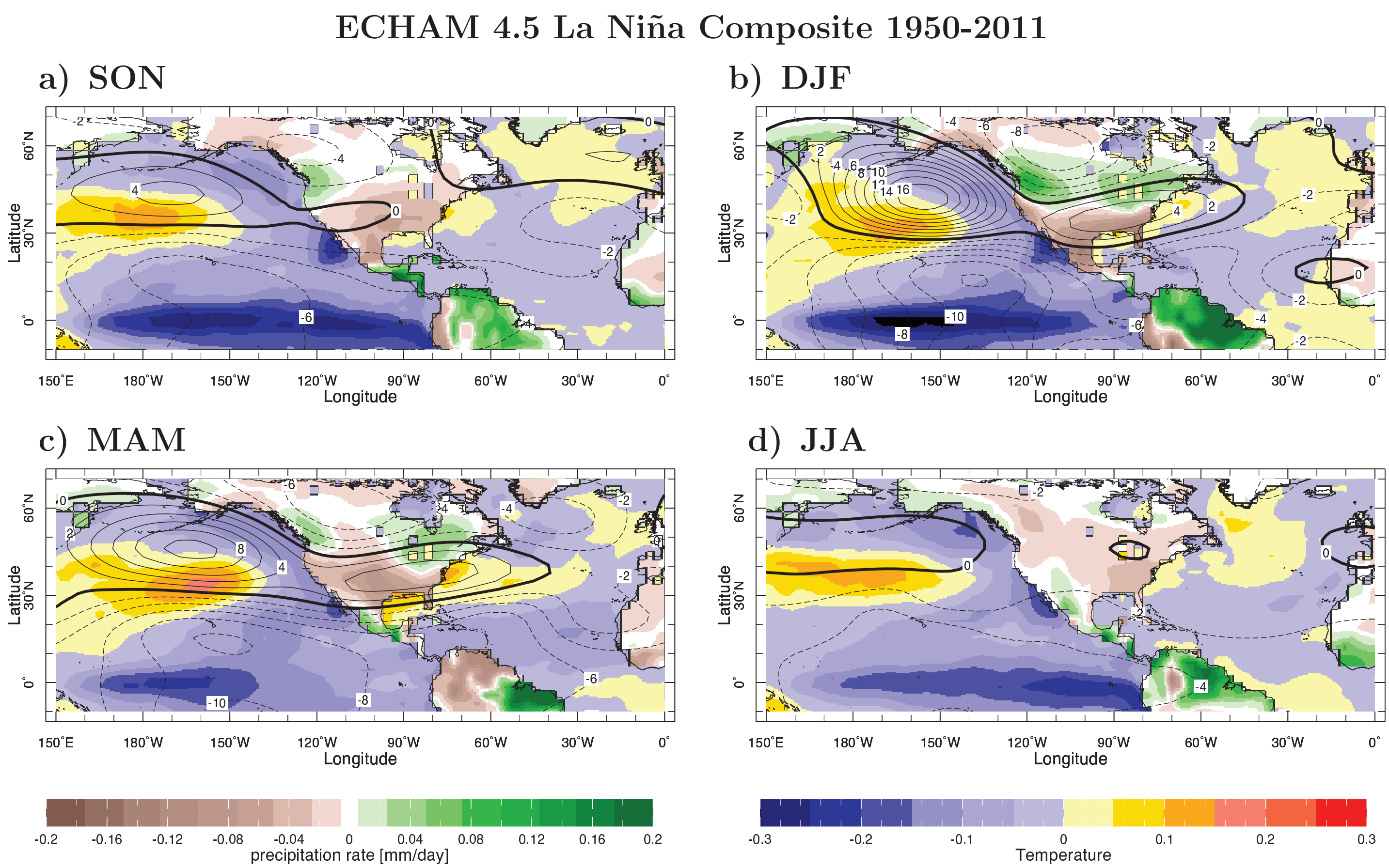

FIG. 3. As for Figure 1 but for the ECHAM4.5 model simulations.

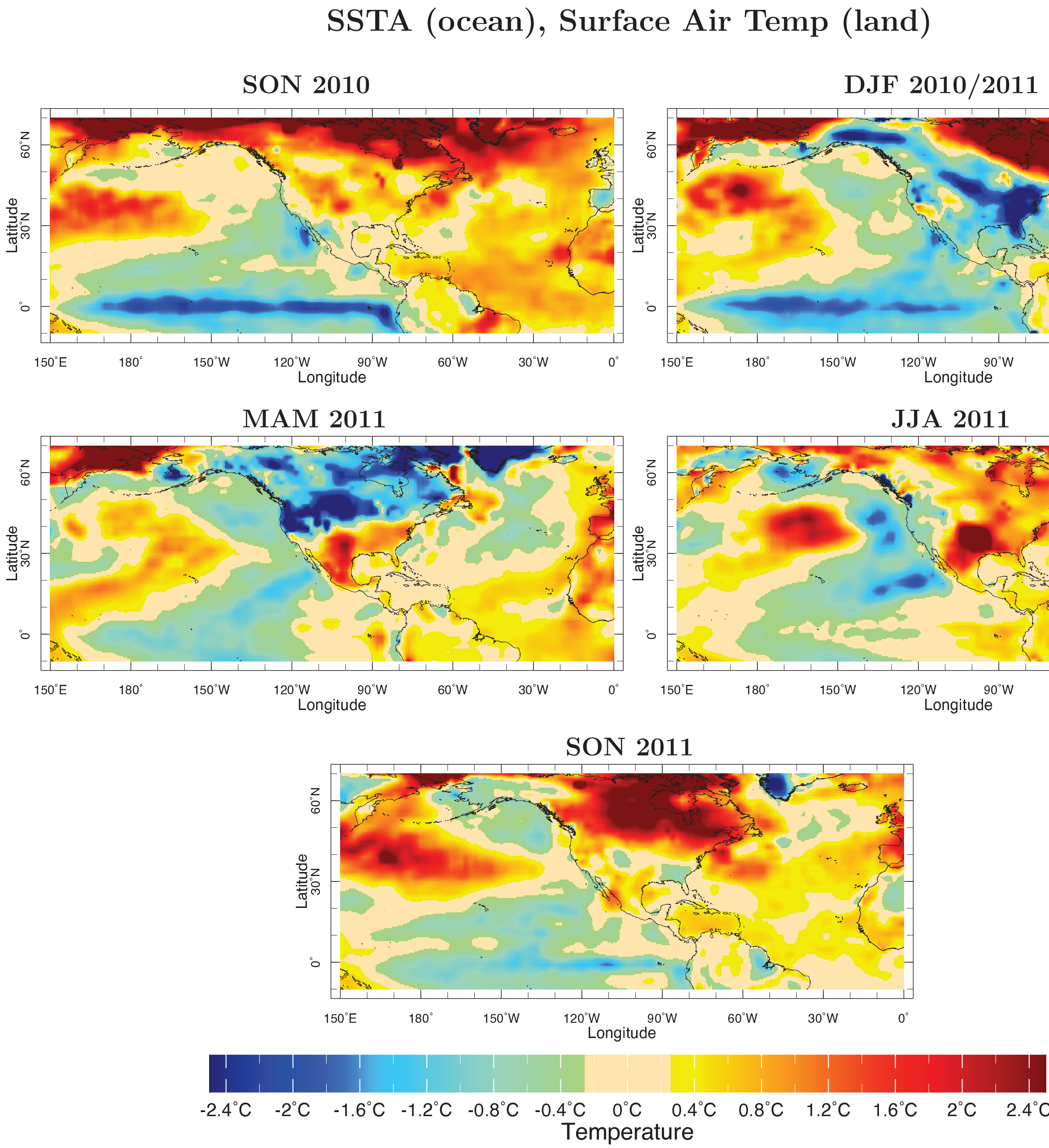

FIG. 4. The history of SST (over ocean) and surface air temperature (over land) during the 2010/11 TexMex drought shown in 3 month averages from September to November 2010 to September to November 2011. Units are Kelvin.

