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Detection and Attribution of Regional Climate Change with a Focus on the Precursors of Droughts - Final LDRD Report

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For centuries, droughts have affected human and environmental systems. Understanding the primary causes of droughts has become even more crucial in the context of global warming, with drier conditions predicted to intensify in already arid regions. The problem of identifying human-induced climate change is typically addressed using so-called climate change "detection and attribution" (D&A) techniques[1], which is a statistical "signal in noise" problem (Hegerl et al., 2007). To date, however, these techniques have seen little application in drought research. Here, we propose to explore whether a novel D&A-derived technique could be applied in this context.

A number of mechanisms have been identified as potential drivers of recent droughts. These include specific and persistent spatial patterns in sea surface temperature (SST) anomalies similar to those under La-Nina conditions[2], and related changes in atmospheric circulation. The ultimate goal of this research will be to determine whether there is an emerging human signal in the frequency and spatial structure of the drought precursors in response to global warming, and how the relative weight of human versus natural contributions to drought evolves over time. Here the progress made to address these questions is discussed.

1. Characterizing drought behavior in models and observations

Internal atmospheric perturbations alone are unlikely to produce long-term deficits in precipitation. Instead, there is considerable evidence that specific, persistent spatial anomalies in Equatorial SSTs (such as La-Nina patterns, with an anomalously warm Central Pacific and cold East Pacific) constitute the major precursors of past droughts in many parts of the word. In addition, future climate warming is likely to be accompanied by an overall acceleration of the hydrological cycle with a latitudinal redistribution of precipitation. This zonal-mean pattern of precipitation change, suggesting that "wet regions will get wetter and dry regions will get drier" (Held and Soden, 2006), has been identified as a continental response to GHG forcing (Zhang et al., 2007). Model projections of future droughts depend, however, on the diagnostic metric that is used. For instance, an index based solely on rainfall amounts projects an overall increase of 5-10% in the total land area experiencing drought by the end of the 21st century, while one based on both temperature and precipitation projects a 30% areal increase (Burke et al., 2006; Burke and Brown, 2008).

To investigate the "teleconnections" between the droughts and their precursors in observations and in model simulations, we need to explore various drought metrics. We computed i) our own drought

[1] Detection is the process of demonstrating that an observed change in climate is unusual in a statistical sense, and is unlikely to be explained by background 'climate noise'. Attribution is a more difficult process of deducing cause and effect relationships, and requires demonstrating that an observed signal is consistent with a given combination of human and natural forcings.

[2] La Niña is an extreme phase of a naturally occurring climate cycle referred to as El Niño/Southern Oscillation (ENSO). Unlike El Niño which is associated with warmer than normal eastern Equatorial Pacific temperatures, La Niña is characterized by anomalously cold waters there.

metric estimated from low-pass filtered precipitation anomalies (hereafter, LPFPA), defined relative to the overall climatological mean[3]; ii) the Standardized Precipitation Index (SPI; McKee et al., 1993), based solely on the monthly-mean precipitation deficit accumulated over a specified time scale (in this study, the 12- and the 60-months timescales), and compared with a statistically defined climatological precipitation amount; iii) the Palmer Drought Severity Index (PDSI) (Palmer, 1965), a widely used hydrologic accounting system (e.g., Cook et al., 1999; Dai et al., 2004) that calculates the soil water balance equation, and incorporates information on antecedent precipitation and accumulated moisture supply/demand derived from surface temperature data and estimated soil moisture. Ultimately, these indices will help to determine whether the inclusion of external forcings yields variations in droughts are consistent with those inferred from historical data and paleoclimatic reconstructions.

The first two indices have been calculated in long unforced control simulations, which provide estimates of the effects of natural climate variability (see section 2), while the third metric has been computed (in collaboration with M. Wehner) from simulations of 20[th] and 21[st] century climate change. To make these calculations, we have mainly used the large sets of Coupled Model Intercomparison Project Phase 3 (CMIP3) climate simulations, but we are currently also incorporating the latest CMIP5 simulations (Taylor et al., 2009) database.

