Chapter 12
Oceanic Planetary Waves and Eddies: A Privileged View from Satellite Altimetry

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12.1 Introduction

Satellite altimetry allows sustained observations of a wide range of ocean dynamics, from features spanning just a few tens of km to the mean global sea level spatially, and from a few days to decades temporally, with profound repercussions on our knowledge of the oceans and how they affect climate. Amongst the many success stories for altimetry, one particularly dear to ocean dynamicists is the systematic detection, characterization and tracking of large- and meso-scale propagating features, virtually ubiquitous in the world's oceans, and their classification as either *planetary waves* or *eddies*, which has involved significant efforts by several research groups. In this chapter we review (in Section 12.3) the main results of these efforts, and highlight the important implications that those findings have had on our understanding of how the ocean works. We also discuss (in Section 12.4) several intriguing questions that have been prompted by the satellite-based observations of propagating features – sometimes challenging the previous knowledge based on insufficient experimental data, other times opening completely new paths of investigation into scientifically uncharted waters. But first we start (in Section 12.2) with a brief explanation of the importance of propagating systems for oceans and climate.

12.2 The Importance of Oceanic Propagating Features

Oceans play a crucial role in the Earth's climate system and in mediating its response to the present radiative forcing imbalance, especially at the longer time scales. Ocean dynamics can be divided into a variety of components, each of which can be considered individually at its own scale, but it is important to keep in mind that it is the interactions between all the components at different scales that makes the

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V. Barale et al. (eds.), *Oceanography from Space*,
DOI 10.1007/978-90-481-8681-5_12,

climate system so complex, intriguing and difficult to understand. Ocean mesoscale features are one of the most important modes of energy transfer in the oceans as well as one of the most important reflections of atmospheric forcing of the oceans.

Energy transfers can occur at a range of scales, from the smallest (such as the transfer of wind energy to the ripples on the sea surface) to the very large (such as the general overturning circulation that ensures that heat is transferred from the equator to the poles). Features of the mesoscale have spatial scales of the order of a few tens to 200 km, periods of the order of 10–100 days and speeds of the order of a few cm/s.

Features at larger scales than this are sensitive to the gradient of Coriolis parameter with latitude. They are characterized by meridional (north-south) oscillatory flow with a westward propagation of their phase. Their behaviour can be easily explained when considering the Earth's shape and rotation: when a parcel of water previously at rest, i.e. with no relative vorticity,[1] is displaced northwards (southward) then its planetary vorticity will increase (decrease). In order to conserve the absolute vorticity it must acquire a negative (positive) relative vorticity, which translates into a counter-clockwise (clockwise) rotation. If a line of particles is subjected to these motions then the changes in the relative vorticity will induce a net westward propagation of the disturbance (Killworth and John, 2001). That these features can propagate at all within the ocean is due to the fact that the ocean behaves as a waveguide: the ocean floor and surface effectively confine energy within these boundaries thus allowing for energy to propagate horizontally within them (Gill, 1982), although there is no westward translation of the water mass associated with the wave propagation. These are called planetary waves (also known as Rossby waves).

Features that propagate westwards can be linear (their propagation speed is largely independent of their amplitude) or non-linear (speed depends on their amplitude). Planetary waves are nearly linear and predominant at the larger scales, (300 km or longer). In contrast larger mesoscale eddies in the form of closed rings (normally of diameters around 100–200 km, see Chelton et al., 2007) propagate with non-linear characteristics, and transfer mass as they propagate. As we will illustrate in detail later, altimetry can be used very successfully to observe both classes of phenomena. Their energy dominates the ocean's energy spectrum at long timescales (Killworth and John, 2001); for example, the kinetic energy associated to mesoscale eddies alone is more than an order of magnitude greater than the ocean's mean (Chelton et al., 2007).

The importance of the westward propagating features within the climate system cannot be underestimated: they have been linked to major climate oscillations such as El Niño Southern Oscillation (ENSO) (Jacobson and Spiesberger, 1998; Fu and Qiu, 2002) and the North Atlantic Oscillation (NAO), they are known to interact with the Meridional Overturning Circulation (Hirschi et al., 2007), they interact

[1] *Relative vorticity* is the vertical component of the vorticity relative to the earth's rotating frame of reference; *planetary vorticity* is the vorticity due to the earth's rotation; *absolute vorticity* is the sum of the relative and planetary vorticity.

and maintain western boundary currents and they can also affect the phytoplankton distribution (hence the biology) of the oceans (Killworth et al., 2004), as we will discuss later.

