Chaotic behaviors of oceanic double-gyre under seasonal forcing

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1. Introduction

  The wind stress curl forces anti-cyclonic subtropical and cyclonic subpolar gyres (i.e., double gyre). Intensive western boundary currents in their gyres in each basin appear at the western flank of oceans, and enter into open-oceans as eastward jets. They carry substantial amounts of heat and momentum and strongly affect on global climate. A typical example of such currents is the Kuroshio, with 100 km width and 2 ms^{-1} velocity at maximum.

  We have interested in whether the oceanic circulation itself can excite inter-annual and/or inter-decadal oscillations and also, how it is related to variations of a western boundary current. Simple models have been particularly useful in understanding various aspects of the dynamics of mid-latitude wind-driven oceanic circulation (Matsuura, 1995; Shimokawa & Matsuura, 1999; Matsuura and Fujita, 2006). Until now, they are limited to the response of oceanic circulation to a constant forcing, and the response of it to a time-dependent forcing remains to be unknown. Therefore, we focus on the response of an oceanic double-gyre to a seasonal forcing.

2. Model and Experiments

  Our model is a 1.5 layer, reduced-gravity, quasi-geostrophic numerical model with a non-slip boundary condition (McCalpin, 1995). The forcing is seasonal varying in time, and north-south varying in space in the followings; $F(t,y)=-A(1.0+\alpha \cos wt)\cos(2*3.14*y/L)$. ($A$: the amplitude of wind stress, α: the amplitude of seasonal variation, w: the period of seasonal variation, y: the location in north-south direction, L: the length of region in north-south direction.) This represents a simplified time-space distribution of wind stress in northern mid-latitudes.

  Control parameters in the experiments are b and Re number which is related to horizontal diffusion and A. We conducted the experiments in the followings; (c1) cases with a constant forcing ($\alpha=0$, Re=26-314). (c2) cases with a seasonal varying forcing, ($\alpha=0.0-1.0$, Re=39, 70, 112, 157, 314). We analyzed the results on flow patterns, time-series of total energy, trajectories of kinetic energy and available potential energy.

3. Results and Discussions

  We would like to state the results of (c2) mainly in this paper. In cases with $\alpha=0.5$ (the most realistic value), the trajectories change to chaotic (Re=39), limit-cycle (Re=70), and chaotic (Re=112) (Figure1).

  In cases with Re=39, the flow pattern shows an unstable inertial sub-gyre. When b increases from 0.0, the trajectories change to limit-cycle, multiple limit-cycle, multiple torus, multi-dimensional torus, and chaos (Figure2). It is found in this case that chaotic behavior appeared with a non-linear interaction between the internal variability of double-gyre itself and the variability of external forcing. This behavior is consistent with the results in a simplified energy model (Matsuura & Shimokawa, 2007).

  In cases with Re=70, the flow pattern shows a stable anti-symmetric gyre. This pattern is very stable, which is inconsistent with the results of a 2-layer shallow water model (Matsuura & Fujita, 2006). There are two possible reasons for the difference between two models in the followings; (1) a nonlinear interaction between barotropic mode and baroclinic mode in 2-layer shallow water model, (2) a asymmetry of double-gyre due to the effect of large displacement interface in 2-layer shallow water model.

