CINECA EPCC CEPBA HLRS IDRIS SARA PSNC PARALLAB TCD CASPUR NTUA

HPC-Europa

Pan-European Research Infrastructure on High Performance Computing

HIGH PERFORMANCE COMPUTING - EUROPA Project

(RII3-CT-2003-506079)
Supported by the European Community
Research Infrastructure Action
under the FP6 "Structuring the European Research Area" Programme

Scientific Report

(2008)

Low-frequency variability of the Kuroshio Extension: model studies in the context of climate dynamics and dynamical systems theory

---

Stefano Pierini

Dipartimento di Scienze per l'Ambiente, Università di Napoli Parthenope,
Naples – Italy (stefano.pierini@uniparthenope.it)

Abstract

This "High Performance Computing - Europa" project was aimed at extending the results of a recent model study of the Kuroshio Extension (KE) low-frequency bimodal variability, that was significantly validated with a comprehensive altimeter data set. In that study a preliminary analysis based on the methods and interpretative tools typical of dynamical systems theory was developed following an empirical continuation method. Such an approach requires performing a large number of runs in which some control parameters are varied, so that the extremely complex structure of phase space can be investigated. However, because of the large size of the computational domain, of the long forward time integrations and of the relatively small time step required for computational stability, a very large CPU time (of (O(10 days)) is needed for each serial run. Thus, the many numerical experiments necessary to carry out a thorough analysis of the KE low-frequency variability could not be performed unless a parallelized version of the code were run on a high performance computing facility. The HPCE project has allowed us to solve this problem by providing the use of the SGI Altix 3700 System of SARA. The obtained results have led to a substantial improvement of our understanding of the structure of phase space as the main dissipative parameter (the lateral eddy viscosity) is varied. In this note we summarize the main results, such as: the local transition from periodic to chaotic oscillations; the existence of a global bifurcation and the emergence of homoclinic orbits; the appearance of sudden and temporary transitions to different dynamical behaviours; the existence of windows of periodic motion within chaos.

1. Introduction

Understanding the mechanisms that produce the Kuroshio Extension (KE) low-frequency variability is relevant not only from a purely oceanographic point of view but also in a more general climatic perspective, as KE changes are associated with vigorous air-sea heat exchanges known to be able to enhance considerably the variability of the midlatitude coupled ocean-atmosphere system in the North Pacific region. In this context a double-gyre reduced-gravity shallow water model [1], validated with altimeter data and interpreted both in terms of geophysical fluid dynamical principles and of dynamical systems theory, suggests that the KE low-frequency (decadal) variability may be basically due to internal nonlinear mechanisms. The model is forced by a time-independent climatological wind and the domain of integration is bounded to the west by a schematic coastline. The obtained flow exhibits a fairly realistic mean jet and chaotic bimodal relaxation oscillations between an energetic meandering state and a much weaker state with a reduced zonal penetration (Fig. 1).

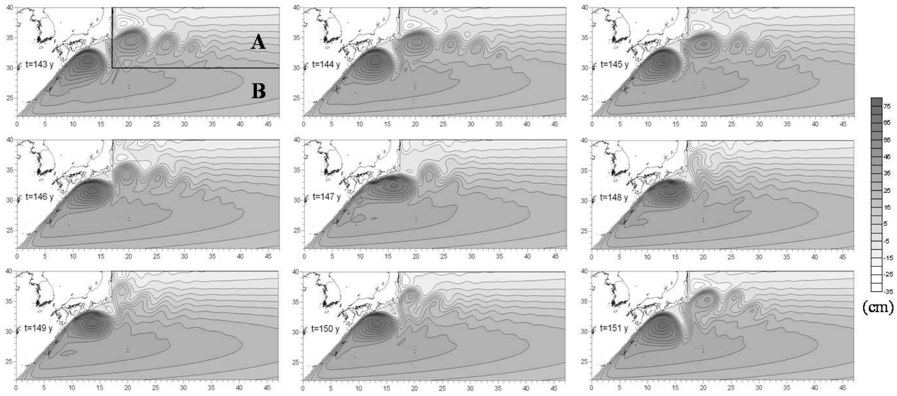

Figure 1. Sequence of snapshots of the modeled sea surface height in a window that contains the most significant part of the flow, showing a decadal bimodal oscillation of the KE (adapted from [1]).