12.3 Observational Evidence of Planetary Waves and Eddies

Of the two classes of ocean phenomena that we review here, eddies are the one that is more easily observed. Most eddies have a clear thermal signature, which makes them observable in SST images, as satellite-borne infrared radiometers have demonstrated since the late 1970s. Moreover, several other water properties in an eddy have significantly different values from the surrounding ocean (because an eddy tends to retain water in its core as it propagates), which along with their limited spatial scale (a few hundred km at maximum) makes them visible in hydrographic sections from ships and has allowed them to be studied extensively since the 1950s. Detecting planetary waves is more complicated. These waves are essentially internal waves, characterized by displacements of the isopycnals (levels of constant potential density) of a few tens of metres, and their signature in the surface elevation if of the order of just a few cm over length scales of hundreds of km. Until the early 1990s there had been only scarce observational evidence of these waves, despite a sound theoretical consensus on their existence for dynamical reasons (Anderson and Gill, 1975; Pedlosky, 1987; Fu and Chelton, 2001).

The advent of high-accuracy satellite altimetry in the early 1990s, with the TOPEX/Poseidon and ERS-1 missions, dramatically changed our viewing capabilities of planetary waves and also opened the way for great improvements in the observation and characterization of eddy dynamics. For the first time we were able to produce a synoptic, global view of the sea surface elevation, showing the ubiquity of westward propagating features at multiple scales, with the clearest signals being initially interpreted as planetary waves in a seminal paper by Chelton and Schlax (1996).

Due to the westward propagation of planetary waves and eddies, it is sufficient to plot east–west (zonal) sections of altimetric Sea Surface Height (SSH) at a chosen latitude (i.e. a section of the data cube in longitude and time, yielding a characteristic diagram called longitude/time plot or Hovmöller plot), to observe some noticeable signals that propagate to the west over time, with the range of speeds expected for eddies and planetary waves. More usually, the quantity plotted is the SSH anomaly with respect to the local mean, which removes the signature of residual geoid errors and of the mean ocean currents. Figure 12.1 shows one such longitude-time plot in the South Pacific at 14°S. The diagonal features apparent in the diagram (diagonal alignments of positive and negative anomalies moving to the west over time) are the surface signatures of planetary waves and eddies, with amplitudes in the range of $\sim$10 cm and propagation speeds of about 10–15 cm/s. The changing slope of the alignments in the longitude/time domain indicates some variability in the propagation speed. A closer look at the figure also reveals a multitude of horizontal scales for the westward propagating features – the most readily visible propagating features

