

Decadal variations produced by period-doubling bifurcations in a two-layer wind-driven oceanic gyre

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Several previous studies suggest that the oceanic variations south of Japan depend both on large-scale wind changes and on local eddy activities. In fact, the Kuroshio is known to show various time scales ranging from short-term (intraseasonal and seasonal) to long-term (interannual and decadal) variations. It has therefore been surmised that these variations in the restricted area might be affected by the basin-scale ocean climate (and vice versa), but no one has given a satisfactory explanation of this potential linkage. In this study, we give a straightforward description of a possible route to chaos in a numerical model of a wind-driven subtropical gyre, leaving detailed physical processes responsible for each transition. In particular, a careful experiment will be made for dynamical regimes just below chaos which could not be well resolved in the previous investigations. In this way, we may speculate the origin of the decadal variability in the real oceans.

The two-layer quasigeostrophic potential vorticity equations are integrated numerically on a square basin with a side of 1000 km under the no-slip condition. In contrast with many previous works on the wind-driven circulation, we choose the strength of the (time-independent) wind stress, τ , as a controlling parameter, whereas the horizontal eddy viscosity is fixed. In each calculation the initial condition was chosen to be the state at rest; we here neglect questions of hysteresis. After transients died out, a time-series data of basin-averaged potential energy P and kinetic energy K were Fourier transformed to produce power spectral densities. These spectra were used to determine the values of τ at which bifurcations take place.

We confirmed the following transitions in order of increasing τ . (1) At $\tau=0.0476$ Pa, the model turns into a singly periodic regime with a period of several months. (2) At $\tau=0.055$ Pa, the first period doubling occurs. The orbit in the (P,K) plane is doubled correspondingly, but the double orbit immediately returns to a single orbit. The primary frequency, however, is not greatly changed during the latter process. (3) At $\tau=0.099$ Pa, the second period doubling occurs. The resulting double orbit in the (P,K) plane remains stable for the values of τ less than 0.1034 Pa. (4) At $\tau=0.1034$ Pa, the double orbit collapses abruptly to form another single orbit. In this case the primary spectral peak disappears, indicating inverse period doubling. (5) At $\tau=0.105$ Pa, an incommensurate lower (interannual) frequency is produced, so that the model moves to a quasiperiodic regime. The energy power spectrum appears to be composed of quintet clusters of spectral peaks. By $\tau=0.1063$ Pa, however, the interannual frequency is phase-locked with the shorter frequencies appearing in (3). (6) From this interannual frequency, three period-doubling bifurcations occur at $\tau=0.10621$, 0.10689 and 0.10704 Pa, respectively, leading directly to the broad spectra. The estimated Feigenbaum number is in reasonable agreement with the theoretical value. This implies that a Feigenbaum scenario exists in the present model.

In other words, the transition includes two period-doubling sequences, one starts from the high frequency due to mesoscale eddies and the other starts from the interannual frequency, and both sequences may be connected via phase-locking. Thus, we can say that the basin-scale decadal variations in our model are produced primarily by period doublings.