Title: Theory, observation, and modelling of westward propagation in the oceans

Part 1: Previous Research Track Record

Dr. Rémi Tailleux has been a lecturer in the Department of Meteorology since August 2007, after being a senior research fellow for two years, as the project manager of the NERC funded RAPID UK intercomparison project. His interests lie in the dynamics and thermodynamics of the oceans and atmosphere, especially in processes important for climate such as waves and clouds, as well as the oceanic thermohaline circulation. He is an author of 13 peer-reviewed papers, and has been an expert member of the Ocean Surface Topography Science Team (OSTST) for the satellite mission JASON since 2004. He has authored or co-authored 8 scientific articles on oceanic Rossby wave propagation, and is currently writing a review paper on the issue.

Dr. Emmanuel Hanert has been a joint lecturer in the Departments of Meteorology and Mathematics at the University of Reading since 2006. His current research interests lie in applying novel numerical techniques, such as the finite element method, to simulate geophysical flows. He is an author of 12 peer-reviewed papers. He is an Associate Editor of “Ocean Modelling”, a leading journal in Oceanography (impact factor 2.897 in 2007).

1.1. Recent work summary

Elucidating mechanisms of westward propagation in the oceans

One of the most spectacular achievements of satellite altimetry over the past decade has been to demonstrate empirically the widespread and ubiquitous presence of westward propagating signals at nearly all latitudes in all oceans, and to question the conventional ideas about the physical processes controlling such signals by establishing significant discrepancies between their observed and theoretically predicted properties. In 1996, a study found empirically that if such signals were interpreted as first-mode baroclinic Rossby waves, then: 1) their propagation speeds appeared too fast by a factor of up to two-to-three at mid- and high-latitudes, but too slow in the equatorial regions; 2) instead of propagating with constant amplitude as expected from conventional theory, the signals appeared to decay off eastern boundaries, but to have significantly enhanced wave amplitude in the western parts of ocean basins, often westward of significant topographic features. Such findings generated much theoretical interest in the community, and the subsequent research focused on elucidating the roles of all the physical processes neglected in the conventional theory, the primary ones being: a) the presence of a background mean flow, b) topography, c) nonlinearities, d) forcing, and e) dissipation. RT’s contribution was:

- To demonstrate the importance of the bottom boundary condition, and to propose that a large fraction of the observed too fast propagation can be accounted for by the surface-intensification of planetary waves by rough topography, with very good agreement with observations (Tailleux and McWilliams, 2001)
- To propose that part of the observed enhanced wave amplitudes in the western parts of ocean basins can be accounted for by the interactions of batropic and baroclinic modes. This was numerically investigated in Tailleux and McWilliams
(2000), and a theory for the energy conversion was formulated for a two-layer model in Tailleux and McWilliams (2002). Tailleux (2004) was a first step toward extending the theory to a continuously stratified fluid.

- The literature had assumed that the observed too-fast propagation should be interpreted as a speed up of the first baroclinic mode. Tailleux (2003) proposed that the topography could also slow down the barotropic mode, yielding similar phase speeds. Tailleux (2006) established that although propagation over topography is dispersive, even in the long wave limit, one can still identify three distinct quasi-nondispersive regimes, which include two westward propagating modes which are respectively faster and slower than the standard case, and one that is strongly affected by topography.

- Colin de Verdiere and Tailleux (2005) demonstrated the role of the curvature of the shear flow to yield either a speed-up or a slow-down of the waves affected by the background mean flow.

- Lecointre et al. (2007) investigated the depth-dependence of the phase speeds, and show that it is inconsistent with the classical assumption stemming from normal mode theory that the phase speed is independent of depth.

- Tailleux and Reason (2007, in preparation) have designed a new method based on the inverse Radon transform to filter out the westward propagating signals

- Tailleux, Lazar, and Reason (2007, submitted) have proposed a theory to link the thermodynamic and dynamic signatures of Rossby waves.

