Chapter 1

Decadal Hydroclimate Variability Across the Americas

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Decadal hydroclimate variability in North America and tropical and extratropical South America is analyzed and possible mechanisms for its origin discussed. Focus is on southwestern North America (including Mexico) and the Great Plains, the northeast United States, northeast Brazil and southeastern South America. The varying roles of ocean forcing, internal atmospheric variability and radiatively-forced hydroclimate change are analyzed. In some regions such as southwest North America and the Plains, and northeast Brazil, decadal variations of hydroclimate are quite well understood and can be attributed to variations in tropical Pacific and tropical North Atlantic sea surface temperatures. The mechanisms of tropical ocean influence are reviewed and a case is made that the precipitation anomalies across the Americas associated with the so-called Pacific Decadal Oscillation are essentially the same as those associated with the El Niño-Southern Oscillation and also derive from the tropical component of the PDO SST anomalies. In other regions, such as the north east United States, strong decadal timescale variations are present but cannot be explained in terms of ocean forcing. Both there and in southeast South America decadal variations cannot easily be distinguished from secular wetting trends given the length of the observational record. Finally, it is shown that across much of the Americas near term future radiatively-forced precipitation change will be of the amplitude of historical decadal precipitation variability indicating an important and predictable change.

1.1. Introduction

Decadal variations of hydroclimate across the Americas have left a substantial mark on the social, economic and agricultural character of the continent. For example, in perhaps the most famous example, the Colorado River Pact of 1922 apportioned river flow between the upper basin and lower basin states based on recorded flows in the immediately preceding decades. However these decades happened to coincide with the early twentieth century North America pluvial (Fye *et al.*, 2003; Cook *et al.*, 2011) and the flows of 22 billion cubic meters (BCM) per year were, as we now know, about the highest to occur in the past millennium, way in excess of both the long term 20th Century average of 18.6 BCM and the tree ring reconstructed average flow over the last 500 years of only 16.7 BCM (Christensen and Lettenmaier, 2007; Meko *et al.*, 2007). Seven U.S. states and Mexico are still trying to grapple with this coincidence of decision making and the quirks of climate variability. Later, the tremendous population growth of the southwest U.S. occurred within the decades of the 1980s and 1990s and was no doubt made easier by that fact that this was another wetter than normal (pluvial) period (Seager *et al.*, 2005b; Swetnam and Betancourt , 1998). On the dry side, the 1930s Dust Bowl drought forced millions to leave their homes, an exodus from the Plains states and a permanent shift in the agricultural, social and economic structure of the Plains and the wider U.S. (Worster, 1979).

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Further back, the 1890s drought was a defining event in the decision to create the Bureau of Reclamation and Federalize the development of the West (Reisner, 1986). At the other end of the Americas a shift in the last few decades to a wetter climate has enabled a vast expansion of agriculture in the sub-humid to semi-arid Pampas of southeast South America (Seager *et al.*, 2010) with tremendous benefit to local agricultural interests and the global food supply.

While it is remarkably easy to draw convincing connections between decadal hydroclimate variability and matters of social import and interest that effect millions, it remains almost impossible to predict how hydroclimate will evolve in coming decades due to natural causes. That may be because it is truly unpredictable. However, while the mechanisms of atmospheric response to SST variations are reasonably well understood, the ocean mechanisms of decadal variability remain poorly understood, and efforts in decadal prediction, while no longer embryonic, are still in their infancy. Hence it might be rash at this point to conclude that decadal variability is unpredictable. Regardless, at this point our ability to predict hydroclimate change in coming decades relies almost entirely on the response to increasing radiative forcing which in some regions of the Americas is likely to quickly become a serious matter (e.g. Seager *et al.* (2007, 2012); Vano *et al.* (2013). On the other hand the amplitude of projected human-induced hydroclimate change in the coming decades is not expected to be outside the range of natural variability (Seager *et al.*, 2012). Of course, unlike natural decadal variability, human-induced change is uni-directional as long as the responsible changes in forcing (e.g. greenhouse gases) do not reverse in sign. Nonetheless, this does imply that for the coming decades probabilistic projections of future hydroclimate need to account for both forced change and evolving natural variability. Which brings us back to the character and cause of natural decadal variability.

In the absence of any proven ability to predict the evolution of naturally occurring modes of hydroclimate variability, the very least we can do is to better understand the nature of this phenomena and reliably attribute past change between natural variability and forced change as one means, together with model projections, of providing guidance, in a probabilistic manner, as to future hydroclimate in key regions of concern. This is what we will attempt to do here. The regions we will focus on are southwestern North America and the Plains, the northeast U.S., northeast Brazil and southeast South America which span a range of tropical to mid-latitude regions, semi-arid to humid climates and states of understanding. In all cases we aim to illustrate the character and causes of decadal hydrolcimate variability across the Americas using nothing more than a simple set of time series and maps. This deliberately simple approach is based on the idea that, to be worth worrying about, decadal variability of hydroclimate must be visible in the raw climate record and evident in the personal experiences of anyone living through it.

1.2. Western North America; A reasonably well understood example of strong oceanic control

We begin with probably the most studied region, that of western North America which for our purposes includes the Plains and regions to the West from central Mexico to the latitude of the California-Oregon border. Considerable work to date has shown that the hydroclimate history of these regions on the interannual to decadal timescales can be quite well reproduced by atmosphere models forced by observed SSTs (Schubert *et al.*, 2004; Huang *et al.*, 2005; Seager *et al.*, 2005b; Herweijer *et al.*, 2006). Here we make this same point again but take the opportunity to show a comparison of soil moisture as simulated by the atmosphere model against that simulated by a land hydrology model forced by the observed history of air temperature and precipitation.

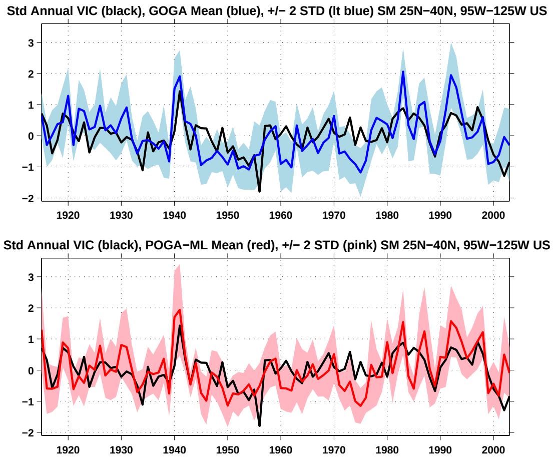

Fig. 1.1. Top, the soil moisture anomaly in southwestern North America as computed by the VIC model forced by observed meteorology (black) and that computed by the global climate model forced by observed global SSTs (GOGA configuration) shown as the 16 member ensemble mean (blue) and the plus and minus two standard deviation spread of the ensemble (blue shading). Bottom, same as top but with the global climate model forced by only tropical Pacific SSTs (POGA-ML configuration).