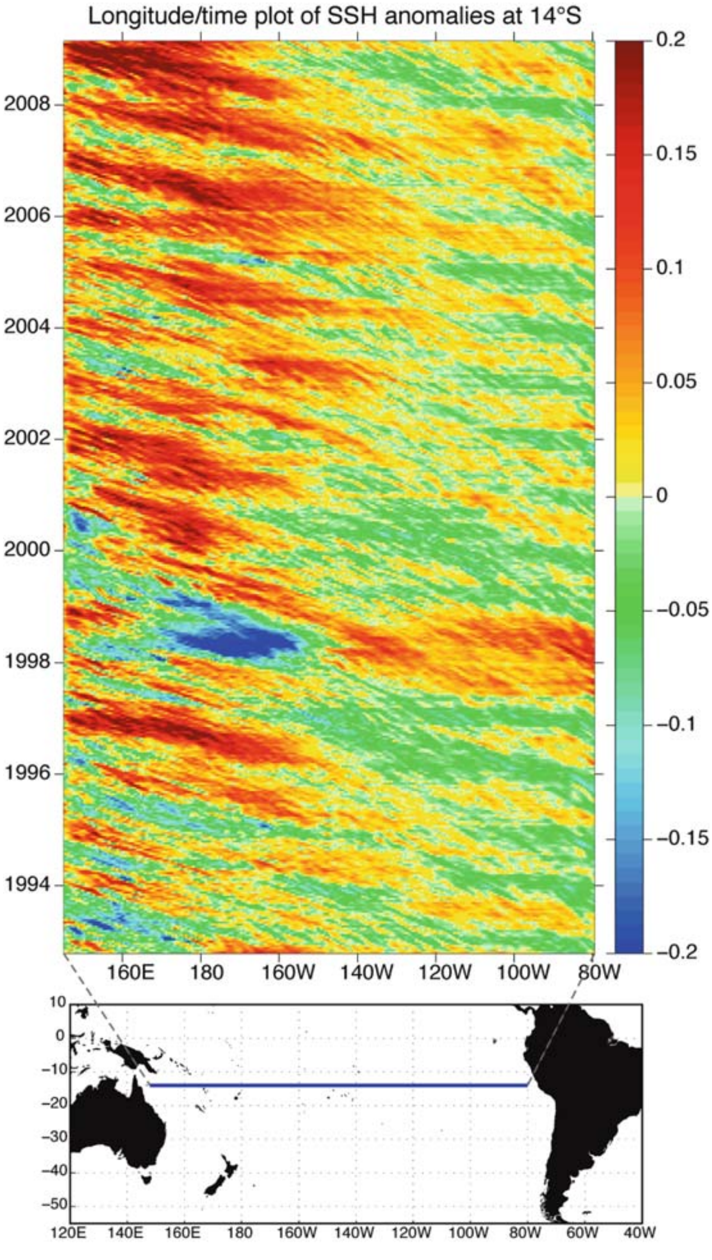

Fig. 12.1 Longitude/time diagram of SSH anomaly at 14°S in the Pacific Ocean (the section is indicated by the *blue line* on the map in the *bottom panel*), clearly showing westward propagating features. Data are SSALTO/DUACS merged multi-mission altimetric SSH distributed by AVISO

have scales of 100–300 km (the finer diagonal stripes in the diagram) but these are superimposed on "bands" of larger longitudinal scale, of the order of 1,000–2,000 km. Similar diagrams have been built for all latitudes in the world's ocean, and westward propagation at many scales is clearly seen almost everywhere. Such diagrams lend themselves to be analyzed with a number of statistical and signal processing techniques, in order to derive objective estimates of the main characteristics of the waves. The two most used analysis tools are the 2-D Fourier Transform, which decomposes the signal into its spectral components, providing an estimation of the zonal wavenumber and frequency for each of those components, and the Radon Transform, a particular image projection that directly offers an objective measure of the main propagation speed of the features. For a detailed description of these two analysis techniques see Cipollini et al. (2006b).

With the build-up of longer altimetric time series, made possible by the various missions that followed (ERS-2, Geosat Follow-On, Jason-1, Envisat and Jason-2, the last three still fully operative at the time of writing in November 2009), the amount of observational studies on planetary waves has increased considerably, giving rise to some important questions for the theoreticians. The most evident discrepancy was the mismatch between the observed propagation speed of the waves and the speeds predicted by the standard (or classic) linear theory of Rossby waves. The observed speeds were up to 2 times faster than the classic theory ones in several regions at mid-latitude, a disagreement already spotted by the early satellite-based studies. This resulted in a formidable amount of work on extending and improving the theoretical models by removing some of the assumptions of the classic one (Killworth et al., 1997; Killworth and Blundell, 1999, 2003a, b; Tailleux and McWilliams, 2000, 2001).

The discrepancy between theoretical and observed speeds is now much reduced with the latest theoretical models (Tailleux and McWilliams, 2001; Killworth and Blundell, 2004, 2005). Figure 12.2 illustrates this concept by showing the comparison of the observed speeds with the speeds predicted by the extended theory by Killworth and Blundell. The observed speeds, displayed in Fig. 12.2a, have been computed over more than 16 years (October 1992–February 2009) of multi-mission SSH anomaly data. The technique employed, which is completely automated, is based on the Radon Transform of longitude/time plots as explained by Cipollini et al. (2006b) using a moving longitude window of 30° and removing the mean value of each longitude-time plot prior to the analysis, as suggested by de la Rosa et al. (2007). Areas within 15° longitude from the coast, where land enters the longitude/time plots, have been blanked out. The theoretical speeds in Fig. 12.2b are from Killworth and Blundell's extended theory (Killworth and Blundell, 2003a, b, 2004, 2005), recomputed with the updated temperature and salinity climatologies of the 2005 World Ocean Atlas (Locarnini et al., 2006; Antonov et al., 2006). A 5° latitudinal band both sides of the equator has been left out of the calculations as the extended theory does not hold for equatorial dynamics; this band is blanked out in Fig. 12.2b.