Unstructured finite-element modelling of the ocean circulation
EH has developed from scratch an unstructured-mesh, finite element ocean circulation model (Hanert et al, 2004, 2005). It is now admitted that the future of ocean modelling belongs to such models, which can take advantage of the flexibility of unstructured meshes. The model equations have been discretized with a coupled continuous-discontinuous finite element scheme that is computationally inexpensive, free of spurious oscillations (Le Roux et al, 2005) and well suited to simulate inertia-gravity and Rossby waves.

1.2. Contribution to society
Realistic simulations of the internal and forced variability of the oceans is the key to assess the physical integrity of numerical ocean models used for predictions of future climate change. The present research focuses on what is arguably one of the most fundamental aspect of this variability, which it is crucial for ocean models to reproduce correctly.

1.3. Specific expertise at host organization
The Department of Meteorology at Reading University is the largest of its kind in the UK, received grade 5* in the last RAE, and has outstanding expertise in all aspects of climate modelling, including theoretical and numerical developments.
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Part 2: Proposed Research

2.1 Background
For decades, the scientific exploration of the oceans has been impeded by the difficulties and cost of collecting the data required to test theories and numerical models of the oceans. For that reason, the development of satellite observations is rightly considered as a true revolution in oceanography, for it has rapidly led to considerable improvement in both fields over the past decade. This is especially true with regard to the issue of westward propagation in the oceans, whether associated with Rossby waves or eddy-like structures, which forms the basis for this proposal. Westward propagation had been anticipated theoretically in the late thirties, and subsequently extensively confirmed in the atmosphere as affecting many weather patterns (e.g., easterly waves, tropical cyclones). In the oceanic case, the relevant theoretical framework until recently was the so-called linear standard theory (LST thereafter), that leads to the widely used concepts of barotropic and baroclinic normal modes. It is only with the advent of satellite altimetry, however, that the importance of westward propagation in the oceans could be truly recognized. The French/US satellite altimeter Topex/Poseidon (TP), launched in 1992, indeed not only revealed the ubiquitous nature of westward propagating signals in all ocean basins at nearly all latitudes, but also the dominance of such signals on the variability of Sea Surface Height Anomalies (SSH) on the seasonal to decadal time scales. Moreover, the TP data allowed Chelton and Schlax (1996) to question the validity of the SLT by showing that: 1) westward propagation speeds observed by TP tended to be systematically faster by a factor of up to two to three at mid- and high-latitudes than that predicted by the LST, but slower than expected in the equatorial regions; 2) enhanced wave amplitudes in the western part of ocean basins, often westward of major topographic features. These results are important, because westward propagation play key roles in the oceans, such as participating in the adjustment of the oceans to changes in the wind and buoyancy forcing, being the primary mean by which the interior upwelling will change in response to changes in the rate of deep water formation, being possibly involved in coupled modes of decadal variability with the atmosphere, and possibly affecting the variability of the Atlantic meridional overturning circulation. As all these issues are important to understand the roles of the oceans on climate, it is therefore
equally important to understand the physical processes affecting westward propagation. The study of westward propagation appears to be furthermore motivated by:

- The fact that they appear as a natural testbed for assessing the ability of numerical ocean to reproduce an essential part of the ocean variability;
- Since satellite observations are limited to the surface, it is important to understand how the surface signature of westward propagation is related to its three-dimensional signature in order to assess the possibility of saying something useful about the subsurface from surface observations alone.

2.2 Physical issues and challenges

2.2.1 Phase speed and amplitude issues

Importance and significance: Understanding the physical mechanisms affecting the propagation and amplitude variations is necessary to understand whether these can be correctly captured by ocean models.

