COVER PAGE FOR FINAL SCIENTIFIC/TECHNICAL REPORT

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Author	Bruce Anderson
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Executive Summary: This project succeeded in detecting systematic changes in observed seasonal-mean precipitation variations and extreme event occurrences over the United States during the last 80+ years. The questions we were interested in answering included: 1) Which observed trends in various precipitation means and extremes could only have occurred under the influence of climate-change processes? 2) Where and during what seasons do these detectable changes in seasonal-mean precipitation variations and extreme events occur most prominently in the United States? 3) Do numerical climate models adequately reproduce the observed detectability of precipitation means and extremes over the United States?

To answer these questions, we constructed stochastic weather-generation models based upon observed station-based daily precipitation, which can be used to quantify the trends in seasonal-mean precipitation and extreme event occurrences that arise solely from the random evolution of daily precipitation. Next, we compared observed and stochastically-generated daily-precipitation time-series to detect changes/trends in the observed means and extremes that could *only* have occurred through a change in the underlying climate. Finally, using daily precipitation estimates from numerical model representations of the climate of the 20th century, we constructed a new stochastic weather-generation model that will allow us to discern the fidelity of the current-generation climate models in representing detectability within the observed climate system and to objectively determine the utility of these model systems for performing detection studies of historical and future climate change.

The benefits of the project include improving our confidence in the climate forecasts for many regions of the U.S by identifying "hot-spot" regions that have been strongly influenced by climate-change processes. Further it establishes the groundwork for a better understanding of the external drivers—either natural or anthropogenic—that give rise to the detectable precipitation changes in these regions. It will also guide future investigations into numerical model systems' portrayal of physical mechanisms that give rise to historical and future trends in seasonal precipitation means and extremes. Taken together, this research will provide greater confidence in predicting the impacts of climate change across the U.S., thereby providing actionable information to benefit the large-scale welfare of the country.

Comparison of the Proposed and Actual Accomplishments: Of the proposed accomplishments, we either met or are in the process of meeting them all, although the time for doing so was longer than expected due to unforeseen circumstances regarding the premature departure of personnel, delays in release of data resources, and the need to develop a new stochastic modeling system for use with numerical climate model output. Specific accomplishments, as they pertain to those enumerated in the proposal, are found in the next *Section.*

Summarize project activities for the entire period of funding:

Research Activity 1): Acquire observed and model-generated daily precipitation data over the continental U.S. We acquired all the necessary observed data for daily precipitation over the continental U.S. and compiled and screened the data, selecting only the stations with consistent (<5% missing) data for the period 1930-2010, which we found provides extensive (>750 stations) coverage for the U.S. while still retaining a relatively long data record. Most importantly, we found that the observational data are robust, extensive, and persistent enough to allow for the construction of stochastic modeling systems for these stations, which in turn has allowed us to quantify the detectability of interannual, decadal and long-term trends in observed seasonal-mean precipitation variations across the U.S. Further we have acquired numerical model data related to historical and future daily precipitation over the continental U.S. using output from five fully-coupled, land-atmosphere-ocean climate model simulations developed for the DOE-sponsored Coupled Model Intercomparison Project Phase 5 (CMIP5).

Research Activity 2: Construct stochastic daily-precipitation models for stations with long-term daily precipitation records. We completed the construction of the stochastic modeling systems for the stations with long-term daily-precipitation observations. To start, we developed an operational procedure for systematically determining the precipitation frequency parameters for all the stations (since the number of stations that need to be analyzed is an order of magnitude more than what we used in our initial analysis over the southwestern U.S.). The most important aspect of this procedure was the introduction of Akiake Information Criteria to determine the appropriate order of the Markov chain model (which is critical for removing short term persistence and thereby isolating and detecting long term variations), and for determining the degree of seasonal pooling of the data. Using the resultant stochastic models we have simulated 1,000 realizations of each station's roughly 100-year historic record (~3x10^10 individual days of precipitation occurrence in total), which then form a distribution of purely stochastic simulated precipitation records for a given station. Next, we completed the statistical characterization of intensity of precipitation at each station and built the daily-precipitation intensity sub-model for each station, using techniques learned from the operational determination of the precipitation frequency parameters discussed above. In combination with the daily-precipitation frequency sub-model, these two comprise the complete stochastic model for daily precipitation, against which we can compare the observed records (see below). The description of the stochastic model system has been made available to the broader community through two publications as well as two national conference presentations.

