Long-Term Variations and Abrupt Changes in a Strong Eastward Jet in a Double-Gyre Ocean Forced by Seasonally Varying Wind Stress

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Summary Abrupt changes and long-term variations of a strong eastward jet (SEJ) with two bumps in a double-gyre ocean are investigated using a 1.5 layer quasi-geostrophic model. The transition from the regular oscillatory state to collapses of SEJ with generation of rings appears intermittently. This phenomenon is triggered by the interaction between the weekly meandering SEJ and eddies generated periodically from the easternmost end of SEJ, and can be explained by a cusp catastrophe.

Introduction

Simmonet (2005)[1] investigated a double-gyre ocean using a QG model, except for the friction terms and the lateral boundary conditions, and showed that linear Rayleigh (interfacial or bottom) friction is necessary to obtain realistic recirculation gyres and an elongated jet stream. The number of bumps in the jet is used to distinguish between supercritical and subcritical regimes and is related to the time scale of the low-frequency variability in the supercritical regime. The low-frequency mode arises from the oscillatory gyre mode, which is generated from the merging between the P-mode (showing the occurrence of multiple-bifurcation) and the L-mode (showing the intensity of double gyre) [2]. When the idea of a stationary Rossby wave is applied to the Kuroshio extension, a modeled jet stream should be elongated with the increase of the wave number [1]. However, the real jet stream is a quasi-steady flow with two bumps, and when unstabilized, it becomes a three bump flow with frequent eddy generation, but the length is almost the same as the two-bump flow [3]. That is, the modeled situation does not always correspond well with the observation. Moreover, most studies on a double-gyre ocean using a middle-range complexity model (e.g., a QG model) have been conducted under constant wind forcing (time-independent forcing). In the real atmosphere and oceans, seasonal wind forcing with westerly and trade winds generates variations in subtropical and subpolar gyres consisting of western boundary currents and internal currents. Thus, the investigation under time-dependent wind-forcing conditions will be important in the real situation. In this study, we focus on the upper stream region of the Kuroshio extension and investigate an abrupt change from a viewpoint of nonlinear dynamics. Using a QG model with seasonally varying wind stress, we show that intermittent transition occurs between stable and unstable states, which corresponds well with the observation of the Kuroshio extension [4], and a decadal/interdecadal variability is generated depending on the amplitude of the time-dependent forcing.

Numerical models and experiments

We used a 1.5-layer, reduced-gravity quasi-geostrophic model [5]. The model is constituted as mid-latitude North Pacific with westerly wind. The control parameter of the experiments is only the amplitude of seasonal variation α： α= 0.0 (no seasonal variation), α=1.0 (the amplitude of seasonal variation of wind stress = the average of wind stress). α can be regarded as a coupling factor of two nonlinear oscillators; the ocean and the forcing. We conducted experiments with parameter range; α＝0.0-1.0. Reynolds number is fixed to 157 for a two-bump case.

Results

For α= 0 (time-independent forcing), the SEJ fluctuates periodically (7.4 months) due to the barotropic instability. Simultaneously, meso-scale eddies separate from the easternmost end of the SEJ (where the SEJ connects to open ocean), and the period is 4 times the period of the barotropic instability, i.e., 2.45 years. When at α= 0.4, a decadal oscillation appears in the SEJ and the potential vorticity distribution shows that there are two distinguished terms: continuous eddy shedding and no eddy shedding from the easternmost end of the SEJ (Fig1.a and Fig2.a). With increasing α, about α= 0.5, eddy detachments start to occur intermittently (Fig.1b and Fig2.b); the interaction of separated eddies and the SEJ (Fig.3) induces a collapse of the SEJ, similar buckling columns. Therefore, strong rings are formed: the cyclonic rings in the subtropical gyre and the anti-cyclonic rings in the subpolar gyre (Fig.4).

Discussions

In the two-bump case (Re=157), it remains unknown whether the low-frequency mode with multiple bumps (which is more realistic than the zero-bump flow [6]) has homoclinic bifurcations. Our study showed that the low-frequency mode with two-bumps also has homoclinic bifurcations for adequate amplitudes of the wind forcing (Fig.5). Therefore, the decadal/inter-decadal variability can be considered to be generated by an intrinsic oscillation of the ocean, in a realistic two-bump flow as well. About α= 0.5, the double gyre becomes fully turbulent. Our study showed that a nonlinear interaction between an intrinsic oscillation of the ocean and an external oscillation of wind forcing generates abrupt changes. The abrupt changes occur between a weak oscillatory two-bump state (torus) and an unstable state with frequent cyclonic/anti-cyclonic eddy shedding. These results correspond well with the observation of the Kuroshio extension [4], and can be explained, using a nonlinear path equation, as an overshooting phenomena (i.e., cusp-catastrophe) with an increase of meander amplitude due to a nonlinear interaction between a main current and eddies generated from the easternmost end of the strong current. In our QG experimental simulation, the decadal oscillation was induced by the climatic seasonal forcing and when the forcing amplitude increased, the intermittency occurred with stable and unstable modes such as the Kuroshio extension regions. In the present study, for which the results are different from the results in [4] and [7], the linear baroclinic Rossby waves generated from the global wind stress do not play an important role in alternately switching between the stable and unstable modes. The decadal oscillation and the intermittency were appeared in the eastward strong current due to the inhomogeneous nonlinear oscillation. Although Simonnet (2005)[1] also showed the nonlinear self-sustained oscillation with a decadal time scale, we extended the related phenomena to the intermittent bursting one.

