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Nonlinear Dynamics of Global Atmospheric and Earth System Processes

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Prepared by:

Barry Saltzman (PI)
Department of Geology and Geophysics
Yale University, P. O. Box 208109
New Haven, CT 06520-8109
(203) 432-3147

NONLINEAR DYNAMICS OF GLOBAL ATMOSPHERIC AND EARTH SYSTEM PROCESSES

During the grant period we continued our ongoing studies aimed at enhancing our understanding of the operation of the atmosphere as a complex nonlinear system interacting with the hydrosphere, biosphere, and cryosphere in response to external radiative forcing. Five papers were completed with support from the grant (NAG 5-2316), representing contributions in three main areas of study: I) theoretical studies of the interactive atmospheric response to changed biospheric boundary conditions measurable from satellites, II) statistical-observational studies of global-scale temperature variability on interannual to century time scales, and III) dynamics of long-term earth system changes associated with ice sheet surges. These works involve the efforts of T. Zhang, M. E. Mann, M. Verbitsky, and the principal investigator. A listing of the papers is followed by the title pages and abstracts of the listed papers.

Published Papers

1. Zhang, T., 1994: Sensitivity properties of a biosphere model based on BATS and a statistical-dynamical climate model. J. Climate, 6, 890-913.

2. Mann, M. E. and J. Park, 1994: Globally correlated variability in surface temperatures. Proceedings of the 6th Conference on Climate Variations, Am. Meteor. Soc., Nashville, TN (Jan. 23-28), 297-301.

3. Mann, M. E. and J. Park, 1994: Global-scale modes of surface temperature variability on interannual to century timescales. J. Geophys. Res., 99, 25, 819-25,833.

4. Verbitsky, M. and B. Saltzman, 1994: Heinrich-type glacial surges in a low-order dynamical climate model. Climate Dynamics, 10, 39-47.

5. Mann, M. E., U. Lall, and B. Saltzman, 1995: Decadal-to centennial scale climate variability: Insights into the rise and fall of the Great Salt Lake. Geophys. Res. Lett., in press.

Title pages (including abstracts) of papers produced with the support of

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Sensitivity Properties of a Biosphere Model Based on BATS and a Statistical-Dynamical Climate Model

TAIPING ZHANG

Department of Geology and Geophysics, Yale University, New Haven, Connecticut

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ABSTRACT

A biosphere model based on the Biosphere-Atmosphere Transfer Scheme (BATS) and the Saltzman-Vernekar (SV) statistical-dynamical climate model is developed. Some equations of BATS are adopted either intact or with modifications, some are conceptually modified, and still others are replaced with equations of the SV model.

The model is designed so that it can be run independently as long as the parameters related to the physiology and physiognomy of the vegetation, the atmospheric conditions, solar radiation, and soil conditions are given. With this stand-alone biosphere model, a series of sensitivity investigations, particularly the model sensitivity to fractional area of vegetation cover, soil surface water availability, and solar radiation for different types of vegetation, were conducted as a first step. These numerical experiments indicate that the presence of a vegetation cover greatly enhances the exchanges of momentum, water vapor, and energy between the atmosphere and the surface of the earth. An interesting result is that a dense and thick vegetation cover tends to serve as an environment conditioner or, more specifically, a thermostat and a humidistat, since the soil surface temperature, foliage temperature, and temperature and vapor pressure of air within the foliage are practically insensitive to variation of soil surface water availability and even solar radiation within a wide range. An attempt is also made to simulate the gradual deterioration of environment accompanying gradual degradation of a tropical forest to grasslands. Comparison with field data shows that this model can realistically simulate the land surface processes involving biospheric variations.

1. Introduction

For a realistic simulation of the climate, the atmosphere, hydrosphere, cryosphere, lithosphere, biosphere, and their interactions with one another should be described simultaneously on the basis of physics. Great achievements have been made in the development and application of general circulation models (GCMs), but many inadequacies remain because of an incomplete understanding of the physics involved and inappropriate parameterizations of some subgrid processes. The land surface processes, or the interactions between the atmosphere and biosphere, are just such processes to which the climate modeling community had not paid much attention until several years ago. There have now been some studies and observations that indicate the existence and the spatial and temporal variation of vegetation on the continent have consequential effects on the maintenance and change of the global climate (Shukla and Mintz 1982; Mintz 1984; Henderson-Sellers 1990; Shukla et al. 1990; Nobre et al. 1991; Gash 1991).

