Potential use of microwave satellite measurements to reconstruct the three-dimensional dynamics of the oceanic upper layers

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Abstract *- We examine the emerging potential offered by satellite microwave measurements to derive the three-dimensional dynamics of the upper ocean. The proposed approach exploits the properties of a theoretical framework based on Surface Quasi-Geostrophic (SQG) equations. Within this framework, Sea Surface Heights (SSH) and Sea Surface Temperatures (SST) are closely related. This provides a way to combine SSH and SST measurements and allows to recover surface currents from a single SST image. On the other side, this framework allows to reconstruct subsurface fields, such as horizontal velocities and density anomaly, in the upper 500m of the ocean from SSH and/or SST measurements. Furthermore, within this framework vertical velocities can also be diagnosed from a single SST and/or SSH snapshot. To demonstrate the feasibility of this approach, first, we have explored the ability to reconstruct the three-dimensional dynamics of the oceanic upper layers using numerical simulation. Then, these results have been applied to existing altimetric measurements and microwave SST data from AMSR-E instrument. Our results confirm the validity of this framework and unveil some limitations in the existing microwave measurements that should be improved in future missions.*

Keywords *- OCEAN DYNAMICS, SURFACE QUASI-GEOSTROPHY, SEA SURFACE HEIGHT, SEA SURFACE TEMPERATURE, MICROWAVE REMOTE SENSING*

INTRODUCTION

Global ocean surface velocities are now routinely estimated from precise altimeter range measurements. Altimeters can provide information about the cross-track geostrophic velocity with a relatively high along-track resolution. However, distances between tracks are generally large, and interpolation methods are required to recover both components of the surface velocity vectors [e.g. 11]. To resolve in more details the complex space and time structure of surface currents, combined altimeters are then necessary to improve the resolution of the velocity fields [e.g. 12]. Up to 4 altimeters appear to be critical for real-time operational systems. But such a requirement may not always be met. To circumvent such a limitation, other sources of satellite data can be considered.

Low frequency microwave radiometers such as the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), which have spatial resolutions of the order 20-50 km, are very weakly depending upon cloud conditions and can provide global SST estimates. In this paper, we consider a new methodology to examine the emerging potential offered by low-resolution satellite microwave radiometer SST measurements. To quantitatively derive the 3D dynamics of the ocean, we consider a spatial scale analysis of the mesoscale SST variability following the application of the Surface Quasi-Geopstrophic (SQG) theory, rather than the standard sequential temporal analysis or singularity analysis [2, 1, 14, 5].

THEORETICAL FRAMEWORK

Recently, it has been showed that, for baroclinic flows, potential vorticity (PV) anomalies in the ocean interior are correlated to the surface PV (or surface buoyancy) anomalies [10]. Then, using this property and the invertibility principle of PV [4], it is possible to diagnose the 3D dynamics in the upper ocean from either the SSH, or the SST under certain environmental conditions. This method, called the 'effective' SQG (eSQG) method (since it is based on the SQG dynamics [3]), allows to get the geostrophic stream-function (ψ) and bouyancy (b) at any depth from observed SST (T_s), using

$$\hat{\psi}(\vec{k}, z) = \frac{g\alpha}{\rho_0 f_0 n_T} \frac{\hat{T}_s(\vec{k})}{k} \exp(n_0 k z) \tag{1}$$

and

$$\hat{b}(\vec{k}, z) = -\frac{g\alpha}{\rho_0} \hat{T}_s(\vec{k}) \exp(n_0 k z), \tag{2}$$

where ˆ stands for the horizontal Fourier transform, $\vec{k} = (k_x, k_y)$ is the wavenumber vector, $k = \|k\|$ its modulus, f_0 is the Coriolis frequency, g the gravity constant, α the thermal expansion coefficient, n_0 is a "mean" Brunt-Väissälä and n_T an "effective" Brunt-Väissälä frequency that takes into account the contribution of the interior PV and the partial compensation of thermal fronts by salinity [10, 7]. n_0 is usually derived from existing observations of the large-scale density field while n_T is usually estimated comparing surface fields with independent observations [6, 7].

Once the 3D stream-function has been reconstructed from SSH or SST, horizontal velocities $\vec{v} = (u, v)$ and relative vorticity (ζ) can be diagnosed as

$$\vec{v}(\vec{x}, z) = \vec{e}_z \times \nabla\psi(\vec{x}, z) \tag{3}$$

and

$$\zeta(\vec{x}, z) = \nabla^2\psi(\vec{x}, z), \tag{4}$$

where $\vec{e}_z$ is the upward normal vector. Furthermore, as it has been shown by [10], vertical velocities can be diagnosed as

$$\hat{w}(\vec{k}, z) = -\frac{1}{n_T^2} \left[\widehat{J(\psi_s, b_s)} \exp(n_0 k z) + \widehat{J(\psi, b)} \right], \tag{5}$$

which is an alternative to the classical Omega equation [4].

This framework can be reformulated to reconstruct the 3D dynamics of the ocean using observed SSH [see 7, 9]. Indeed, from equation 1 and taking into account that SSH (η) is related to the surface stream-function (ψ_s) by

$$\psi_s(\vec{x}) = \frac{g}{f_0} \eta(\vec{x}), \tag{6}$$

then, SSH and SST are related by

$$\hat{\eta} = \frac{\alpha}{n_T \rho_0} \frac{\hat{T}_s}{k}. \tag{7}$$

As before we'll need to set two parameters, n_0 and a new "effective" Brunt-Väissälä (n_η) that relates SSH with buoyancy.

