Closeout of Award No. DE-FG02-04ER63881

Final Report

Title: Studies of regional-scale climate variability and change: Hidden Markov models and coupled ocean-atmosphere modes

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Award No. DE-FG02-04ER63881
Award period: 07/15/04-07/14/08

This project was a continuation of previous work under DOE CCPP funding, in which we had developed a twin approach of probabilistic network (PN) models (sometimes called dynamic Bayesian networks) and intermediate-complexity coupled ocean-atmosphere models (ICMs) to identify the predictable modes of climate variability and to investigate their impacts on the regional scale. We had developed a family of PNs (similar to Hidden Markov Models) to simulate historical records of daily rainfall, and used them to downscale GCM seasonal predictions. Using an idealized atmospheric model, we had established a novel mechanism through which ocean-induced sea-surface temperature (SST) anomalies might influence large-scale atmospheric circulation patterns on interannual and longer time scales; we had found similar patterns in a hybrid coupled ocean-atmosphere-sea-ice model.

The goal of the this continuation project was to build on these ICM results and PN model development to address prediction of rainfall and temperature statistics at the local scale, associated with global climate variability and change, and to investigate the impact of the latter on coupled ocean-atmosphere modes. Our main results from the grant consist of extensive further development of the hidden Markov models for rainfall simulation and downscaling together with the development of associated software; new intermediate coupled models; a new methodology of inverse modeling for linking ICMs with observations and GCM results; and, observational studies of decadal and multi-decadal natural climate results, informed by ICM results.

A particularly timely by-product of this work is an extensive study of clustering of cyclone tracks in the extratropical Atlantic and the western Tropical Pacific, with potential applications to predicting landfall. Each of these project components is elaborated on below, followed by a list of publications resulting from the grant.

Development of Hidden Markov models

Nonhomogeneous Hidden Markov Models (NHMMs) have been developed to model local daily observed rainfall on a regional network of raingauge-stations, and to study the "downscalability" of climate variability to local daily scales. As part of this work we have developed statistical estimation techniques, parameter fitting algorithms, and software in C code, for a general class of NHMMs. Our algorithms and software generalize earlier work to apply of NHMMs to downscaling. In general, an NHMM is characterized by three modeling components: (1) an unobserved finite-state discrete-time Markov process S(t), (2) a vector of observations R(t) at time t that has a stochastic dependence on the Markov state S(t), and (3) an exogenous set of measurements X(t) that modulate the state transition probabilities.

(a) Methodological development

Building on our previous work, for each of the following modeling and algorithmic features the basic theory of statistical estimation was developed and subsequently implemented into the software toolbox:

* We developed a general theory and methodology for NHMM models that used tree-structured and auto-regressive dependence relations (Kirshner et al. 2004) for modeling the relation of observation vectors and states over time. This class of models can simulate precipitation with more realistic spatial dependencies compared to conditional independence models.

* We implemented a model for precipitation amounts as a conditional mixture (given the weather state variable) of a Dirac delta component (for zero precipitation) and several components defined on the positive reals. The estimation algorithms for several such components such as exponential, gamma, and log-normal were developed and implemented.

* We combined the precipitation amount models with the tree-dependence model, again providing more realistic spatial dependencies compared to conditional independence models.

* We implemented binary sigmoidal networks to model higher order dependencies for weather states (both in the standard and auto-regressive HMM framework).

* Implemented tree-dependence model for multivariate Gaussians

* We developed a general capability to handle missing precipitation occurrence and amount data in an appropriate statistical manner for the models described above, using a missing-completely-at-random assumption. Missing data is particularly prevalent in historical daily rainfall records from many regions of the world, and thus, it is essential to be able handle such records in a statistically sound manner.

* We extended our earlier NHMM estimation algorithms from a maximum-likelihood framework to a maximum a posteriori framework, allowing for the use of priors (e.g., Dirichlet priors for Markov transition matrix probabilities or precipitation occurrence probabilities), and providing more robust estimation in the presence of sparse data (e.g., when zero counts occur in certain state-observation combinations).