Corresponding author address: Taiping Zhang, Department of Geology and Geophysics, Kline Geology Laboratory, Yale University, P.O. Box 6666, New Haven, CT 06511-8130.

The vegetation on the land surface, by altering the surface albedo, the drag coefficient, and the partitioning of available energy into sensible and latent heat fluxes, greatly complicates the surface processes, particularly the exchange of energy, mass, and momentum between the surface and the atmosphere. The maintenance of soil moisture is also closely related to the existence of vegetation cover. Attempts have been made to describe and parameterize the surface processes, but even the most sophisticated models give only a first approximate estimate. In addition, the requirement for satisfactory modeling of the surface processes at much higher resolutions than is feasible for GCMs gives rise to added difficulties in incorporating the biosphere model into the GCMs.

The state-of-the-art representatives of biosphere models for GCMs are the Simple Biosphere Model (SiB) of Sellers and Mintz (1986), the Biosphere-Atmosphere Transfer Scheme (BATS) of Dickinson et al. (1986), and the Bare Essentials Model of Pitman (1988), which have been incorporated into GCMs of the Goddard Laboratory for Atmospheric Sciences, the National Center for Atmosphere Research, and the Canadian Climate Centre, respectively. These submodels, though elaborate compared with previous ones, are conceptually much simpler than reality and are still so-called "big-leaf" models, a concept first in-

Heinrich-type glacial surges in a low-order dynamical climate model

Mikhail Verbitsky, Barry Saltzman

Department of Geology and Geophysics, Yale University, P.O. Box 208109 New Haven, CT 06520-8109, USA

Abstract. Recent studies suggest the occurrence of sporadic episodes during which the ice streams that discharge ice sheets become enormously active, producing large numbers of icebergs (reflected in North Atlantic sea cores as "Heinrich events") and possibly causing the partial collapse of the ice sheets. To simulate the mechanism of internal thermo-hydrodynamical instability implied by such behavior in the context of a more general paleoclimate dynamics model (PDM), we introduce a new sliding-catastrophe function that can account for ice-sheet surges. In particular, using simple scaling estimates derived from the equations of motion and thermo-conductivity for ice flow, we express this function in terms of the thickness, density, viscosity, heat-capacity, and heat-conductivity of ice. Analysis of the properties of this function suggests that these Heinrich-type instability events might be of three possible kinds: the first type of event occurs in periods of glacial maximum when temperature conditions on the ice surface are extremely cold, but internal friction within bottom boundary layer is also at its maximum and is strong enough to melt ice and cause its surge. The second type of event may happen during an interglacial, when the ice thickness is small but relatively warm climatic conditions on the upper surface of ice can be easily advected with the flow of ice to the bottom where even a small additional heating due to friction may cause melting. The third and, perhaps, most interesting type of event is one that may occur during ice sheet growth; in this period particles of ice reaching the bottom still "remember" the warm temperature conditions of the previous interglacial and additional heating due to increasing friction associated with the growing ice sheet may again cause melting. To the extent that the upper glacier surface temperature depends on atmospheric carbon dioxide concentration, this third case introduces the interesting possibility that earlier CO_2 concentrations may be as important for the present-day climate as its current value. We present results of numerical experiments demonstrating how these

three kinds of instability can originate and interact with other components of the global climate system to produce variations of the Heinrich-event type. In particular, according to our model the climate system seems more vulnerable to surges during the penultimate interglacial period than in the present one, which may contribute to an explanation of the recent results of the Greenland Ice Core Project.