2. The role of sea surface temperatures (SST) in drought initiation

"La Niña-type" SST patterns are widely recognized as a key factor in triggering droughts. For instance, each of the six multi-year droughts events which occurred in western North America over the past 150 years coincided with persistent "La Niña-like" events (Seager et al., 2007). To date, such connections between anthropogenic forcing and the changes in those patterns have not been explored with formal D&A methods. Questions to be addressed include: Can atmospheric circulation responses to El Niño–

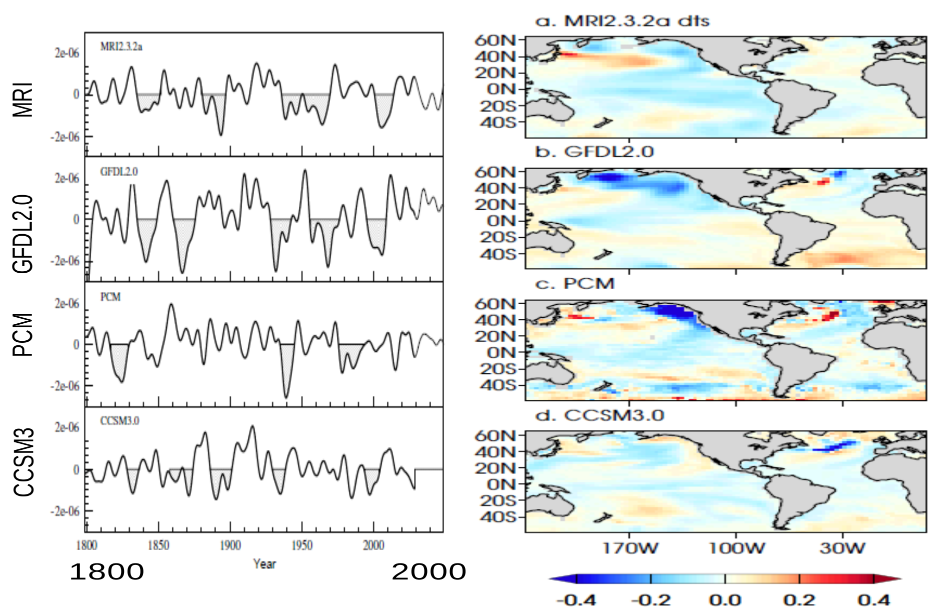

Figure 1 Southwestern U.S. megadroughts and associated SSTs in four CMIP3 Coupled Ocean-Atmosphere Control simulations.

[3] According to our definition, a megadrought must be at least 7-years long, with 90% of these months showing a negative anomaly, where 15% of these months are very dry (< -1.28σ; to ensure high intensity), and no more than 15% very wet (>1.28σ; to avoid a recovery).

Southern Oscillation (ENSO) be distinguished from those associated with anthropogenic increases in greenhouse gases? Will drought-conducive "La Nina-type" SST patterns show significant increases in intensity and/or frequency in the future?

Several attempts have been made (e.g. Hoerling and Kumar 2003; Shin et al., 2010) to identify SST patterns in the tropical Atlantic and Indian Oceans that complement a La-Niña phase in tropical Pacific to produce an SST pattern "optimally" conducive for triggering droughts. We explored various techniques in our search for such a pattern. First, we used three precipitation-based metrics (LPFPA, SPI_{12}, SPI_{60}) for the identification of megadroughts in the Western U.S. in all CMIP3 model control simulations. We then used a composite analysis to construct the associated drought-conducive SST patterns (and their corresponding changes in circulation) for each model. We finally compared the SST patterns of the Community Climate System Model (CCSM3.0), in later versions to be used for future megadrought modeling work, with those of other CMIP3 models. We found that for each model, megadrought occurrences and SST anomaly patterns are relatively insensitive to the choice of precipitation-based metric (Figure 1). While SST patterns are similar across many of the CMIP3 models, we found that the results from the CCSM3.0 (Figure 1d) deviated substantially from those of other models. We found however, that the CCSM3.5 version of the model shows considerable improvement in representing the expected SST pattern (not shown).

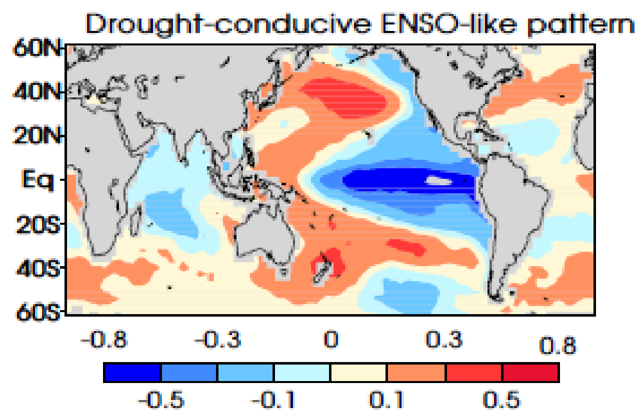

Figure 2 Drought-conducive ENSO-like pattern (ENSOL) inferred from an EOF analysis of observed SST anomalies (HadISST1.1).

