2009 – 2011	Modeling continuum climate variability: Atmosphere, ocean, land and ice
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1. Introduction

Continuum temperature variability represents the response of the Earth's climate to deterministic external forcing. Scaling regimes are observed which range from hours to millennia with low frequency fluctuations characterizing long-term memory. The presence of 1/f power spectra in weather and climate is noteworthy: (i) In the tropical atmosphere 1/f scaling ranging from hours to weeks is found for several variables; it emerges as superposition of uncorrelated pulses with individual 1/f spectra. (ii) The daily discharge of the Yangtze shows 1/f within one week to one year, although the precipitation spectrum is white. (iii) Beyond one year mid-latitude sea surface temperatures reveal 1/f scaling in large parts of the global ocean. The spectra can be simulated by complex atmosphere-ocean general circulation models and understood as a two-layer heat diffusion process forced by an uncorrelated stochastic atmospheric. Long-term memory on time scales up to millennia are the global sea surface temperatures and the Greenland ice core records (GISP2, GRIP) with $\delta^{18}O$ temperature proxy data during the Holocene. Complex atmosphere ocean general circulation models reproduce this behavior quantitatively up to millennia without solar variability, interacting land-ice and vegetation components. Progress during the first years of the fellowship on continuum climate variability has been achieved in several directions: (i) role of compartments (mainly soil) and mechanisms, (ii) in the statistical analysis and in (iii) predictability and prediction studies. Furthermore, model development led to a spectral ocean model congruent with atmospheric models. The main results are summarized.

1. Compartments and mechanisms

Short and long-term memory of soil moisture: Soil moisture variability is analyzed in the reanalysis data ERA-40 of the European Centre for Medium-Range Weather Forecasts (ECMWF) which includes four layers within 189 cm depth. Short-term correlations are characterized by an e-folding time scale assuming an exponential decay, whilst long-term memory is described by power law decays with exponents determined by detrended fluctuation analysis. On a global scale, the short-term variability varies congruently with long-term memory in the surface layer. Key climatic regions (Europe, Amazon and Sahara) reveal that soil moisture time series are non-stationary in arid regions and in deep layers within the time horizon of ERA-40. The physical processes leading to soil moisture variability are linear according to an analysis of volatility (the absolute differences), which is substantiated by surrogate data analysis preserving the long-term memory.

Memory in convection (CAPE and CIN): The memory of convective precipitation is estimated via the analysis of the convective parameters convective available potential energy (CAPE) and convective inhibition (CIN). The variability of mixed layer (ML) CAPE and CIN in present-day climate is presented in terms of a linear decay time scale for short-term memory and the Hurst exponent for long-term memory (determined by detrended fluctuation analysis). Regional and global memory in CAPE and CIN is compared between observations (ECMWF re-analysis, in 1979–2001) and simulated data (ECHAM5/MPIOM, 20C simulation, in 1900–2001). Both datasets agree on the memory pattern in CAPE and CIN with highest values of the Hurst exponent along the equatorial Pacific which decrease towards higher latitudes; however, longest memory up to decades is found in CAPE south-east of Greenland. The memory in CIN is weaker than in CAPE regarding strength and spatial extent. To determine the origin of memory in CAPE and CIN, ML temperature and specific humidity, enthalpy, and latent heat equivalent of precipitable water (LPW) are analyzed. In the tropics the spatial characteristics of the memory in CAPE coincide with memory in LPW, while in the extra-tropics ML temperature and humidity have the strongest impact.

Dynamics (Eurasian information flow mechanisms): Based on the ERA-40 reanalysis data, dryness and wetness over the Tibetan Plateau are categorized according to the monthly standardized precipitation index. The atmospheric features associated with severe and extreme dryness and wetness reveal two cross-Eurasia wave trains: the Scandinavia-East Asia wave train and the Mediterranean-East Asia wave train. Severe and extreme dryness is associated with an anomalous cyclone over south and southeast Asia, which directs the moisture supply from the Arabian Sea, the Bay of Bengal, and the South China Sea directly eastward towards the western Pacific, thus bypassing the Tibetan Plateau. This cyclone anomaly constitutes part of the Scandinavia-East Asia wave train, which is sustained by the divergence and convergence of the anomalous transient eddy heat transport associated with a more southwest-northeast oriented North Atlantic storm track and a northward shift of the polar front jet in the North Atlantic. In contrast, severe and extreme wetness over the Tibetan Plateau is associated with a more zonally elongated North Atlantic storm track; wave trains excited from there have a high probability to reach the Mediterranean region and to propagate eastward following the subtropical westerly jet. This Mediterranean-East Asia wave train generates anticyclonic anomalies around the Tibetan Plateau and East China, which bring more moisture supply from the Arabian Sea, the South China Sea, and the western Pacific towards the Tibetan Plateau and enhance the moisture convergence there. This paper demonstrates how atmospheric bridging processes affect regional climate variability under present day climatic conditions, which are also relevant for understanding past climates.