Introduction

Recent geological studies (e.g., Andrews and Tedesco 1992) relate pulses of detrital carbonate-rich sediments in cores from the Labrador Sea to episodes in the late Pleistocene history of the Laurentide ice sheet when ice streams from the Hudson Strait become active enough to be able to deliver sediments onto the deep-sea plain. These incidents correlate highly with "Heinrich events" in North Atlantic sedimentary cores (Heinrich 1988; Broecker et al. 1992; Grousset et al. 1993). Another, theoretical, study (MacAyeal 1992) suggests that the West Antarctic ice sheet experienced sporadic collapses throughout its last-million-year's evolution. Although the first group of events has a periodicity on the order of 10 ky and the second group (according to the numerical experiments) took place only a few times during the last million years, we shall treat them both as Heinrich-type events because it is not unlikely that both of these types of episodic behavior have the same physical explanation, i.e., internal thermo-hydrodynamical instability inherent to the large ice sheets due to basal processes (e.g., Paterson 1981; Hughes 1992).

The aim of our study here is (1) to describe this kind of instability on the basis of simple scaling estimates derived from the motion and thermo-conductivity equations of large ice masses, (2) to enlarge the physical content of our previous paleoclimate dynamics model (PDM) described in Saltzman and Verbitsky, i.e., S-Verb 1993, by including the possibility for this

Correspondence to: M Verbitsky

Global-scale modes of surface temperature variability on interannual to century timescales

Michael E. Mann and Jeffrey Park

Department of Geology and Geophysics, Yale University, New Haven, Connecticut

Abstract. Using 100 years of global temperature anomaly data, we have performed a singular value decomposition of temperature variations in narrow frequency bands to isolate coherent spatio-temporal "modes" of global climate variability. Statistical significance is determined from confidence limits obtained by Monte Carlo simulations. Secular variance is dominated by a globally coherent trend, with nearly all grid points warming in phase at varying amplitude. A smaller, but significant, share of the secular variance corresponds to a pattern dominated by warming and subsequent cooling in the high latitude North Atlantic with a roughly centennial timescale. Spatial patterns associated with significant peaks in variance within a broad period range from 2.8 to 5.7 years exhibit characteristic El Niño-Southern Oscillation (ENSO) patterns. A recent transition to a regime of higher ENSO frequency is suggested by our analysis. An interdecadal mode in the 15-to-18 years period range appears to represent long-term ENSO variability. This mode has a sizeable projection onto global-average temperature, and accounts for much of the anomalous global warmth of the 1980s. A quasi-biennial mode centered near 2.2-years period and a mode centered at 7-to-8 years period both exhibit predominantly a North Atlantic Oscillation (NAO) temperature pattern. A potentially significant "decadal" mode centered on 11-to-12 years period also exhibits an NAO temperature pattern and may be modulated by the century-scale North Atlantic variability.

1. Introduction

In the face of possible anthropogenic effects on global climate, there is a need to characterize better the nature of historical climate variability. Aside from possible episodic volcanic forcing [e.g., *Bradley and Jones*, 1992], organized interannual climate variability seems to be associated largely with the El Niño-Southern Oscillation (ENSO) [e.g., *Philander*, 1990], the quasi-biennial oscillation (QBO) [e.g., *Trenberth and Shin*, 1984], and regional climate processes, such as the North Atlantic Oscillation (NAO) [e.g., *Bjerknes*, 1964; *van Loon and Rogers*, 1978; *Rogers*, 1984; *Lamb and Peppler*, 1987] which may have hemisphere- or even global-scale influence. Decadal and interdecadal variability is less well understood and has variously been attributed to internal variability in the thermohaline circulation of the oceans [*Levitus*, 1989; *Ghil and Vautard*, 1991; *Stocker and Mysak*, 1992; *Read and Gould*, 1992], coupled cryosphere-ocean-atmosphere cycles [*Mysak and Power*, 1992], and external astronomical forcing due

to the 18.6-year soli-lunar tide [*Currie and O'Brien*, 1992; *Mitra et al.*, 1991], the ~11-year solar cycle [*Labitzke and van Loon*, 1988; *Mitra et al.*, 1991; *Currie and O'Brien*, 1992] and its 22-year subharmonic or "Hale" cycle [*Vines*, 1986]. On century and longer timescales, thermohaline and cryosphere variability [*Stocker and Mysak*, 1992], solar forcing [*Friis-Christensen and Lassen*, 1991], and anthropogenic factors [e.g., *International Panel on Climate Control (IPCC)*, 1990] have been argued to be important.