The land hydrology model is the Variable Infiltration Capacity (VIC) model of Liang *et al.* (1994) and covers 1915 to 2003. The atmosphere model is a 16 member ensemble of simulations with the National Center for Atmospheric Research (NCAR) Community Climate Model 3 (CCM3) (Kiehl *et al.*, 1998). In the first configuration (Global Ocean Global Atmosphere - GOGA) the model is forced by Kaplan *et al.* (1998) SSTs in the tropical Pacific and Hadley Centre SSTs elsewhere (Rayner *et al.*, 2003). In the second configuration (tropical Pacific Ocean Global Atmosphere - POGA-ML) the model is forced only by tropical Pacific Ocean observed SSTs and is coupled to a mixed layer ocean which computes the SST elsewhere. The reader is referred to Seager *et al.* (2005b) for more details and explanation of these choices. Both simulations cover 1856 to 2011.

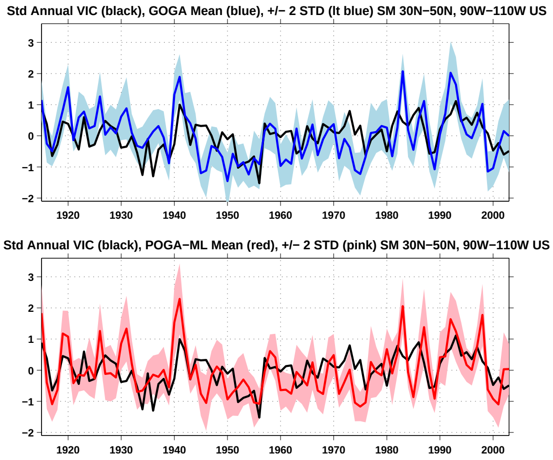

Fig. 1.2. Same as Figure 1 but for the Great Plains region.

Figure 1 shows that, for the common period, the GOGA modeled soil moisture tracks the VIC observationally-based estimates remarkably well including the early to mid 1950s drought, the overall wet conditions in the 1980s and 1990s and the shift back to drier conditions following the 1997/98 El Niño. That this is so indicates that hydroclimate in southwest North America is strongly influenced by variations of SSTs. The correlation coefficient between the observed and modeled time series is 0.52 indicating that a quarter of the variance in the former is controlled by ocean variability. Figure 2 shows the same comparison for the Great Plains ($30-50°N, 110-90°W$) where the GOGA model tracks VIC soil moisture with only slightly less skill than in the southwest and with both regions sharing many of the same decadal scale droughts and pluvials. For both regions the lower panels show the POGA-ML simulations which also have high skill and indicate that the part of the global SST forcing that matters most in the GOGA simulations is the tropical Pacific Ocean. Note that forcing by SST variability can create trends in precipitation of multidecadal length and that, therefore, assuming that late twentieth century trends, or even trends over the whole twentieth century, will necessarily represent radiatively-forced hydroclimate change are almost certainly misguided.

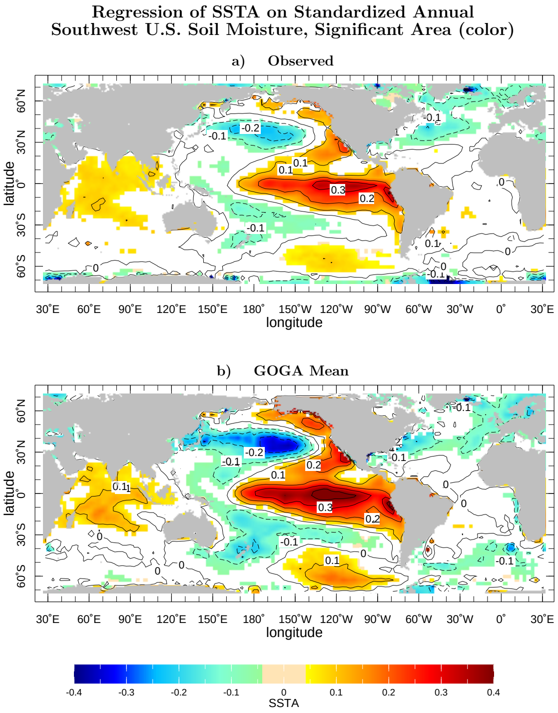

Fig. 1.3. The regression of annual mean global SST anomaly on the VIC (top) and GOGA modeled (bottom) annual mean soil moisture anomaly in southwest North America. Areas of significance at the 5% level are colored.

The driving role of the tropical Pacific is further illustrated in Figure 3 where the regression of global SST anomalies on annual mean southwest North America soil moisture is shown for observations (with VIC soil moisture) and the GOGA model. Colors are only shown where the regression is significant at the 5% level. The association of wet (dry) conditions with warm (cold) tropical Pacific SSTs is clearly seen. The relationship is stronger in the model due to the isolation in the ensemble mean of the SST forced component. These relations between soil moisture and SSTs are weaker than those between precipitation and SSTs (see Seager *et al.* (2005b)) but still easily retain significance indicating a clear association between the tropical Pacific Ocean and land surface hydrological conditions.

Although not seen in Figure 2, dry conditions in the southwest and Plains are also associated with warm tropical Atlantic SST anomalies and these have been shown to play a generally secondary role relative to the tropical Pacific anomalies but are important for generating the 1930s and 1950s droughts (Schubert *et al.*, 2004; Seager *et al.*, 2005b; Seager, 2007; Seager *et al.*, 2008). The mechanisms of the tropical Atlantic-North America precipitation link are detailed in Kushnir *et al.* (2010).

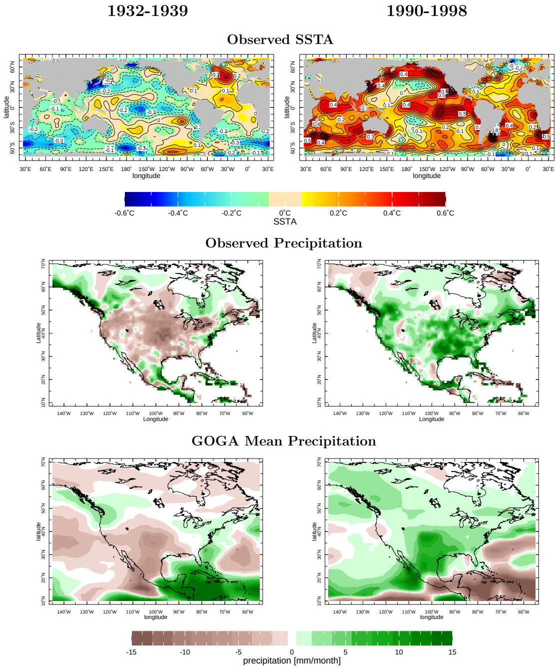

Fig. 1.4. The observed SST (top) and precipitation (middle) and modeled precipitation (bottom) anomalies for the 1932-39 Dust Bowl period (left column) and 1990-98 pluvial period (right column) in North America.