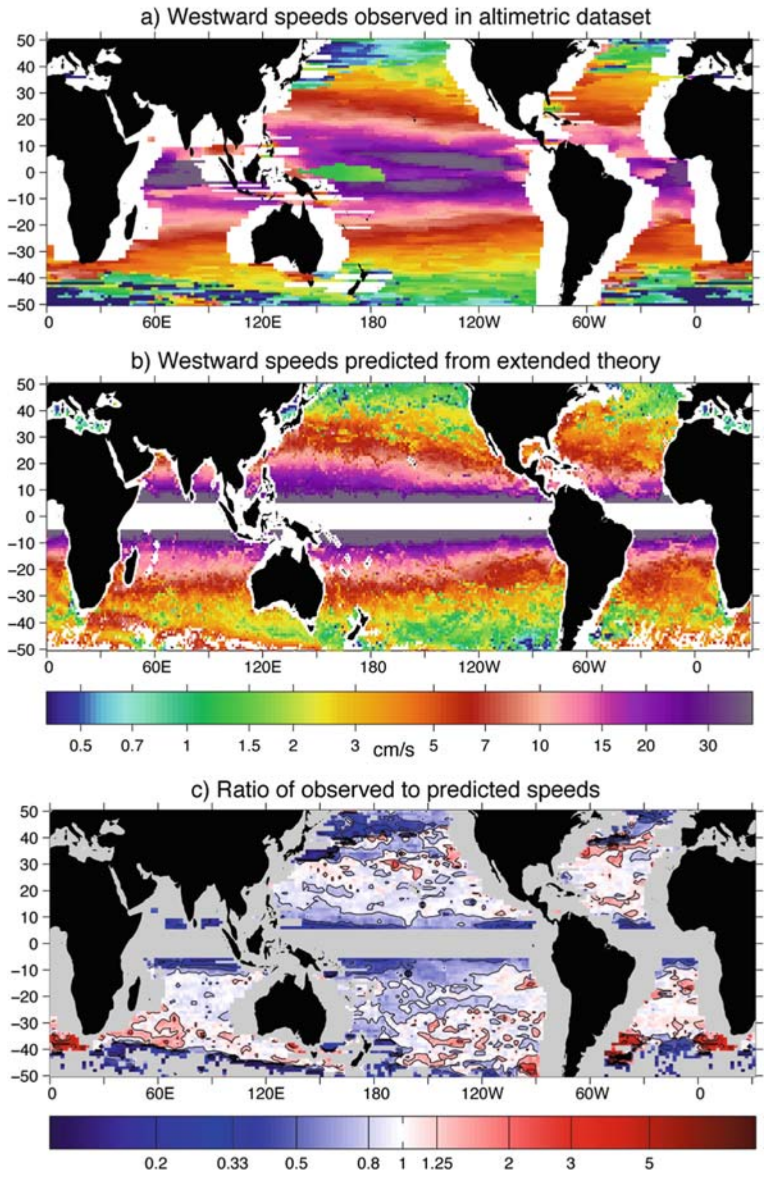

Fig. 12.2 Speeds of planetary waves: (**a**) observed in satellite altimetry; (**b**) predicted by the extended theory; (**c**) ratio of (**a**–**b**). See text for details of the derivation

The level of agreement between the observed and predicted speeds shown in Fig. 12.2a, b can be more easily assessed by looking at their ratio, shown in Fig. 12.2c. Observations and predictions are generally in good accord in the 10–35° latitude band, but slightly less satisfactorily in the South Pacific, for

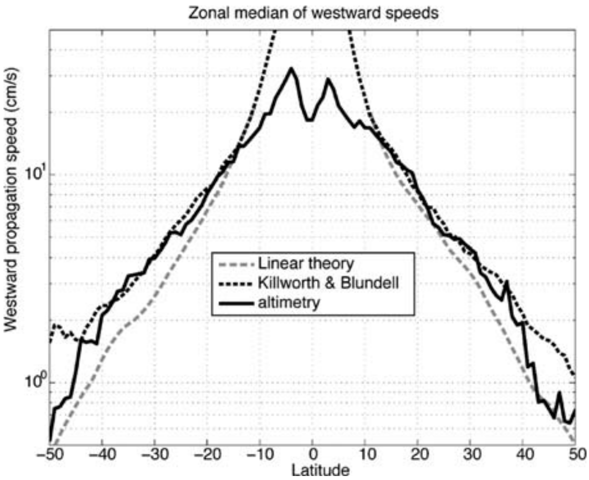

Fig. 12.3 Zonal median of the speeds of planetary waves from the old linear theory (*light gray dashed line*), Killworth and Blundell's extended theory (as in Fig. 12.2b, *dark gray dashed line*) and observed in satellite altimetry (as in Fig. 12.2a, *solid line*)