These high and low energy states are found to be very similar to the "elongated" and "contracted" modes of the KE as detected through in situ and altimetric measurements. More specifically, the characteristic period (of around 10 years), flow patterns and transition details of a typical bimodal cycle are found to be in significant agreement with an altimeter data set [2] obtained by merging TOPEX/Poseidon, Jason-1 and ERS-1/2 measurements for the period 1992-2004.

A complex dynamical mechanism explaining such oscillations, and involving the bimodal behavior of the Kuroshio south of Japan, is proposed. The same variability is interpreted in the framework of dynamical systems theory as a homoclinic orbit in phase space resulting from a global bifurcation associated with the reconnection of the stable and unstable manifolds of the saddle fixed point corresponding to the weak (contracted) jet state.

2. Motivations of this HPC-Europa project

In relation to the model study described in Sect. 1, the main objective of this HPC-Europa project was to extend substantially the preliminary results that concern the interpretation of the variability in terms of dynamical systems theory (e.g., see [3] in the context of physical oceanography). In [1] the empirical continuation method adopted by several authors (starting from the pioneering work [4]), and imposed also by the very large dimension of the domain of integration, was used. Such an approach requires performing a large number of runs in which some control parameters are varied, so that the extremely complex structure of phase space can be investigated. However, because of the large size of the computational domain (about 400x500 grid points in the horizontal), of the long forward time integrations (100/200 years) and of the relatively small time step (20 min) required for computational stability, a very large CPU time (of O(10 days)) is needed for each serial run. Thus, the many numerical experiments necessary to carry out a thorough analysis of the KE low-frequency variability could not be performed unless a parallelized version of the code were run on a high performance computing facility.

The HPCE project has allowed us to solve this problem by providing the use of the SGI Altix 3700 System of SARA. The Fortran code, developed by S. Pierini and parallelized by A. Riccio, was run using 9 processors, which turned out to be the best choice taking into account the parallel speedup and the available CPU budget. The host researcher, H. A. Dijkstra, of the "Institute for Marine and Atmospheric Research" of Utrecht University, provided an ideal scientific environment.

3. The results

The obtained results have led to a substantial improvement of our understanding of the structure of phase space as the main dissipative parameter (the lateral eddy viscosity A_H) is varied. It has now been possible to draw a bifurcation diagram (Fig. 2) in which the range of variation of the kinetic energy of the flow integrated in sector A (see the first panel of Fig. 1) is reported as a function of A_H.

For A_H>400 m^2/s a single line would emerge, the state being stationary. At A_H≈400 m^2/s a first Hopf bifurcation occurs, when the nonlinear saturation of the linear instability of the stationary solution produces stable small amplitude oscillations.

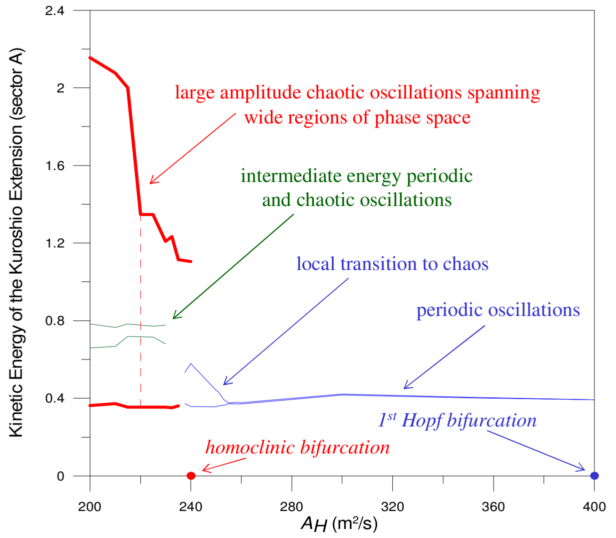

Figure 2. Bifurcation diagram, with the control parameter given by the lateral eddy viscosity.