2. Trends

Climate trends in weather forecast model predictions: The lead time dependent climates of the ECMWF weather prediction model, initialized with ERA-40 reanalysis, are analyzed using 44 years of day-1 to day-10 forecasts of the northern hemispheric 500hPa geopotential height fields. The study addresses the question whether short-term tendencies have an impact on long-term trends. Comparing climate trends of ERA-40 with those of the forecasts, it seems that the forecast model rapidly loses the memory of initial conditions creating its own climate. All forecast trends show a high degree of consistency. Comparison results suggest that: (i) Only centers characterized by an upward trend are statistical significant when increasing the lead time. (ii) In mid-latitudes, an upward trend larger than the one observed in the reanalysis characterizes the forecasts, while in the tropics there is a good agreement. (iii) The downward trend in reanalysis at high latitudes characterizes also the day-1 forecast which, however, increasing lead time approaches zero.

Trends of drought and wetness: Linear and nonlinear trends of drought and wetness are analyzed in terms of the gridded Standardized Precipitation Index (SPI) determined from monthly precipitation in Europe (NCEP/NCAR). In characterizing the meteorological and hydrological aspects, the index is computed on a seasonal and on a bi-annual time scale. Two datasets are compared: one from 1949 to 1997 and the other one includes the update of the last decade (to February 2009). The following results are noted: (i) time series of drought and wetness area coverage (number of grid points above/below the severity threshold) show a remarkable linear trend until about the end of the last century, which is reversed in the last (update) decade. This recent trend reversal is an indication of a nonlinear trend, which is more pronounced on the hydrological time scale. (ii) A nonlinear trend analysis is performed based on the time series of the principal component (PC) associated to the first spatial SPI-eigenvector after embedding it in a time delay coordinate system using a sliding window of 70 months (singular spectrum analysis). Nonlinearity appears as a clear feature on the hydrological time scale. (iii) The first spatial EOF-patterns of the shorter and the longer (updated) SPI time series fields show similar structure. An inspection of the SPI time behavior at selected grid points illustrates the spatial variability of the detected trends.

Extreme temperatures: We have applied the relation for the mean of the expected values of the maximum excursion in a bounded random walk to estimate the random walk length from time series of eight independent global mean quantities (temperature maximum, summer lag, temperature minimum and winter lag over the land and in the ocean) derived from the NCEP twentieth century reanalysis (V2) (1871-2008) and the ECHAM5 IPCC AR4 twentieth century run for 1860-2100, and also the Millennium 3100 yr control run mil01, which was segmented into records of specified period. The results for NCEP, ECHAM5 and mil01 (mean of thirty 100 yr segments) are very similar and indicate a random walk length on land of 24 yr and over the ocean of 20 yr. Using three 1000 yr segments from mil01, the random walk lengths increased to 37 yr on land and 33 yr over the ocean. This result indicates that the shorter records may not totally capture the random variability of climate relevant on the time scale of civilizations, for which the random walk length is likely to be about 30 years. For this random walk length, the observed standard deviations of maximum temperature and minimum temperature yield respective expected maximum excursions on land of 1.4 and 0.5°C and over the ocean of 2.3 and 0.7°C, which are substantial fractions of the global warming. "The annual cycle is the largest climate signal, however its variability has often been overlooked as a climate diagnostic, even though global climate has received intensive study in recent times, e.g. IPCC (2007), with a primary aim of accurate prediction under global warming".