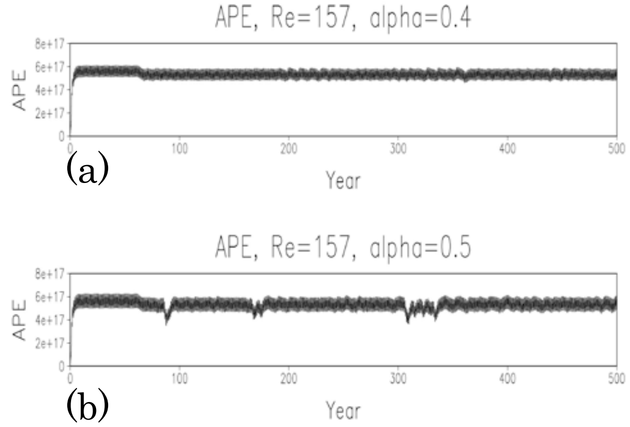

Figure1 Time series of total energy at Re=157 for (a) α=0.4, (b) α=0.5.

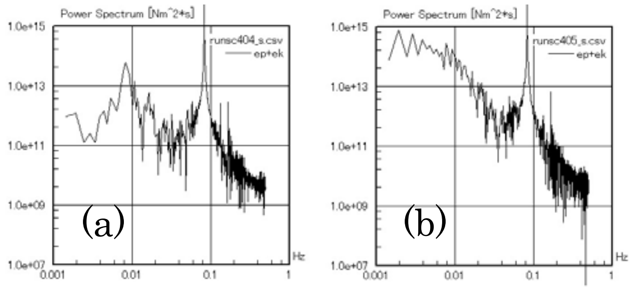

Figure2 Power spectra of total energy for (a) α=0.4, (b) α=0.5

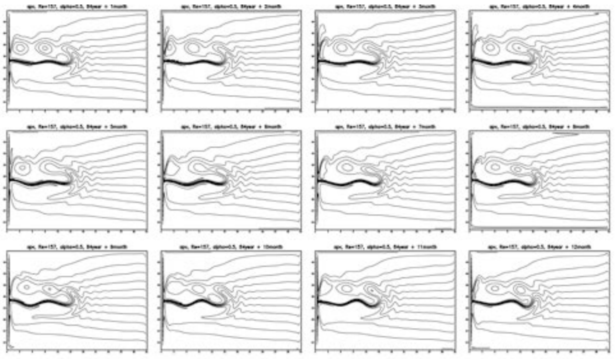

Figure3 Time series of potential vorticity patterns for 84th year.

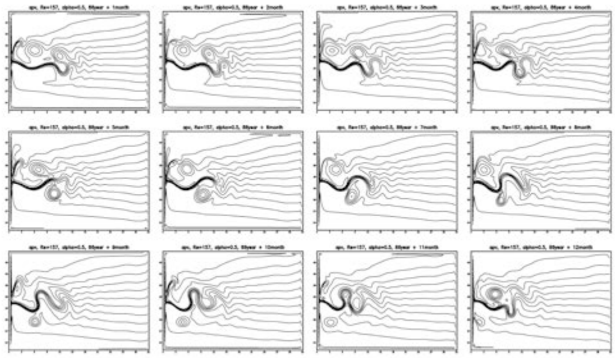

Figure 4 Time series of potential vorticity patterns for 86th year.

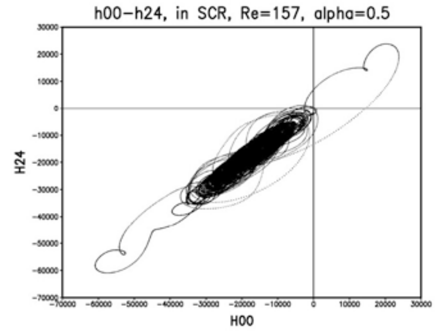

Figure6 Trajectories in two-dimensional phase space of the interface anomalies h_0 and those after 36 hours h_{36}

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