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Invited review

The Mexican Drought Atlas: Tree-ring reconstructions of the soil moisture balance during the late pre-Hispanic, colonial, and modern eras

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ABSTRACT

Mexico has suffered a long history and prehistory of severe sustained drought. Drought over Mexico is modulated by ocean-atmospheric variability in the Atlantic and Pacific, raising the possibility for long-range seasonal climate forecasting, which could help mediate the economic and social impacts of future dry spells. The instrumental record of Mexican climate is very limited before 1920, but tree-ring chronologies developed from old-growth forests in Mexico can provide an excellent proxy representation of the spatial pattern and intensity of past moisture regimes useful for the analysis of climate dynamics and climate impacts. The Mexican Drought Atlas (MXDA) has been developed from an extensive network of 252 climate sensitive tree-ring chronologies in and near Mexico. The MXDA reconstructions extend from 1400 CE–2012 and were calibrated with the instrumental summer (JJA) self-calibrating Palmer Drought Severity Index (scPDSI) on a 0.5° latitude/longitude grid extending over land areas from 14 to 34°N and 75–120°W using Ensemble Point-by-Point Regression (EPPR) for the 1944–1984 period. The grid point reconstructions were validated for the period 1920–1943 against instrumental gridded scPDSI values based on the fewer weather station observations available during that interval. The MXDA provides a new spatial perspective on the historical impacts of moisture extremes over Mexico during the past 600-years, including the Aztec Drought of One Rabbit in 1454, the drought of El Año de Hambre in 1785–1786, and the drought that preceded the Mexican Revolution of 1909–1910.

The El Niño/Southern Oscillation (ENSO) is the most important ocean-atmospheric forcing of moisture variability detected with the MXDA. In fact, the reconstructions suggest that the strongest central equatorial Pacific sea surface temperature (SST) teleconnection to the soil moisture balance over North America may reside in northern Mexico. This ENSO signal has stronger and more time-stable correlations than computed for either the Atlantic Multidecadal Oscillation or Pacific Decadal Oscillation. The extended Multivariate ENSO Index is most highly correlated with reconstructed scPDSI over northern Mexico, where warm events favor moist conditions during the winter, spring, and early summer. This ENSO teleconnection to northern Mexico has been strong over the past 150 years, but it has been comparatively weak and non-stationary in the MXDA over central and southern Mexico where eastern tropical Pacific and Caribbean/tropical Atlantic SSTs seem to be more important. The ENSO teleconnection to northern Mexico is weaker in the available instrumental PDSI, but analyses based on the millennium climate simulations with the Community Earth System Model suggest that the moisture balance during the winter, spring, and early summer over northern Mexico may indeed be particularly

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sensitive to ENSO forcing. Nationwide drought is predicted to become more common with anthropogenic climate change, but the MXDA reconstructions indicate that intense "All Mexico" droughts have been rare over the past 600 years and their frequency does not appear to have increased substantially in recent decades.

1. Introduction

Aridity prevails over most of Mexico, including the Valley of Mexico, the seat of powerful pre-Hispanic city-states and the location of modern Mexico City, one of the largest urban centers in the world. The impressive pre-Hispanic archaeological record of cultural development and decline in Mexico appears to have been influenced in part by severe decadal drought (Coe, 1984; Hodell et al., 1995; Brenner et al., 2001; Haug et al., 2003). The post-Conquest colonial and modern record is rich in detail on prolonged drought, famines, epidemic disease, international migration, and warfare. However, Mexico does not have a high quality nationwide instrumental climate record before 1920, and the available weather recording stations are in fact sparsely distributed prior to 1940 (Jauregui, 1979; Douglas, 2007). There are also very few centuries-long, high-resolution paleoclimate records in Mexico with which to test hypotheses concerning climate change, the internal and external forcing of climate variability, or the possible role of climate in socioeconomic extremes during the late pre-Hispanic, colonial, or early modern eras. In this article we describe the Mexican Drought Atlas (MXDA) that provides annually resolved and spatially detailed tree-ring reconstructions of the summer moisture balance from 1400 CE–2012 and now covers the entire Republic of Mexico. These reconstructions are most reliable for the last 400 years during the colonial and modern periods when the network of predictor tree-ring chronologies is most spatially complete and internally well replicated.