Then, following a methodology developed in Bonfils and Santer (2010), we applied an empirical orthogonal function (EOF) analysis on two observational SST datasets4 (in which the global spatial mean has been removed at each time step). We identified a new global ENSO-like (ENSOL; Figure 2) mode of climate variability that acts as a natural trigger of historical droughts. We found that the spatial component of ENSOL includes the main spatial characteristics of ENSO (cold phase), the Pacific Decadal Oscillation (PDO; cool phase)

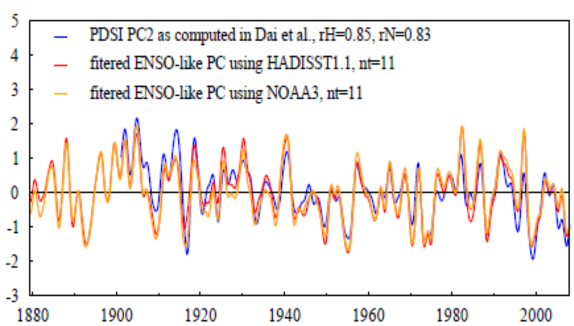

Figure 3 We found that the second PC of the observed Palmer Drought Severity Index (the "PDSI PC2" blue line; Dai et al., 2004) responds with a 3-month lag to the temporal component of the ENSOL mode (computed with the HadISST1.1 (red) and the NOAA3 (orange) SST datasets). Negative values in the ENSO-like PC time-series are associated with a "la Niña-type" pattern (as shown in Figure 2) and more subtropical droughts. All monthly time-series are lowpass-filtered with a Lynch and Huang (1992) digital filter having half-power at a period of 11 months (Santer et al. 2006) to capture the interannual variability.

[4] The Extended Reconstructed SST dataset (Smith et al., 2008) and the U.K. Meteorological Office Hadley Centre Sea Ice and SST dataset (Rayner et al., 2006), which use different reconstruction procedures to infill missing SST data.

and the Atlantic Multi-decadal Oscillation (AMO; positive phase) that are all conducive to subtropical droughts and tropical pluvials through well-known teleconnections. We also found that the principal component (PC) time series associated with the ENSOL pattern is significantly correlated with occurrences of historical droughts in the Southwest U.S., and with the second PC of the monthly observed PDSI (PDSI PC2) computed by Dai et al. (2004). Overall, we determined that the ENSOL PC explains a large fraction (59%) of the global variance of the observed monthly PDSI. These results are robust to current structural uncertainties in observed SST data.

We then applied a D&A-derived technique using SST outputs from the CMIP3 database. In the typical D&A study, the "fingerprint" searched for in the observational record is an expected spatial pattern of climate-change response to human activities (estimated from runs including time-varying anthropogenic changes in greenhouse gases, ozone, and aerosols). Here, we chose the ENSOL pattern as the fingerprint, and we projected SST data from spliced anthropogenically-forced 20th century simulations and simulations of future climate change onto this fingerprint, to produce future pseudo-PC time series of ENSOL[5]. Each of the projection time series was (1) examined to assess the ability of the global climate models to reproduce this drought-conducive mode for the current climate; (2) statistically analyzed to assess whether the temporal statistics of the ENSOL mode will evolve in response to future simulated global warming, or whether the statistical SST/drought relationships will change over time.