Research Activity 3: Determine the detectability of variations and trends in seasonal-mean precipitation and extreme event occurrences across the continental U.S. We successfully used the stochastic modeling system to detect climate-induced variations and trends in seasonal-mean precipitation and extreme event occurrences across the continental U.S. In particular, we found that trends in the annual occurrence of precipitation are predominantly positive while trends in the length of longest dry spell--an indictor of meteorological droughts that affects agriculture and water resources--are predominantly negative. In addition, trends in the occurrence of precipitation during the (climatologically) wettest and driest seasons at each station are predominantly positive, particularly during the dry season when (significant) positive trends exceed (significant) negative trends by 8-fold. Further, we identify "hot-spot" regions in which trends in precipitation characteristics are already emerging from within the envelope of stochastic variability, including (but not limited to): the emergence of positive trends in annual occurrence across the Interior and Great Plains, the Colorado Plateau, the Northwest, and the Northeast; the emergence of negative trends in annual occurrence across the Southeast Plains and the Mid-Atlantic states; the emergence of positive trends in annual intensity and heavy-event accumulations across the Interior Plains and around the Great Lakes; the emergence of negative (positive) trends in dry spell duration over the Colorado Rocky Plateau (desert Southwest); and a systematic shift in the timing of the wet and dry seasons such that there is now a delayed summertime monsoon onset over the southwestern U.S. and an earlier onset of spring precipitation over the Central Plains and winter precipitation over the Northwest. Further, our analysis has identified "sentinel" metrics that show the most "emergent" signal—*e.g.* annual precipitation occurrence and intensity—which should be the focus of future attribution studies, while also identifying those that show the least detectability—*e.g.* seasonal total precipitation and extremes—and hence are unlikely to be attributable to any physically meaningful process. Finally and most recently, this research has serendipitously revealed a heretofore undocumented mode of atmospheric variability—termed the Pacific Decadal Precession (PDP)—that spans the tropical and extratropical North Pacific and has signatures that extend from the ocean's surface through to the stratosphere. More importantly, the PDP is accompanied by persistent, multi-year shifts in atmospheric circulations and concomitant changes to regional climates that impose significant pressures on physical, biological and socio-economic systems, recent manifestations of which include the extended droughts across California, record fire seasons across western Canada, and destabilization of marine ecosystems in the North Pacific. The results of these analyses have been made available to the broader community through seven publications, eleven national conference presentations and two international conference presentations.

Research Activity 4: Evaluate numerical model fidelity in reproducing detectability of variations and trends in seasonal-mean precipitation and extremes for different regions and seasons. Having obtained the daily precipitation data from the numerical climate model simulations we recognized that the original stochastic daily-precipitation models for station based precipitation amounts were unsuitable for characterizing grid-point precipitation within numerical models. As such, we needed to develop a variant of the original stochastic modeling system that could be applied universally to both grid-point data (which tends to have excessive frequency of precipitation but smaller intensity than observed), as well as station data. Therefore, the last 9 months have been spent developing a generalized stochastic modeling system—termed the G-SSWM—that can be applied to both the station-based and gridded data. As with the original stochastic modeling system the G-SSWM is a time series model designed to optimally represent the climatology and short-memory persistence in a given precipitation dataset. However unlike the original stochastic modeling system it uses semi-parametric multivariate probability distributions that model occurrence and intensity simultaneously, which better accounts for the propensity for high-occurrence, low-intensity "drizzle" within gridded data. A key step in the method is the transformation of daily precipitation depths (including zeros, i.e. days with no rain) to a Gaussian distribution in which the zero values are assigned uniform random numbers between zero and an arbitrarily small precipitation amount (or for rain gauges, the detectability limit of the gauge itself) prior to transformation. Then for each day of the year, the daily precipitation data along with the lagged values (up to ~10 days) are used to create a joint probability distribution using Gaussian kernels, which are analytically amenable to calculations of marginal and conditional probabilities. The number of lags is determined for each day using cross validation to prevent over/under-fitting, as is the functional form/bandwidth of the kernels themselves. Once estimated, the conditional probabilities provided by the kernels for a given day, based on the previous days' precipitation sequence, are integrated forward to generate time sequences of (transformed) precipitation. These time sequences then are re-transformed using the original distribution (for the appropriate day) to create a precipitation time series that preserves the daily statistics of the original precipitation data including the frequency of dry days, as well as the short-term memory structure between/among dry and wet day occurrence and intensity. This methodology allows us to analyze station data (which tends to have many dry days), gridded data (which has fewer dry days, but many low-intensity "drizzle" days), and climate model data (which tends to have almost no dry days, and very many "drizzle" days) with a single, consistent methodology. The methodology paper for the G-SSWM is nearly complete; in addition the G-SSWM modeling framework is currently being applied to both the observed and simulated numerical climate-model data for daily precipitation over the continental U.S., at which point the analysis for Research Activity 4 can be completed. We expect that within the next 1-2 weeks the stochastic modeling of daily precipitation will be complete and that the full analysis will be submitted for publication within the next 3 months.