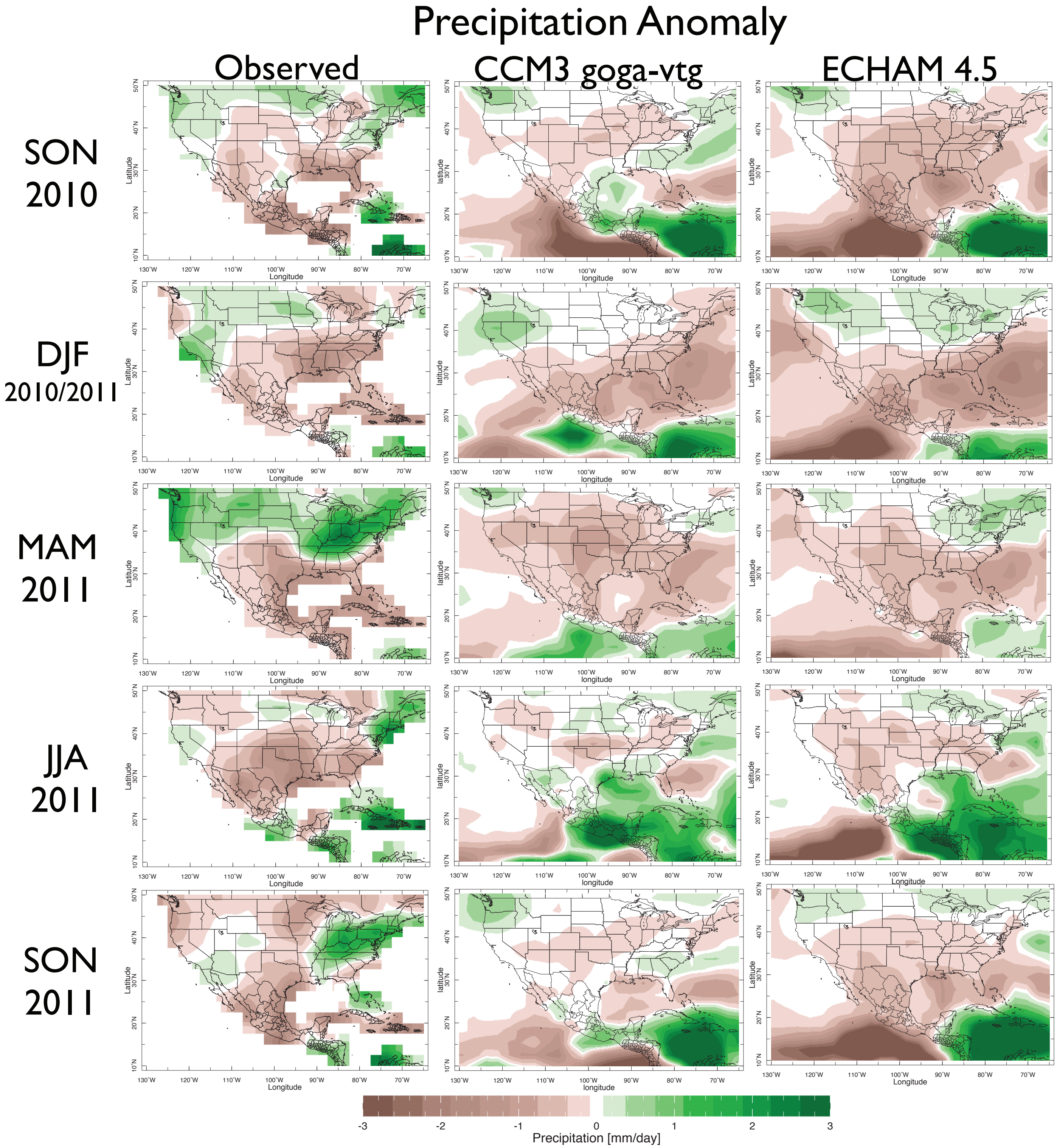

Fig. 5. The observed (left) and modeled with the CCM3 (middle) and ECHAM4.5 (right) model precipitation anomalies by season during the 2010/11 TexMex drought. Units are mm/day.

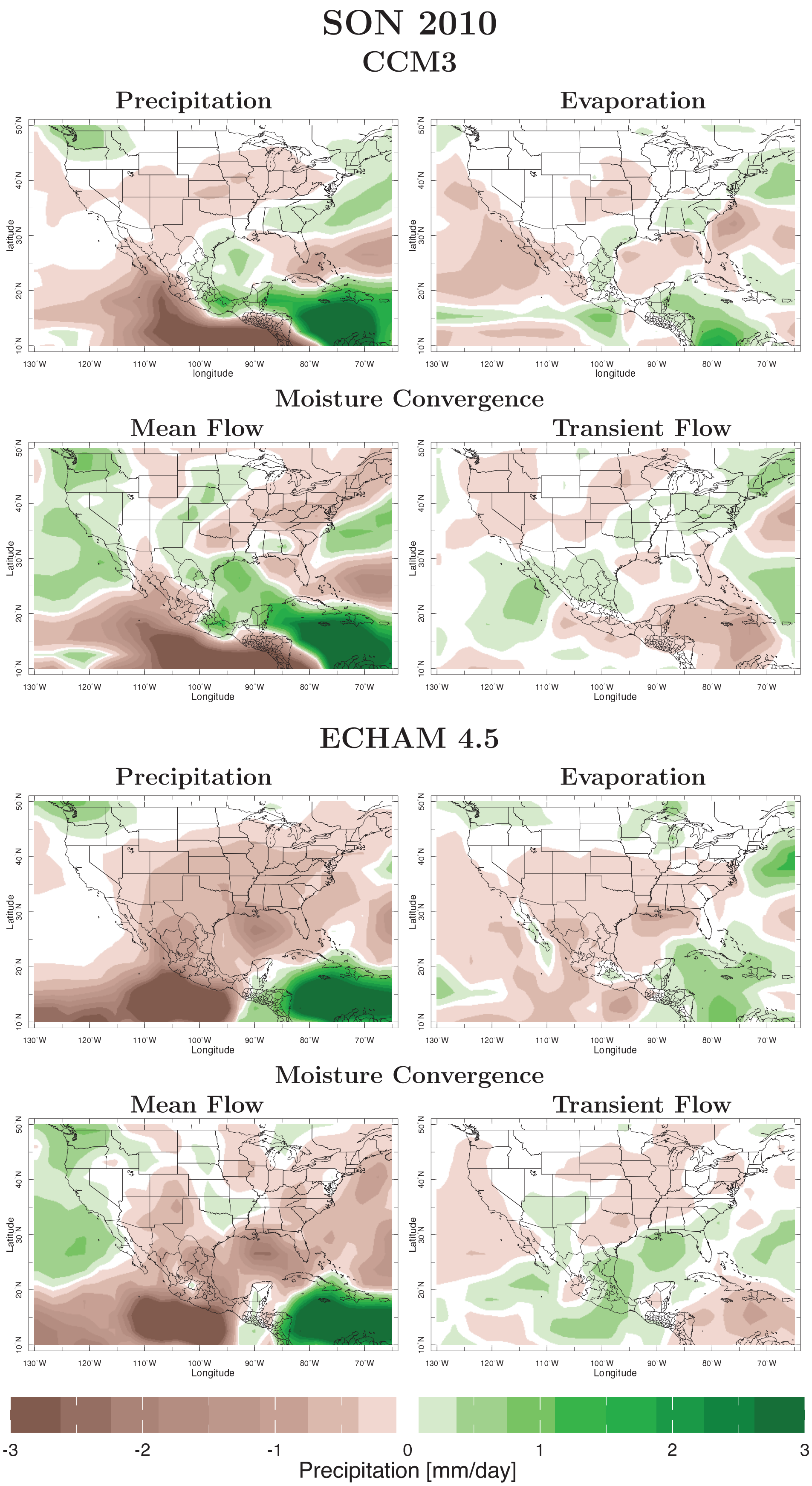

FIG. 6. The modeled moisture budget anomalies for the CCM3 models (top four panels) and the ECHAM4.5 model (bottom forum panels). In each coup of four panels the model precipitation anomaly is at top left, the evaporation anomaly at top right, the vertically integrated mean flow moisture convergence anomaly at bottom left and the vertically integrated transient eddy moisture convergence anomaly at bottom right. Results are for fall (SON) of 2010. All panels are in units of mm/day.