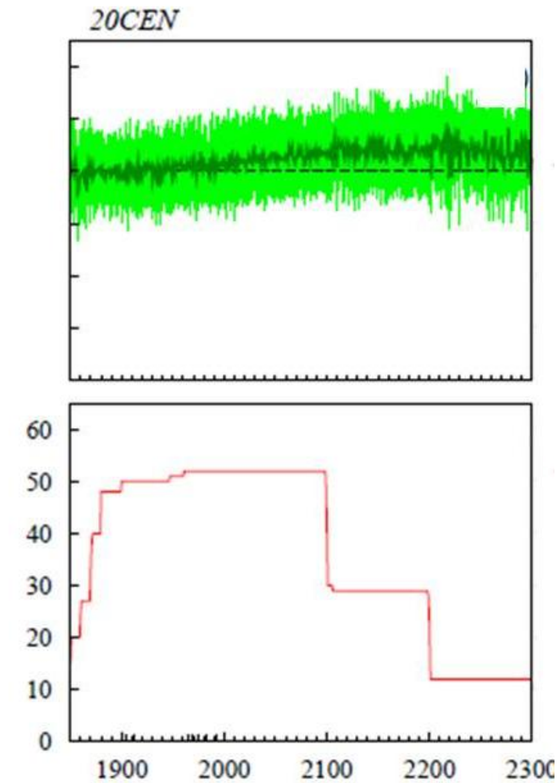

Figure 4 Annual mean ENSOL-PC time-series (green lines) using the average of the 21 CMIP3 20CEN-A1B models (top panel). The green envelope is the 1σ confidence interval computed from all runs. The number of spliced 20CEN-A1B runs used for those calculations are indicated in the bottom panel.

In Figure 4 (top panel) is shown the annual mean ENSOL-PC time-series using the average of the 21 CMIP3 20CEN-A1B models. The multi-model ensemble mean of ENSOL-PC indices is used in order to drastically reduce the internally-generated noise, and to highlight a possible climate response to external forcing. The projected ENSOL-PC index exhibits a small trend toward less La Niña-like (and more El Niño-like) conditions during the 21st century that cannot be explained by natural internal climate variability alone. (By comparison, we did not find any statistically significant change in the intensity of the events--not shown.) That is, in the absence of other global warming-induced effects, the future ENSOL variability will potentially initiate fewer subtropical droughts, but more tropical droughts. However, because most CMIP3 models predict an overall increase in future subtropical droughts, we anticipate that any shift in future drought characteristics would be driven more by another climate response to the slowly evolving greenhouse-warming forcing, rather than by a change in ENSOL

[5] The approach of projecting observational and model data onto a unique basis function provides a uniform comparison between all models and observations, thus ensuring that trend and frequency information in the resulting projection time series are directly comparable (Sperber et al., 2005; Bonfils and Santer, 2010).

variability. For instance, it is possible that globally warmer SSTs, or a poleward extension of the Hadley cell may become increasingly important as alternative drought initiators. An alternative outcome is that the future likelihood of extreme subtropical drought events in response to La-Niña phases of the ENSO may increase due to combined or non-linear mechanisms, or to stronger teleconnections.

We are now extending this work to the CMIP5 simulations, and producing six 100-year simulations with the global climate CESM to better address these questions (within the DOE-funded IMPACTs project). Posters on this topic have been presented at different conferences (see list below). More drought analyses also are being conducted, and a manuscript is in preparation.

1. Bonfils, C., B. Santer, T.J. Phillips, M. Wehner, 2011: Investigating the nature and causes of historical changes in droughts: Exploration phase. WCRP Workshop on Drought Predictability and Prediction in a Changing Climate: Assessing Current Knowledge and Capabilities, User Requirements and Research Priorities, Barcelona, Spain, 2-4 March.
2. Bonfils, C., B.D Santer, T.J. Phillips, M.F. Wehner, 2011: The Drought Interest Group: Climate variability and drought projection in a changing climate. Poster presentation at the World Climate Research Program Open Science Conference, October 24-28, 2011, Denver, CO.
3. Bonfils, C., B. D. Santer, T.J. Phillips, and M.F. Wehner, 2011: Observed and simulated drought-conducive mode of variability and teleconnections. Poster presentation at the American Geophysical Union (AGU) Fall Meeting, December 5-9, 2011, San Francisco, CA.

3. Future plans for this drought research

This LDRD project helped to explore the feasibility of this type of drought research, and led to an Early Career Research Program (ECRP) proposal that successfully received funding through the Department of Energy Office of Science. With this award, the PI will continue to improve the scientific understanding of the nature and causes of past droughts. This will be done by investigating the naturally driven and externally forced components of presumed large-scale drought precursors, such as specific sea surface temperature patterns, or a poleward shift in atmospheric circulation. Particular attention will be given to the sensitivity of the results to specific uncertainties.

4. Aknowledgements

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