ALTIMETRY, SEA SURFACE TEMPERATURE AND OCEAN COLOUR UNVEIL THE EFFECTS OF PLANETARY WAVES ON PHYTOPLANKTON

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ABSTRACT

In the present paper we discuss the manifestation of planetary waves in sea surface temperature (SST) and ocean colour, and the insight that can be gained by comparing those observations with altimetry. We focus in particular on the discovery of planetary waves in ocean colour, which implies some effects of the waves on phytoplankton. A critical assessment of the various mechanisms that may be responsible for the formation of a signal in ocean colour highlights the important role played by horizontal advection of phytoplankton. However, vertical mechanisms such as upwelling of nutrients cannot be ruled out completely at this stage, and there remains ample scope for a systematic global study of the wave signature in height, colour and SST.

1. INTRODUCTION

Oceanic planetary waves, also known as Rossby waves, play a significant role in ocean circulation and climate [1][2]. Satellite techniques, and altimetry in particular, have allowed a quantum leap in our knowledge of these long-wavelength, westward-travelling waves. The progress since the late 1980s is reviewed, for planetary waves outside the equatorial region, in another paper in the present volume [3]. Although the main impetus to this advance has to be credited to altimetry, in the last 10 years there have also been observations of planetary waves in satellite-derived sea surface temperature (SST) and ocean colour. In the present paper we first discuss the manifestation of planetary waves in those non-altimetric datasets, and we focus in particular on their presence in ocean colour, which implies some effects of the waves on phytoplankton. Then we describe the various mechanisms that can be responsible for the wave signature, and we review critically a few studies that help to establish the relative importance of those mechanisms. Finally we suggest a possible approach to future research on this intriguing topic.

2. OBSERVATIONS OF PLANETARY WAVES IN NON-ALTIMETRIC SATELLITE DATASETS

2.1. SST

Soon after it had been shown that extra-tropical planetary waves are ubiquitous in altimeter-derived sea surface height (SSH) [4], scientists started looking for their signature in SST. In a waveguide of enhanced planetary wave energy around 34°N in the Atlantic, [5] and [6] showed that waves are visible in the temperature record from the Along-Track Scanning Radiometer (ATSR) on board ERS-1, and suggested that the SST observations in that zonal (east-west) band may emphasize the higher order (2^{nd} and 3^{rd}) baroclinic modes. Improvements in the quality of ATSR corrections and processing allowed the detection of the SST signature of planetary waves globally [7]; the ubiquity of planetary waves in SST was later confirmed also by an AVHRR-based study [8]. The nature of the planetary wave signature in SST is still being investigated, however it is worth noting that this signature is important as influential for the processes of ocean-atmosphere interaction, as discussed by [7].

2.2. Ocean Colour

A suggestion that planetary waves may be responsible for some features seen in SeaWiFS chlorophyll concentration images over the subtropical convergence zone south of Africa was in [9], however the first global studies which detected unambiguous large-scale westward propagation in satellite-derived chlorophyll were [10] and [11].

These observations opened important new questions on what mechanisms are responsible for the ocean colour signal, and on whether planetary waves can play a significant role in primary production, in turn affecting the global carbon cycle. Both [10] and [11] speculated that vertical mechanism could play a role in the generation of the planetary wave signal in ocean colour, and [11] estimated that the variance explained by the signal could reach as much as 20% of the total chlorophyll variance in the most oligotrophic regions of the world's oceans. It was however clear from the very start of this area of research that both a detailed formulation of the several possible mechanisms and a quantitative investigation of their significance were required; these have been carried out, at least in part, in a number of studies, which are reviewed in the following sections.

3. POTENTIAL MECHANISMS AFFECTING PHYTOPLANKTON

The possible mechanisms by which planetary waves are capable, in theory, of affecting phytoplankton growth in the ocean range from purely physical to biological-physical.

3.1. Horizontal advection of phytoplankton

The mechanism of horizontal advection is schematized in fig. 1, taken from [12]. Phytoplankton is advected meridionally (north-south) by geostrophic currents associated with planetary waves, whose maximum magnitude is on the sides of the wave. This mechanism, originally proposed for SST as one of the possible explanations of the thermal signature of planetary waves [7], can be considered purely physical, and can only create a detectable phytoplankton anomaly where the existing phytoplankton field possesses a non-zero meridional gradient.