The blue color indicates solutions that remain near the unsteady stationary state. Within this range (A_H≈240-400 m^2/s) one can distinguish two sub-ranges. In the first one (A_H≈260-400 m^2/s) the solutions are very small amplitude periodic oscillations. In the second sub-range (A_H≈240-260 m^2/s) a local transition to chaos occurs. Fig. 3 shows such a transition. The higher frequency oscillations are due to wall-trapped modes (corresponding to periods of ~10 days), while the lower frequency ones are due to gyre modes (corresponding to periods from ~4 to ~8 years, and shown by the dark blue lines), which are much more intense in the KE region (sector A) rather than south of Japan (sector B, note the different y-scales in the two sets of time series).

Just below A_H≈240 m^2/s a “homoclinic” bifurcation [5] occurs, and the typical KE relaxation oscillations are obtained, as shown in Fig. 1 (for A_H=220 m^2/s). They correspond to the red lines in Fig.s 2 and 4: as an example see the case A_H=230 m^2/s in Fig. 4, and refer to Fig. 5 for the corresponding homoclinic orbit projected onto an appropriate plane. In this case the orbit leaves the unstable saddle fixed point corresponding to the weak (contracted) jet state (inside the oval of Fig. 5) along its unstable manifold (see the outgoing arrow), and then spans a wide region of phase space. The unstable manifold is however reconnected to the stable one, and its along the latter (see the ingoing arrow in Fig. 5) that the orbit eventually goes back to the original phase space region. It is also important to notice that the chaotic orbit visits occasionally a region (where it remains trapped

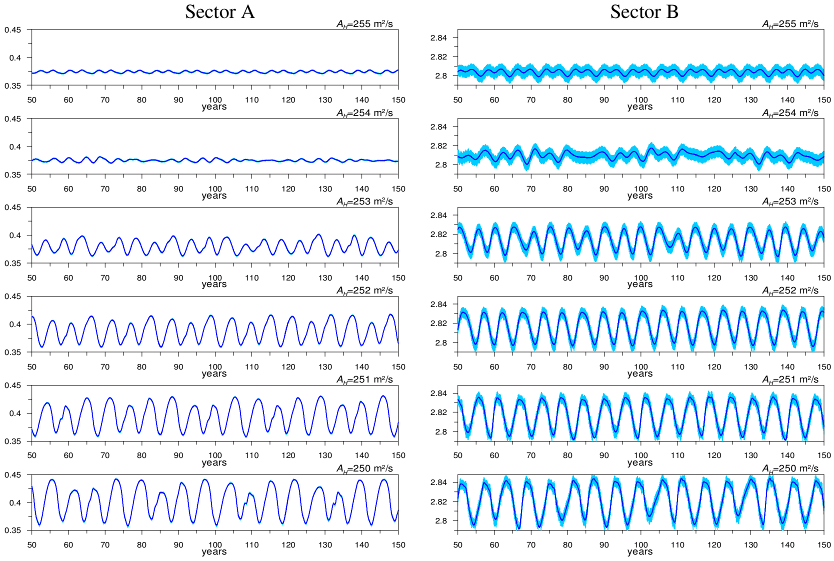

Figure 3. Light blue lines: kinetic energy integrated in sectors A and B (see Figure 1, first panel) for A_H= 250-255 m^2/s. Dark blue lines: same signals filtered over a 200-day period.