reasons not yet completely understood and that warrant further investigation. The agreement is also lower in the very energetic regions of the western boundary currents, where current-related instabilities affect the satellite estimates, as well as in the region within ±10° the equator, where the observed speeds are significantly lower than predicted. The discrepancy in this latter region is most likely due to a sampling problem: in fact a longitudinal window with a fixed width of 30° becomes too narrow to capture the dominant wavelengths of planetary waves, which may well exceed 2,000–3,000 km when approaching the equatorial band (Polito and Liu, 2003). Despite these problems over specific regions, the extension of the theory prompted by the altimetric observations represent a dramatic improvement on the classic linear theory, as clearly visible in Fig. 12.3 which shows that the zonal medians (i.e. the median values at each latitude) of the speeds predicted by the new extended theory match the observed speeds significantly better (outside the ±10° band) than those predicted by the classic linear theory.

The development of an accurate theory can also increase our understanding of the processes and dynamics that occur within the oceans. The fact that waves were seen to propagate faster than predicted has led to the discovery of the importance of contributions from sources such as the ocean's background mean flow, local bathymetry and external forcing. The inclusion of a mean background baroclinic flow in the planetary wave theory (Killworth and Blundell, 1999) led to an increase in the predicted wave speeds, reinforcing the idea that the ocean's local properties factor greatly into how the waves propagate. This opens-up a new avenue for thought, as one has to consider the climate scenario in which we live.

With predictions for a heating world and the implications that might have on the oceanic internal structure, the possibility for changes in the properties of planetary waves and eddies is a real one. How those changes might impact on the manner in which momentum and information are distributed across the oceans, begs for further research. In light of this, Fyfe and Saenko (2007) modelled the alteration in stratification of the ocean's upper layers, based on the changes predicted by all the IPCC emissions scenarios. Using only linear theory, the authors found that the heating of the ocean's upper layers would induce a wave speed-up that begins to show at the lower latitudes by the end of the twentieth century, extending to the higher latitudes as time progresses.

The model runs showed a 20–40% increase across all the model scenarios and in particular a 35% speed increase for scenario A2 by the end of the twenty-first century (all compared to pre-industrial era speeds). These results reinforce the notion that the expected changes in ocean properties will change planetary wave speeds, decreasing the ocean's response time to external forcing. This has the potential to change ocean dynamics, such as the time-set of the ENSO, ocean-gyre circulation and western boundary currents, thus impacting on climate. A proper understanding of planetary wave speeds seems therefore to be fundamental to our knowledge of the oceans/climate system and the way we model it.

The coexistence of multiple altimeters with different spatial and temporal sampling patterns (due to the different orbital configuration of the satellite platforms, which results in different orbit inclinations and orbital repeat cycles) has prompted for a merging of the data, based on optimal interpolation techniques (Le Traon et al., 1998; Ducet et al., 2000) in order to increase the resolution of the SSH fields. This merging has improved our view of the mesoscale, allowing a much better resolution of those scales typical of oceanic eddies (for a review see Le Traon and Morrow, 2001). Chelton et al. (2007) have investigated the mesoscale variability of the global ocean using the improved fields (namely, merged TOPEX/Poseidon and ERS-1 and ERS-2 satellite datasets distributed by AVISO), finding that a significant fraction of that variability is accounted for by eddies, mostly non-linear, with amplitudes of 5–25 cm and diameters of 100–200 km. This study and other recent studies on eddies are reviewed by Fu (Chapter 9) in this same volume. Ongoing research is attempting to decompose the westward propagating energy into spectral "macro-components" that can be unambiguously mapped into different processes, and its early results confirm the co-existence of eddies and planetary waves over most of the ocean, with linear waves larger within 20–30° of the equator and non-linear eddies prevailing outside of that band (Matthew Thomas, Personal communication).

12.4 Current Research and Open Questions

Current research on westward propagating features is now focusing on a few questions opened by altimetric observations, alone or in combination with other satellite datasets. In this section we review two classes of "open questions": those that only concerns the physics of the propagating features, and those that instead concern the features' impact on the biology.