3.2. Vertical advection of phytoplankton (uplifting)

This mechanism consists of the vertical displacement of phytoplankton cells (which therefore become more visible from the surface and from space) as a consequence of the modification of the isopycnals due to the wave passage. As such, it is mainly a physical mechanism, although the change in depth and therefore in light availability may affect the growth of light-limited cell populations and their physiological state. A formulation of phytoplankton vertical displacement in terms of uplifting of the deep chlorophyll maximum and its mixing into the surface layer was suggested by [13] on the basis of a comparison between a biological-physical coupled model and SeaWiFS observations at 12°N in the Indian Ocean. Reference [13] found a significant increment of primary production, which however was not associated with any significant input of nutrients into the surface layer. More recently, [14] have studied the uplifting mechanism in the South Atlantic Subtropical Convergence Zone by means of radiative transfer modelling, and conclude that uplifting is capable of yielding a discernible signal, which compares well with the observed anomalies in that specific area.

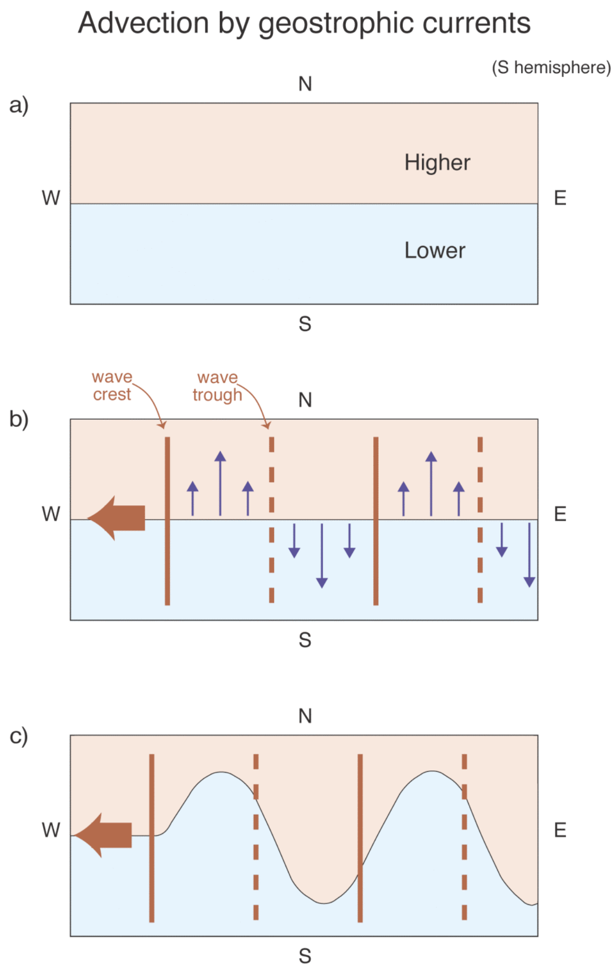

Figure 1. Schematic of the horizontal advection of a meridional gradient of phytoplankton by north-south geostrophic velocities (blue arrows) associated with a planetary wave field. (a) Background tracer field (For the sake of simplicity the gradient has been represented as a sharp front); (b) Tracer field with superimposed a planetary wave field and the associated geostrophic velocity field (indicated by the blue north-south arrows). The bold red arrow shows the direction of propagation of the planetary waves; (c) A possible resulting perturbation in the tracer field. Figure taken from [12].

