Low-frequency variability of a two-layer ocean forced by periodic winds

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Motivated by the low-frequency variability of the large-scale ocean circulation we have conducted numerical experiments with a two-layer quasigeostrophic fluid on a square plane bounded by no-slip walls. We find that the model ocean responds to sinusoidal wind forcing periodically or chaotically but experiences no 2-cycles (1/2 subharmonics): as the forcing amplitude is increased, the time series of global and local quantities associated with the flow field exhibit a sequence of n-cycles from n larger than 10 to n=3 until the states with a continuous spectrum are reached. The transition between neighbouring n-cycles takes place through brief quasiperiodic and/or chaotic regimes, so that the response frequency changes like a devil's staircase whose width decreases with increasing n at nearly a constant rate.

Our model ocean thus acts as a frequency divider. It is known that in 1D nonlinear oscillators forced periodically, such as electronic circuits, a 2-cycle is likely to occur if either the nonlinear restoring force or the external force is unsymmetrical. Although our model ocean satisfies the latter condition, it suppresses the 1/2 subharmonics. Thus, as far as subharmonic responses are concerned, we may say that a two-layer rotating fluid bounded by no-slip walls is unlikely to be reduced to a nonlinear oscillator having one degree of freedom.

As for the transition to chaos, the present case is quite different from the case in which the wind forcing is time-independent (Sakamoto, Joint Meeting 2004). In the latter case the basin modes of the baroclinic Rossby waves, which are free oscillations in the bounded stratified ocean, are locked in the mesoscale eddies and appear to determine the prime frequency of the entire system. As the wind magnitude is increased, an oscillation with an interannual period is produced, followed by successive period-doubling bifurcations that lead to continuous spectra. We speculate that in the periodically forced ocean there is a conflict between subharmonic resonances and Feigenbaum cascades associated with the instabilities of the large-scale waves.

One of the implications for the ocean climate is that the subtropical gyre driven by the prevailing seasonal winds may display variations on time scales of 3 years or longer which are produced internally by the nonlinear processes. By contrast, it seems plausible that additional external mechanisms, such as stochastic forcing and ocean-atmosphere coupling, should be taken into account to explain interannual variations whose time scale is less than 3 years. Although there is a tremendous gap between our model ocean and the real ocean, we take a step forward to suggest the role played by the nonlinearity in selecting the low-frequency variations and the peculiarity of the time scale of 3 years in the North Pacific under the seasonal winds. It should be mentioned that the time scales around 3 years are shared by some prominent atmospheric and oceanic phenomena, including El Nino/Southern Oscillation (ENSO) events and the path variation of the Kuroshio.