# Entrainment and Intermittency in the Response of a Quasi-geostrophic Oceanic Double Gyre to Seasonal External Forcing

Shinya Shimokawa*[a], Tomonori Matsuura**
*National Research Institute for Earth Science and Disaster Prevention, Tsukuba, 305-0006, Japan
**University of Toyama, Toyama, 930-0887, Japan

*Summary* Nonlinear oscillations of the ocean under seasonally changing external forcing are investigated using a 1.5-layer quasigeostrophic model for 0-bump case. The authors found that entrainment (at 2 times the period of the forcing) and intermittency (on–off type), phenomena emerge with increasing amplitude of the forcing. They seem to be related to the generation mechanism and characteristics of long-term (from inter-annual to decadal) variations in the strong current region of subtropical gyres.

## Introduction

The configuration consisted of two large scale circulations with opposite rotations (i.e., oceanic double gyre) such as sub-tropical gyre and sub-arctic gyre is the most basic one in the oceanic general circulation. Thus far, most studies of oceanic double gyres using middle-range complexity have been conducted under constant (time-independent) wind forcing. In the real atmosphere and oceans, seasonal wind forcing with westerly and trade winds generates subtropical and subpolar gyres arising from western boundary currents and internal currents. Many problems, especially those with nonlinear aspects, remain unresolved. For example, entrainment as rhythmic phenomena in a nonlinear system [1] has not yet been investigated in the ocean system. Entrainment is an adjustment (e.g., frequency and/or phase locking) of rhythms of two or more self-sustained oscillating systems, which have different periods, because of their nonlinear interaction. We consider that entrainment of a characteristic oscillation of the ocean itself to a seasonal oscillation of an external forcing can occur in the ocean system when both periods are similar. Therefore, it is interesting and important to clarify the nonlinear interaction between a characteristic oscillation of the ocean and a seasonal oscillation of an external forcing, which is the main topic of this study [2].

Moreover, we discuss an intermittency caused by chaotic modulation in the transition from laminar flow to turbulent flow [3]. In particular, an additional mechanism for generating intermittency is related to the transverse instability of chaotic attractors confined to a manifold whose dimension is smaller than that of the full phase space [4]. The intermittency in this case is called on–off intermittency.

## 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 11 experiments with parameter range; α＝0.0-1.0. Reynolds number is fixed to 39, which corresponds to 0-bump case.

## Results

For α=0.0, only intrinsic oscillation (with 2.45 years) of the ocean system can be seen (Figs. 1a, 1g and 2a). In α=1.0, only seasonal oscillation (1 year) of the external forcing can be seen (Figs. 1f, 1l). In the intermediate α=0.18, the oscillation has both aspects (Figs. 1c, 1i). In fact, here, the entrainment occurs at 2 times the period of the forcing (2 years; Fig.2c). With increasing α, the intermittency appears (α>0.4; Fig.1e, 1f). The intermittency has periods from few years to few decades (Fig.3). Intermittent transitions occur between stable modon-like pattern (alongside path, Fig4a) and unstable cyclonic/anti-cyclonic eddy shedding patterns (large meander path, Fig4b, 4c).

## Discussions

In the experiments, the coupling factor of two chaotic oscillators is the strongest when entrainment occurs. With weakening the coupling factor, intermittency appears, which is an aperiodic switching between static or laminar behavior (off-state, in which two chaotic oscillators move as unite system) and chaotic bursts of oscillation (on-state; in which two chaotic oscillators move as independent systems.). This is one of typical routes to Chaos (e.g., [6]). In our cases, with small $\alpha$ (i.e., large coupling factor), entrainment occurs, and with increasing $\alpha$ (i.e., decreasing coupling factor) intermittency appears. If the external forcing is constant, entrainment can't occur and the way to reach intermittency will be different [7]. Therefore, we consider that the seasonally changing external forcing is important for the real situation.

Our results suggest that the decadal variability is caused by intermittency between the stable modon-like and unstable eddy shedding modes due to nonlinear interaction between an intrinsic oscillation of the ocean and seasonal oscillation of an external forcing. Our results are consistent with a suggestion by [8] that time-dependent forcing may be important

a) Corresponding author: simokawa@bosai.go.jp

for rapid switching between two stable and unstable modes, which appeared in their primitive equation ocean model with time-independent forcing.

It has often been considered that variations in the western boundary current are caused by local instability. An increasing number of observations, however, indicate that the variations are also considered to be part of the instability of the entire gyre [9]. The entrainment and intermittency observed in this study are also considered to be related to the entire system. Therefore, these phenomena may be crucial to understanding the generation mechanism and characteristics of long-term variations in the strong current region of subtropical gyres such as the Kuroshio and its extension region.

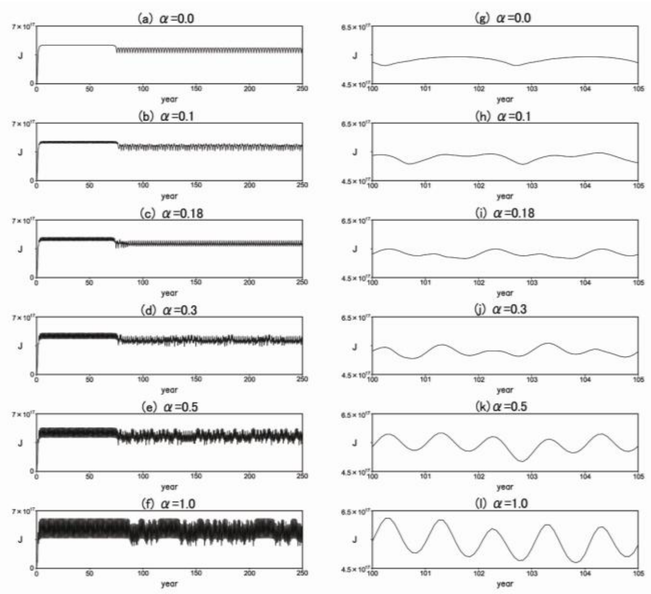


Figure 1 Time series of total energy for $\alpha$ = (a) 0.0, (b) 0.1, (c) 0.18, (d) 0.3, (e) 0.5, and (f) 1.0 for 250 years. Figs. (g)–(l) are the same but during years 100–105.

