Long-term Variability and Non-linear Aspects of the Oceanic Double-gyre

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1. Introduction

The oceanic double-gyre (i.e., sub-tropical and sup-polar gyres) is one of the basic configurations of large-scale surface ocean circulation. Recently, the long-term variability (over a decade) has been studied in relation to climate variability [1)]. Firstly, to clarify the long-term variability of the oceanic double-gyre, we investigate Re dependency on the state of the oceanic double-gyre using a quasi-geostrophic model under constant forcing.

Thus far, however, most studies of oceanic double gyres using middle-range complexity (e.g., quasi-geostrophic model) have been conducted under constant forcing. In the real atmosphere and oceans, wind forcing changes seasonally. Many problems related to time dependent forcing, especially those with nonlinear aspects remain unresolved; for example, entrainment (an adjustment of rhythms of two or more self-sustained oscillating systems) [2)] and intermittency (a chaotic modulation in the transition from laminar flow to turbulent flow) [3)]. Therefore, it is also important to clarify the nonlinear interaction between a characteristic oscillation of the ocean itself and a seasonal oscillation of an external forcing.

2. Numerical model and experimental method

The numerical model used in this study is a 1.5 layer, reduced-gravity, quasi-geostrophic numerical model with a non-slip boundary condition [4)]. The model domain is a rectangle of 3600 km × 2800 km and the forcing wind has only an east-west component and is north-south varying in space, representing the mid-latitude North Pacific. Further details of the numerical model are shown in Shimokawa and Matsuura (2010) [5)].

Control parameters in the experiments involve Reynolds number (Re) and 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). We conducted the experiments over 250 years for Re = 26, 31, 39, 70, 95,112, 157, 209, and 314 under constant forcing (α＝0.0) and those for Re=39 and 157 under time-dependent forcing (α＝0.0-1.0).

3. Results

3.1 Constant forcing case

The changes can be classified into four groups as follows: a) Re = 26, 31, 39, b) Re = 70, 95, 112, c) Re = 157, 209 and d) Re = 314 by the average energy level and the length of the strong eastward jet (Fig. 1). In particular, the states for Re = 209 and 314 are turbulent, but it can be considered that they are different qualitatively.

For Re = 209, kinetic energy (KE, Fig. 2b) decreases with the decrease of available potential energy (APE, Fig. 2a) and the time lag is only a few months. On the other hand, for Re = 314, APE (Fig. 2c) shifts to KE (Fig. 2d) over a long-term (about a decade) and then KE oscillates intensely. These differences are considered to represent differences in the instability. The instabilities for Re=209 and Re=314 are considered to be related to oscillation of G-mode [6)] and shear instability [7)], respectively. In the unstable state for Re=314, eddy shedding occurs not only from the easternmost tip of the jet but also in the path of the jet (see Fig. 6a).

3.2 Time dependent forcing case

For Re=39, in α=0.0, only characteristic oscillation (with 2.45 years) of the ocean itself can be seen (Figs. 3a, 3g and 4a). In α=1.0, only seasonal oscillation (1 year) of the external forcing can be seen (Figs. 3f and 3l). In the intermediate α=0.18, the oscillation has both aspects (Figs. 3c and 3i). In fact, here, the entrainment occurs at 2 times the period of the forcing (2 years; Fig. 4c).

With increasing α, the intermittency appears (α>0.4; Figs. 3e and 3f). The intermittency has periods from few years to few decades (i.e., the long-term variability). Intermittent transitions occur between stable modon-like pattern (alongside path, Fig. 5a) and unstable anti-cyclonic/cyclonic eddy shedding patterns (large meander path, Figs. 5b and 5c). In the unstable state for Re=157, eddy shedding occurs not only from the easternmost tip of the jet but also in the path of the jet (Fig. 6b), which is similar to the result for Re=314 under constant forcing (Fig. 6a).

4. Conclusions and Discussions

We found that intermittency (i.e., the long-term variability) can be generated and eddy shedding occurs not only from the easternmost tip of the jet but also in the path of the jet for both constant and time dependent forcing cases. In addition, the intermittency can be generated at a smaller Re for time dependent forcing case, compared to constant forcing case.

The relation and interaction between the mechanisms of the intermittency for constant and time dependent forcing cases remain unknown. It, however, can be speculated that only one mode can't generate intermittency under constant forcing, but increasing Re and/or changing forcing to time-variant may occur two (or multiple) mode nonlinear coupling and then generate intermittency. This needs a further study.

It has often been considered that the long-term variability in the western boundary current is caused by local instability. An increasing number of observations, however, indicate that the variability is also considered to be part of the instability of the entire gyre (i.e., the oceanic double gyre) [8)]. The phenomena observed in this study, in particular entrainments and intermittency, are also considered to be related to the entire gyre. Therefore, these phenomena may be crucial to understanding the generation mechanism and characteristics of long-term variability in the strong current region of sub-tropical/sub-polar gyres such as the Kuroshio and its extension region.