To make the links between tropical SSTs and decadal hydroclimate variations over North America more clear we show in Figure 4 the observed SST anomaly and the observed and GOGA modeled precipitation over North America for the dry decade of 1932 to1939 and the wet decade of 1990 to 1998. Much like the regression derived pattern, which accounted for both interannual and longer timescales, these decadal timescale maps emphasize the role of the tropical Pacific: the cold SSTs in the 1930s and the warm SSTs in the 1990s. The warm tropical North Atlantic, partly responsible for the Dust Bowl drought, is also seen in the 1930s. The degree to which the 1930s and 1990s were the opposite of each other in SST and precipitation anomalies (apart from a general warming of the oceans) is quite striking. The model precipitation anomalies also reasonably reproduce the observed patterns, emphasizing the extent of oceanic control on precipitation anomalies at these timescales.

However it must be noted that the modeled Dust Bowl drought is centered in the southern Plains and northern Mexico whereas the observed drought was centered in the Central to northern Plains. The model drought pattern is typical of droughts forced by cool tropical Pacific and warm tropical North Atlantic SST anomalies and is, for example, very similar to the modeled (and observed) pattern of the 1950s drought. The more northern-centered Dust Bowl drought was quite unusual (Seager *et al.*, 2008) but this drought was also unusual in that it was the only one that was associated with widespread soil erosion and dust storms which have been attributed to the post World War I expansion of agriculture into the region and the farming practices of the time (Worster, 1979; Hansen and Libecap, 2004). Recently, Cook *et al.* (2008, 2009, 2010) have performed simulations of the Dust Bowl period with imposed SSTs, loss of crop cover and exposure of bare earth (in areas as indicated by contemporary Soil Conservation Service surveys). The model had an interactive dust module that simulates the emission of dust, its transport, interaction with radiation and ultimate deposition. That work found that the dust storms reflect solar radiation and induce an anomalous radiative sink which the atmosphere balances by subsidence and low level divergence, suppressing precipitation. This intensifies the drought in the regions of dust aerosol loading which also means the model drought shifts its center from the southwest into the central Plains better matching the observed pattern. Comparison of modeled circulation anomalies to those in the 20th Century Reanalysis (Compo *et al.*, 2010) shows that it is only when active dust storms are included that the model can catch the observed continental scale subsidence that occurred during the Dust Bowl.

If the dust storms were important to the character and intensity of the Dust Bowl drought then the drought was not just a natural disaster but one for which human activity was in part, however unwittingly, responsible. In contrast, Hoerling *et al.* (2009) have argued that the SST forcing of the Dust Bowl drought was weak and that the strength arose from internal atmospheric variability unconnected to oceanic conditions. Of course, it is likely that some combination of SST forcing, internal atmospheric variability and dust aerosol feedbacks on both of these was ultimately responsible. Future research may be able to unravel the relative roles of each which will probably require a more fine grained approach than has been attempted to date, looking at individual seasons and years in the Dirty Thirties.

1.3. North Eastern North America: A poorly understood example of strong multidecadal variability

Northeastern North America is a wet region of the continent and does not experience the frequent multiyear droughts that the sub-humid to semi-arid regions of the Plains and southwest do. However hydroclimate has undergone serious decadal to mulitidecadal fluctuations over the past century. In a recent paper Seager *et al.* (2012) examined the precipitation history of the Catskill Mountains region (where 87% of New York City's water comes from) which is representative of a wider northeast U.S. region. Here the major features of the last century are a severe multiyear drought between 1962 and 1966 followed by an early 1970s abrupt transition to a wetter climate that has persisted to the present day.

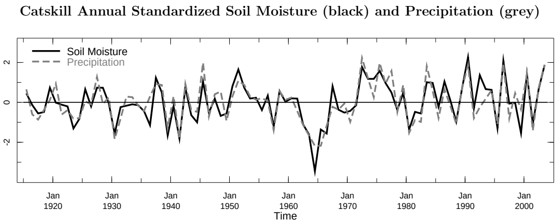

Fig. 1.5. The observed precipitation and soil moisture (as modeled by the VIC land surface hydrology model forced by observed precipitation and temperature) in the Catskill Mountains region of the northeast United States which provides 87% of the New York City water supply. The unique 1960s drought and the subsequent shift in the early 1970s to a wetter climate are clear with the latter being an unexplained mystery.

These are clearly seen in the gridded precipitation data from the University of East Anglia Climatic Research Unit (CRU, `http://www.cru.uea.ac.uk/data/`) as well as in the VIC soil moisture data (Figure 5). The amplitude of the multidecadal variability in this region is truly impressive: in fall the precipitation has increased by about 25% over the last century. None of this observed hydroclimate history (precipitation and soil moisture) is reproduced in atmosphere models forced by observed SSTs indicating that, unlike for western North America, the observed history has not been strongly influenced by the past variations of the oceans (Seager *et al.*, 2012). Further, while northeast North America is expected to get wetter in response to rising greenhouse gases (Hayhoe *et al.*, 2007), the wetting trend in the region up to 2007 is an order of magnitude greater than that which the models participating in the Coupled Model Intercomparison Project 3 (CMIP3), and assessed by Intergovernmental Panel on Climate Change Assessment Report 4 (IPCC AR4), indicate should have occurred in response to changes in radiative forcing. The CMIP5 model simulations do not alter this disagreement.

The inability to simulate the past century of northeast precipitation variability in terms of either ocean or radiative forcing suggests that it instead arose from internal and natural atmospheric variability. The 1960s drought was diagnosed by Seager *et al.* (2012) to have arisen from circulation anomalies that persistently placed northerly descending air over the region with a role for the highly negative North Atlantic Oscillation (NAO) during these years. In regard to the subsequent shift to a wetter climate - pluvial - Seager *et al.* (2012) provide some tantalizing evidence that this was associated with a strengthening of the mid-latitude storm track from the east Pacific across North America to the Atlantic that occurred quite abruptly in the early 1970s. This storm track strengthening was identified earlier by Chang and Fu (2002) and Harnik and Chang (2003) in reanalyses and radiosonde observations and Seager *et al.* (2012) identified it again in the 20th Century reanalysis (Compo *et al.*, 2010) which only assimilates surface pressure data while being SST forced. After the early 1970s storm track strengthening it remained stronger until the present. This storm track behavior appears real in that it is seen in reanalyses, radiosonde observations and also surface pressure data but does not align with any well known climate transitions such as the 1976/77 tropical Pacific climate shift (Zhang *et al.*, 1997), trends in the NAO (Hurrell, 1995) or the Atlantic Multidecadal Oscillation (Kushnir, 1994; Ting *et al.*, 2009). It has also received very little attention and appears almost like an embarrassing uncle in the climate family. However its reality, impacts and causes deserves more attention. It might be that the mid-latitude atmosphere on its own, absent the influence of the ocean and changes in composition, can generate variability on decadal and longer timescales that, viewed from our short period of instrumental observations, appear as 'climate change'. Another clue is that, according to a recent tree ring reconstruction of Palmer Drought Severity Index in the nearby Hudson River Valley region, the 1960s drought was a brief interruption in a multi century trend towards a wetter climate (Pederson *et al.*, 2013) that is also found across the eastern U.S. (Seager *et al.*, 2009; Pederson *et al.*, 2012). However it is not known if these changes are caused by centennial or millennial variability, or if the wetting trend has gone on for millennia and is potentially of orbital origin.