While there is scant evidence for truly periodic historical interannual climate signals (that is, phase-coherent sinusoidal variations) there is nonetheless strong evidence that certain climatic processes are quasi-periodic. Such processes exhibit well-defined timescales of oscillation but are frequency or amplitude modulated on a longer timescale, often in an unpredictable manner. Thus spectral energy is spread out in a finite band about some dominant frequency. For example, ENSO variability appears to concentrate into distinct low-frequency (4-6 year) and high-frequency (2-3 year) bands [e.g., *Barnett*, 1991; *Keppenne and Ghil*, 1992; *Dickey et al.*, 1992; *Ropelewski et al.*, 1992]. Quasi-periodic modes of climate variability, then, should be identifiable as statistically significant, relatively narrowband peaks in the spectra of global climate records. Any global modes of climate variability should also be associated with spa-

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GLOBALLY CORRELATED VARIABILITY IN SURFACE TEMPERATURES

Michael E. Mann and Jeffrey Park

Dept. of Geology and Geophysics

Yale University

New Haven, Connecticut

1. INTRODUCTION

Several workers (eg., Folland et al 1984; Ghil and Vautard, 1991) have examined records of globally- and hemispherically-averaged land air and/or sea surface temperature anomalies for signals on interannual to century time scales. Mann and Park (1993) (herafter MP93) demonstrated that interdecadal temperature variability exhibits spatial variability that leads to significant cancelation in a global average. An analysis based only on modes which have large projections onto global-average temperature thus gives an incomplete, and perhaps misleading, picture of global-scale variability. We seek to isolate the *spatial* modes of global temperature variability on interannual to century-long time scales. This approach allows us to examine climate processes associated with changes in atmospheric circulation that lead primarily to a redistribution of heat over the surface of the earth, as well as those related to changes in the overall surface heat budget.

Quasi-periodic variability, such as the El-Nino /Southern Oscillation (ENSO), can be distinguished by correlated patterns of variability, or teleconnections, between widely spaced portions of the Earth's surface. Our data analysis seeks such patterns that are statistically distinguished from a locally white-noise background.

2. METHOD

We use gridded land air and sea surface temperature anomalies distributed on a 5° longitude by 5° latitude grid (see Jones and Briffa, 1992) spanning $N = 1200$ months from 1891 through 1990, keeping only a subset ($M = 449$ grid points) with nearly continuous monthly sampling. Potential biases in the data set are discussed elsewhere (eg., Jones 1986). Because the data samples the Earth's surface unevenly, poorly sampled regions may be weakly represented in the analysis, while well-sampled regions may exert influence out of proportion with its true place in the global climate system. Few historical climate datasets of significant length, however, are free from this shortcoming.

We demean and normalize the mth grid point time series $x'^{(m)}_n$ ($n = 1, \ldots, N$ months) by its monthly standard deviation $\sigma^{(m)}$ to assure that regions with

Corresponding author address: Michael E. Mann, Yale University, Dept. of Geol.& Geophys., New Haven, CT 06511.

high variance (e.g., continent centers) do not inordinately influence our analysis. To study quasi-periodic phenomena, we transform from the time to the spectral domain using multitaper spectral analysis (Thompson, 1982). Given the set of normalized time series, $x_n^{(m)} = x'^{(m)}_n / \sigma^{(m)}$ we calculate the tapered Fourier transforms $Y_k^{(m)}(f) = \sum_{n=1}^{N} w_n^{(k)} x_n^{(m)} e^{i2\pi f n \Delta t}$ where $\Delta t = 1$ month is the sampling interval and $\{w_n^{(k)}\}_{n=1}^{N}$ is the kth member in an orthogonal sequence of Slepian tapers. A set of k tapers that have power concentrated over a half-bandwidth of $p f_R$ are referred to as $p\pi$-prolate Slepian tapers, where $f_R = (N \Delta t)^{-1}$ is the Rayleigh frequency. The choice of K represents a compromise between the variance and resolution of the spectral representation, as the tapers average over a half-bandwidth of $p f_R$ and only the first $2p - 1$ tapers are usefully resistant to spectral leakage.