* The code was extended and optimized from earlier versions to efficiently handle large numbers of stations (observations) and has been successfully used with data sets of over 300 station observations per day.

* We carried out experiments with large spatial networks, to explore the impact of segmenting them into multiple smaller networks, and compared HMMs fitted to a single large network, versus a set of smaller ones. Preliminary results indicate no obvious degredation of the HMM simulations if the large network is considered as a single entity. However, this conclusion may change in NHMMs and this is a topic for potential further investigation.

(b) The MVNHMM Software Package

Under CCPP support we have made our NHMM software publicly available with full documentation. The software is downloadable at http://www.stat.purdue.edu/~skirshne/MVNHMM/, where MVNHMM stands for "multivariate nonhomogeneous hidden Markov models." We have developed and tested this MVNHMM code across three different operating system platforms (Microsoft Windows XP, Mac OS X, and Linux) and have performed extensive numerical testing to ensure consistent results across all three platforms. We also developed an easy-to-use cross-platform Java GUI interface, built on top of the MVNHMM code, that allows a user to apply the MVNHMM algorithms to precipitation data from networks of station data. This GUI is publicly available http://iri.columbia.edu/climate/forecast/stochasticTools/index.html. The GUI allows a user to interactively select from a wide menu of both HMM and NHMM models, including tree-structured dependence models, different amount models, and missing data estimation. In addition the interface provides the user with the ability to interactively visualize the data and the fitted models to assist the user in interpretation, including display of the spatial and occurrence/amount characteristics of the states learned by the model, as well as visualization of Viterbi-estimated sequences of most-likely states in a time-series data set. A number of research groups in the climate community have downloaded the tool and are currently actively using it and and we expect further significant community uptake in the future.

(c) Application of NHMMs to long observed rainfall records and GCM downscaling

The NHMMs developed by this project have been applied and tested in several regional contexts to model daily rainfall at the station scale, and to downscale from general circulation model (GCM) seasonal simulations, including NE Brazil (Robertson et al. 2004), Queensland Australia (Robertson et al. 2006), India (Greene et al. 2008), as well as Kenya and the Philippines. They have been coupled to a crop model over SE United States (Robertson et al. 2007). Chow-Liu tree spatial models have been tested over southwest Australia (Kirshner et al. 2004). We have compared the NHMM method of GCM downscaling over Senegal with approaches based on local scaling, K-nearest neighbor and weather-classification methods (Moron et al. 2008b). All of these studies have indicated that the seasonal predictability of rainfall frequency is greater than that of seasonal rainfall total, and much greater than that of mean rainfall intensity. Indeed, the risk of dry spells, which is a key variable for agriculture, follows the rainfall-occurrence distribution and is found to be relatively predictable. We have followed up these results by analyzing in detail the spatial coherence characteristics of tropical seasonal anomalies in these rainfall statistics, finding that the spatial incoherence of rainfall intensity can account for its lack of predictability (Moron et al. 2007; Moron et al. 2008a). This work has reached a level of maturity in assessing seasonal predictability in weather-within-climate statistics.

Work was also undertaken to apply NHMMs to decadal timescales (Greene et al. 2008). A 70-year record of daily monsoon-season rainfall at a network of 13 stations in central western India was analyzed using a 4-state homogeneous hidden Markov model. The diagnosed states are seen to play distinct roles in the seasonal march of the monsoon, can be associated with 'active' and 'break' monsoon phases and capture the northward propagation of convective disturbances associated with the intraseasonal oscillation. Interannual variations in station rainfall are found to be associated with the alternation, from year to year, in the frequency of occurrence of wet and dry states; this mode of variability is well correlated with both all-India monsoon rainfall and an index characterizing the strength of the El Nino Southern Oscillation. Analysis of low-passed time series suggests that variations in state frequency are responsible for the modulation of monsoon rainfall on multidecadal time-scales as well.