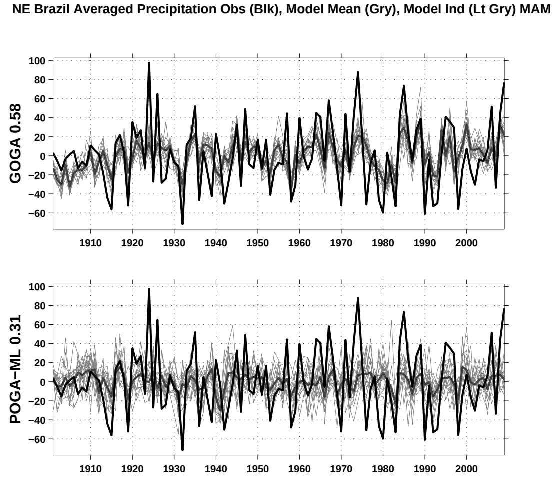

Fig. 1.6. The observed (solid black line) precipitation anomaly for the March-April-May season in Northeast Brazil and that modeled with global SST forcing (GOGA, top) and tropical Pacific only SST forcing (POGA-ML, bottom) shown as both the ensemble mean (thick gray line) and the 16 individual ensemble members (thin gray lines). Correlation coefficients between the observed and ensemble mean time series are shown at left.

1.4. Northeast Brazil or ''Nordeste': A very well understood case of strong ocean control

Northeast Brazil (or the 'Nordeste' as it is known in Brazil) is a climate oddity: a semi-arid equatorial region placed to the west of a warm tropical ocean and under the influence of easterly trade winds. The Nordeste sits between the Atlantic Intertropical Convergence Zone (ITCZ) to its north and the South American Monsoon and South Atlantic Convergence Zone to its southwest. As such it has a climatic affinity to dry regions of the equatorial West Pacific Ocean but why this oceanic character extends over land into the Nordeste is not clear. (Another region of aridity to the west of a tropical ocean exists in East Africa but appears to have different causes but which are again not clear.) The aridity of the Nordeste, together with an endless cycle of disrupting climate anomalies, has long ensured that the Nordeste is one of the poorest regions in Brazil and the source of migrants to wealthier regions. A harrowing description of the late 1870s drought and famine in the Nordeste is given by Davis (2001) . It is estimated that about 500,000 people died then and that between the 1930s and 1950s 1.5 million inhabitants fled the region with drought as a prime, but not sole, cause (Siegel, 1971).

The essential dynamics of Nordeste rainfall variability were deduced from observations by Hastenrath and Heller (1977) and, during drought years, involve an anomalous cross equatorial SST gradient with the warm anomaly to the north, and/or cold anomaly to the south, and a northward displaced ITCZ that prevents rains from reaching their southernmost latitude over the Nordeste in southern hemisphere summer to fall. This relation was then modeled successfully with a GCM by Moura and Shukla (1981). El Niño events also create a tendency to dry conditions in the Nordeste, as noted early on by Covey and Hastenrath (1978), which occurs both by warming the tropical troposphere creating widespread stability, by altering the Walker Circulation and, also, by remotely warming the tropical North Atlantic Ocean and displacing the ITCZ northwards (Chiang *et al.*, 2002; Giannini *et al.*, 2004; Hastenrath, 2006).

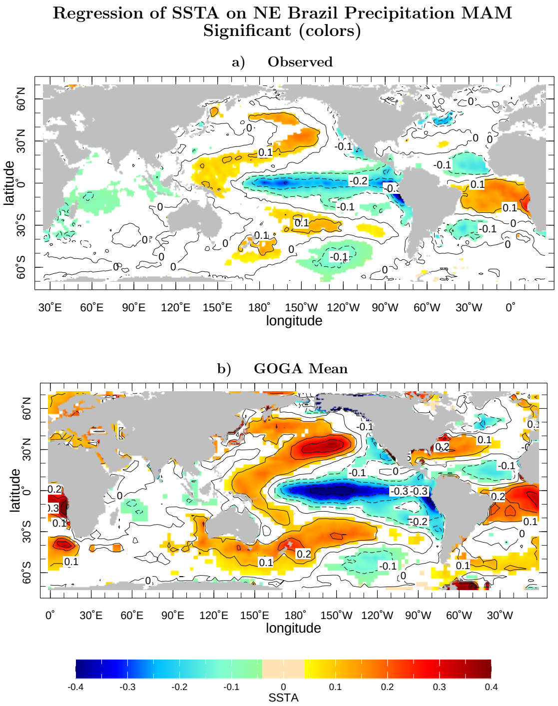

Fig. 1.7. The regression of March-April-May global SST anomaly on the observed (top) and GOGA modeled (bottom) March-April-May soil precipitation anomaly in Northeast Brazil. Areas of significance at the 5% level are colored.

Giannini *et al.* (2004) showed that the oceanic control on Nordeste precipitation is sufficiently strong that an atmosphere model forced by observed SSTs was able to accurately reproduce the variability of March-April-May (MAM, the Nordeste wet season) precipitation in the 1950 to 1994 period. We expand upon this by showing, in the top panel of Figure 6, the modeled (with global SST forcing) and CRU observed MAM precipitation history for the much longer period of 1901 to 2008. In a departure from our usual plotting practice, we show both the ensemble mean and the individual ensemble members, which is made visually tractable here because of the strong correlation between ensemble members. The tight relationship between model and observed precipitation from 1950 to 1994 noted by Giannini *et al.* (2004) extends up through the last two decades and also through the first half of the 20th Century[a]. Many observed strong precipitation departures (e.g. 1932) are reproduced in almost all ensemble members indicating a quite high SST-forcing-signal-to-internal-atmospheric-variability-noise ratio. The lower panel in Figure 6 shows the same comparison but for the tropical Pacific SST-only forced ensemble and makes clear that much of the good agreement in the case with global SST-forcing derives from SST anomalies outside the tropical Pacific Ocean.

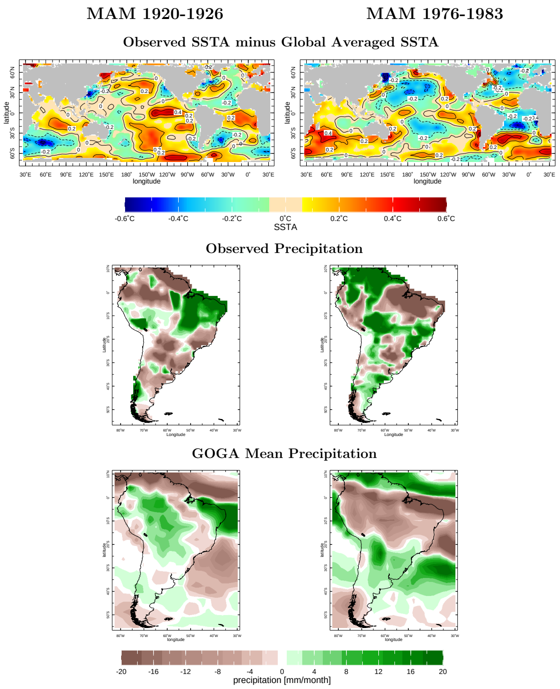

Fig. 1.8. The observed SST (top) and precipitation (middle) and modeled precipitation (bottom) anomalies for the 1920 to 1926 wet period (left column) and 1976 to 1983 dry period (right column) in Northeast Brazil.