  In cases with Re=112, the flow pattern shows an unstable extension along north-south boundary of gyres. The changes of b seem not to affect on the results, and all the trajectories show chaos. The results with higher Re show the transition from a stable extension like laminar flow (Re=157) to an unstable extension like turbulent flow (Re=314) (Figure 3). This behavior may correspond to the transition between a non-meander path and a meander path of the Kuroshio. It is considered that the global changes of wind stress, which determines the Re and the resultant flow flux, is important in the transition of the Kuroshio.
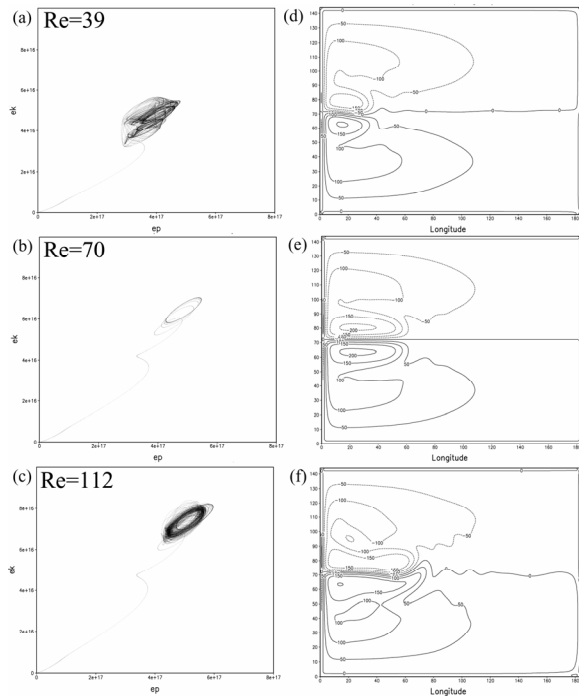
Figure 1. Trajectories of total energy and flow patterns of double-gyre (upper layer thickness at year 250) in the case with seasonal forcing (α=0.5). (a), (d) Re=39, (b), (e) Re=70, (c), (f) Re=112.
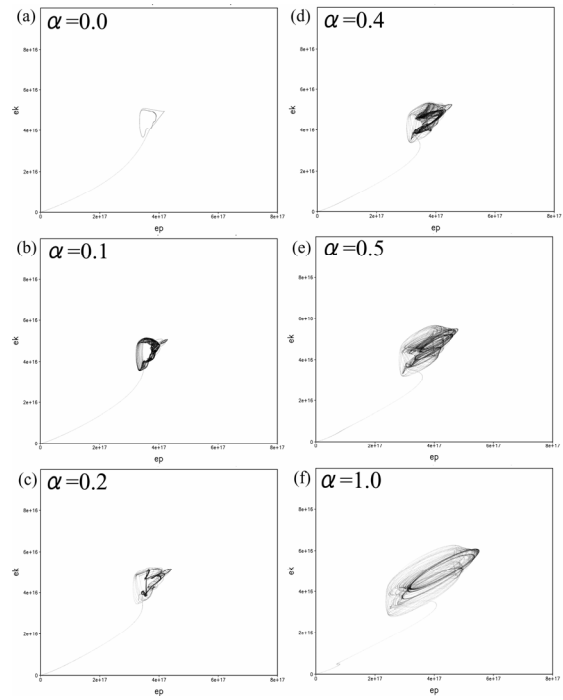
Figure 2. Trajectories of total energy in the case with seasonal forcing and for Re=39. (a) α=0.0, (b) α=0.1, (c) α=0.2, (d) α=0.3, (e) α=0.5, (f) α=1.0.
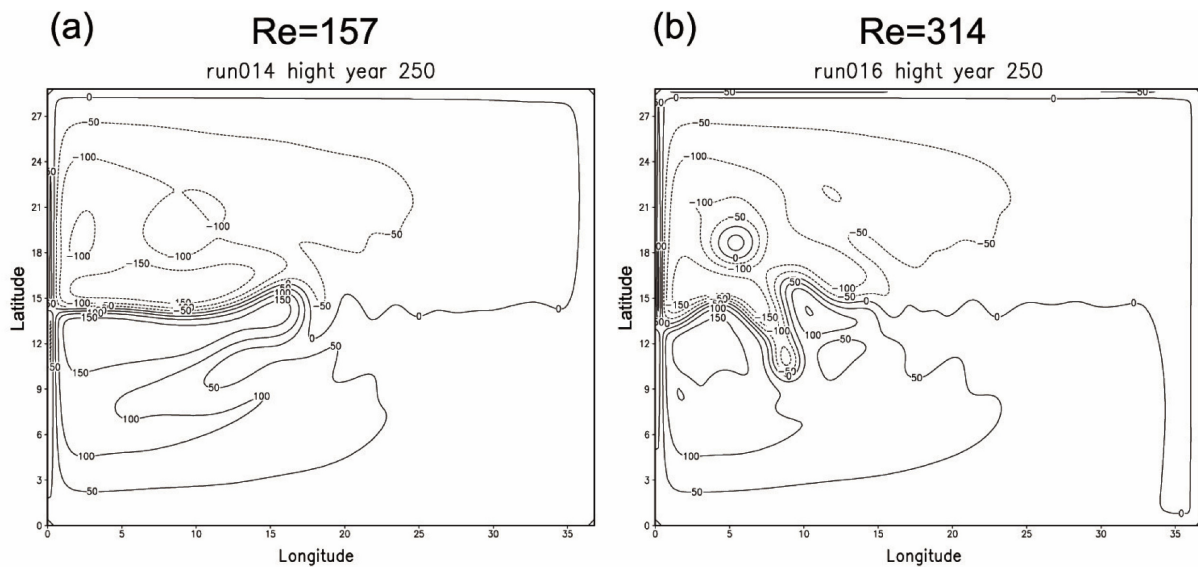
Figure 3. Flow patterns of double-gyre (upper layer thickness at year 250) in the case with constant forcing. (a) Re=157, (b) Re=134.

Refferences:
McCalpin, J. D. (1995): J. Phys. Oceanogr., 25, 806-824. Matsuura, T. (1995): J. Phys. Oceanogr., 25, 2298-2318. Matsuura, T. and M. Fujita (2006): J. Phys. Oceanogr., 36, 1265-1286. Matsuura, T & S. Shimokawa (2007): Proceedings of the Oceanogr. Soc. Japan 2007-Autumn. Shimokawa, S. and T. Matsuura (1999): J. Oceanogr., 55, 449-462.