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Low-frequency variability and heat transport in a low-order nonlinear coupled ocean–atmosphere model

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HIGHLIGHTS

- A low-order, fully coupled ocean–atmosphere model for mid-latitudes is developed.
- A coupled mode of low-frequency variability (LFV) with a 20-year period is found.
- The Hopf bifurcation giving rise to the long-periodic oscillatory mode is described.
- A chaotic attractor develops around this orbit and is confined in a slow subspace.
- The predictability of the coupled system drastically increases when LFV is present.

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ABSTRACT

We formulate and study a low-order nonlinear coupled ocean–atmosphere model with an emphasis on the impact of radiative and heat fluxes and of the frictional coupling between the two components. This model version extends a previous 24-variable version by adding a dynamical equation for the passive advection of temperature in the ocean, together with an energy balance model.

The bifurcation analysis and the numerical integration of the model reveal the presence of low-frequency variability (LFV) concentrated on and near a long-periodic, attracting orbit. This orbit combines atmospheric and oceanic modes, and it arises for large values of the meridional gradient of radiative input and of frictional coupling. Chaotic behavior develops around this orbit as it loses its stability; this behavior is still dominated by the LFV on decadal and multi-decadal time scales that is typical of oceanic processes. Atmospheric diagnostics also reveals the presence of predominant low- and high-pressure zones, as well as of a subtropical jet; these features recall realistic climatological properties of the oceanic atmosphere.

Finally, a predictability analysis is performed. Once the decadal-scale periodic orbits develop, the coupled system's short-term instabilities – as measured by its Lyapunov exponents – are drastically reduced, indicating the ocean's stabilizing role on the atmospheric dynamics. On decadal time scales, the recurrence of the solution in a certain region of the invariant subspace associated with slow modes displays some extended predictability, as reflected by the oscillatory behavior of the error for the atmospheric variables at long lead times.

1. Introduction and motivation

The variability at annual, interannual and decadal time scales of the coupled ocean–atmosphere system is currently a central concern in improving extended-range weather and climate forecasts. The oceans' long-term variability and their interaction with the atmosphere has been extensively explored in the Tropical Pacific, due to the climatological importance of the El Niño–Southern Oscillation (ENSO) phenomenon (e.g. [1–3]). The ocean and the atmosphere also interact in the mid-latitudes through both wind stress and buoyancy fluxes [4,5], although the impact of this interaction on the long-term variability of the atmosphere is still controversial [6,7].

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On physical grounds, interactions between the two components of the coupled climate system in mid-latitudes are obviously essential to its functioning on multiple time scales. The main direction of the coupling, however, is a matter of debate: Is the slower ocean responding to the wind stress forcing in an essentially passive way [8] – i.e., is its feedback to the atmosphere too weak to qualitatively modify the dynamics of a stand-alone atmosphere – while, at the same time, playing the role of a heat bath that provides boundary forcing for the atmosphere [9]? Or is the ocean playing a more active role in atmospheric dynamics [10–12]? Marshall et al. [13], for instance, discuss these questions in detail.

From a dynamical point of view, one possible answer to these questions translates into a search for the presence of coupled modes between the ocean and the atmosphere, such as found for instance in observational data [14]. In the context of coupled global climate models, the answer, however, differs from one investigation to another or from a modeling setup to another; this answer depends, to a large extent, on whether the forcing is generated by deterministic or stochastic, linear or nonlinear processes [15–17].

Part of our motivation is that a low-frequency nonlinear oscillation has been found in intermediate-order, coupled nonlinear ocean–atmosphere models. This coupled mode operates by triggering the displacement of the atmospheric jet position [18,19]. The physical origin of this coupled mode is, however, not fully understood as yet, nor is its existence generally agreed upon.

To understand the qualitative behavior of the coupled ocean–atmosphere dynamics, several low-order models have been developed. Such models allow one to isolate the essential processes believed to be at play in a specific problem at hand, by using as building blocks only the minimal ingredients describing the dynamics.

This approach – originating in the works of Saltzman [20] and Lorenz [21] and, from then on, in the development and applications of nonlinear dynamics to the environmental sciences – attempts to reduce complicated dynamics to its essential features. It has been quite successful, so far, in increasing our understanding of the dynamics of the ocean alone, in particular the multimodality of the thermohaline circulation [4,22], as well as the development and variability of the mid-latitude oceanic gyres [12,23–25].

To the best of our knowledge, it is Lorenz [26] who applied this approach first to the coupled system and developed a pseudo-spectral, low-order model based on the primitive equations for the atmosphere, coupled to an ocean heat bath. Vannitsem [27] used this model to evaluate the impact of climate changes on model error biases. Nese and Dutton [28] extended the model by adding an ocean dynamics similar to the one proposed by Veronis [25] and based on four dominant ocean modes. These authors found that accounting for the heat transport helps increase the coupled model's predictability.