12.4.1 Waveguides and Normal Modes

One important dynamical problem is why there appear to be distinctive *waveguides* of enhanced westward propagation in the oceans, as noted for instance at 33–34°N in the Atlantic (Cipollini et al., 1997; Cromwell, 2001). Simulations done with a ray tracing approach (Killworth and Blundell, 2004, 2005) do yield zonal waveguides of enhanced propagation energy due to the convergence of many rays, but sometimes at different latitudes from those observed in the data.

Another significant problem for ocean dynamicists is to ascertain the occurrence and relative importance of the different normal modes of propagation. The barotropic (i.e. depth-independent) mode of planetary waves is believed to propagate too fast to be properly resolved by altimetry, especially when the data are gridded on 10- or 7-day time steps; however Fu (2004) has been able to demonstrate a significant presence of "fast" westward-propagating barotropic energy in some oceanic basins by using TOPEX/Poseidon data gridded on a 3-day orbital sub-cycle. This suggests that at least part of the barotropic energy could be mapped by adopting spatially coarse grids with time resolution of the order of 1 day or less, something that might become feasible with a constellation of small number (<10) of altimeters.

Maharaj et al. (2007) have looked at the significance of the different baroclinic (i.e. variable with depth) modes in the South Pacific by splitting the energy in wavenumber-frequency spectra of SSH anomalies on the basis of "spectral boundaries". These boundaries are dictated by the dispersion curves for the different modes predicted by the various theories of planetary wave propagation. The adoption of Killworth and Blundell's extended theory in place of the classical linear theory results in explaining up to 60% more of the variance in the observed power spectral energy as planetary waves.

As far as the relative importance of the different modes, Maharaj et al. (2007) found that mode 1 is by far the most important, and that mode 2 is significant in places, while modes 3 and 4 are negligible, as shown in Fig. 12.4. The dominance of the first baroclinic mode is evident also in a modelling study carried out over the north Atlantic by Lecointre et al. (2008), and based on the ATL6-ERS26 1/6° simulation (Penduff et al., 2004) performed during the French CLIPPER project. In addition, Lecointre et al. (2008) found a puzzling result that calls for further investigation: while at the surface the model wave speeds agree reasonably well with their counterparts observed in altimetry, below the surface the westward propagating disturbances in the model exhibit a systematic deceleration with increasing depth, by a factor that appears to vary geographically.

This questions the usual normal mode assumption that the speed of propagation of the disturbances is independent of depth. A crucial contribution to a better understanding and full 3-D characterization of the modal structure of planetary waves (and eddies) is expected from the integration of altimetric data and vertical profiles of temperature and salinity (hence density) from the ARGO floats (Gould et al.,