The study by Chelton and Schlax (1996) prompted much theoretical work aimed at accounting for the “too-fast” Rossby waves. Initially, theories focused on nondispersive waves, i.e., on wavelengths greater than the first Rossby radius of deformation. Fig. 1 illustrates the performances of the three main theories for a continuously stratified ocean, namely: (top) the bottom-pressure decoupling theory of Tailleux and McWilliams (2001) (TMC01); (middle) the zonal mean flow theory of Killworth, Chelton and de Szoeke (1997), and (bottom) the SLT, where the observed phase speeds were measured by using the so-called Radon Transform applied to longitude/time sections of the data. While TMC01 and KCS97’s theories are seen to improve upon the SLT, they do so with a remaining scatter of comparable magnitude in both cases, suggesting that neither one can be regarded as fully satisfactory on its own. In subsequent years, the merging of different satellite altimeter products (TP, ERS-1/2, ENVISAT, and recently JASON) provided a satellite altimeter data with significantly improved spatial resolution that justify an analysis of dispersive effects, i.e., of the phase speed dependence upon the wavenumbers, which Fu and Chelton (2001) argued can help
in discriminating between different theories, and assessing the possible importance of nonlinear effects. Fig. 2 provides an empirical determination of the zonal wavenumber/frequency distribution from the new merged data, superimposed with a dispersive SLT, as well as a dispersive extension of the KCS97 and TMC01 theories (Tailleux et al., 2007, in preparation). Recently, Chelton et al. (2007) suggested that a large fraction of what they interpreted 10 years earlier as linear waves, was in fact more consistent with eddy-like features. As eddies propagate by retaining their shape, this suggests that their phase speeds is rather independent of the wavelengths constituting them. This could explain why, in the Fig. 2, the observed shape of the wavenumber/frequency spectrum of the waves appear to be nondispersive, and does not display much evidence of a bend as linear wave theories do. Dispersion is also possibly important in accounting for the observed decay of boundary-driven waves off eastern boundaries observed by Fu and Qiu (2002) and illustrated in Fig. 3. For a long time, boundary-driven waves were thought to propagate all the way across ocean basins, but this appears to be not the case. In fact, such a result appears to be consistent with the finding by Schopf et al. (1981), often overlooked, that linear dispersion induces a caustic line that originate from the critical latitude with a southwestward shape that effectively prevents the westward penetration of boundary-driven waves. A different theory is that proposed by Lacasce and Pedlosky (2004), who argues that the westward penetration of boundary-driven waves is limited by the baroclinic instability of baroclinic waves. The present challenge is to unify these different ideas in a unifying framework that can be tested against observations.

2.2.2 Vertical structure of westward propagation

and existence of normal modes

Importance and significance: The knowledge of the vertical structure of westward propagating is necessary to make inferences about the subsurface signature of the signals from their surface observations alone, i.e., to extend the capabilities of satellite observations to the ocean interior. It is also necessary to discriminate between physically distinct theories that can’t be discriminated from surface observations alone.
According to the SLT, westward propagating signals possess a normal mode structure in the vertical that is the solution of a classical Sturm-Liouville eigenvalue problem. This is important, for this allows one, in principle, to infer the three-dimensional structure of the waves from the observation of their surface signature alone. In practice, this could be used to extend part of the sea surface observations to the interior, depending on the feasibility of determining the vertical structure of the eddy/wave with confidence. To that end, the first step is to understand how the presence of the background mean flow and topography affect the vertical structure of the waves. In most recent theories based on the WKB approximation, the vertical structure is still assumed to be the solution of an eigenvalue problem, which is modified by the mean flow and topography. A recent numerical study by Aoki et al. (2007) suggests that the vertical structure of planetary waves in a high-resolution numerical ocean model is well accounted for by the first eigenmode of such an eigenvalue problem where only the zonal mean flow is retained, as proposed by KCS97, as well as the bottom boundary condition of vanishing pressure, as proposed by TMC01. In particular, the meridional mean flow and the assumption of slowly-varying topography of Killworth and Blundell (2004, 2005) do not appear needed. Fig. 4 shows example of surface-intensified eddy structures near the tip of South Africa, in qualitative agreement with the vertical structure predicted by the bottom-pressure compensation theory of TMC01. In another recent numerical study, Lecointre et al. (2007) found the phase speeds of westward propagating signals to decrease with depth, whereas one would expect them to be independent of depth for a truly vertical normal mode structure, as is the case in the SLT for instance. Of the many recent extended Rossby wave theories, only the theory by Yang (2000) does not rely on the normal mode assumption, and appears able to account for this slow down as a consequence of the decrease of the zonal mean flow with depth. Because Yang (2000)’s theory focuses on 3D ray propagation, however, it is not able to satisfy the no-normal flow boundary conditions at the ocean surface and bottom, and it is therefore unclear how such a framework could account for topographic effects for instance. The present challenge, therefore, is to understand how to combine all existing theoretical frameworks into one that can satisfactorily account for both the vertical variations in amplitude and phase speeds observed in numerical OGCMs. Finally, another related issue is concerned with what happens to the second and higher-baroclinic modes predicted by the SLT in presence of mean flow and topography. Indeed, there has been so far little evidence of such modes in SSH and SST data. Most likely, this is probably because higher-baroclinic modes, if they are not suppressed by critical-level interactions, may no longer propagate westward in presence of mean flow. Moreover, higher baroclinic modes are also expected to have a weaker signature than the first baroclinic mode, making them harder to detect. The present challenge is to understand how the second and higher-baroclinic modes are modified by the background mean flow, topography, and nonlinearities, in order to assess the possibility of observing them.

