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Manifestation of oceanic Rossby waves in long-term multiparametric satellite datasets

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ABSTRACT

The characteristics of westward copropagating features in satellite altimetry, sea surface temperature and ocean colour data are investigated throughout the global oceans between 50° north and 50° south for the period 1998–2008. A new 'hybrid' filtering approach allowing features with periods between 37 and 410 days to pass polewards of 20° north and south and features with periods between 37 and 205 days to pass within 20° of the equator is found to isolate features whose speed is consistent with predictions of long planetary wave theory throughout much of the oceans. Features with wavelengths between 300 and 800 km and periods between 205 and 410 days are shown to be a significant source of temperature and chlorophyll variability between 20° and 50° north and south, whilst within 20° of the equator, signals in the 800–1500 km and 37–205 days range are predominant. Between 15° and 50° north and south, observed propagation speeds are found to closely match those predicted for first-mode baroclinic Rossby waves by theory. In the equatorial Pacific and Atlantic Oceans, features with wavelengths (800–2000 km), periods (15–40 days) and phase speeds (20–50 cm s^{-1}) characteristic of tropical instability waves are preferentially observed. The amplitude and phase relationship between copropagating signals in ocean colour and altimetry and sea surface temperature and altimetry is interpreted in terms of the horizontal (meridional) advection of mean temperature and chlorophyll gradients by Rossby waves, similar to what has recently been observed for non-linear eddies at shorter length scales. The observed phase relationships are in good agreement with the range of phases expected for horizontal advection throughout much of the oceans and consistent with the sign of the mean meridional gradients of temperature and chlorophyll. These results support the view that horizontal advection (be it from waves and/or eddies) is the dominant mode of covariation of temperature and chlorophyll with sea surface height throughout most of the oceans, although the agreement between predicted and observed amplitude and phase relationships is insufficient to completely rule out vertical mechanisms in a few regions. We believe that a 'one size fits all' approach for global Rossby wave studies can no longer be considered valid, and although we have modified our technique to take this into account, we advocate future work to develop a fully latitudinally dependent filtering methodology.

1. Introduction

Oceanic planetary waves play a crucial role in ocean circulation and climate (Gill, 1982). They maintain the intense western boundary currents (Gill, 1982), and are a key mechanism by which the oceans respond to large-scale atmospheric forcings over timescales of months to years (Jacobs et al., 1994; Polito & Liu, 2003; White et al., 1998). The work of Carl Gustav Rossby in the 1930s (Rossby, 1940; Rossby et al., 1939) was instrumental in developing the fundamental linear theory of planetary waves in the atmosphere and oceans, hence their alternative name 'Rossby waves'. However, the need for observations over long periods and of large spatial extent means Rossby waves in the oceans cannot be adequately characterised using in situ methods (Fu & Chelton, 2001). Kessler (1990), and the references therein, provide an excellent account of efforts to this effect. They have a small surface signature, requiring altimetry with a precision of a few centimetres for their observation.

The advent of satellite-borne altimeters with such resolution (and suitable orbital configuration) in the 1990s enabled oceanic Rossby waves to be studied globally for the first time (Chelton & Schlax, 1996), with a surprising conclusion: observed phase speeds were often at least twice, and at worst 4.5 times, as fast as predicted by the existing theory. This demonstrated that the existing theory, historically invaluable in explaining other oceanic features, could no longer be considered adequate for explaining freely propagating, baroclinic Rossby waves (Chelton & Schlax, 1996; Killworth et al, 1997). The inclusion of background mean oceanic flows, which alter

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the potential vorticity gradient and thus directly affect the speed of Rossby waves, greatly reduced this discrepancy (Killworth et al., 1997). Bottom topography variations were also found to be important on the local scale (Killworth & Blundell, 1999), leading Killworth and Blundell (2003a, 2003b) to develop their extended theory of planetary wave propagation, including both mean flow and topography. However, inferred speeds have, until now, still diverged significantly from predicted speeds polewards of about 35° (Killworth et al., 2004).

Following the initial observations of Rossby waves in the satellite sea surface height (SSH) record, subsequent studies have demonstrated the occurrence of westward propagating features in sea surface temperature (SST; Cipollini et al., 1997; Hill et al., 2000) and in chlorophyll inferred through ocean colour (Cipollini et al., 2001; Uz et al., 2001). Comparison of westward propagating signatures in SSH and SST data (Cipollini et al., 1997; Hill et al., 2000) revealed a broad correlation between the temporal and spatial variation of wave speeds, which also showed a good alignment with Rossby wave speeds predicted from Killworth et al.'s (1997) initial development of the original theory. The presence of westward propagating features in the ocean colour record is somewhat more ambiguous than that found in the SSH and SST data sets, owing in part to the difficulties in extracting the relatively weak westward propagating signature from that of the annual phytoplankton cycle (Cipollini et al., 2001). However, it is clear that westward propagating features may be observed in the ocean colour record at many locations in the major ocean basins (Cipollini et al., 2001; Uz et al., 2001).

The near-ubiquity of apparently Rossby wave-like signals in the global SST and ocean colour records has raised interesting questions about the physical–biological mechanisms through which Rossby waves may affect the upper ocean. Various mechanisms have been suggested, which are discussed in detail by Killworth et al. (2004). If one assumes the presence of a meridional (north–south) gradient in temperature or chlorophyll, it is possible that the geostrophic velocities associated with planetary waves could cause horizontal advection of the parameter in question, and therefore account for the observed signal (Killworth et al., 2004; Quartly et al., 2003). Whilst this theory appears to hold for SST (Hill et al., 2000), discrepancies become apparent when the chlorophyll signal is examined, raising the possibility that other mechanisms may be responsible for the observed wave-like signals in ocean colour at some locations (Cipollini et al., 2001, 2006; Killworth et al., 2004).