3.3. Vertical advection of nutrients (upwelling)

Fig. 2 illustrates the upwelling mechanisms. Nutrient-rich water is advected upwards by the lifting of the nutricline on the leading side of the density wave (which corresponds to the trailing side of the wave in SSH) and stimulates phytoplankton growth (new production). Nutrient-depleted water is dragged down on the other side, so that the response to the linear process of upwelling is non-linear (rectification). This mechanism notably differs from eddy-induced pumping of nutrients in that eddies tend to retain water in their core and only advect water vertically when they intensify or weaken, whereas planetary waves would upwell nutrients (and downwell nutrient-depleted water) all along their propagation path – hence the name 'rototiller effect' [15]. Such a mechanism would be of particular interest to biologists, as planetary waves could be one of the 'missing factors' for the supply of nutrients to the upper layer to match observed new production, a question that is still open over large oligotrophic areas of the oceans [16]

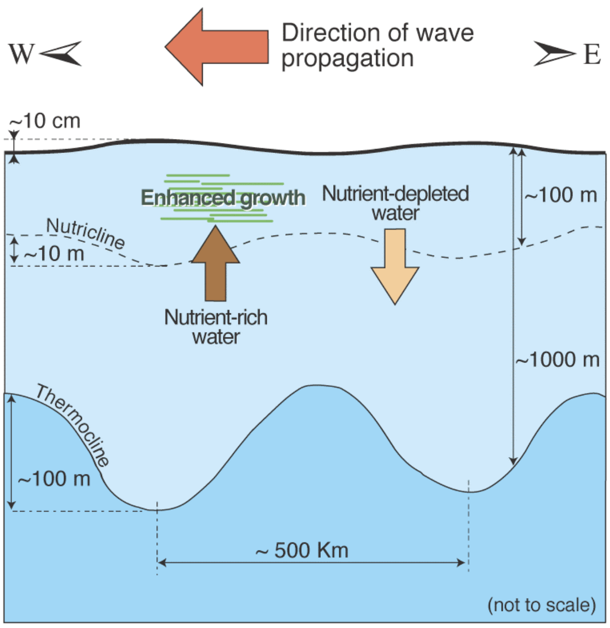

Figure 1. Scheme of the upwelling mechanism for a first mode-baroclinic planetary wave field, with the order of magnitude of the scales of the various features ('thermocline' indicates the midlatitude permanent thermocline). Figure from [12]

3.4. Modelling of the mechanisms and comparison with satellite data

A notable attempt to model the different mechanisms and assess their relative importance has been carried out by [12]. Their approach is based on predicting what the ratio of the amplitude of the chlorophyll signal to the amplitude of the SSH signal, and their phase difference, would be for each one of the diverse mechanisms. Then they move to examine, by cross-spectral analysis of satellite chlorophyll and SSH, the amplitude and phase relationship of the westward-propagating signals in the two datasets, and compare those with the modelled relationships. As an example, fig. 3 shows the modelled phase relationship between chlorophyll and SSH for the horizontal advection mechanisms described in §3.1., versus the observed chlorophyll/SSH phase in the satellite data. The two plots show a broad agreement, and in particular the phase from the data, although noisy, displays the same phase discontinuities of ~π which appear very clearly in the model, and which are due to the change of sign in the meridional gradient of phytoplankton. This fact that the phase discontinuities in the data happen in the same places where the meridional gradient of phytoplankton changes sign is strongly suggestive of horizontal advection being responsible for at least part of the signal. However, phase ambiguities between different 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, led [12] to conclude that vertical mechanisms (uplifting and upwelling) cannot be ruled out everywhere.

4. CRITICAL ASSESSMENT OF THE VARIOUS MECHANISMS

4.1. Horizontal mechanisms

As reported in the previous section, the phase relationship between westward-propagating signals in satellite-derived chlorophyll and SSH, observed by [12], points to the significance of horizontal advection for the formation of a signature of planetary waves in ocean colour. This is in agreement with the findings in SST global studies [7][8]. The advection of meridional gradients of chlorophyll is also the most significant mechanism suggested by [17] to explain some results from a global study of high frequency (<200km) covariation of chlorophyll and SST. Moreover, regional SSH/SST/chlorophyll case studies in the Indian by [18] and [19] also point to this mechanism as predominant in those places.