Other minimal-order coupled models [29,30] allowed for the possibility of the ocean's developing a thermohaline circulation. In the latter work, Van Veen [30] performed a bifurcation analysis and showed the active role of the ocean in setting up the dynamics when close to the bifurcation points of the atmospheric model. While Deremble et al. [31] did not consider full coupling, they did point out some of the similarities between the bifurcation trees of the atmospheric and oceanic dynamics in a mid-latitude setting.

More recently, Vannitsem and colleagues [32,33] have developed two coupled model versions based on a quasi-geostrophic atmospheric model proposed by Charney and Straus [34] and further studied in [35,36], and on the ocean model of Pierini [23]. The coupling in both of these versions was based solely on a mechanical transfer of momentum via wind friction. In particular, these authors showed that their coupled model displays decadal variability within the ocean, similar to that found in idealized, intermediate [12,37] and low-order models [38,39,24]. Furthermore, the investigation of this coupled model's stability properties showed that the momentum transfer coupling between the two components contributes to an increase of the flow's instability, in terms of both the magnitude of the positive Lyapunov exponents and their number.

This model [32,33] is, however, missing an important ingredient of the coupled dynamics, namely the energy balance between the ocean and the atmosphere. The present work proposes a new model version, in which the thermal forcing affecting only the atmosphere is replaced by an energy balance scheme [40,41,31]. It will allow us to disentangle the respective roles of the heat and radiative fluxes through the ocean surface vs. the transport of heat within the ocean in affecting the coupled system and its predictability.

The model equations are described in Section 2, for the dynamics [32,33] and thermodynamics, respectively; they are reduced to a low-order system in Section 2.5. In Section 3, a bifurcation analysis of the basic solutions is first performed (Section 3.1); it reveals the presence of low-frequency variability (LFV) in the form of a set of long-periodic, attracting orbits that couple the dynamical modes of the ocean and the atmosphere. The model dynamics is further explored through the analysis of the climatological properties of the solutions in Section 3.2, while the dependence of the decadal-scale orbits on model parameters and their predictability are studied in Sections 3.3 and 3.4, respectively. A summary of the results and future prospects are then provided in Section 4.

2. The model equations

2.1. Equations of motion for the atmosphere

The atmospheric model is based on the vorticity equations of a two-layer, quasi-geostrophic flow defined on a β-plane [42,5]. The equations in pressure coordinates are

$$\begin{aligned}
&\frac{\partial}{\partial t}\left(\nabla^2\psi_{\rm a}^1\right)+J(\psi_{\rm a}^1,\nabla^2\psi_{\rm a}^1)+\beta\frac{\partial\psi_{\rm a}^1}{\partial x}\\
&\quad=-k_d'\nabla^2(\psi_{\rm a}^1-\psi_{\rm a}^3)+\frac{f_0}{\Delta p}\omega,\\
&\frac{\partial}{\partial t}\left(\nabla^2\psi_{\rm a}^3\right)+J(\psi_{\rm a}^3,\nabla^2\psi_{\rm a}^3)+\beta\frac{\partial\psi_{\rm a}^3}{\partial x}\\
&\quad=+k_d'\nabla^2(\psi_{\rm a}^1-\psi_{\rm a}^3)-\frac{f_0}{\Delta p}\omega-k_d\nabla^2(\psi_{\rm a}^3-\psi_{\rm o});
\end{aligned}\tag{1}$$

here $\psi_{\rm a}^1$ and $\psi_{\rm a}^3$ are the streamfunction fields at 250 and 750 hPa, respectively, and $\omega = dp/dt$ is the vertical velocity, f_0 is the Coriolis parameter at latitude ϕ_0, with $\beta = df/dy$ its meridional gradient there.

The coefficients k_d and k_d' multiply the surface friction term and the internal friction between the layers, respectively, while $\Delta p =$ 500 hPa is the pressure difference between the two atmospheric layers. An additional term has been introduced in this system in order to account for the presence of a surface boundary velocity of the oceanic flow defined by $\psi_{\rm o}$ (see the next subsection). This would correspond to the Ekman pumping on a moving surface and is the mechanical contribution of the interaction between the ocean and the atmosphere.

Eq. (1) has been nondimensionalized, as discussed in Appendix A.

2.2. Equation of motion for the ocean

The ocean model is based on the reduced-gravity, quasi-geostrophic shallow-water model on a β-plane (e.g., [43,23,5]):

$$\frac{\partial}{\partial t}\left(\nabla^2\psi_{\rm o}-\frac{\psi_{\rm o}}{L_R^2}\right)+J(\psi_{\rm o},\nabla^2\psi_{\rm o})+\beta\frac{\partial\psi_{\rm o}}{\partial x}=-r\nabla^2\psi_{\rm o}+\frac{{\rm curl}_z\tau}{\rho h}.\tag{2}$$