In addition to horizontal advection of surface chlorophyll gradients, two vertical mechanisms have been suggested to explain the observed interaction of Rossby waves and biology. The first mechanism involves uplifting of phytoplankton cells or a deep chlorophyll maximum (DCM) through movement of the isopycnals by the passing of a Rossby wave (Charria et al., 2003; Cipollini et al., 2001; Kawamiya & Oschlies, 2001). In a similar manner, Rossby waves could also cause uplifting of the thermocline and therefore vertical effects may influence sea surface temperature in regions characterised by strong vertical temperature gradients. The second mechanism concerns wave interactions with the surface ocean biology whereby nutrients upwelled into the mixed layer through physical processes are used by nutrient-limited phytoplankton for growth (Cipollini et al., 2001; Uz et al., 2001): the so-called 'Rototiller Effect' (Siegel, 2001).

Although the uplifting of phytoplankton cells may change the measurable surface chlorophyll concentration, and perhaps has a limited effect on growth in light-limited populations (Killworth et al., 2004), the effect on total depth integrated concentration would likely be negligible (Charria et al., 2003; Cipollini et al., 2001). In contrast, if upwelling of nutrients stimulates new production in the surface ocean the associated sequestration of carbon could provide an important additional term to the global carbon cycle (Cipollini, 2003), a process akin to the pumping of nutrients to surface waters by eddies (McGillicuddy et al., 1998). In contrast to eddies, which can only advect nutrients vertically as they form or intensify, Rossby waves could uplift nutrients continuously along their propagation path (Siegel, 2001), and the resulting sequestration of carbon might contribute significantly to the global carbon cycle (Charria et al., 2008). Dandonneau et al. (2003) suggested a fourth process by which the accumulation of organic detritus in wave convergence zones could influence surface chlorophyll measured from space (the 'Hay Rake' mechanism). However, Killworth (2004) argued such a phenomenon could not occur from planetary wave effects.

Chelton et al. (2007) suggested that westward propagating signals observed poleward of 25° in altimetric data can be explained through the propagation of nonlinear mesoscale ocean eddies, casting doubt on the interpretation of observed features as Rossby waves. Subsequent tracking of ~36,000 mesoscale features by Chelton et al. (2011b) demonstrated that most of the observed westward-propagating SSH variability consists of isolated nonlinear mesoscale eddies, although the percentage of SSH variance that is explained by them remains difficult to quantify. However, Tulloch et al. (2009) showed that the interpretation of altimetry observations in terms of Rossby waves remains valid up to 30° of latitude. They suggest that nonlinear interactions between Rossby waves and turbulence may explain the observations, in that Rossby waves are readily excited at low latitudes by turbulent geostrophic motion occurring on similar timescales. Poleward of 30° geostrophic turbulence and Rossby waves timescales do not overlap and the resulting energy field is often dominated by turbulence, making it difficult to identify the features as planetary waves. Chelton et al. (2011a) suggest that, on time scales longer than 2–3 weeks, the dominant mechanism giving rise to variability in surface chlorophyll is horizontal advection by eddies.

The potential implications of westward propagating signals (be they waves or eddies) in ocean colour for oceanic primary production and the global carbon cycle have led to a number of recent studies investigating the contribution of the various mechanisms to observed perturbations in the surface chlorophyll field, employing both qualitative analysis of remotely sensed data and quantitative modelling considerations (e.g. Bonhomme et al., 2007; Charria et al., 2003, 2006; Killworth et al., 2004).

Killworth et al. (2004) reported a phase relationship between observed chlorophyll and SSH anomalies that strongly advocated horizontal advection as the dominant mechanism for the formation of features, interpreted as Rossby waves, in ocean colour data. Similarly, in a regional study of SSH, SST and chlorophyll in the Indian Ocean, Quartly et al. (2003) found the phase relationship between the signals in SST and chlorophyll to correlate strongly with the sign of their meridional gradients, supporting horizontal advection as the regionally dominant mechanism by which copropagations may influence both temperature and phytoplankton. However, horizontal advection alone may not account for the full amplitude of the signal in ocean colour data globally (Killworth et al., 2004), leading other authors (e.g. Charria et al., 2006; Gutknecht et al., 2010) to suggest vertical mechanisms may also be important in parts of the World's oceans.

Although the uplifting of chlorophyll is likely to be only a small component of the total signal except in regions where the vertical gradient of chlorophyll is great (for example the South Atlantic Subtropical Convergence Zone; Charria et al., 2003), upwelling of nutrients may contribute significantly in many locations (Killworth et al., 2004). Charria et al. (2006), through a statistical decomposition of the modelling method used in Killworth et al. (2004), found horizontal advection to dominate the observed signal south of 28°N in the North Atlantic Ocean (accounting for more than 70% of the signal). In contrast, polewards of 28°N around 50% of the observed signal amplitude was shown to be due to upwelling of nutrients. With a similar analysis applied to the South Atlantic, Gutknecht et al. (2010) found horizontal advection to prevail outside of the Subtropical Gyre, while in the Gyre upwelling and uplifting together generate approximately half of the observed signal; throughout the whole South