NUMERICAL EXPERIMENTS

The validity of this approach was first tested using an Ocean General Circulation Model simulation representing the North Atlantic in winter (POP model 1/10°). The method is quite successful in reconstructing the velocity field from SST at the ocean surface and in the upper 500 m for mesoscales (between 30 and 300 km). The success of the method mainly depends on the quality of the SST as a proxy of the density anomaly at the base of the mixed layer (ML). This situation happens after a mixed-layer deepening period. Therefore the ideal situation for the application of this method to SST would be after strong wind events. Furthermore, the eSQG framework can further be applied to the reconstruction of subsurface fields using surface information such as SSH as previously seen. Results have shown that the reconstruction of velocities and vorticity from surface fields are reasonably good (down to 500 meters) although the reconstruction of subsurface density anomaly is quite limited [7].

The Ocean General Circulation Model used to investigate the reconstruction capabilities of the eSQG approach didn't had enough spatial resolution to correctly reproduce vertical velocities. Therefore, we have investigated its reconstruction using the high resolution (2 km) numerical simulations of an unstable flow in a channel done by P. Klein at the Earth Simulatior Centre forced by high frequency observed winds [8]. The simulated fields had a mesoscale eddy field with large Rossby numbers and an active ML. Results revealed that despite the presence of energetic near-inertial motions, a snapshot of high resolution SSH or SST allows the reconstruction of the Low Frequency motions, including the vertical velocities, but only for scales between 400 km and 20 km and for depths between the ML base and 500 m. Although both SST and SSH could be used, best results were found when de reconstruction was done from SSH.

APPLICATION TO MICROWAVE MEASUREMENTS

In addition of the tests done with numerical simulations, the eSQG framework was applied to real SST from AMSR-E data and then compared with the surface fields derived from altimetric maps. For the SST we used time-averages (3 days) of SST maps from version 5 of AMSR-E ocean products provided by Remote Sensing Systems (RSS) in California (USA), which have a spatial resolution of 1/4 by 1/4 degrees and uses correlation scales of 4 days and 100 km for the optimal interpolation [15]. While, for the SSH we have used Delayed-Time

Maps of Absolute Dynamic Topography (DT-MADT-Ref) produced by Collecte Localisation Satellites (CLS) in Toulouse (France) and distributed by AVISO, which combine the signal of two altimeters onto a 1/3 degree Mercator projection grid every 7 days [13]. For comparison with SST data, SSH fields were interpolated to the AMSRE-E SST grid.

Our esults show that there is indeed a robust statistical relationship of SQG type relating the SST and Sea level spectral level. Using gridded composite products, the highest correlation is found for wavelengths between 100 km and 300 km in accordance with the theoretical predictions. Most importantly, the phase information, within this scale range, is generally very close for the two filtered fields. This phase relationship leads to local high direct correlation between filtered fields. However, strict application of eSQG is apparently hampered by the use of SST fields. Indeed, the approach here proposed will be accurate only when SST would be a good proxy of the density related to mesoscale ocean structures, as seen from numerical experiments. As understood, the eSQG shall best apply to environmental conditions favouring the mixed-layer homogenization, i.e. after strong wind events, and the reduction of air-sea surface fluxes. Nonetheless, for our demonstration using 3-day composite low-resolution radiometer data, concentrating on the largest gradients of SST fields filtered between 100 km and 300 km, the eSQG estimated velocities within this band are found very close to the altimeter estimates (see example of Fig 1.).

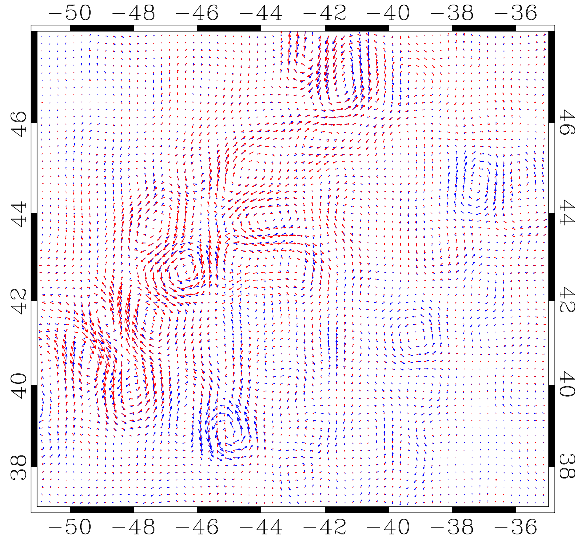

Fig. 1 Velocities derived from microwave SST (red) and altimetry (blue) (band-filtered retaining scales between 100 km and 300 km) in the region delimited by the white rectangular box in figure 1

In spite of the good agreement between the velocities derived from AMSR-E SST and those derived from altimetric maps, the use of these data sets is limited by the low sensitivity of the AMSR-E instrument to detect small thermal gradients and by the lack of synopticity associated to altimetric measurements.

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