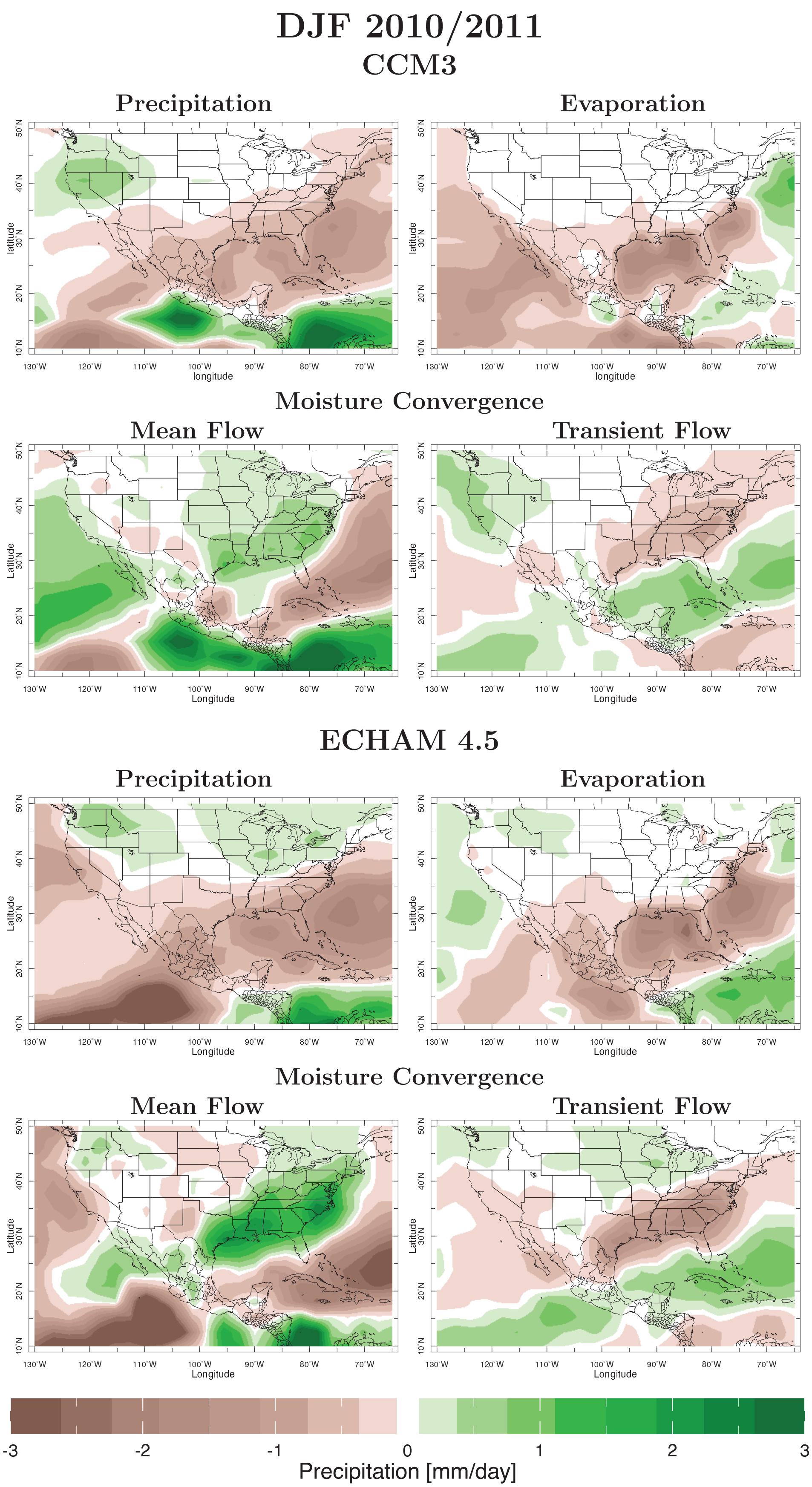

FIG. 7. Same as Figure 3 but for DJF 2010/11.

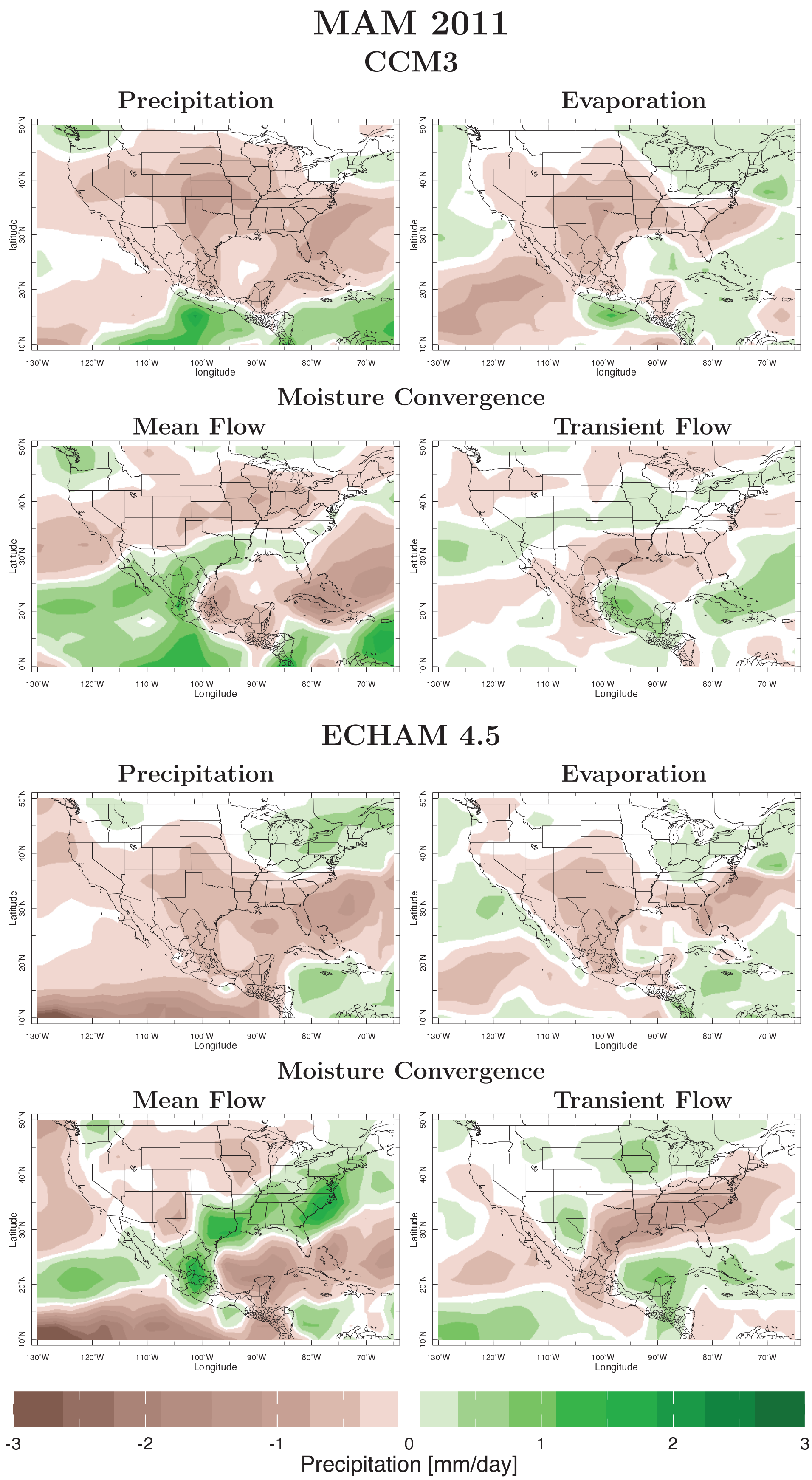

FIG. 8. Same as Figure 3 but for MAM 2011.