Figure 7 shows the regression of global SST onto MAM Nordeste precipitation for the 1900 to 2008 period with colors applied where the relation is statistically significant for both the

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[a] To our knowledge this is the first presentation of an SST-forced model simulation of Nordeste precipitation during the first half of the last century.

observations (top) and the GOGA model (bottom). There actually is a significant relationship between dry conditions and El Niños in the Pacific which is reliably simulated by the model. In addition, the association between dry conditions and warm SSTs in the tropical north Atlantic and/or cold SSTs south of the mean ITCZ is also very clear and this is again well represented by the model.

The Nordeste is obviously a region of strong interannual precipitation variability but much longer timescale variations exists too. For example the early to mid 1920s appear to have been a wet period which was immediately followed by a dry period culminating in the 1932 drought while the mid 1970s to mid 1980s were an extended dry period. Since the early 20th Century has not received the attention of the later period here we show in Figure 8 the SST anomalies and observed and modeled precipitation anomalies for the MAM seasons of the 1920 to 1926 wet period and contrast this with the 1976 to 1983 dry period. The observed decadal patterns of precipitation anomalies across South America, with wet in the Nordeste in the earlier period and dry in the later period, are reproduced with some degree of success in the global SST forced model. The 1920-26 period was perhaps weakly El Niño-like, which would not be expected to cause wet conditions in the Nordeste, while the tropical Pacific anomalies were indistinct in the later period. Instead it appears that the tropical Atlantic was the dominate control on these decadal Nordeste precipitation anomalies with opposite signed north-south cross equatorial SST anomalies in the two periods consistent with precipitation-SST relationships expected on the basis of the regression analysis.

1.5. Southeast South America: A mixed message of strong oceanic forcing and a mysterious long term wetting trend

Our final example is the southeast of South America, a region that is influenced by both mid-latitude dynamics, the southern part of the South American monsoon and the South Atlantic Convergence Zone. This region has become tremendously important to the global food production system in recent years as the growing of grains and legumes has expanded into the sub-humid to semi-arid Pampas in recent decades to take advantage of a long term wetting trend (Seager *et al.*, 2010). This is also a region where the tropical oceans exert a considerable influence on interannual and decadal timescale fluctuations in precipitation. Figure 9 shows the observed variations of annual mean precipitation for the region from 1901 to 2010 together with the ensemble mean and plus/minus two standard deviation spread of the model forced by global SSTs. The agreement between the observations and ensemble mean is impressive and, as shown in Seager *et al.* (2010), does not derive from the tropical Pacific forcing alone, even though El Niño events are typically wet in the region and La Niña events dry (see Seager *et al.* (2010) and Mo and Berberry (2011) and references therein). Seager *et al.* (2010) in fact argue that the multidecadal precipitation variability in southeast South America precipitation is influenced by mutlidecadal tropical North Atlantic SST variability. Their argument is that warm tropical North Atlantic SSTs cause an intensified Atlantic ITCZ with anomalous divergent winds aloft which interact with the mean flow vorticity field to force a remote response that includes subsidence, and precipitation suppression, over southeast South America. This mechanism draws some support from the modeling experiments examined by Mo and Berberry (2011). Thus much of the decadal precipitation variability in this region can be explained in terms of a combination of tropical Pacific and tropical north Atlantic SST variability, rather like for the Nordeste.

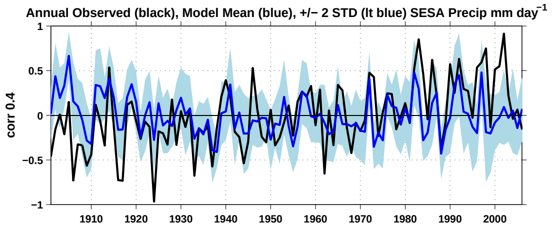

Fig. 1.9. The observed precipitation anomaly for southeastern South America and that computed by the global climate model forced by observed global SSTs (GOGA configuration) shown as the 16 member ensemble mean (blue) and the plus and minus two standard deviation spread of the ensemble (blue shading). The correlation coefficient between the observed and ensemble mean time series is shown at left.

However we cannot explain the long term wetting trend easily in terms of tropical SSTs. Figure 10 shows the SST anomalies and observed and modeled precipitation anomalies for the 1920 to 1938 period of a drier climate and 1980 to 2003 period of a wetter climate in southeast South America. The model does a good job of reproducing the early 20th century drought in southeast South America but can only produce the sign, not the amplitude, of the late 20th century pluvial. In the earlier period the tropical Pacific was actually weakly warm, which is not expected to go along with dry in southeast South America, while the later period has only weak tropical Pacific SST anomalies. However the tropical North Atlantic was warm in the earlier period and cold in the later period which would be expected to go along with dry and then wet in southeast South America according to Seager *et al.* (2010) and Mo and Berberry (2011). That is, on the decadal timescale, the tropical North Atlantic appears to exert a strong influence on southeast South America precipitation.

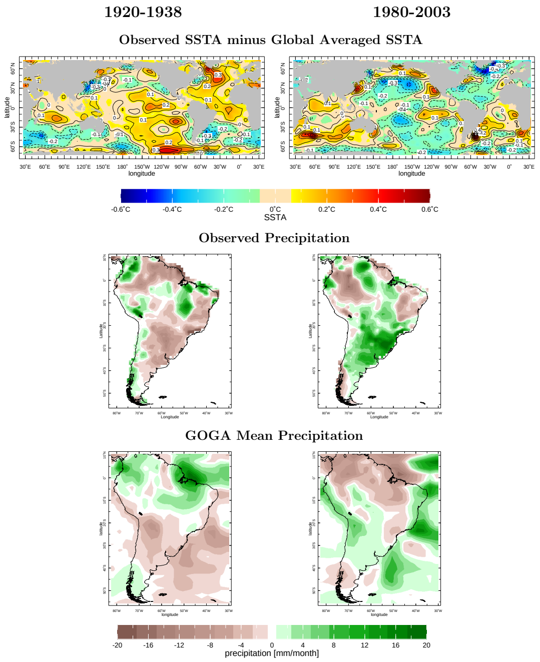

Fig. 1.10. The observed SST with global mean removed (top) and precipitation (middle) and modeled precipitation (bottom) anomalies for the 1920 to 1938 dry period (left column) and 1980 to 2003 wet period (right column) in southeast South America.