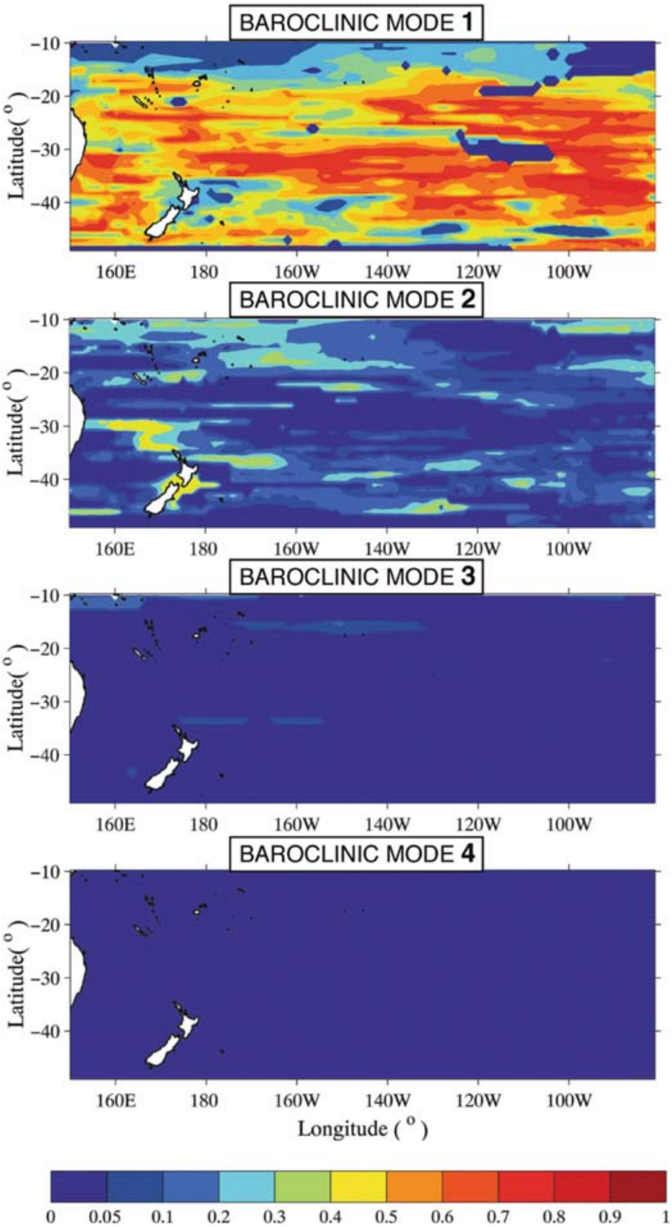

Fig. 12.4 Proportion of the total westward variance in the wavenumber/frequency spectra of SSH over the South Pacific that is assigned to each of the first four baroclinic modes of planetary wave propagation, on the basis of Killworth and Blundell's extended theory predictions. Figure from Maharaj et al. (2007)

2004), whose concentration has been rising in recent years and is approaching the desired level of one float for every 3° × 3° box.

12.4.2 Westward Propagation in Temperature and Ocean Colour

The existence of a signature of westward propagating features in satellite-derived Sea Surface Temperature (SST) data has been known for some time. Hill et al. (2000) were the first to show, using SST data from the ATSR infrared radiometer on board ERS-1, that this signature was almost ubiquitous and at speeds close to those expected for planetary waves, therefore strongly supporting the hypothesis that, in addition to eddies, planetary waves are also visible in these data. This SST signature is important as influential for the processes of ocean-atmosphere interaction.

An even bigger surprise came to the scientific community when, at the beginning of this century, a couple of studies (Cipollini et al., 2001; Uz et al., 2001) showed global, unambiguous evidence of wave-like, westward propagating signals in longitude-time plots of chlorophyll concentrations from ocean colour satellites. Figure 12.5 shows an example of this at around 32°N in the North Atlantic. This prompted several questions on which mechanisms provoke this signature, and more importantly whether its presence indicates a net effect on primary production and ultimately on the carbon budget. A number of studies have investigated these issues in recent years, but this new field of research on the biological effect of planetary waves has not been completely explored and more surprises could be around the corner.

The possible mechanisms involved in the generation of the ocean colour signature of planetary waves can be horizontal – like horizontal advection of meridional (i.e. north–south) gradients of phytoplankton – and/or vertical – like vertical advection of phytoplankton or even upwelling of nutrient due to the passage of the wave, that in turn stimulates growth: this latter mechanism has been dubbed *rototiller effect* (Siegel, 2001). It has also been suggested that the features could be due to convergence/divergence of particles at the surface, with the waves acting as a "hay rake" (Dandonneau et al., 2003) but there does not seem to be widespread consensus on this (Killworth, 2004). While little or no impact on production is to be expected from horizontal and surface mechanisms, the vertical ones are more interesting for their potential effects on the carbon cycle, so it is crucial to ascertain whether and where they occur.

To date, the most comprehensive attempt to model the signals due to all the different processes by which planetary waves would impact on the ocean colour field is the one by Killworth et al. (2004). In parallel to their process modelling, Killworth et al. (2004) performed a global cross-spectral analysis of satellite-derived SSH and chlorophyll which allowed them to estimate which processes were taking place in the real ocean, through the comparison of the observed cross-spectral amplitudes and phases with those predicted for the various processes. Their conclusion is that horizontal advection seems to be the dominant mechanism, but vertical mechanisms cannot be completely ruled out, due to both phase ambiguities between different