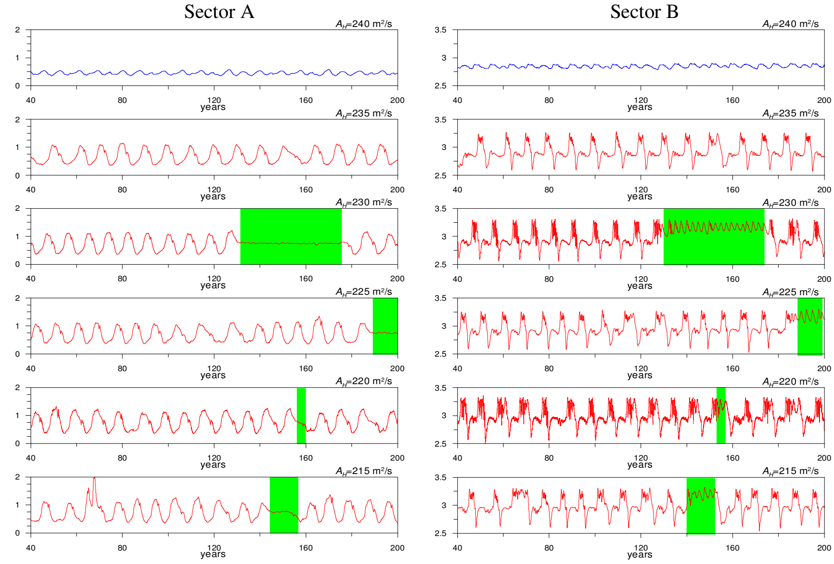

Figure 4. Filtered kinetic energy integrated in sectors A and B (see Figure 1, first panel) for A_H= 215-240 m^2/s. The green areas identify the transition to a different behavior.

for some time) in which intermediate energy, small amplitude oscillations of a completely different character arise. Events of this kind are identified by the green areas in Fig. 4 and 5 and are interpreted as heteroclinic connections.

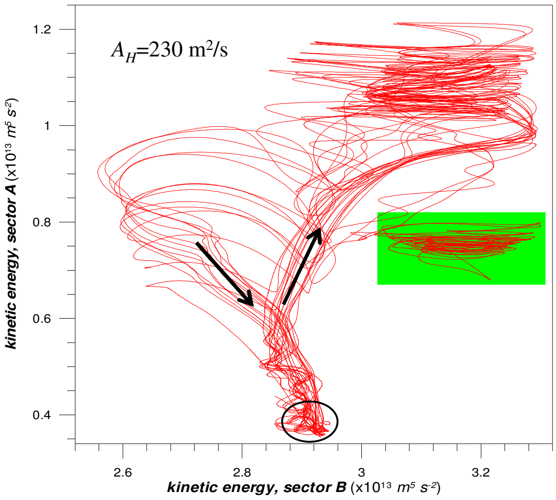

Figure 5. Projection of flow trajectory onto the *KinEn*(sector B)-*KinEn*(sector A) plane for A_H=230 m^2/s. The green area corresponds to the one reported in the corresponding time series of Figure 4. For the oval and arrows see the text.

Finally, it is interesting to notice that windows of periodic motion appear within both local and global chaos, as it is typical in chaos theory. This is found to occur both before the homoclinic bifurcation (for values of A_H slightly larger than 240 m^2/s) and for the intermediate energy oscillations (identified by the green areas in Fig. 4).

For a complete description and interpretation of the obtained results that goes far beyond this brief note the reader should refer to [6].

Acknowledgments

This work was carried out in January-February 2007 under the HPC-EUROPA Project (RII3-CT-2003-506079) with the support of the European Community - Research Infrastructure Action under the FP6 “Structuring the European Research Area” Programme. The host institution was the Institute for Marine and Atmospheric Research of Utrecht University, and the high performance computing facilities were provided by SARA (Amsterdam). The hospitality and scientific support of Henk A. Dijkstra is most gratefully acknowledged.

Publications

[1] Pierini S., 2006: A Kuroshio Extension System model study: decadal chaotic self-sustained oscillations. *J. Phys. Oceanogr.*, 36, 1605-1625.

[2] Qiu B., and S. Chen, 2005: Variability of the Kuroshio Extension jet, recirculation gyre, and mesoscale eddies on decadal time scales. *J. Phys. Oceanogr.*, 35, 2090-2103.

[3] Dijkstra H. A., 2005: *Nonlinear Physical Oceanography – A Dynamical Systems Approach to the Large Scale Ocean Circulation and El Niño*. Springer, 532 pp.

[4] Jiang S., F. Jin, and M. Ghil, 1995: Multiple equilibria, periodic and aperiodic solutions in a wind-driven, double-gyre, shallow-water model. *J. Phys. Oceanogr.*, 25, 764-786.

[5] Simonnet E., M. Ghil, and H. Dijkstra, 2005: Homoclinic bifurcations in the quasi-geostrophic double-gyre circulation. *J. Mar. Res.*, 63, 931-956.

[6] Pierini S., H. A. Dijkstra, and A. Riccio, 2008: A nonlinear theory of the Kuroshio Extension bimodality. In preparation.