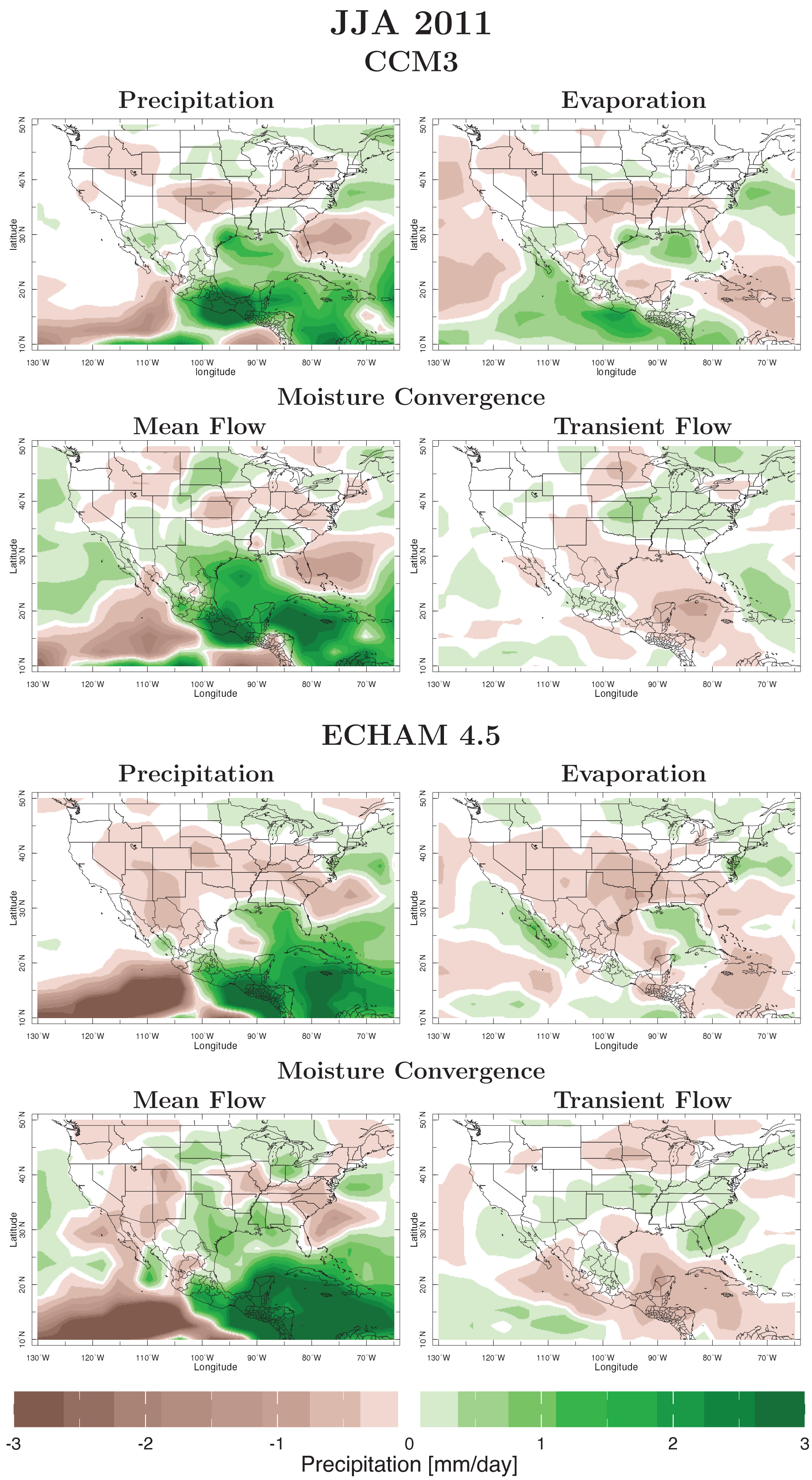

FIG. 9. Same as Figure 3 but for JJA 2011.

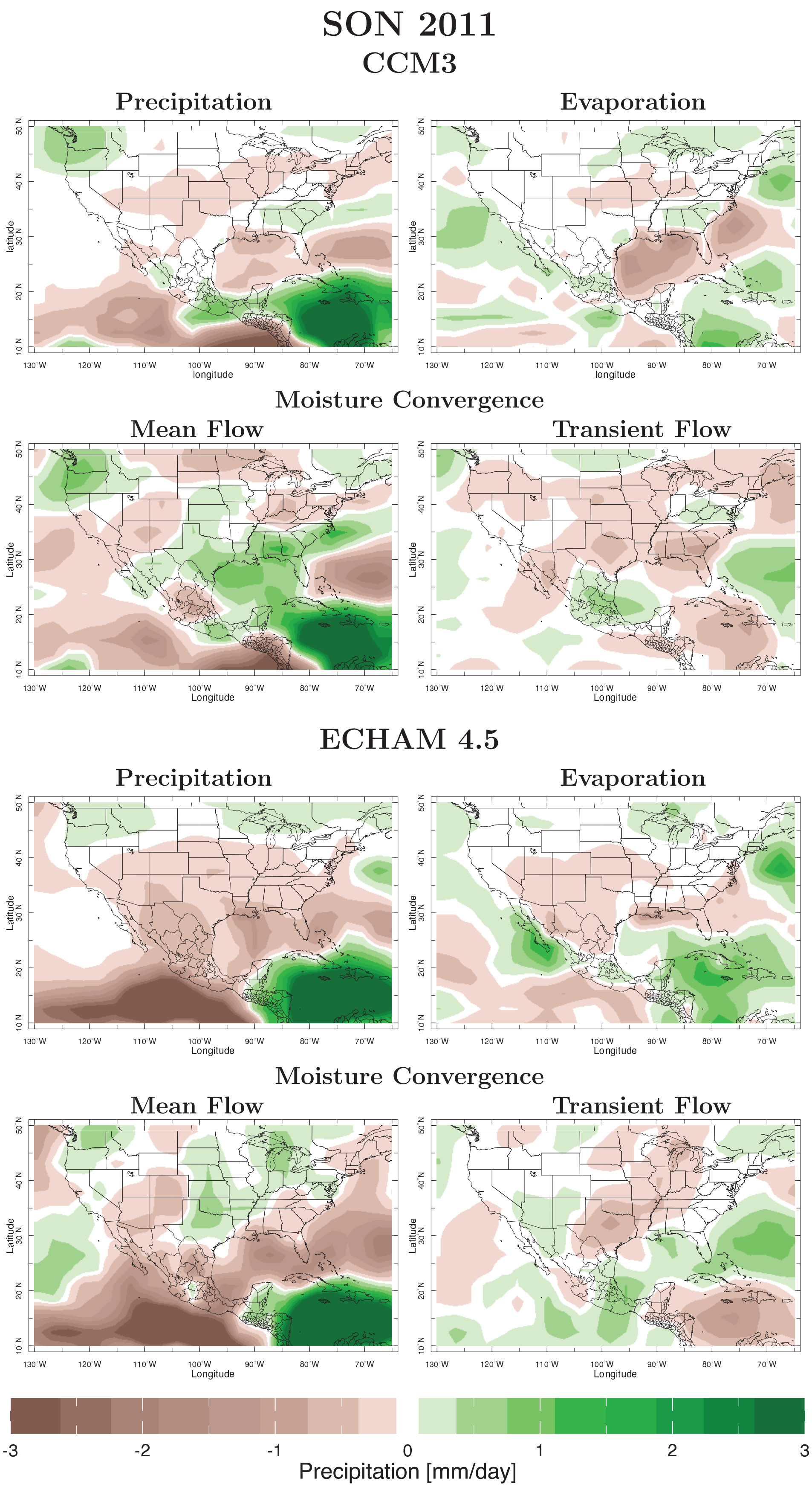

FIG. 10. Same as Figure 3 but for SON 2011.