Despite this evidence of ocean influence, the late 20th century was much wetter than can be explained in terms of SST forcing alone. There is no model-based evidence that such a strong long term wetting trend in the region is a response to rising greenhouse gases Seager *et al.* (2010); Gonzalez *et al.* (2013). On the other hand model evidence does suggest that ozone depletion caused a wetting in the region over the late 20th Century that can explain perhaps a quarter of the observed trend (Gonzalez *et al.*, 2013). Even so, that would leave the majority of the wetting trend unexplained and, as for the northeast U.S., perhaps it is evidence of very long timescale natural variability that arises from processes, perhaps atmospheric, unrelated to SST variability.

1.6. Mechanisms of decadal hydroclimate variability across the Americas

The dynamics that link ENSO SST anomalies to North American hydroclimate anomalies have become increasingly well understood in recent years. Tropical Pacific SST anomalies force convective heating anomalies above with upper level divergence anomalies that force Rossby waves that propagate north and east towards North America. The waves alter the mean flow which then alters the propagation of transient eddies whose altered momentum fluxes then feedback onto the mean flow. The final transient and mean flow response to ENSO SST anomalies is, therefore, a result of the mean flow anomalies forced directly by tropical heating anomalies and the subsequent eddy-mean flow interaction it brings into play (Seager *et al.*, 2010; Harnik *et al.*, 2010). How these circulation anomalies relate to the moisture divergence anomalies that force precipitation anomalies has also been studied and it appears that the mean flow divergence anomalies are the most important and themselves dominated by the change due to the circulation change (as opposed to the humidity change). Transient eddy moisture convergence anomalies appear to play a secondary role (Seager *et al.*, 2005a; Seager and Naik, 2012). (This work could, however, be done with the most up to date atmospheric reanalyses and in more detail in order to clearly determine the causes of ENSO-forced hydroclimate anomalies over the Americas.) Also, the dominance of mean flow moisture divergence anomalies over transient eddy moisture flux divergence anomalies does not suggest that transient eddies play a secondary role overall. This is because transient momentum flux anomalies are themselves a main driver of the mean flow circulation anomalies. A breakdown of ENSO hydroclimate anomalies into components due to mean and transient circulations that takes account of this coupling has not been attempted (perhaps for good reason!).

It has been possible to use the increased understanding of the ENSO teleconnection to hydroclimate in the Americas to develop improved understand of tropical Pacific forcing of decadal hydroclimate. For the case of persistent North American droughts, such as the 1930s Dust Bowl, the 1950s southwest drought, the 1998-2002 turn-of-the-century drought, the 1856-65 'Civil War' drought and the 1870s and 1890s western droughts, the causes were essentially the same as those during a La Niña season. That is because in all these six cases the tropical Pacific adopted an extended (though weak) La Niña like state with no El Niño events. Similarly, the wet North American decade of the 1990s went along with persistent El Niño-like conditions between 1990 and 1998 except for a weak cold interval in winter 1996/97. Huang *et al.* (2005) extended this reasoning to show that the overall wetter climate in North America and extratropical South America between 1977 and 1998, relative to the 15 years before 1976, could be reproduced within an atmosphere model forced by the tropical Pacific SST difference between the two periods. This was so whether the time average SST difference was imposed or whether the atmosphere model saw the actual time history of SST indicating the essential linearity of the hydroclimate response. That is, the wet northern and southern mid-latitudes in the post 1976 two decades can be understood as a response to the change in the long term decadal mean tropical Pacific SSTs and is not a rectified effect of the difference in El Niño and La Niña events between the decades before and after 1976 or influenced by any nonlinearity between SST anomalies and the precipitation response. This was a significant work in advancing and simplifying our understanding of decadal variations of hydroclimate across the Americas.

The longer timescales of Atlantic Ocean SST variability make interpretation of Atlantic forcing of hydroclimate more straightforward. Going back to Schubert *et al.* (2004), it has been

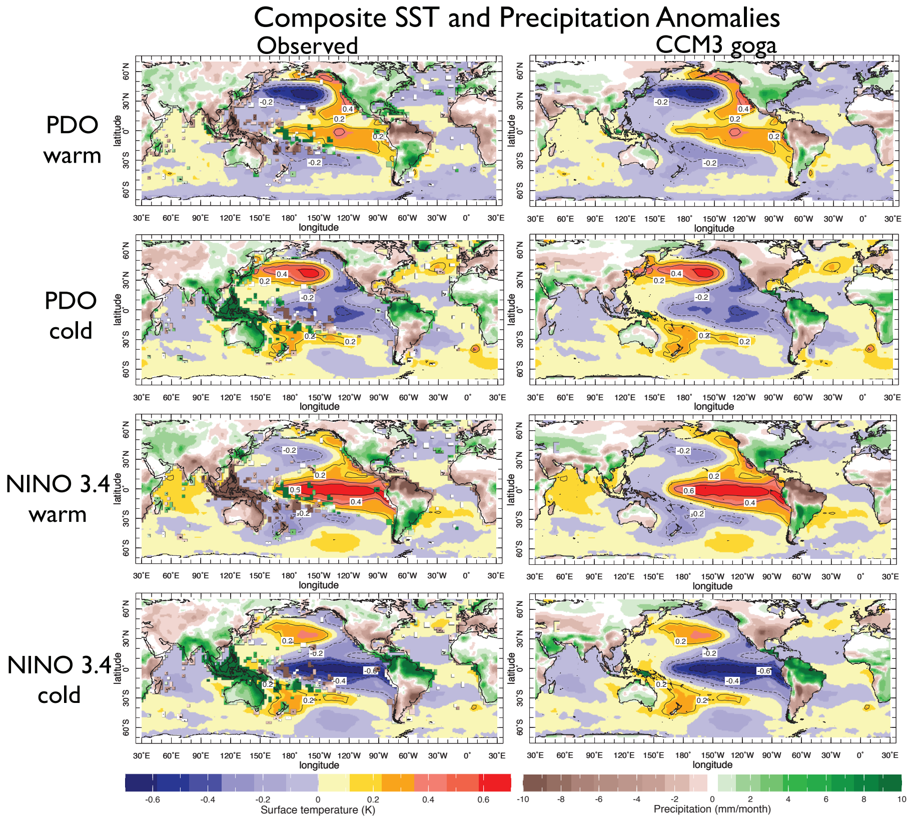

Fig. 1.11. The warm (top) and cold (upper middle) phase composites of the PDO for observed SST and observed (left) and modeled (right) precipitation over land. The lower two rows show similar composites but for El Niño and La Niña.

recognized that it is SST anomalies in the tropical North Atlantic that exert an influence on North American hydroclimate. More recently Kushnir *et al.* (2010) have shown that, in the summer season, the response is essentially that given by the Gill-model solution to a subtropical heating anomaly: warm SSTs induce deep atmospheric heating and poleward and ascending flow above with equatorward and descending air on the western flank of the forced cyclonic anomaly. The scale is set by Rossby wave dispersion and is such that the equatorward, descending air is over the southern Plains and southwest where precipitation is suppressed. In contrast winter season tropical North Atlantic SST anomalies appear to first impact tropospheric temperatures and moist static stability and then tropical Pacific precipitation which then forces a wave response, akin to that during ENSO, that reaches North America. This winter response has a certain Rude Goldberg character but does appear robust across models, has some observational support and may indeed be one means of inter-basin coupling of relevance to hydroclimate variations in the Americas (Kushnir *et al.*, 2010).