2.2.3 Dynamical/Thermodynamical coupling
Importance and significance: The dynamical/thermodynamical coupling is of importance for discriminating between waves and eddies, and to understand the possible dynamical coupling of such motions with mixed layer variations.

Westward propagation, although most easily evidenced in altimeter data, also possesses a signature in Sea Surface Temperature (SST), first discussed by Hill et al. (2000), but little exploited so far. It is usually assumed that such a signature is induced by the meridional velocity anomaly associated with the waves across the zonal mean isotherms, but an attempt at verifying such an hypothesis was not very successful (Tailleux, Lazar, and Reason 2004, unpublished). This failure could be the result of a large fraction of the observed propagating signals being eddies rather than linear waves (Chelton et al. 2007), in which case the above mechanism is not expected to work, for one expects the SST signature of eddies to be rather determined by the prevailing thermodynamic conditions at the time of creation of the latter, rather than by the mean SST gradient through which such features propagate. Moreover, an additional complication in seeking a theoretical understanding of the link between the SST and SSH signature of westward propagation stems from the possibility that the waves or eddies can modulate mixed layer variations through their impact on the shear production of Turbulent Kinetic Energy (TKE), as argued by McGillicuddy and Robinson (1997). The present challenge is to provide a unifying theoretical framework for these different possibilities that can account for the observed dynamical/thermodynamical signature of westward propagation.

2.2.4 Mechanisms of generation and demise
Importance and significance: Understanding the generation and dissipation mechanisms of westward propagating signals is necessary to assess whether these can be correctly captured by numerical ocean models, so as to ensure that the appropriate level of variability can be reproduced by the latter.

So far, the issue of how westward propagating waves and eddies are created in the oceans has received little attention. The main model for the generation of boundary-driven waves is that by White (1977), who suggested that baroclinic Rossby waves are created along eastern boundaries because the geostrophic flow cannot satisfy the no-normal flow condition on its own. Tailleux and McWilliams (2002) suggested that enhanced wave amplitude observed by CS96 in the western parts of ocean basins could be partially accounted for by the excitation of baroclinic modes over topographic features by an
incident barotropic mode, where the coupling is associated with the localized breakdown of WKB theory (Fig. 5). Another widely cited generation mechanism is baroclinic instability. The present challenge is to organize these different ideas in a unified consistent formulation that can be tested observationally.