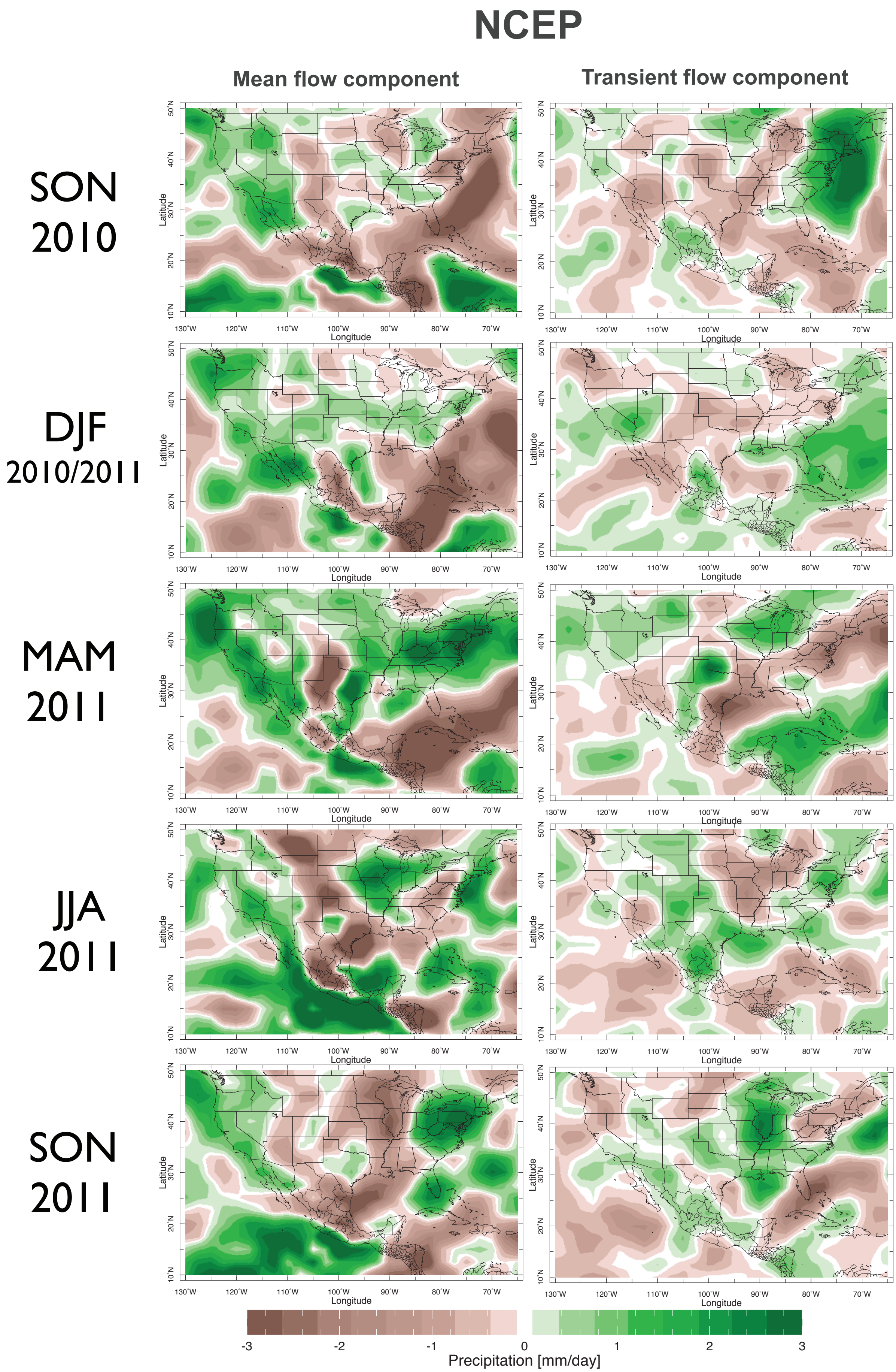

Fig. 11. Anomalies of the convergence of the vertically integrated moisture transport in the NCEP-NCAR Reanalysis due to (left) anomalies in the monthly mean state and (right) the covariance of the sub-monthly transient states for the seasons of the 2010/11 drought.

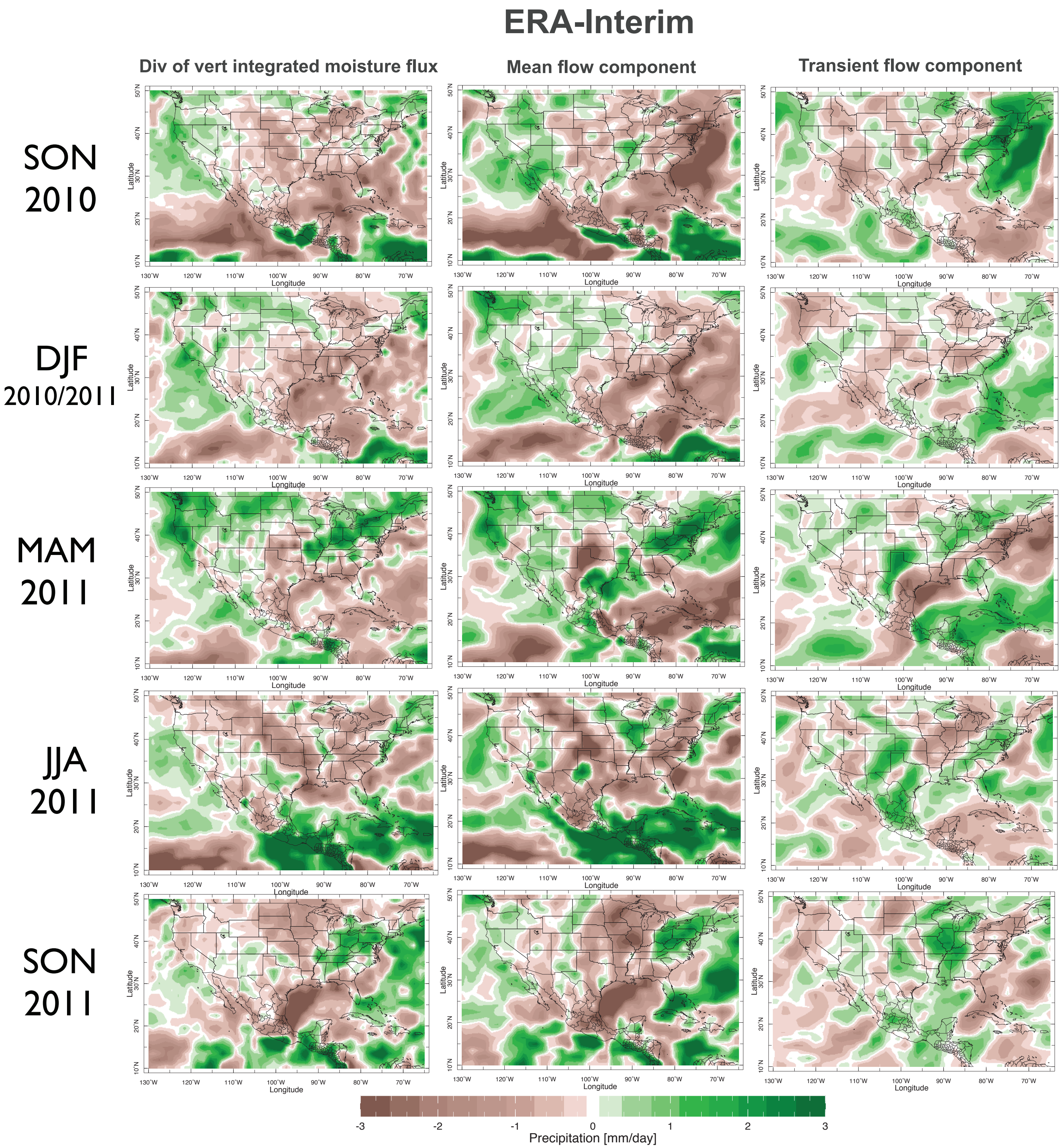

Fig. 12. Same as Figure 8 but using the ERA-Interim Reanalysis (relative to a 1979 to 2011 climatology. The monthly mean state and transient contributions are in the middle and right columns, respectively while the left column shows the anomalies in the convergence of the vertically integrated moisture transports as reported within the ERA-Interim data and which is well approximated by the sum of the two contributions.