However ENSO is possibly not the only thing that happens in the Pacific Ocean. A decade and a half ago Zhang *et al.* (1997) showed that, in addition to the ENSO cycle with its characteristic irregular, interannual period, there is a longer timescale 'ENSO-like' pattern of variability. This became known as the Pacific Decadal Oscillation (PDO, e.g. Mantua and Hare (2002)) and is different from interannual ENSO in that its North Pacific SST anomalies are larger relative to its tropical SST anomalies, the tropical SST anomalies are more meridionally broad and it has a timescale of a few decades. Famously the Pacific Ocean shifted from a phase of the PDO with cold tropical Pacific SST anomalies to the phase with warm anomalies (and opposite signed anomalies in the central North Pacific Ocean) during 1976/77. This is the shift whose associated precipitation anomalies were modeled by Huang *et al.* (2005). Shifts to the cold phase occurred in the early to mid 1940s (Deser *et al.*, 2004) and, seemingly, in 1997/98. The problem with the PDO is that it is so highly correlated to ENSO, and shares the same hemispheric symmetry (Garreaud and Battisti, 1999), that it is not clear yet whether it is anything more than a basin-wide low frequency response to tropical Pacific conditions.

Here we put aside the matter of the origin of the PDO and restrict attention to the precipitation anomalies across the Americas associated with its characteristic SST pattern. The PDO is, as usual, defined as the first empirical orthogonal function of monthly Pacific Ocean SST anomalies north of $20^\circ N$ after the global mean SST anomaly has been subtracted from each point to remove longer term trends due to climate change. The associated Principal Component (PC, or the time series describing the temporal evolution of the EOF pattern) was formed into annual means and standardized. Global SSTs, observed and modeled precipitation, for years with values greater than one standard deviation, were composited into a warm phase PDO composite and, for years with values less than one standard deviation, into a cold phase PDO composite. For comparison the observed and modeled SST and precipitation anomalies for years with greater and less than one standard deviation of the NINO3.4 SST index were averaged to derive El Niño and La Niña composites of SST and precipitation anomalies.

The results are shown in Figure 11. The PDO SST anomalies are only a fraction of a Kelvin and quite meridionally broad, in agreement with the earlier studies. Also, the warm phase and cold phase PDO-associated precipitation anomalies across the Americas are essentially the opposite of each other indicating a first order linearity. The sign is such that during the warm phase the tropics are dry and the extra tropics of North and South America are wet, all within patterns that are large scale and strikingly coherent. In contrast to the PDO, the SST anomalies for the El Niño and La Niña composites have much stronger equatorial Pacific features. The ENSO precipitation response is again, to first order, essentially linear and, despite the differences in SST forcing patterns, is extremely similar to that of the PDO. Of course it might be thought that the PDO-ENSO precipitation pattern similarity arises from the response to the large ENSO events contained within the PDO composites, a result of the strong temporal correlation between the PDO and ENSO indices. (The annual mean PDO and NINO3.4 time series have a correlation coefficient of 0.64.) However the work of Huang *et al.* (2005) shows that the decadal timescale precipitation response would be the same if the details of the ENSO events in any one period were replaced with the decadal timescale SST anomalies. That is, the PDO precipitation response shown in Figure 11 is an actual physical response to the weak PDO SST anomalies.

Of course one might wonder which part of the PDO SST anomalies is responsible for the precipitation response across the Americas. Huang *et al.* (2005), in looking at the decadal precipitation change across the 1976/77 climate shift, addressed this by forcing an atmosphere model first with the global SST change and then with the tropical Pacific change alone and found that the latter explained essentially all the precipitation change in the former. We have also made PDO precipitation anomaly composites from simulations with the same atmosphere model used for Figure 11 but forced by the time history of tropical Pacific SSTs alone. The tropical Pacific-forced PDO composites look essentially identical across the Americas as for the case of PDO composites with global SST forcing. Hence it is in fact the tropical Pacific part of the PDO SST anomalies that overwhelmingly dominates the precipitation response and the similarity of the PDO and ENSO precipitation responses is no coincidence. This comparison reinforces the idea that the PDO and its hydroclimate impact across the Americas is nothing more than a low frequency realization of the tropical Pacific climate variability familiar in the form of ENSO.

1.7. Decadal timescale radiatively-driven hydroclimate change across the Americas

Natural variability of the atmospheres and oceans is a potent source of hydroclimate change on decadal timescales across the Americas. Another source is radiatively-forced climate change and climate models robustly predict that hydroclimate will change in systematic ways in the coming decades with the wet regions of the tropics and mid to high latitudes getting wetter and the dry regions of the subtropics getting drier and expanding poleward (Held and Soden, 2006; Seager *et al.*, 2007, 2010). Any reliable, probabilistic, projection of hydroclimate in coming decades must take account of the possible evolution of natural decadal variability and the human-induced, radioactively-forced, change over the same time period. Therefore, given the presence of the natural variability, it is reasonable to wonder when the radiatively-forced change will make its presence known. In this regard tests of statistical significance of the forced change might be too demanding a criteria. As one practical alternative in common use in seasonal-to-interannual prediction, the probability of a season's precipitation being in the lower, middle or upper tercile of the historical distribution is reported. For example a strong El Niño event might generate, say, a 60% chance that precipitation in southwest North America will be in the upper tercile and this would be considered a useful forecast even though it might fall short of statistical significance at the usual 5% or higher levels.

Here we turn to the Coupled Model Intercomparison Project Five (CMIP5) multimodel ensemble and adopt the tercile approach. We use 28 models with one run from each that is continuous over the 1900 t0 2050 period using estimated past radiative forcings and the Representative Concentration Pathway 8.5 (rcp85) as the future scenario. For the 1901 to 2000 period we divide the precipitation anomalies, relative to the 1901-2000 period, into ten non-overlapping decades and compute the means for each. The ten decadal means are ranked and the lower boundary of the upper tercile is taken to be the seventh highest value and the upper boundary of the lower tercile as the fourth highest value. The near-term climate change signal for each model is taken to be the precipitation in the 2031-2040 decade minus the climatological average of the second half of the twentieth century (1951-2000). We then determine for each model whether the climate change precipitation signal is in the upper, middle or lower tercile of that model's distribution of decadal means. We also determine the multimodel ensemble mean climate change precipitation signal as the average across the models of the 2031-2040 precipitation minus that for 1951-2000. We then count up the number of models that have a climate change precipitation signal in the upper or lower terciles of the distributions and the same sign change as the multimodel ensemble mean change.