2.3 Programme and Methodology

2.3.1 Aims

The main aim of the proposal is to improve our theoretical understanding of the physical processes governing westward propagating waves and eddies in the oceans in order to devise practical ways to: 1) maximise the information contents of satellite altimeter and temperature data; 2) to assess the possibility of relating the observable sea surface signatures of westward propagating features to their poorly observable vertical structure; 3) to assess the ability of numerical models to correctly represent westward propagation. The long term objective of the proposal will be to refute or confirm the following hypothesis regarding the nature of westward propagation in the oceans:

**Hypothesis:** Observed westward propagating signals can be interpreted either as boundary-driven waves or eddy-like structures generated in the ocean interior. Boundary-driven waves are generated by wind fluctuations near eastern boundaries; their westward decay is the result of linear dispersion and/or nonlinear instability effects. Eddy-like structures are generated by nonlinear instability mechanisms and/or barotropic/baroclinic interactions over topographic features. The vertical structure of the waves is primarily determined by the bottom-pressure decoupling effect, with corrections from the mean flow. The degree of vertical coherence of the waves is primarily determined by the degree of the nonlinearity of the signal, the vertical coherence increasing with the degree of nonlinearity. The observed zonal wavenumber/frequency spectrum of westward propagation can be explained at leading order by linear theories, but nonlinear corrections are required to account for the observed lack of dispersion at the shortest wavelengths.

2.3.2 Objectives and programme of work

The specific objectives of the proposal are organised into the four work packages detailed below. The objectives will be achieved by combining theoretical/analytical work, idealised and numerical modelling, and analysis of satellite data (altimeter SSH data and microwave SST data). Each work package will generally be done in collaboration with one or several partners whose particular area of expertise are the following:

- Remi Tailleux (Reading): linear and nonlinear theories, observational test of theories, development of numerical methods for idealized numerical studies
- Dudley Chelton (Oregon State University): data analysis, empirical characterization of westward propagation, automatic eddy-tracking methods. Supplier of the microwave SST data.
- Angela Maharaj (MacQuarie University): data analysis, observational test of theories, empirical properties of westward propagation
- Julien Le Sommer (Grenoble): Expertise in nonlinear waves, nonlinear dispersion relations, realistic numerical modelling
- Thierry Penduff (Grenoble): Realistic high-resolution numerical modelling. Supervisor of a PhD student (Albanne Lecointre) involved in the analysis of the vertical structure of westward propagation in numerical ocean models. Comparison models/observations. Supplier of the high-resolution numerical ocean model data.
- Emmanuel Hanert (University of Reading): Finite-element modelling of the ocean circulation, development of idealised models. Specialist in numerical methods.

**Work Package 1:** Theoretical models for dispersive and nonlinear effects on zonal wavenumber/frequency spectrum of westward propagating signals. Assessment of the different linear dispersive theories to account for the observed frequency/zonal wavenumber spectrum (currently underway). Non-linear corrections to linear dispersion relations in wind-driven one- and two-layer QG models with and without topography by analysis of the convolution integral. Empirical investigation of the eastern decay of boundary-driven waves in finite-element shallow water models with one and several layers, with and without topography.

**Work Package 2:** Theoretical models for the vertical structure of westward propagation. Empirical analysis of vertical structure. Assessment of the feasibility of relating the vertical structure of the waves to their surface signature alone. Investigation of higher order baroclinic modes.

**Work Package 3:** Theories for the dynamical/thermodynamical coupling of westward propagation depending on the wave or eddy nature of the signals. Theory for the interaction of the waves/eddies with the mixed layer.


2.3.3 Feasibility and timeline
Preliminary investigation into the feasibility of most issues has generally already been done in most cases, so that we do not anticipate at this time any significant difficulty in delivering all work packages by the end of the project. In any case, the work packages have been designed so that they can be investigated independently of each other. As a result, we expect to be able to complete the objectives of the proposal at a fast pace of a minimum of one publication every six months. The project will be done in partnerships that have been established in the context of a proposal submitted to the French spatial agency for participating in the Ocean Surface Topography Science Team to which DC, TP, and RT already belong. Furthermore, the PI is also interacting regularly with Peter Killworth and Jeffrey Blundell, as well as Paolo Cipollini at the National Oceanographic Center, Southampton. Thus, the present project involves directly or indirectly a large majority of experts with direct expertise on the issue of westward propagation.
References


Tailleux, R., 2003: Comments


Tailleux, R., 2006: Quasi-nondispersive regimes