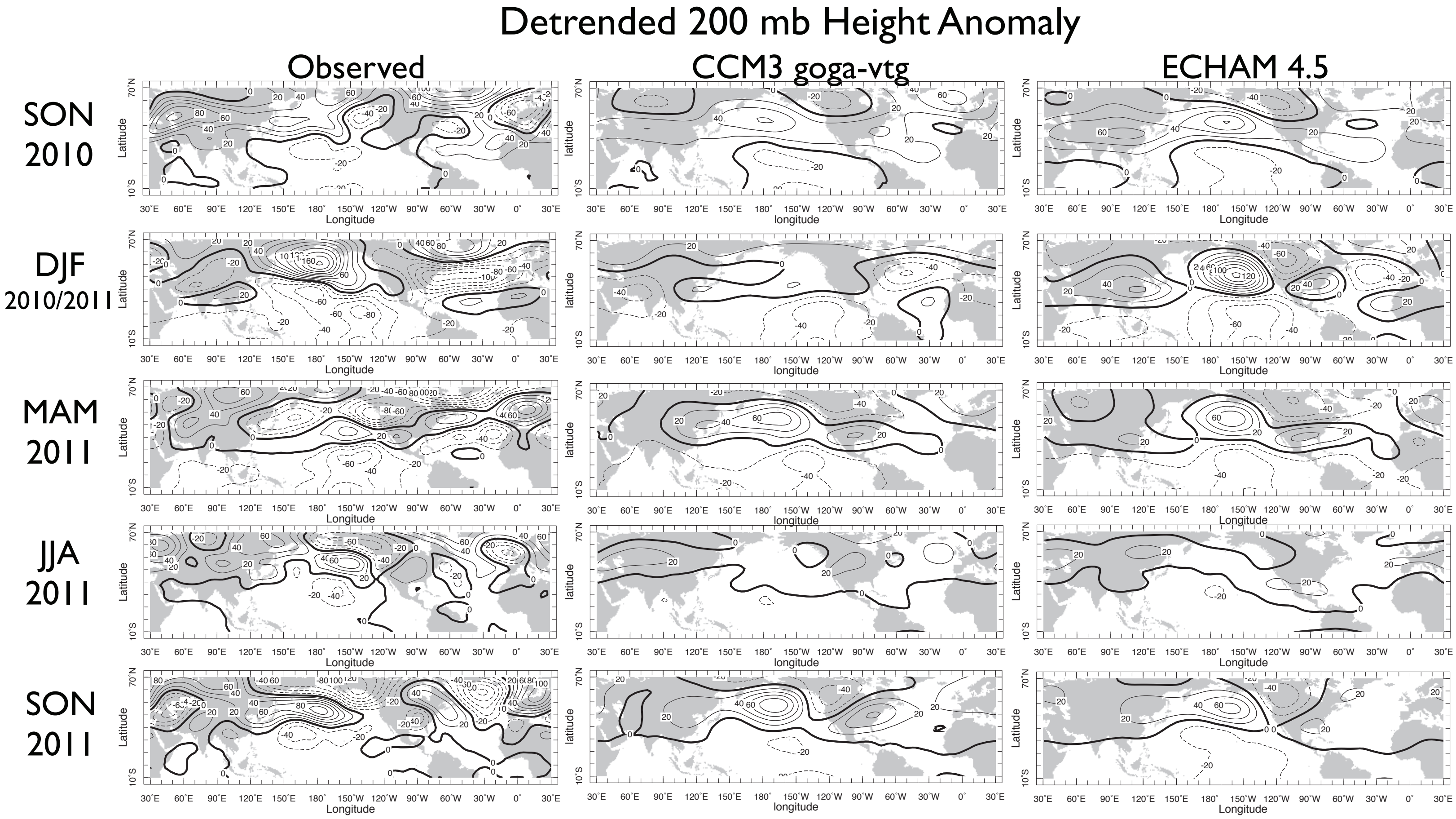

FIG. 13. The 200mb geopotential height anomalies for the seasons from SON 2010 to SON 2011 for the NCEP-NCAR Reanalysis (left), the CCM3 model (middle) and the ECHAM4.5 model (right). Heights were detrended to remove an overall increase caused by global warming. Units are meters.

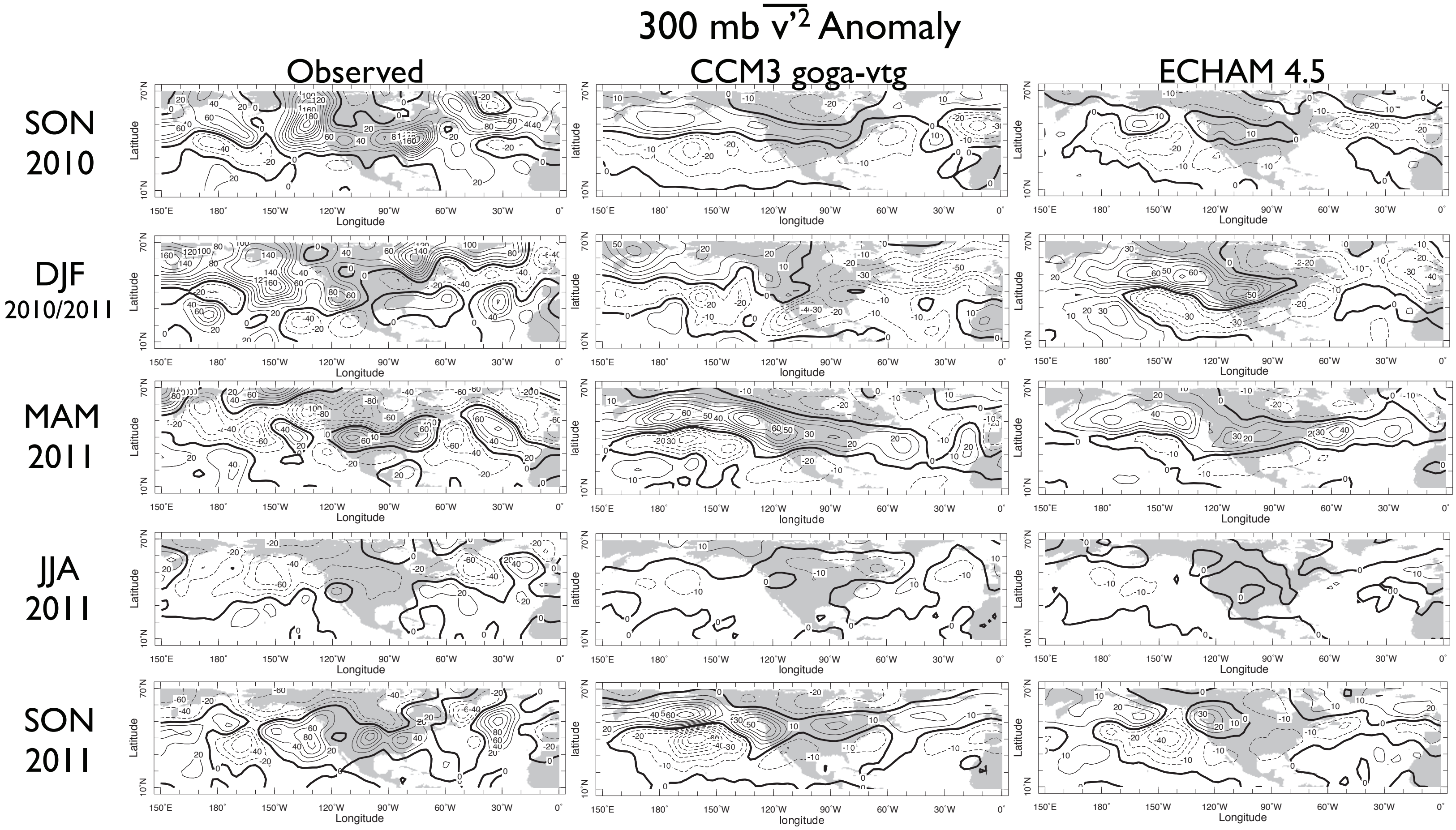

FIG. 14. Same as Figure 8 (with no detrending) but for the 300mb sub monthly eddy meridional velocity variance. Units are meters squared per second squared.