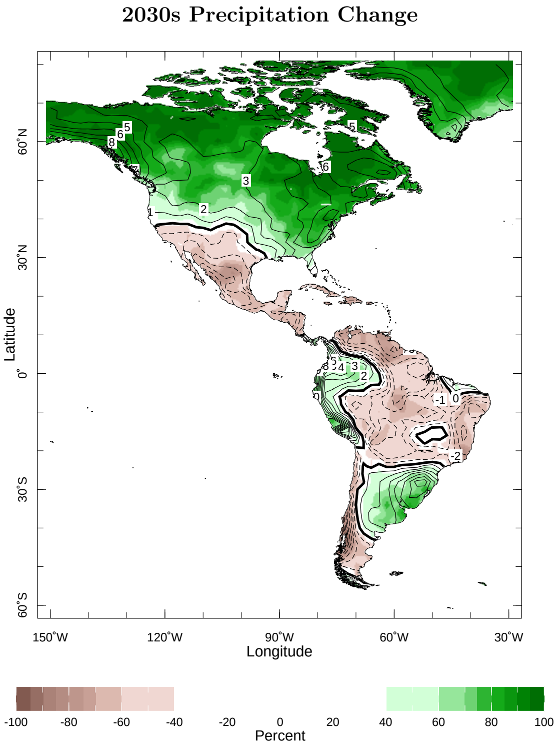

Fig. 1.12. The percentage of models that have a 2031-2040 less 1951-2000 precipitation shift in the upper (green colors) or lower (multiplied by minus one, brown colors) of that model's distribution of decade mean precipitation anomalies over the 1901 to 2000 period *and* with the shift having the same sign as the multimodel ensemble mean. Single continuous runs of 28 CMIP5 models were used. The multimodel ensemble mean precipitation shift is shown as contours.

In the absence of any forced climate trends it would be expected that for each model there would be equal probabilities of the 2031-2040 decadal mean anomaly falling in the three terciles while the multimodel mean change would have equal probability of being positive or negative. Hence more than 17% of the models having a climate change precipitation signal in the upper or lower tercile, and the same sign change as the multimodel ensemble mean, is the very minimum required to identify a climate change signal with an amplitude equivalent to this measure of natural variability.

The tercile results, along with the multimodel mean precipitation shift, are shown in Figure 12. Quite remarkably, across vast regions of the Americas, more than 60% of the models have precipitation shifts in the outer terciles of the historical variability. In some parts of the northeast U.S., Canada and Alaska the number of models reaches up to 100%. This result makes clear that for most of the Americas radiatively forced changes in precipitation in the near term future will be of equivalent magnitude to the decadal variations that have occurred in the past, and which caused significant social impacts. The difference is that the past decadal variations were temporary and were followed by decades of more normal precipitation totals or opposite sign anomalies, while the radiatively-forced changes are of the same sign decade to decade and, indeed, intensify as the century advances.

1.8. Conclusions

Thanks to much research in recent years decadal variability of hydroclimate across the Americas is not as much of a mystery as it was a decade or so again. To a very large extent decadal periods of drier than normal or wetter than normal (pluvial) periods in the tropical and extratropical regions of the Americas can be attributed to similarly persistent anomalies of tropical Pacific and Atlantic SST anomalies. Further, the dynamics that link the tropical oceans to precipitation anomalies in the Americas on decadal timescales appears to be essentially the same as those operating on the seasonal to interannual timescales and which are becoming increasingly well understood. In addition, as for the case of seasonal to interannual variability, it is the tropical oceans that play the dominant role influencing precipitation on decadal timescales. Of course this is expected given the lack of evidence of an atmospheric response, at any timescale, to extratropical SST anomalies that can compete in amplitude with the response to tropical SST anomalies. It may be that on decadal timescales extratropical SST anomalies are larger, relative to tropical anomalies, than they are on shorter timescales but the physics of atmosphere-ocean coupling still biases the atmospheric to being most sensitive to the tropical components of the anomalies. This understanding of the causes of decadal hydroclimate variability works best for, of the regions studied, southwestern North America and the Plains, northeast Brazil and southeast South America. Indeed a quite astonishing amount of longer than interannual variability in these regions can be explained in terms of tropical ocean forcing.

However decadal hydroclimate variability across the America still contains some mysteries. Although southeast South America precipitation is strongly influenced by the tropical Pacific and Atlantic Oceans it also has experienced a century long wetting trend, most marked since the 1960s, that cannot be so explained. Similarly the northeast U.S. - a region where the oceans exert negligible influence on precipitation variability - shifted to a much wetter climate in the early 1970s. Atmosphere models forced by observed global SSTs cannot reproduce these trends. It does seem as if ozone depletion caused a small portion of the wetting trend in southeast South America, however (Gonzalez *et al.*, 2013). However, in both extratropical regions, models forced by changes in trace gases, solar irradiance, aerosol concentrations etc. do not produce wetting trends anywhere near as strong as those that happened. Consequently, it is probably worth examining climate model simulations to determine if atmosphere variability alone can generate such long term changes in precipitation. This unexplained variability also highlights the need for longer term climate records that can be gained from, for example, tree ring records. In regard to the north east U.S., for example, Pederson *et al.* (2013) show that the late 20th Century shift to a wetter climate is only the end of a wetting trend that has been ongoing since at least the early 16th Century. Knowing that does not make it any easier to explain but does help us know what we need to explain. In this case of the northeast U.S., for example, it appears we need to examine decadal variability in the light of hydroclimate changes over the last millennium and, probably, the Holocene and examine possible contributions from changes in solar irradiance, volcanism, orbital configuration and unforced variability at longer than decadal timescales.

We have not concerned ourselves here with the predictability of the ocean states that drive decadal variability across the Americas. It remains to be demonstrated whether tropical Pacific Ocean SST variations beyond the interannual timescale are predictable. The one suggestion that they might be is that of Karspeck *et al.* (2003) and Seager *et al.* (2004). They used an ensemble prediction with the Zebiak-Cane ENSO model initialized in 2003 to claim that the equatorial east Pacific in the period from 1998 to 2013 would be cooler than during the 15 years before 1993, which it has been. Our own efforts to locate multiyear to decadal predictability of tropical Pacific SSTs in initialized predictions with state-of-the-art global models have been unsuccessful. In contrast there does seem some success in developing predictive capacity for decadal Atlantic Ocean variations (Meehl *et al.*, 2013). However, whether this translates into prediction of the SST variations of most importance for forcing Americas hydroclimate is not clear. Hence, certainly for now, naturally occuring decadal variations in hydroclimate across the Americas will remain unpredicted. The steadily evolving changes in precipitation across the Americas forced by rising greenhouse gases appear to be more predictable in the coming decades and reach the level of natural decadal variability in the near term future. In terms of hydroclimate, the radiatively-forced changes in precipitation shown here will combine with the even more predictable effects of rising temperatures to cause notable decreases in precipitation less evaporation in many subtropical regions of the Americas. Merging assessments of the range of natural decadal variations with the range of forced changes to prepare probabilistic assessments of potential future hydroclimates in the Americas that might be of use in scenario developments for applications purposes.

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