Assuming a locally white spectral background, the multitaper technique produces K tapered Fourier transforms at a given frequency f for each of the M grid points, from which we construct the matrix

$$\mathbf{A}(f) = \begin{bmatrix} Y_1^{(1)} & Y_2^{(1)} & \ldots & Y_K^{(1)} \\ Y_1^{(2)} & Y_2^{(2)} & \ldots & Y_K^{(2)} \\ \vdots & & & \\ Y_1^{(M)} & Y_2^{(M)} & \ldots & Y_K^{(M)} \end{bmatrix} \quad (1)$$

We decompose $\mathbf{A}$ with a complex-valued SVD into K orthonormal left-eigenvectors $\mathbf{u}_k$, representing empirical orthogonal functions (EOFs) in the spatial domain, and K orthonormal right-eigenvectors $\mathbf{v}_k$, representing EOFs in the spectral domain. The $\mathbf{v}_k$ are complex-valued K-vectors, and can be inverted to obtain the slowly-varying envelope of the kth mode. The $\mathbf{u}_k$ are complex-valued M-vectors which determine the amplitude and relative phase of temperature variations among grid points. The singular value λ_k scales the amplitude of the kth mode. We order the singular values $\lambda_1(f) \geq \lambda_2(f) \geq \ldots \geq \lambda_K(f) \geq 0$.

Park (1992) shows how the slowly-varying envelope $A(t)$ of a quasi-periodic signal $x(t) = \Re\{A(t)e^{-i2\pi f t}\}$ can be estimated from a set of eigenspectra $Y_k(f)$, $k = 1, \ldots K$. In the multivariate case, the kth time-domain signal is reconstructed from $\mathbf{v}_k(f)$, with some additional constraints. We minimize the first-derivative of the discrete representation of the envelope $A(t)$

Decadal-to-Centennial-Scale Climate Variability: Insights into The Rise and Fall of the Great Salt Lake

Michael E. Mann

Department of Geology and Geophysics, Yale University, New Haven, Connecticut

Upmanu Lall

Utah Water Research Laboratory, Utah State University, Logan, Utah

Barry Saltzman

Department of Geology and Geophysics, Yale University, New Haven, Connecticut

Abstract. We demonstrate connections between decadal and secular time scale global climatic variations, and historical variations in the volume of the Great Salt Lake. The decadal variations correspond to a low-frequency north-south shifting of storm tracks which influence winter precipitation and explain nearly 18% of the interannual and longer-term variance in the record of monthly volume change. The secular trend accounts for a more modest ∼1.5% of the variance.

Introduction

The prospect of anthropogenic climate change has renewed interest in the study of low frequency variability in hydroclimatic processes [*Aguado et al.*, 1992; *Rasmusson and Arkin*, 1993; *Lins and Michaels*, 1994]. Such concerns are especially pertinent with respect to water availability in arid regions. Permanent closed basin lakes are unique in that they reflect a precarious long term balance of precipitation and evaporation in an arid region, and amplify persistent imbalances. Several studies have established linkages between regional hydrological patterns and large-scale atmospheric circulation [*Rasmusson and Arkin*, 1993; *Lins*, 1985; *Cayan and Peterson*, 1989; *Ely et al.*, 1993; 1994]. Here, we demonstrate the connection between large-scale climatic signals and the fluctuations in the volume of the closed-basin Great Salt Lake (GSL). The GSL (Figure 1a) provides a particularly useful hydrological case study because of its dramatic historical fluctuations (Figure 1b), emphasizing lower frequencies through a spatial and temporal integration of climatic processes. The monthly volume change (ΔV–Figure 1c)

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