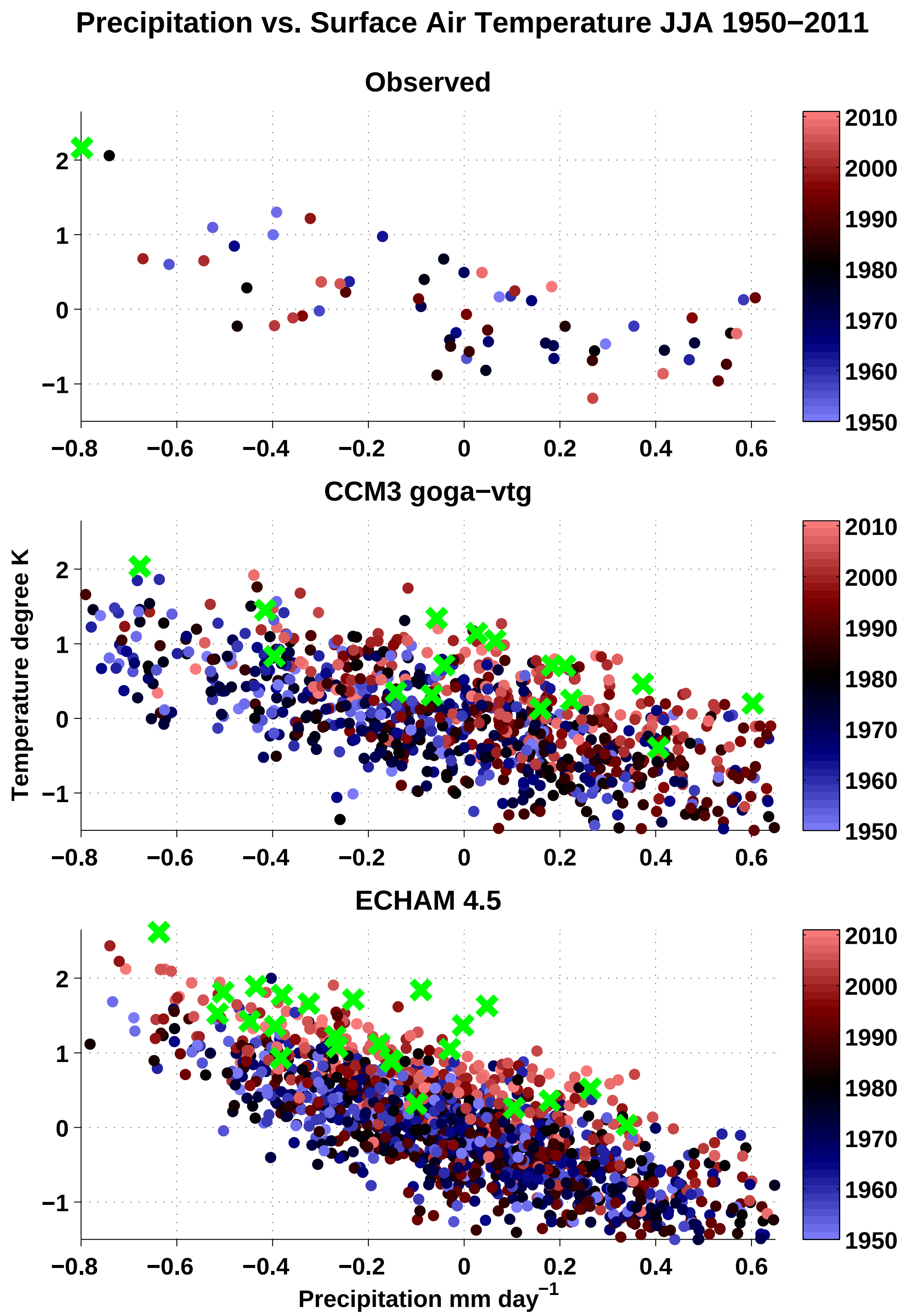

FIG. 15. Scatter plots of JJA temperature (Kelvin) and precipitation (mm/day) anomalies for the TexMex region and the 1950 to 2011 period for observations (top), the CCM3 model (middle) and the ECHAM4.5 model (bottom).

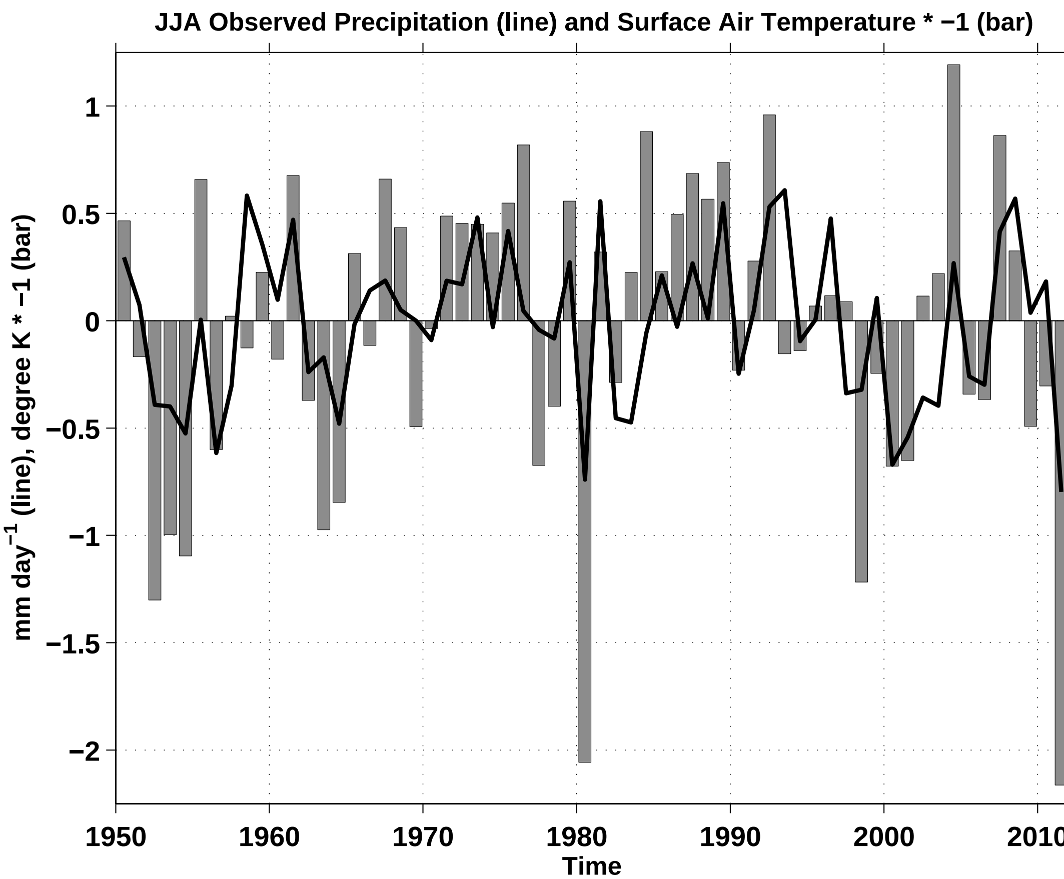

FIG. 16. Time history of observed JJA temperature (bars, Kelvin) and precipitation (line, mm/day) anomalies for the TexMex region and the 1950 to 2011 period.