Products

a. Publications/Presentations

1. Anderson, B.T., D.J. Gianotti, and G. D. Salvucci, 2015: Detectability of historical trends in station-based precipitation characteristics over the Continental United States. *J.Geophys. Res.* DOI: 10.1002/2014JD022960
2. Anderson, B.T., D.J. Gianotti, and G. D. Salvucci, 2015: Characterizing the potential predictability of station-based seasonal extremes in precipitation accumulations and dry-spell durations. *J.Hydrometeor.*, 16, 843–856
3. Anderson, B.T., D.J. Gianotti, J.C. Furtado, and E. Di Lorenzo, 2015: A decadal precession of atmospheric pressures over the North Pacific. *J.Geophys. Res.* (in review)
4. Anderson, B.T., D.J. Gianotti, G. D. Salvucci and J.C. Furtado, 2015: Dominant timescales of potentially predictable precipitation variations across the continental United States. *J. Climate.* (*in review)*
5. Gianotti, D. J., B.T. Anderson, and G. D. Salvucci, 2014: The potential predictability of precipitation occurrence, intensity, and seasonal totals over the continental United States. *J.Clim.*, 27, 6904–6918.
6. Pal, I, B.T. Anderson, G.D. Salvucci, and Gianotti, D. 2013: Shifting seasonality and increasing frequency of precipitation in wet and dry seasons across the U.S. *Geophys. Res. Lett.*. doi: 10.1002/grl.50760
7. Gianotti, D., B.T. Anderson, and G.D. Salvucci, 2013: What do rain gauges tell us about rainfall's predictability? *J. Climate* doi: http://dx.doi.org/10.1175/JCLI-D-12-00718.1
8. Anderson, B.T., D.J. Gianotti, J.C. Furtado, and E. Di Lorenzo, 2015: South Central Climate Science Center Workshop, Fort Worth , TX. The Pacific Decadal Precession and its links to US Climate
9. Short Gianotti, D.J., G.D. Salvucci and B.T. Anderson, 2015: AGU Chapman Conference on California Drought: Causes, Impacts, and Policy, Irvine CA. California Drought, Weather Variability, and Climate Variability
10. Salvucci, G., D. Gianotti, and B.T. Anderson, 2014: AGU Fall Meeting, San Francisco, CA. Stochastic analysis of California's recent precipitation drought in the context of the last one hundred years
11. Gianotti, D., B.T. Anderson, and G. Salvucci, 2014: AGU Fall Meeting, San Francisco, CA. Characterizing weather and climate variability for precipitation: A data-based stochastic modeling framework
12. Anderson, B.T. Gianotti, D., and G. Salvucci, 2014: U.S Department of Energy Principal Investigators Meeting, Washington DC. Detection of historical precipitation variations and trends over the continental U.S.