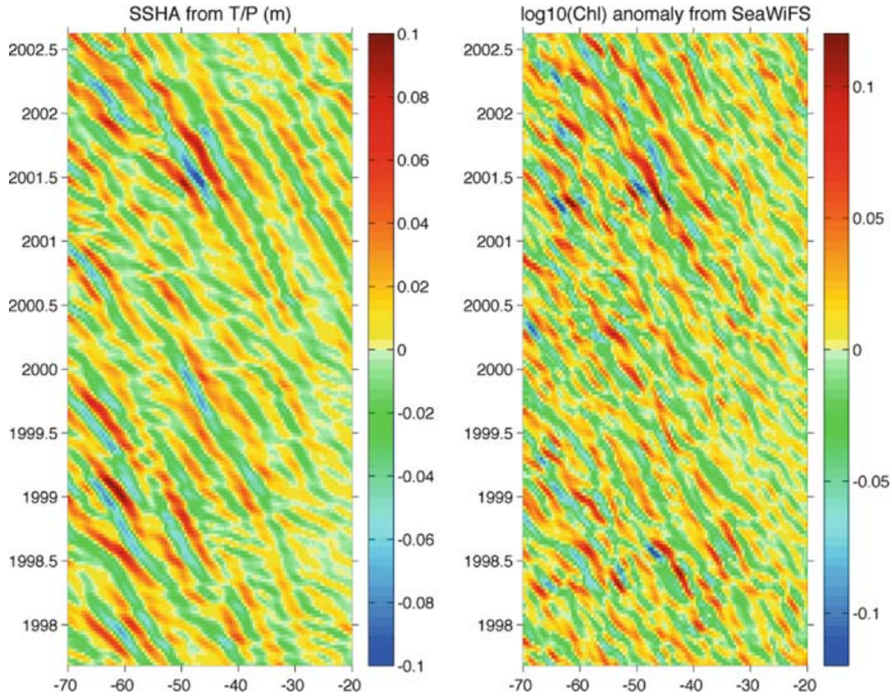

Fig. 12.5 Longitude/time plots of SSH Anomaly (SSHA, *left*) from TOPEX/Poseidon and log10 of the Chlorophyll concentration anomaly from SeaWiFS at 32°N in the Atlantic, clearly showing the signature of similar westward propagating features in the two datasets. The two datasets have been bandpass filtered to retain wavelengths expected for eddies and planetary waves in the westward-propagating quadrants

mechanisms, and the fact that the predicted amplitude for the horizontal advection case is in places lower than the signal observed in the real data.

Charria et al. (2006) have attempted to further quantify the contribution of the different mechanisms with a statistical decomposition of the observed wave signal in ocean colour in the North Atlantic, based on Killworth et al. (2004) models. Their results are obviously strongly dependent on both the process modelling adopted and the statistical assumptions in the decomposition, but nevertheless show a strong prevalence of horizontal advection south of 28°N, while polewards of 28°N horizontal advection and upwelling each contribute approximately half of the observed signal.

The contribution of uplifting is everywhere much smaller than the other two. More recently, Charria et al. (2008) have used a 3-D coupled physical-biogeochemical model to look for the direct influence of planetary waves on primary production, and found some significant local effects, namely increases (generally associated with the chlorophyll wave crest) and decreases (generally associated with the chlorophyll wave trough) in primary production of about ±20% of the estimated background primary production. The symmetric increase/decrease suggests a net weak effect over the basin, but the question is still open and will undoubtedly be the subject of further studies. These will have to make the most of the intrinsic synergies between biogeochemical modelling and satellite observations, but, as ever, altimetry is expected to be the reference for the detection and characterization of the propagating features.

12.5 Conclusions

The clarity with which eddies and planetary waves manifest themselves in altimetric SSH fields has allowed for an unprecedented progress in our knowledge of these important features of ocean dynamics. Brilliant scientific advances – like the characterization of planetary waves that has prompted physical oceanographers to revisit the theoretical framework – have been accompanied by puzzling discoveries (like the occurrence of planetary wave signals in ocean colour fields) that deserve further research. This chapter has reviewed some of the findings and looked briefly at several of the questions still open on planetary waves and eddies.

A very important possibility that opens now, by virtue of the altimetric record now approaching 18 year long, is to detect decadal-scale changes and trends in the occurrence and qualities of eddies and planetary waves, changes that in some cases might be related to climate change. This possibility is certainly going to be explored in detail in the immediate future, while forthcoming altimetric missions hold a lot of promise to extend and further improve the formidable altimetric record that is the foundation for this branch of research.

Acknowledgements We are grateful to Jeff Blundell for his advice and for providing the theoretical speeds from the extended theory. The altimeter products were produced by SSALTO/DUACS and distributed by AVISO with support from CNES via the web site www.aviso.oceanobs.com/duacs/

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