The Vertical Pump Organized by the Mesoscale Oceanic Eddies

Project Leaders
Patrice Klein Laboratoire de physique des Oceans, Institut Francais de Recherche pour l'Exploitation de la Mer
Hideharu Sasaki The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

Authors
Patrice Klein [*1], Bach Lien Hua [*1], Sylvie Le Gentil [*1] and Hideharu Sasaki [*2]
*1 Laboratoire de physique des Oceans, Institut Francais de Recherche pour l'Exploitation de la Mer
*2 The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

The purpose of this project is to study the dynamics of the upper oceanic layers (the first 1000m below the surface) and principally to get new insights on the effectiveness of the oceanic vertical pump at a basin scale through numerical experiments using ultra-high resolution. If the magnitude of this vertical pump when using such a resolution is much larger than anticipated, then the expected results should have an important impact on basin-scale SST and circulation through the vertical fluxes of heat and potential vorticity. Indeed preliminary studies already indicate the significant contribution of this eddy vertical pump to the modification of the surface layers heat content ([1], [2]). Thus the expected new results should be of importance for climate studies. Furthermore they should provide a clue for the missing physical mechanisms that should allow to close the phytoplankton balance in oceanic basins ([3], [4]).

Keywords: mesoscale oceanic eddies, submesoscale dynamics, vertical pump.

1. Research Objectives

The scientific context is the following. Recent numerical simulations ([5], [6]) have investigated the impact of high horizontal resolution (up to 1/64th degree) on the oceanic circulation in the North Atlantic. Such high resolution leads to an explosion in the number and strength of mesoscale (O(100 km)) and small-scale (O(10 km)) eddies and fronts in all oceanic regions, with a resulting eddy kinetic energy increase by *a factor of* 10 when compared with a resolution of 1/6th degree. This strong eddy kinetic energy increase and the qualitative nature of the mesoscale structures that emerge (involving coherent vortices as small as 10 km) are consistent with recent satellite and in-situ observations ([7], [8]). However, because of computer resource limitations, these simulations have a poor resolution in the vertical (6 layers at most). As a consequence some important dynamical features, such as the vertical velocity related to the eddy field, are still underestimated. A quantitative assessment of this vertical velocity field, that entirely controls the exchanges between the deeper and upper layers, requires to put the effort on both the horizontal and the vertical numerical resolution through a three-dimensionally consistent discretization ([9]). The reason is that the nonlinear dynamics of mesoscale and small-scale structures is characterised by a Burger number value of the order one. This generic property implies that horizontally thin structures are also vertically thin.

With the advent of computers such as the Earth Simulator, it is now possible to get new insights on the effectiveness of the vertical pump on the oceanic general circulation at a basin scale by using an appropriate 3-D ultra-high resolution. This resolution should be better than 1/64th degree in the horizontal and not larger than 3 m on the vertical (at least in the first 500 meters below the surface). Using such a resolution should allow to reproduce the magnitude and properties of the vertical pump. For this project, the numerical code used is ROMS (Regional Ocean Modelling System), a Primitive Equations model developed at Rudgers University (USA) and UCLA (USA). This code distributed freely to the international community is vectorized, includes MPI routines and uses highly accurate (3rd order) advection schemes for the momentum, density and tracers. Such numerical code can be used to perform simulations at a basin scale comparable to the North Atlantic or North Pacific with ultra- high resolution in the upper oceanic layers.

We intend through this project to quantify the impact of the eddy vertical pump, in an idealized domain, on the basin-scale SST and circulation. The new feature that should be taken into account is the contribution of the submesocale structures (with a size between 2 and 10 km) to the vertical pump.