3. Predictability and prediction

Long-term memory and interannual predictability Climate forecast skills are evaluated for surface temperature time series at grid points of a millennium control simulation from a state-of-the-art global circulation model [ECHAM5–Max Planck Institute Ocean Model (MPI-OM)]. First, climate predictability is diagnosed in terms of potentially predictable variance fractions and the fluctuation power-law exponent (using detrended fluctuation analysis). Long-term memory (LTM) with a fluctuation exponent (or Hurst exponent) close to 0.9 occurs mainly in high-latitude oceans, which are also characterized by high potential predictability (Fig. 1). Next, explicit prediction experiments for various time steps are conducted on a grid point basis using an autocorrelation predictor. In regions with LTM, prediction skills are beyond that expected from red noise persistence - exceptions occur in some areas in the southern oceans and over the Northern Hemisphere continents. Extending the predictability analysis to the fully forced simulation shows a large improvement in prediction skills.

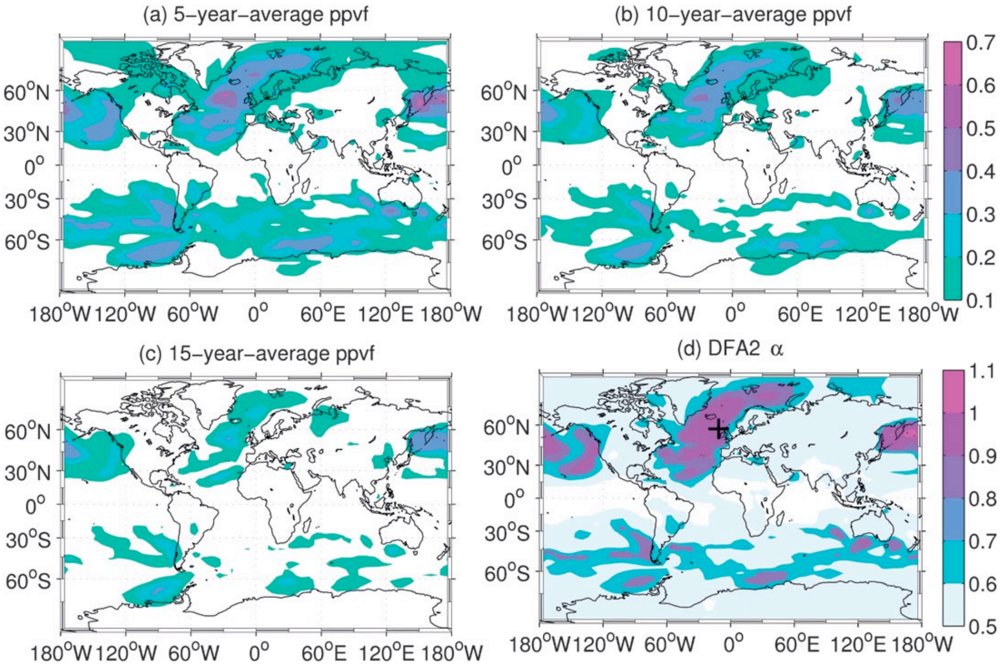

FIG. 1. (a)–(c) Potential predictability variance fraction (Ppvf) for the 5-, 10-, and 15-yr averages (values < 0.1 are not colored). Panels (a)–(c) share the top colorbar. (d) DFA-2 fluctuation exponent a for 2000-yr near-surface temperature estimated between 100.8–101.8 yr [;(6–60 yr)]; values < 0.5 are not colored.

Future climates from bias-bootstrapped weather analogs: The authors describe a statistical analog resampling scheme, similar to the ‘‘intentionally biased bootstrap,’’ for future climate projections whose only constraint is a prescribed linear temperature trend. It provides a large ensemble of day-to-day time series of single-station weather variables and other climatological observations at low computational cost. Time series are generated by mapping time sequences from the observed past into the future. The Yangtze River basin, comprising all climatological sub regions of central China, is used as a test bed. Based on daily station data (1961–2000), the bootstrap scheme is assessed in a cross-validation experiment that confirms its applicability. Results obtained for the projected future climates (2001–40) include climatological profiles along the Yangtze, annual cycles, and other weather-related phenomena (e.g., floods, droughts, monsoons, typhoons): (i) the annual mean temperature and, associated with that, precipitation increase; (ii) the annual cycle shows an extension of the Asian summer monsoon season with increasing rainfall, linked to a small summer temperature reduction in the Yangtze lower reaches (Fig. 2); (iii) coupling between monsoon circulation and monsoon rainfall strengthens; (iv) while drought occurrence is reduced, Yangtze floods do not change considerably; and (v) the number of typhoon days in the East China Sea shows a reduction of about 25%; the proportion of intense typhoons with landfall increases. GCM scenario simulations produce similar results.