Severe sustained drought has caused serious socioeconomic impacts in Mexican history (Liverman, 1990; O'Hara and Metcalfe, 1997) and has been implicated in political unrest and social change among colonial and modern societies (Florescano, 1980, 1986; Dell, 2012). Ironically, human influences may now be aggravating drought severity and persistence over 21st century Mexico, as may have occurred during the pre-Hispanic era with widespread anthropogenic deforestation in the Mayan Lowlands (Cook et al., 2012). Extensive regional land cover changes can impact moisture exchange between the land surface and atmosphere, and may be partially responsible for the dramatic escalation of maximum afternoon temperatures recorded during the last 40 years over central Mexico (Englehart and Douglas, 2005; Pascual et al., 2015). Simultaneously, the accumulation of anthropogenic greenhouse gases may be causing both rising global temperatures and the intensification of the Hadley circulation, with potential regional consequences over Mexico (Seager et al., 2007; Feng and Fu, 2013; Cook et al., 2015a). Modern industrialized Mexico is not immune to drought and this vulnerability crosses many socioeconomic sectors, from subsistence farming to industrial agriculture, and from municipal and industrial water supply to hydroelectric power generation.

The recurrence and societal impacts of drought may be partially predictable because Mexican hydroclimatic variability is often modulated by large-scale ocean-atmospheric interactions, including the El Niño/Southern Oscillation (ENSO). However, the impact of these remote influences on Mexican climate varies by latitude and season, and from one event to another. There are also many unanswered questions regarding the stability of these large-scale teleconnections, and the magnitude of climate variance they might actually explain, which have bearing on the potential predictability of seasonal drought and wetness over Mexico. Tree-ring chronologies can provide an exactly-dated, annually-resolved extension of the climate record into the centuries prior to instrumental observations to better understand the magnitude and duration of drought and wetness extremes, their frequency of recurrence, and the climate dynamics involved.

The North American Drought Atlas (NADA) was developed by Cook et al. (1999, 2004, 2007, 2010a,b) and provided tree-ring reconstructions of the Palmer Drought Severity Index on a regularized grid over most of North America, including much of Mexico. However, very few tree-ring chronologies were available for inclusion in the NADA from central and southern Mexico. The NADA was also restricted to chronologies dating back to 1700 CE or earlier. The network of climate sensitive tree-ring chronologies in and near Mexico has been greatly expanded since the development of the NADA, including many new chronologies at least 150-years in length that now cover most of the Republic of Mexico, largely exclusive of the Baja and Yucatan peninsulas. The Mexican Drought Atlas has been developed to utilize this greatly expanded network of tree-ring chronologies to reconstruct the summer (JJA) self-calibrating Palmer Drought Severity Index (scPDSI) on a 0.5° latitude/longitude grid. These gridded reconstructions are linked continuously with the instrumental PDSI data and extend from CE 1400–2012. The MXDA now provides a modern and pre-modern perspective on hydroclimatic variability over Mexico that will be useful in the study of social and environmental change. The MXDA will also be useful for investigating the influence of ENSO and other ocean-atmospheric interactions on Mexican climate and will help document the natural climate background to anthropogenic climate changes now apparently taking place over Mexico.

This article begins with a review of the large-scale influences on climate variability and the socioeconomic impact of drought over Mexico. The network of tree-ring chronologies and the calculation of the MXDA are described, along with the derived calibration and validation statistics. The MXDA is then used to document the spatial extent and severity of extreme droughts and pluvials in Mexico over the past 600-years, including during drought events identified with pre-Hispanic and historical records. The history of inter-annual to decadal variability in soil moisture is estimated for four large sub-regions of Mexico where the tree-ring network is best replicated. The influence of ENSO, the Atlantic Multidecadal Oscillation (AMO), and the Pacific Decadal Oscillation (PDO) on instrumental and reconstructed PDSI are examined beginning in the 1870s when direct measurements of ENSO and the AMO become available. The ENSO teleconnection appears to influence development of a north-south anti-phasing or "dipole" in moisture variability over Mexico, but climate modeling suggests that anthropogenic global warming may overwhelm this gradient and lead to an increase in nationwide "All Mexico" dryness. The frequency of these two spatial patterns of moisture variability is examined over the past 600-years with the new tree-ring reconstructions in the MXDA.