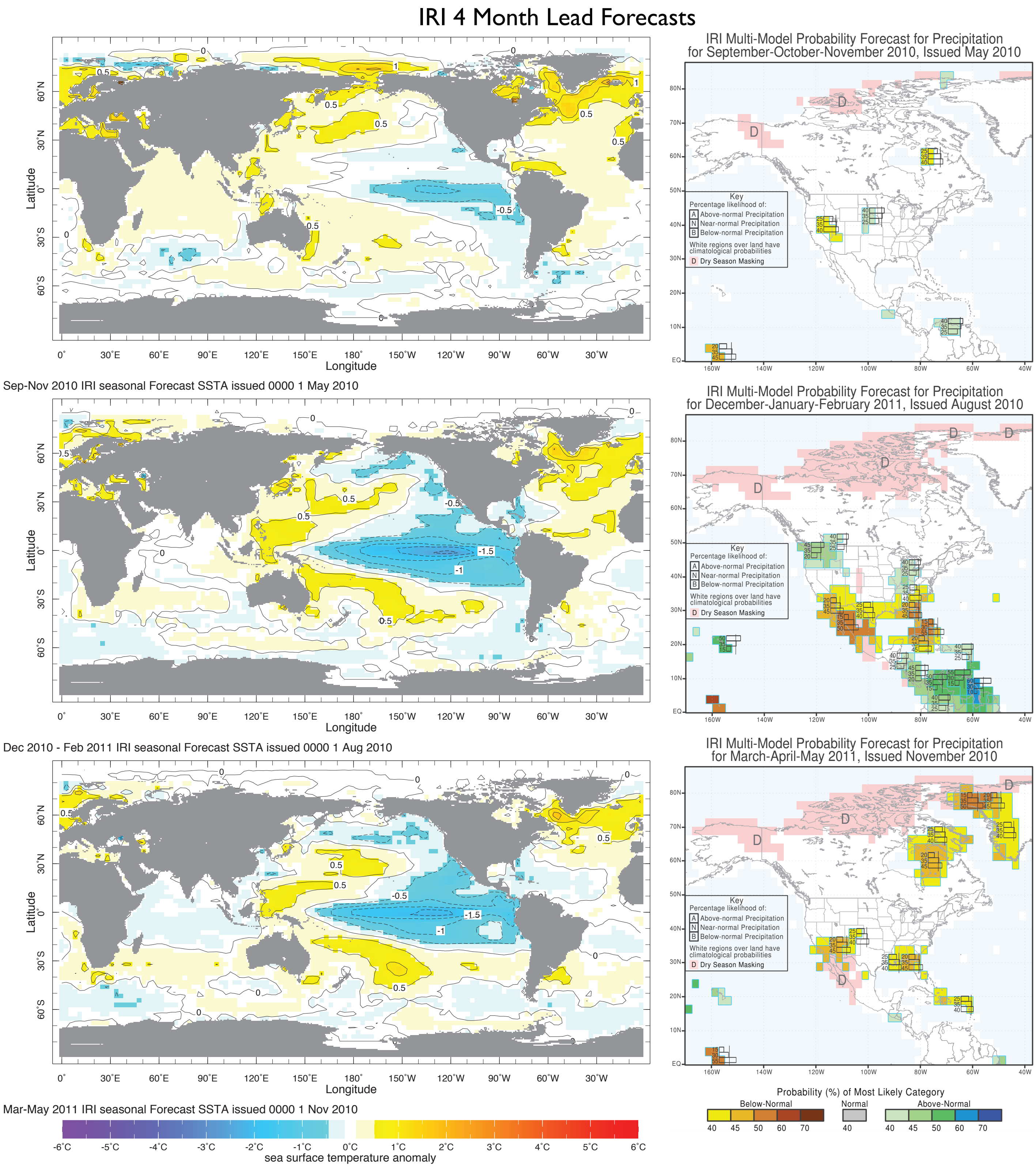

FIG. 17. The 4 month lead time forecasts of SST (left) and North American precipitation (right) from the IRI seasonal-to-interannual prediction system for SON 2010 from May 2010 (top), DJF 2010-11 from August 2010 (middle) and MAM 2011 from November 2010 (bottom).

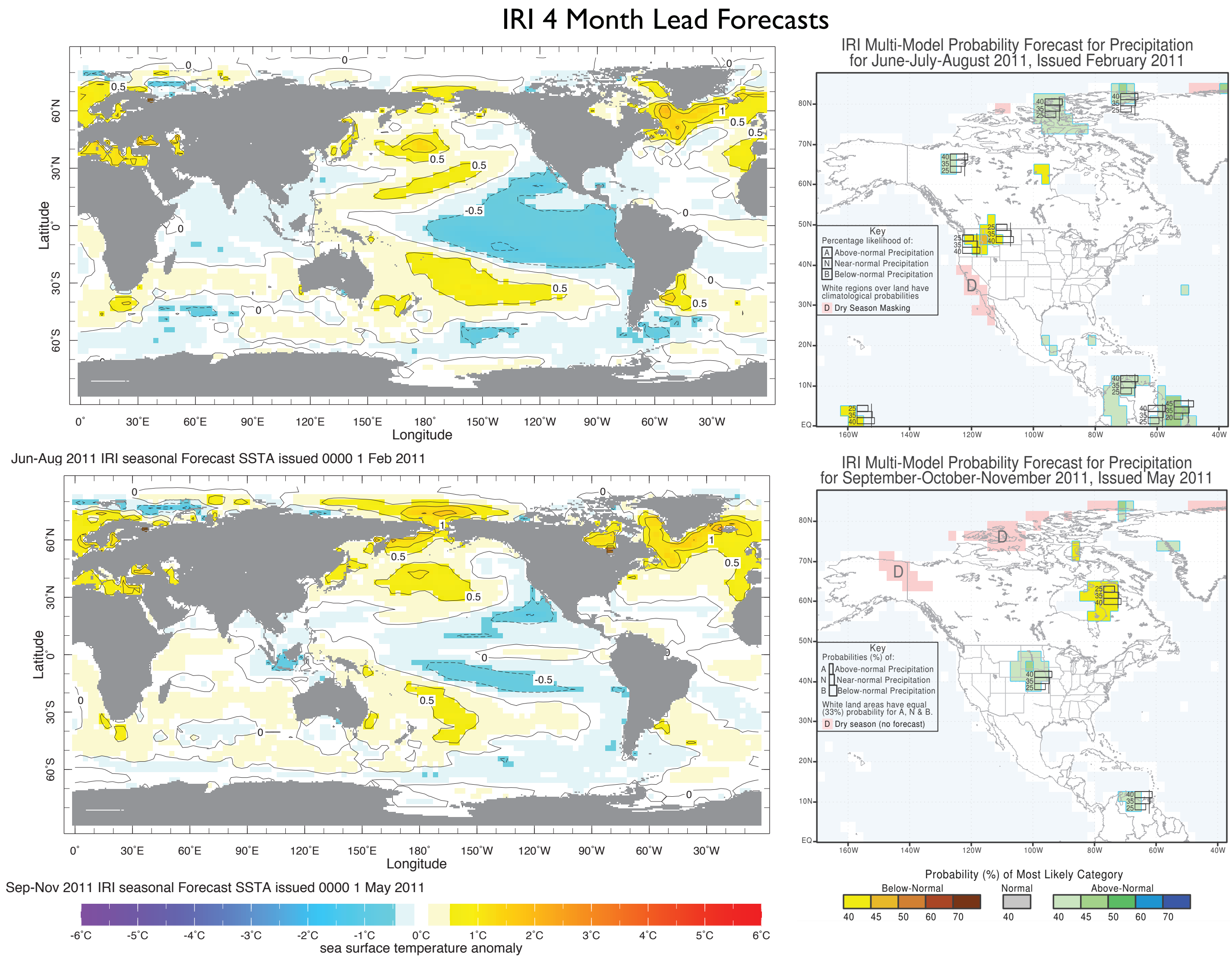

Fig. 18. Same as Figure 13 but for forecasts of JJA 2011 from Febtuary 2011 (top) and SON 2011 from May 2011 (bottom).