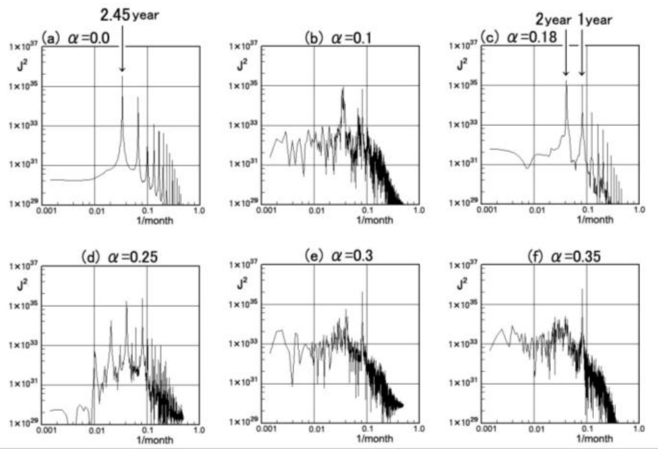


Figure 2 Power spectra of total energy for $\alpha$ = (a) 0.0, (b) 0.1, (c) 0.18, (d) 0.25, (e) 0.3, and (f) 0.35.

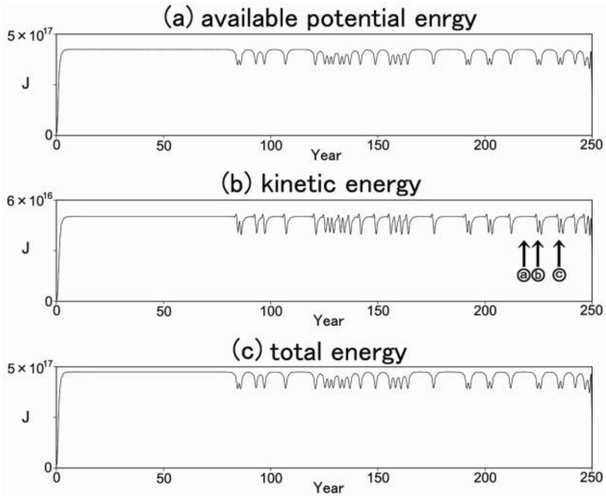


Figure 3 Time series of (a) available potential energy, (b) kinetic energy, and (c) total energy for $\alpha$ = 0.7. Frequencies lower than 1/18 month are filtered out. Flow patterns for ⓐ, ⓑ, and ⓒ in (b) correspond to (a), (b), and (c) in Fig. 4.

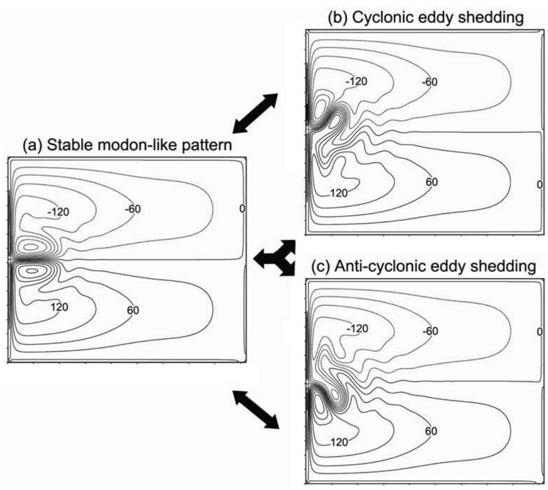


Figure 4 Three typical patterns (h) of double gyres in Q-G model for $\alpha$ = 0.7. (a) Stable modon-like pattern, (b) cyclonic eddy shedding, and (c) anticyclonic eddy shedding (contour interval is 30 m).

## References

[1] Kuramoto, Y.: Chemical Oscillations, Waves, and Turbulence. Springer-Verlag, 153 pp, 1984.

[2] Shimokawa S. and Matsuura T.: Chaotic behaviors in the response of Q-G oceanic double-gyre to seasonal external forcing. J. Phys. Oceanogr., **40**, 1458-1472, 2010.

[3] Berge, P., Pomeau Y., Vidal C.: Order within Chaos: Towards a Deterministic Approach to Turbulence. Harmann, 380 pp, 1984.

[4] Pikovsky, A. S., 1983: A new type of intermittent transition to chaos. J. Phys., 16A, L109–L112.

[5] McCalpin, J. D.: The statistics and sensitivity of a double-gyre model: The reduced-gravity, quasigeostrophic case. J. Phys. Oceanogr., 25, 806–824, 1995.

[6] Pikovsky, A. S., Rosenblum M., Kurths J., 2001: Synchronization: A Universal Concept in Nonlinear Sciences. Cambridge University Press, 411 pp.

[7] Pierini, S., Dijkstra H. A., Riccio A.: A nonlinear theory of the Kuroshio Extension bimodality. J. Phys. Oceanogr., 39, 2212–2229, 2009.

[8] Primeau, F., Newman D.: Elongation and contraction of the western boundary current extension in a shallow-water model: A bifurcation analysis. J. Phys. Oceanogr., 38, 1469–1485, 2008.

[9] Qiu, B.: Interannual variability of the Kuroshio Extension system and its impact on the wintertime SST field. J. Phys.Oceanogr., 30, 1486–1502, 2000.