This is the final report for our project, "Changes in Intense Precipitation Events in West Africa and the central U.S. under Global Warming", K.H. Cook (P.I.) and E.K. Vizy (co-P.I.). The purpose of the proposed project was to improve our understanding of the physical processes and large-scale connectivity of changes in intense precipitation events (high rainfall rates) under global warming in West Africa and the central U.S., including relationships with low-frequency modes of variability. This was in response to a requested subject, namely, the "simulation of climate extremes under a changing climate … to better quantify the frequency, duration, and intensity of extreme events under climate change and elucidate the role of low frequency climate variability in modulating extremes." We primarily used regional climate modeling, and emphasized an understanding of the physical processes that lead to an intensification of rainfall.

The following projects were completed with support from this award:

1. Vizy, E.K. and K.H. Cook, 2012. Mid-21st century changes in extreme events over Northern and Tropical Africa, *J. Climate*, **25**, 5748-5767.

A regional climate model is used to predict changes in temperature and rainfall extremes across tropical and northern Africa for 2041-2060 under a mid-line emissions forcing scenario. Six indicators are examined, including annual extreme and daily diurnal temperature ranges, heat wave days, number of dry days, number of extreme wet days, and extreme wet day rainfall intensity. Confidence in the projections is evaluated by examining the ensemble spread and the validation of extreme events in the 20th c. simulation.

Despite an increase in both the daily minimum and maximum temperatures, diurnal temperature ranges decrease from West Africa to Ethiopia during spring and fall, over the Sahel during summer, and over the Congo basin during winter and spring. Diurnal temperature ranges increase over the Horn of Africa during boreal winter, and over Kenya and Tanzania during boreal summer associated with a decrease in relative humidity. The number of heat wave days increases north of 8°N, with the largest increase (60 – 120 days) over the western Sahel. The number of dry days decreases over the Congo basin and the central Sahel, but increases over East Africa, the latter associated with a reduction in the springtime long rains. The number of extreme wet rainfall days is projected to increase over West Africa, the Sahel, and the Ethiopian highlands but decrease over the Congo. The predicted changes in extreme wet rainfall intensity are highly regional.

2. Crétat, J., E. K. Vizy, and K. H. Cook, 2015: The relationship between African easterly waves and daily rainfall over West Africa: observations and regional climate simulations. *Clim. Dyn.* **44**, 385-404.

The relationship between summer African easterly waves (AEWs) and daily rainfall is assessed in West Africa for 1998-2008 using various reanalyses, satellite-derived rainfall products, and a regional climate model (RCM) run at 90- and 30-km resolutions. 3-5 and 6-9 day AEWs are extracted by filtering daily 700 hPa meridional wind time series at 1A degrees W and 11.5A degrees N, and 1A degrees W and 17.5A degrees N, respectively. Both observed and simulated rainfall anomalies are of larger magnitude over West Africa during 3-5-d than 6-9-d AEWs. The RCM simulates larger rainfall rates in phase with the 3-5-d wave trough instead of ahead, unlike the observations, and overestimates the intensity and spatial coverage of rainfall associated with 6-9-d AEWs. The observed and simulated co-variability between 3-5-d (6-9-d) AEW activity and daily rainfall is strong (weak) and mostly located south (north) of 15A degrees N. However, the RCM overestimates the spatial coverage of the AEW-rainfall relationship in the longitudinal (latitudinal) direction in the case of 3-5-d (6-9-d) AEWs. Observed and simulated daily intense rainfall events, extracted using a percentile threshold approach, are mostly located south of 15A degrees N during summer. The observed relationship between their frequency of occurrence and active 3-5-d AEWs is maximal west of 8A degrees E, while extends up to southern Chad in both RCM simulations. Their magnitude is also largely overestimated by the RCM, indicating an exaggerated coupling between the wave activity and the convection. Finally, observed and simulated 3-5-d AEWs establish the most favorable synoptic conditions for the development of intense rainfall events over West Africa.

3. Crétat, J., E. K. Vizy, and K. H. Cook, 2014: How well are daily intense rainfall events captured by current climate models over Africa? *Clim. Dyn.*, **42**, 2691-2711.

The ability of state-of-the-art climate models to capture the mean spatial and temporal characteristics of daily intense rainfall events over Africa is evaluated by analyzing regional climate model (RCM) simulations at 90-km and 30-km along with output from four CMIP5 GCMs in both AMIP and CMIP modes. Daily intense rainfall events are extracted at grid point scale using a 95^{th} percentile threshold approach applied to all rainy days (i.e., daily amount ≥ 1 mm day^{-1}) of the 1998 – 2008 period for which two satellite-derived products are available.

Weakly sensitive to the horizontal resolution, the two RCM simulations generally accurately captures the observed spatial and temporal characteristics of intense events, despite their tendency to overestimate their number and underestimate their intensity.