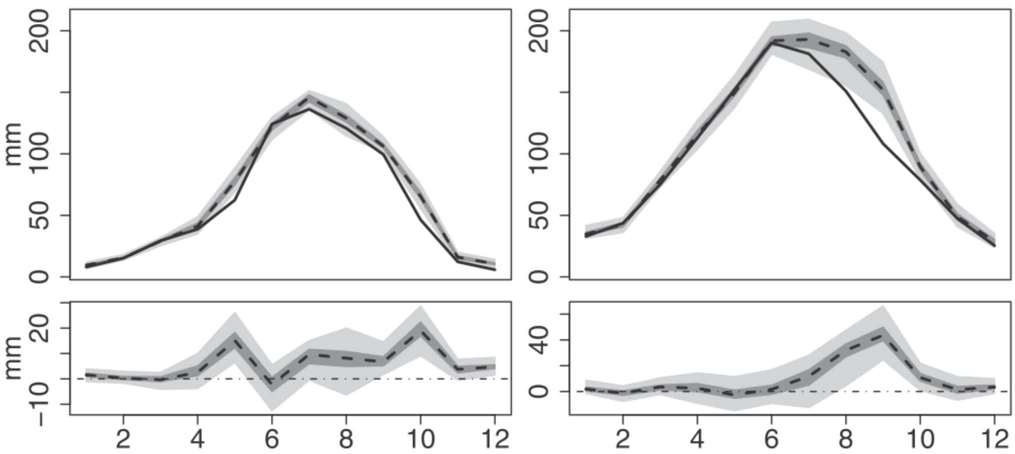

FIG. 2. Annual cycles (monthly means/sums) of precipitation for the (left) upper and (right) lower reach of the Yangtze: annual cycles from the observed station data 1961–2000 (full line); spread (light gray shading), interquartile range (dark gray shading), and median (dashed black line) of the STAR ensemble projections (2001–40). Differences of future projections minus training period observations (bottom).

4. Model diagnostics and development

Diagnosing the entropy budget of a climate model: A general circulation model (GCM) of intermediate complexity (Planet Simulator) is subjected to an analysis of the entropy budget and its sensitivity. The entropy production is computed directly based on temperature and temperature tendencies and estimated indirectly based on boundary fluxes. For indirect estimates, the model shows reasonably good agreement with observations. The direct computation indicates deficits of the indirect measures, as they, for example, overestimate the material entropy production (that is, the production by turbulent fluxes). Sensitivity analyses of entropy production are provided, which, depending on changing parameters, hint to a possible applicability of maximum entropy production (MEP) under the constrained dynamics of a complex GCM.

A spectral barotropic model of the wind-driven world ocean: A global spectral barotropic ocean model is introduced to describe the depth-averaged flow. The equations are based on vorticity and divergence (instead of horizontal momentum); continents exert a nearly infinite drag on the fluid. The coding follows that of spectral atmospheric general circulation models using triangular truncation and implicit time integration to provide a first step for seamless coupling to spectral atmospheric global circulation models and an efficient method for filtering of ocean wave dynamics. Five experiments demonstrate the model performance: (i) Bounded by an idealized basin geometry and driven by a zonally uniform wind stress, the ocean circulation shows close similarity with Munk's analytical solution. (ii) With a real land–sea mask the model is capable of reproducing the spinup, location and magnitudes of depth-averaged barotropic ocean currents. (iii) The ocean wave-dynamics of equatorial waves, excited by a height perturbation at the equator, shows wave dispersion and reflection at eastern and western coastal boundaries. (iv) The model reproduces propagation times of observed surface gravity waves in the Pacific with real bathymetry. (v) Advection of tracers can be simulated reasonably by the spectral method or a semi-Lagrangian transport scheme. This spectral barotropic model may serve as a first step towards an intermediate complexity spectral atmosphere–ocean model for studying atmosphere–ocean interactions in idealized setups and long-term climate variability beyond millennia.

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