2. Empirical mode reduction (EMR) and clustering of cyclone tracks

We have developed a new statistical methodology of empirical mode reduction (EMR) (Kravtsov et al., 2005b; Kondrashov et al., 2005, 2006) that allows one to construct a low-dimensional, nonlinear stochastic model based entirely on observations (actual or model generated) of climate variables. These EMR models are typically characterized by a useful forecast skill, sometimes comparable to that of the state-of-the-art GCMs. The construction of an EMR model involves choosing an appropriate subspace of climate variables of interest and uses regularization techniques to avoid overfitting (fitting unpredictable noise, rather than a useful signal). The choice of EMR subspace should be based on the insights provided by dynamical climate models. EMR is a powerful tool for climate analysis and diagnosis, with potential applications ranging from downscaling and estimates of regional climate to global climate prediction.

A probabilistic clustering technique was developed for classification of wintertime extratropical cyclone (ETC) tracks over the North Atlantic. We used a regression mixture model to describe the longitude-time and latitude-time propagation of the ETCs. A simple tracking algorithm was applied to 6-hourly mean sea-level pressure fields to obtain the tracks from either a general circulation model (GCM) or a reanalysis data set. Quadratic curves provide the best description of the data. We selected a three-cluster classification for both data sets, based on a mix of objective and subjective criteria. The track orientations in each of the clusters are broadly similar for the GCM and reanalyzed data; they are characterized by predominantly south-to-north (S–N), west-to-east (W–E), and southwest-to-northeast (SW–NE) tracking cyclones, respectively. The reanalysis cyclone tracks, however, are much more tightly clustered geographically than those of the GCM.

For the reanalysis data, a link is found between the phase of the North Atlantic Oscillation (NAO) and the occurrence of cyclones belonging to different clusters of trajectory shape. The positive phase of the NAO is associated with the SW–NE oriented cluster, whose tracks are relatively straight and smooth, with cyclones that are typically faster, more intense, and of longer duration. The negative NAO phase is associated with more erratic W–E tracks, with typically weaker and slower-moving cyclones. A more transient geopotential trough accompanies the S–N cluster over the western North Atlantic. No clear associations were found in the case of the GCM composites. The GCM is able to capture cyclone tracks of quite realistic orientation, as well as subtle associated features of cyclone intensity, speed and lifetimes. The clustering clearly highlights, though, the presence of serious systematic errors in the GCM's simulation of ETC behavior.

A similar analysis was carried out for typhoon tracks in the western North Pacific, were seven distinct clusters describe the best-track data set for the 1950–2002 time interval. These clusters were analyzed in terms of genesis location, trajectory, landfall, intensity, and seasonality. Both genesis location and trajectory play important roles in defining the clusters. Several distinct types of straight-moving, as well as recurving, trajectories are identified. Intensity and seasonality of cyclones, though not used by the clustering algorithm, are both highly stratified from cluster to cluster. Three straight-moving trajectory types have very small within-cluster spread, while the recurving types are more diffuse. Tropical cyclone landfalls over East and Southeast Asia are found to be strongly cluster-dependent, both in terms of frequency and region of impact.

The relationships of each cluster type with the large-scale circulation, sea surface temperatures, and the phase of the El Niño–Southern Oscillation were also investigated. Two of the seven clusters are typical of El Niño events; their genesis locations are shifted southeastward and they are more intense. The largest cluster is recurving, located northwestward, and occurs more often during La Niña events. Two types of recurving and one of straight-moving tracks occur preferentially when the Madden–Julian oscillation is active over the region of interest.

3. Intermediate coupled modeling (ICM)

Our research activities involving intermediate coupled models were focused on studies of the coupled behavior in the models with and without active thermohaline circulation and/or mesoscale intrinsic variability in the ocean. Two types of ocean models were used: (a) three-layer quasi-geostrophic model in turbulent regime, in which the ocean small-scale eddies are active and contribute to the coupled system variability -- the active thermohaline circulation is, however, not considered in the model; (b) 15-layer, 4x4 degree resolution primitive equation model. In the latter model, both wind-driven and thermohaline circulation are resolved, but the small-scale ocean eddies are effectively damped by large horizontal viscosity inherent in such large-scale circulation models. The two models concentrate, therefore, on separate processes, each of which might be, in its own right, potentially important for the coupled dynamics. The coupled models that stem from (a) and (b) both use identical atmospheric components, represented by a two-layer quasi-geostrophic channel model. The central aspect of the latter model is bimodal behavior at low frequency, which is characterized by the transitions between two anomalously persistent zonal-jet states displaced north and south of the jet's time-mean position.