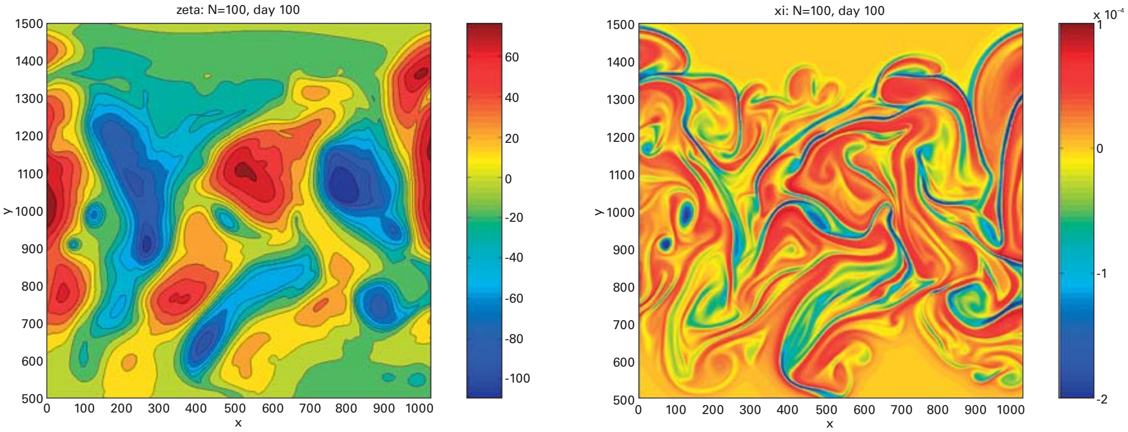

Fig. 1 (a) Snapshot of the Sea Surface Height (Units in colorbar are centimeters). Domain size is 1000 km*1000 km. (b) Corresponding relative vorticity field near the surface (Units on colorbar are s^{-1}. Colorbar is limited to 2*f*, but minima attain 5 *f* (*f* is negative)).

2. First results

During December 2004 we visited the Earth Simulator Center for 10 days to make the performance tests and run some preliminary simulations with ROMS. The successful tests allow us to use at least 64 nodes (512 processors). We made another 10-day visit in March 2005 to perform some high resolution simulations close to those required to fully study the vertical pump. The simulations run in March concern the nonlinear equilibration of a baroclinic unstable flow in a zonal beta-plane channel. The parameter setting roughly corresponds to the Antarctic Circumpolar Current region, one of the regions of the real ocean where the idealized geometry and forcings we used well apply. The numerical resolution is 1 km*1 km in the horizontal and involves 100 levels on the vertical, with a vertical grid spacing ranging from 2 m near the surface to 100 m near the bottom. The domain size is 2000 km*3000 km in the horizontal and 4000 m in the vertical. Fig. 1a shows a snapshot of the Sea Surface Height (1000 km*1000 km) that displays eddies with size varying from 200 km to 10 km.

First analysis of the non-linear regime reveals that the dynamics in the upper layers is strongly ageostrophic. The mean Rossby number is close to one and the Burger number is of order one. Relative vorticity reaches magnitudes as strong as five time the Coriolis frequency (*f*). The relative vorticity field (see fig. 1b) displays strong filaments (with a value larger than *f*) that are stable and therefore elongated on a large scale. The stability of such strong filaments was not expected. Large vortices with a diameter of about 200 km have a value that can be close to *f* but strong coherent cyclonic vortices with a size as small as 10 km have a vorticity magnitude that can attain 5 *f*.

A quick analysis of the vertical velocity field in the upper layers (fig. 2) reveals the dominance of the submesocale structures. The increase of the vertical velocity variance when the resolution is increased is mostly captured by the finest submesoscale elongated structures where the vertical velocity (*w*) can attain, at a depth of 200 meters, values as strong as 300 m per day. As expected we observe a strong skewness of w at those depths with the downward velocities having the largest values and located within thinner elongated filaments. Such skewness and asymmetry is present in the first 500 m and the w-structures become broader at larger depths.

Analysis of some vertical sections has displayed a feature we never observed before. The vertical velocity in front regions displays slanted features organized in the form of bands. First tests indicate that these features do not result from a numerical artifact. The Ertel Potential Vorticity keeps the same sign on those regions but its values are close to zero where the bands are observed. This would suggest a possible role of the symmetric instability. A further thorough analysis needs to be done to understand those features.

3. Future Works

The first results obtained indicate an energetic dynamics associated with the submesoscale structures that are resolved with a 1 km resolution. The rich spectrum of small-scale mechanisms displayed should have an important impact on the underlying mixing in the upper ocean. However simulations with a much longer time duration are needed in order to attain the full nonlinear equilibrium (so far the simulations done do not exceed a total duration of 300 days). Such simulations should allow to study and quantify the impact of the energetic submesoscale physics on the mesoscale eddy turbulence and in particular on the energy and enstrophy cascades. Another item is to activate a tracer equation in order to characterize the effects of the finer submesoscale motions on the vertical exchange (at a basin scale) of any properties between the surface layers and the ocean interior. At last we