13. Gianotti, D., B.T. Anderson, and G. Salvucci, 2013: Climate Diagnostics and Prediction Workshop. College Park, MD. Potential Predictability of Precipitation: Occurrence or Intensity?
14. Anderson, B.T., D. Gianotti and G.D. Salvucci, 2012: Regional Spectral Modeling Workshop, Scripps Institution of Oceanography, San Diego CA - Historical expansion of the summertime monsoon over the southwestern United States: What can regional models tell us about its causes?
15. Gianotti, D., B.T. Anderson, and G.D. Salvucci, 2012: Climate Diagnostics and Prediction Workshop, Fort Collins, CO - Establishing Potential Predictability of U.S. Precipitation Using Rain Gauge Data
16. Pal, I., B.T. Anderson, G.D. Salvucci, and Gianotti, D., 2012a: Climate Diagnostics and Prediction Workshop, Fort Collins, CO - Magnitude and significance of observed trends in precipitation frequency over the U.S.
17. Pal, I., B.T. Anderson, G.D. Salvucci, and Gianotti, D., 2012b: AGU Fall Meeting, San Francisco, CA - Magnitude and significance of observed trends in precipitation frequency over the U.S
18. Anderson, B.T., D. Gianotti and G.D. Salvucci, 2011a: WCRP Open Science Conference, Denver CO – Detection of historical summertime monsoon precipitation variations and trends over the southwestern United States
19. Anderson, B.T., D. Gianotti and G.D. Salvucci, 2011b:Department of Energy Principal Investigators Meeting, Washington DC – Detection of historical precipitation variations and trends over the continental United States
20. Gianotti, D., B.T. Anderson, and G.D. Salvucci, 2011: AGU Fall Meeting, San Francisco, CA - Stochastic and deterministic aspects of observed seasonal-mean precipitation variations and extreme event occurrences over the U.S.

b. Website: N/A

c. Networks/Collaborations fostered: On-going collaborations that have been fostered by this research include working with colleagues at Boston University interested in developing a similar technique for determining the predictability of temperature for use in economic forecasting (with a specific focus on estimating Cooling Degree Days and Heating Degree Days on intra-seasonal to multi-decadal time-scales). In addition, we have been working with other colleagues at Boston University and Worcester Polytechnic Institute on combining these models with daily tide gauge date to generate “stochastic storm surge models" that can more fully represent the range of plausible, yet unrealized, storm surges to which communities and infrastructure may be exposed.

d. Technologies/Techniques: The most important technology to come from this project is the recent development of the "generalized stationary stochastic weather model" (G-SSWM) framework for systematically determining the precipitation frequency and intensity parameters for both station-based and numerically-simulated precipitation data. In fact, this technology is crucial for evaluating the detectability of variations and trends in seasonal-mean precipitation and extremes at the differing spatial scales of station observations (~1m) and numerical model simulations (~100km), without recourse to bias correction, re-calibration, or re-gridding, thereby providing a more consistent, objective, and independent evaluation between models and observations. As we note in the technical paper that accompanies the model, the method is also generalizable and can easily be applied by other researchers to study the detectability of seasonal precipitation variations in other regions of the world, of climate processes/variables other than precipitation, and of processes/variables outside the climate sciences altogether. For instance, we have been working with colleagues at Boston University interested in developing a similar technique for determining the predictability of temperature for use in economic forecasting as well as with tidal gauge data for flood forecasting. As such, the intention is to publish the numerical code for the G-SSWM framework with its own DOI, such that it can be referenced separately from the paper (for instance by those working outside of the field of climate sciences).

e. Inventions: N/A

f. Data: As part of these research efforts, we have published the observed and stochastic variance values and trend values for each station, each annual and 91-day period (centered on all 365 Julian Days) and each metric—including mean precipitation intensity, occurrence, and total accumulation, and dry and wet extremes (i.e. extreme consecutive dry day length and extreme-event accumulations)—as Supplementary Data Files in our papers, so as to allow others in the research, operations and user communities to explore the location, timing, and metric of most relevance to them

Computer Modeling Outcomes: N/A