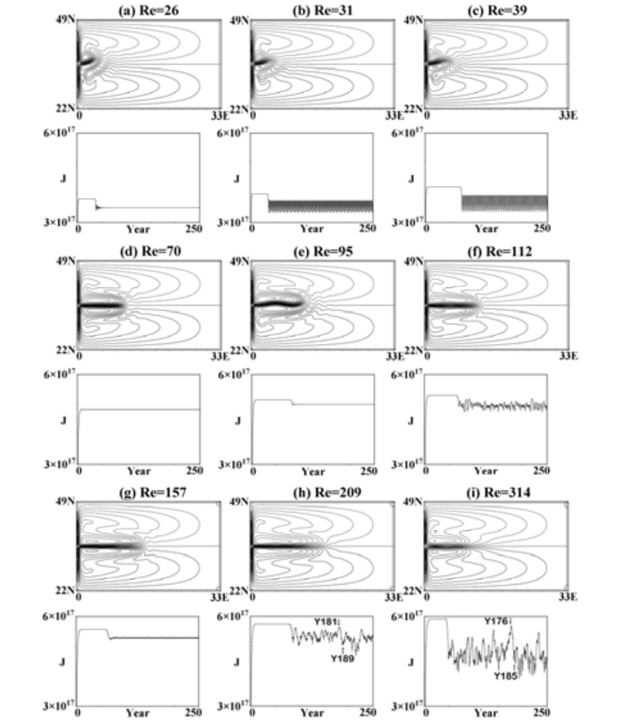

Figure 1 Average flow patterns (1st layer thickness, upper panels) and time series of total energy (lower panels) for (a) Re = 26, (b) Re = 31, (c) Re = 39, (d) Re = 70, (e) Re = 95, (f) Re = 112, (g) Re = 157, (h) Re = 209 and (i) Re = 314. The periods indicated by arrows in (h) and (i) are included in those of Fig. 2.

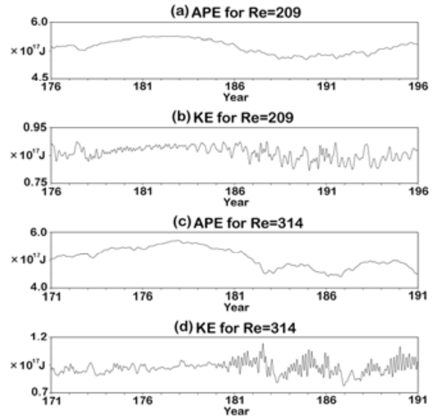

Figure 2 (a) Available potential energy and (b) kinetic energy for Re = 209 during years 176-195 and (c) available potential energy and (d) kinetic energy for Re = 314 during years 171-190.

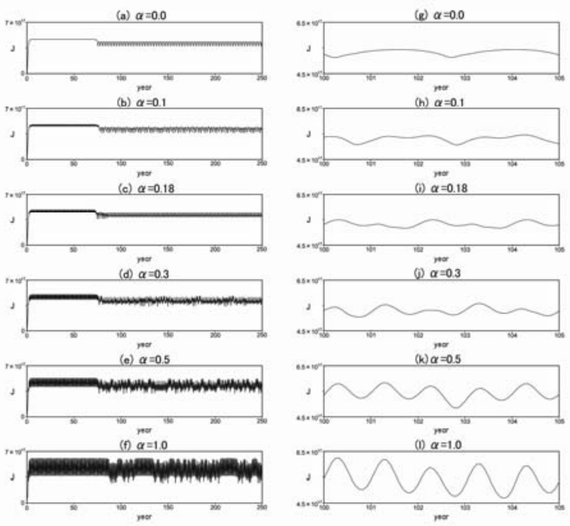

Figure 3 Time series of total energy for (a) α =0.0, (b) α =0.1, (c) α =0.18, (d) α =0.3, (e) α =0.5, and (f) α =1.0 for 250 years. Figs. (g) - (l) are the same but during years 100–105.

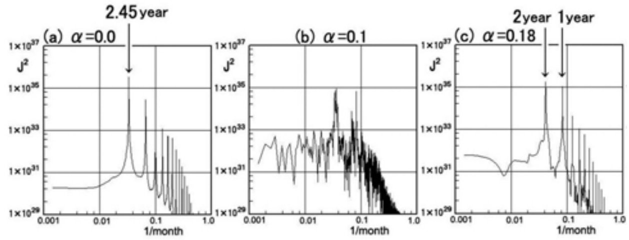

Figure 4 Power spectra of total energy for (a) α =0.0, (b) α =0.1, and (c) α =0.18.

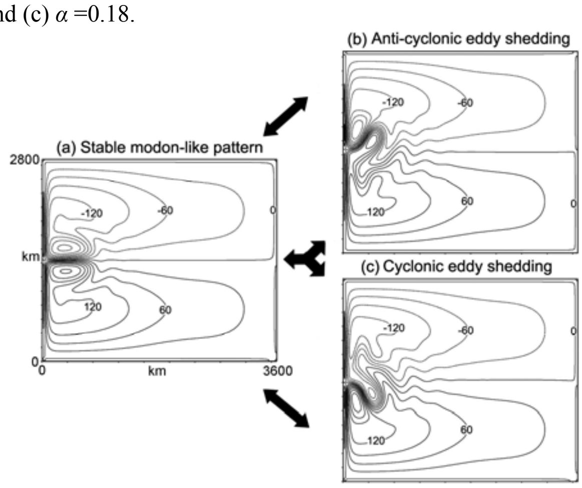

Figure 5 Three typical flow patterns (monthly averaged 1st layer thickness, CI=30m) of double gyres in Q-G model for α = 0.7. (a) Stable modon-like pattern, (b) anti-cyclonic eddy shedding, and (c) cyclonic eddy shedding.

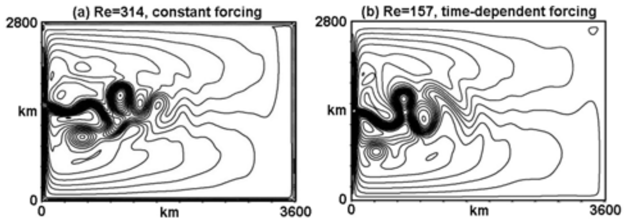

Figure 6 Flow patterns (monthly averaged 1st layer thickness, CI=20m) for (a) Re=314, constant forcing at 86 years, 11 months and (b) Re=157, time-dependent forcing at 184 years, 3 months.

References

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