Our intermediate coupled modeling has identified a new mechanism of interdecadal climate variability (Kravtsov et al. 2007). The key aspects of this mechanism include sensitivity of nonlinearly selected persistent atmospheric anomalies (Kravtsov et al. 2005a) to ocean-induced sea-surface temperature (SST) anomalies in middle latitudes; the latter anomalies are maintained for many years due to a symbiotic relationship between mean wind-driven circulation and the associated eddy field (Kravtsov et al. 2006a, 2007b). Nonlinear atmospheric sensitivity has also been shown to modify quantitatively another, decadal climate mode, which appears to be associated with the dynamics of the oceanic thermohaline circulation.

Our findings thus point to the potential importance of strongly nonlinear processes for decadal and multi-decadal climate variability. The associated phenomena involve interaction between processes on a very broad range of time scales, and also between the processes operating on the spatial scales as small as kilometers, and large-scale (basin-scale and global-scale) processes. One of the key aspects of our proposed work will be to build on the prior understanding we achieved using ICM emphasizing wind-driven and buoyancy-driven oceanic circulations (the latter is arguably more climatically relevant) and estimate uncertainties in decadal global climate projections due to omission of the small-scale ocean eddy processes from the current generation of global-climate GCMs. This will require a climate model that could provide multi-century integrations of the eddy-resolving thermohaline circulation.

4. Observations of decadal and multi-decadal natural climate variability

The inferred link between the dynamics of both modes and atmospheric nonlinear properties, and careful diagnosis of these modes, provided guidance for the novel analysis of observational data sets, which was geared specifically to emphasize the nonlinear connections between the ocean and the atmosphere. Several types of analysis have been conducted.

We have found signatures of both decadal and bi-decadal modes in observations of the Northern Hemisphere's winds and sea-surface temperatures (Kravtsov et al. 2006a, 2008b), as well as in the updated records of the upper-ocean heat content. In particular, the observed time scales, phase relations, and spatial patterns of the bi-decadal mode, have all been consistent with the ICM: both observations and model show a 20-yr period, with oceanic heat content leading the atmospheric jet's variability by a few years; similar correspondences exist for a decadal mode.

The above results are also supported by our new observational analysis (Tsonis et al. 2007), in which we used the concepts of graph theory to show that observed teleconnection patterns tend to synchronize with a 20-yr periodicity, and that significant climate shifts result if this synchronization is preceded by an increased coupling between the modes. These findings also explain some of the climate projections obtained using a GFDL AR-4 coupled model simulation. Another interesting piece of novel observational evidence that indicates a presence and global importance of the 20-yr coupled mode predicted by our ICM modeling comes from a diagnosis of observational and GCM-generated data sets using the concepts of the graph theory, which emphasizes collective behavior of connected climate modes (Tsonis et al. 2007). In particular, the authors have established that various observed climate modes expressed through teleconnection patterns tend to synchronize with a 20-yr periodicity, and that major climate shifts result if this synchronization is preceded by an increased coupling between the modes (increased coupling means a stronger phase relationships between different modes). These results have been consistent with the behavior of some of the climate projections obtained using a GFDL coupled model simulation performed in support of the IPCC AR-4 report.

Finally, by subtracting the grand multi-model ensemble mean of the IPCC AR-4 models over the 20th century from the observed surface temperature record, we have identified a 60--70-yr residual that strongly resembles the so-called Atlantic Multidecadal Oscillation [AMO] (Kravtsov and Spannagle 2008). This mode is thought to be associated with the dynamics of the oceanic thermohaline circulation. Our results emphasize a stronger influence of AMO on the tropical SSTs than was contemplated previously; these findings are consistent with other recent modeling studies.

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