Results from the four GCMs are weakly impacted by the experimental protocol over the African continent. Their skill appears similar to previous GCM generations, all of them largely overestimating the frequency of intense events (except MRI-CGCM3), particularly over the tropics, failing at simulating the observed intensity (except CNRM-CM5 and MIROC5 which are close to the RCM and fall between the two satellite-derived products), and systematically overestimating their spatial coverage.

The RCM is shown to perform at least as well as the best GCM, demonstrating a clear added-value and its usefulness to investigate the physics leading to such events and how they may change under warmer conditions.

4. Patricola, C. M., and K. H. Cook, 2013a: Mid-twenty first century climate change in the central United States. Part I: Regional and global model predictions. *Climate Dyn.*, **40**, 551-568.

A well-validated regional climate model constrained by future anomalies from atmosphere-ocean general circulation model (AOGCM) simulations is used to generate mid-21st century climate change predictions at 30-km resolution over the central U.S. The regional model predictions are compared with those from 15 AOGCM and 7 regional model downscaling simulations to identify robust climate change signals.

Precipitation predictions across the central U.S. include wetter springs and 10-30% rainfall reductions in summer. Wetter winters are also projected for the northern Great Plains and Midwest. While monthly precipitation changes reach up to +/- 15%, annual changes are near zero. Predictions in extreme precipitation events include scattered increases over the central U.S. in the (1) annual total of precipitation delivered in extreme events; (2) number of days with extreme rainfall; (3) monthly maximum of daily precipitation rates; (4) number of consecutive dry days.

Annual-mean near-surface air temperatures are projected to warm by 1.4 - 1.8 K (2.5 - 3.2°F), with maximum warming in August and minimum in March. Projected changes in extreme events include a (1) decrease in the annual number of ice days by 1 week, and frost days by 2 weeks; (2) 1 – 2 week increase in the irrigated growing season length; (3) 4-6 week increase in the annual number of warm days; (4) 0.5-1.5 week decrease in the number of annual cool days; (5) 1.5-3 week lengthening of warm spell duration.

5. Patricola, C. M., and K. H. Cook, 2013b: Mid-twenty first century climate change in the central United States. Part II: Climate change processes. *Climate Dyn*., 40, 569-583.

Ensemble regional model simulations over the central U.S. with 30-km resolution are analyzed to investigate the physical processes of projected precipitation changes in the mid-21st century under greenhouse gas forcing. An atmospheric moisture balance is constructed, and changes in the diurnal cycle are evaluated.

Positive central U.S. rainfall anomalies in April and May occur most strongly in the afternoon and evening, supported primarily by anomalous moisture convergence by transient eddy activity, indicating enhanced daytime convection. In June, increased rainfall over the northern Great Plains is strongest from 0000 - 0600 LT. It is supported by anomalous time-mean meridional moisture convergence related to a strengthening of the GPLLJ accompanied by an intensification of the western extension of the North Atlantic subtropical high. In the Midwest, decreased rainfall is strongest at 1500 LT and 0000 LT. Both a suppression of daytime convection as well as changes in the zonal flow in the GPLLJ exit region are important. Negative precipitation anomalies over the northern Great Plains in summer and are triggered by weakened daytime convection, and the drying persists throughout August and September when the deficit in soil moisture and strong land-atmosphere feedbacks dominate.

6. Druyan, L., J. Feng, K. H. Cook, Y. Xue, M. Fulakeza, S. M. Hagos, A. Konare, W. Moufouma-Okia, D. P. Rowell, and E. K. Vizy, 2010: The WAMME regional model intercomparison study. *Climate Dynamics,* DOI 10.1007/s00382-009-0676-7.

Results from five regional climate models (RCMs) participating in the West African Monsoon Modeling and Evaluation (WAMME) initiative are analyzed. The RCMs were driven by boundary conditions from National Center for Environmental Prediction reanalysis II data sets and observed sea-surface temperatures (SST) over four May-October seasons, (2000 and 2003-2005). In addition, the simulations were repeated with two of the RCMs, except that lateral boundary conditions were derived from a continuous global climate model (GCM) simulation forced with observed SST data. RCM and GCM simulations of precipitation, surface air temperature and circulation are compared to each other and to observational evidence. Results demonstrate a range of RCM skill in representing the mean summer climate and the timing of monsoon onset. Four of the five models generate positive precipitation biases and all simulate negative surface air temperature biases over broad areas. RCM spatial patterns of June-September mean precipitation over the Sahel achieve spatial correlations with observational analyses of about 0.90, but within two areas south of 10A degrees N the correlations average only about 0.44. The mean spatial correlation coefficient between RCM and observed surface air temperature over West Africa is 0.88. RCMs show a range of skill in simulating seasonal mean zonal wind and meridional moisture advection and two RCMs overestimate moisture convergence over West Africa. The 0.5A degrees computing grid enables three RCMs to detect local minima related to high topography in seasonal mean meridional moisture advection. Sensitivity to lateral boundary conditions differs between the two RCMs for which this was assessed. The benefits of dynamic downscaling the GCM seasonal climate prediction are analyzed and discussed.