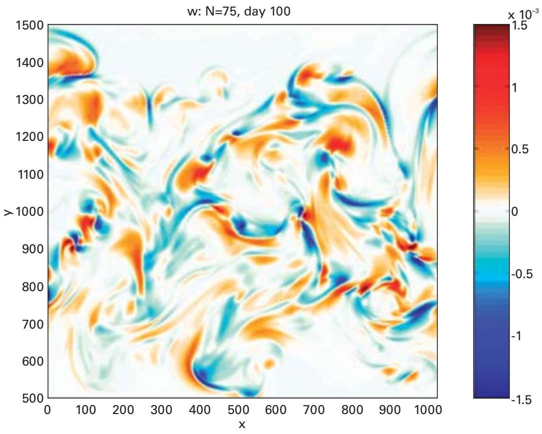

Fig. 2 As fig. 1 but for the vertical velocity field at 100 m (units in colorbar are m/s).

intend to use a higher resolution on the vertical to understand the effects of the vertical resolution on the small-scale vertical structures (such as the slanted structures). All these items should be completed within the fiscal year 2005-2006 to better characterize the vertical pump organized by the mesoscale eddies.

References

1) J. Marshall, H. Jones, R. Karsten, and R. Wardle, "Can Eddies Set Ocean Stratification?", J. Phys. Oceanogr., vol.32, pp.26-38, 2002.
2) G. Lapeyre, P. Klein, and B.L. Hua, "How frontogenesis helps in the ocean restratification", submitted to the Jour. Phys. Oceanogr, 2004.
3) D. J. McGillicuddy, L. A. Anderson, S. C. Doney, and M. E. Maltrud, "Eddy-driven sources and sinks of nutrients in the upper ocean: result from a 1/10th degree resolution model of the North Atlantic", Global Biogeochem. Cycles., vol.17, pp.1035, 2003.
4) M. Levy, P. Klein, and A. M. Treguier, "Impact of submesoscale physics on production and subduction of phytoplankton in an oligotrophic regime", J. Mar. Res., pp.535-565, 2001.
5) H. E. Hurlburt and P. J. Hogan, "Impact of 1/8th to 1/64th resolution on Gulf Stream model-data comparisons in basin-scale subtropical Atlantic Ocean models", Dynamics of Atmosphere and Ocean, vol.32, pp.283-329, 2000.
6) A. Siegel, J. B. Weiss, J. Toomre, J. C. McWilliams, P. S. Berloff, and I. Yavneh, "Eddies and vortices in ocean basin dynamics", Geophys. Res. Lett., vol.28, pp.3183-3186, 2001.
7) D. Stammer, "Global characteristics of ocean variability estimated from regional TOPEX/POSEIDON altimeter measurements", J. Phys. Oceanogr., vol.27, pp.1743-1769, 1997.
8) D. L. Rudnick, "On the skewness of vorticity in the upper ocean", Geophys. Res. Lett., vol.28, pp.2045-2048, 2001.
9) B. Barnier, B.L. Hua, and C. Le Provost, "On the catalytic role of high baroclinic modes in eddy-driven large-scale circulation", J. Phys. Oceanogr., vol.27, pp.976-997, 1991.

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プロジェクトリーダー
Patrice Klein　フランス国立海洋開発研究所（IFREMER）
佐々木英治　海洋研究開発機構　地球シミュレータセンター

著者
Patrice Klein [*1], Bach Lien Hua [*1], Sylvie Le Gentil [*1], 佐々木英治 [*2]
＊1　フランス国立海洋開発研究所（IFREMER）
＊2　海洋研究開発機構　地球シミュレータセンター

海洋の表層（1000 m以浅）では、渦などの小さなスケールの構造による鉛直運動、いわゆるVertical Pumpにより熱や渦度が鉛直に輸送され、海面温度や循環場に影響をおよぼすため、そのDynamicsを明らかにすることは、海洋生態系などの気候研究において重要な課題のひとつである。そこで、中規模渦より小さなスケール現象を解像できる水平解像度1 km、鉛直100層の超高解像度モデルを用い、β面近似の海盆スケールの領域に初期値場として傾圧不安定を設定し、数値計算を実施した。数値計算によって得られた渦度分布によると、直径が約200 km程度の比較的大きな渦の他に、直径10 km程度の小さい強い低気圧性渦、大きな渦から引き延ばされたように見えるフィラメント構造などの小さいスケールの構造が確認できた。また、鉛直流の分布では、これらの小スケールの渦やフィラメント構造に対応して、大きな鉛直流が分布し、数kmスケールの渦やフロント構造がVertical Pumpに重要であることを示した。今後、海洋表層と内部領域間の物質輸送やエネルギ解析を行うとともに、鉛直方向の解像度を上げた数値実験を行い、そのインパクトについて研究を進める予定である。

キーワード：mesoscale oceanic eddies, submesoscale dynamics, vertical pump