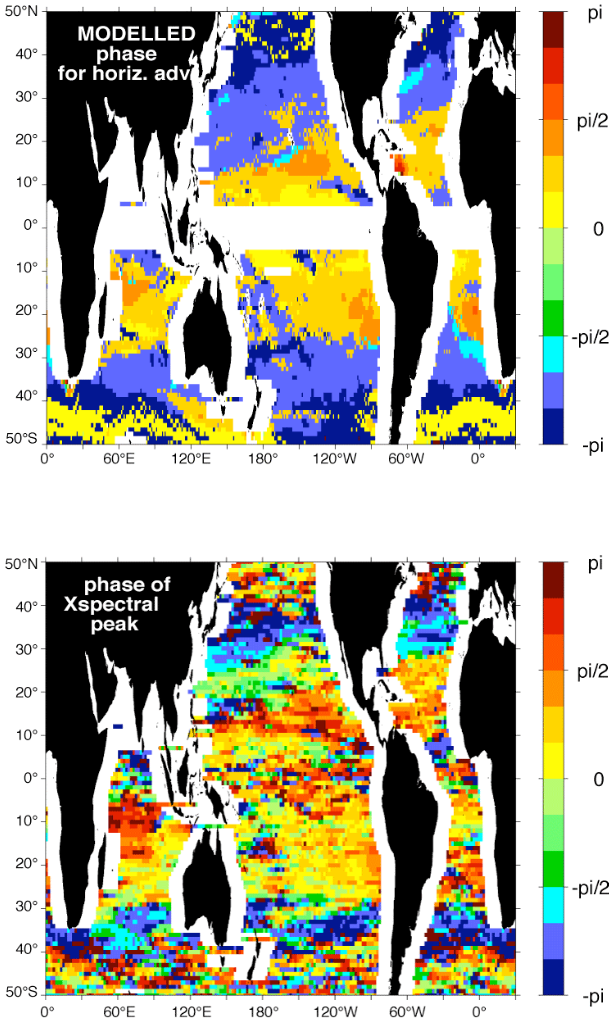

Figure 3. Example of comparison between results from process modelling and results of cross-spectral analysis of satellite data. Upper panel: modelled chlorophyll vs SSH phase for the horizontal advection mechanism; lower panel: chlorophyll vs SSH phase (phase of the largest cross-spectral peak) from cross-spectral analysis of satellite data. Figure from [12]

We can certainly conclude that horizontal advection of chlorophyll must happen, and that in many places it explains a significant part of the signal observed in ocean colour. However, as noted by [12], in several regions of the world's oceans this mechanism does not completely explain the amplitude of the observed signal.

4.2. Vertical mechanisms

The contribution by uplifting of phytoplankton has been found by [12] to be small almost everywhere with existing vertical climatologies of chlorophyll, except in a few areas characterized by very strong vertical gradients. One such area is the South Atlantic Subtropical Convergence Zone studied by [14].

The modelling exercise in [12] suggests that upwelling ('rototiller effect') might be capable of contributing a strong signal in many places. Some independent studies seem to support this hypothesis. These include a global study [20] which found that TOPEX/Poseidon SSH and SeaWiFS chlorophyll are mainly (but not exclusively) negatively correlated at global scale, and a study from TOPEX/Poseidon and in situ data from a mooring off Hawaii [21], which found a nitrate increase and a change in phytoplankton community structure on arrival of planetary waves from east. Recently, [22] have investigated vertical mechanisms by means of a dynamic ocean model with a thermodynamic upper layer coupled with a NPZ ecosystem model. Both uplifting and upwelling give discernible signal in phytoplankton, with upwelling contributing about 75% of signal.

A statistical decomposition of the observed wave signal in ocean colour in the North Atlantic, based on [12], has been tried by [23]. Such a decomposition of the observed signal into contributions due to the different mechanisms needs further statistical assumptions, but then it can provide an estimate of the importance of the various mechanisms. The results in [23] (obviously strongly dependent on both the process modelling adopted and the statistical assumptions in the decomposition) 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.

4.3. The 'hay rake': a non-phytoplankton mechanism?

A possible non-phytoplankton mechanism, the 'hay-rake'-style accumulation of particles at surface, due to convergence/divergence by planetary waves, has been suggested by [24]. The signal detected by the ocean colour sensor would detect the signature of these particles, rather than a change in chlorophyll. There appears not to be full consensus on this mechanisms, as it has been noted [25] that particles may not converge when wave phase speed is taken into account, although the presence of the mean background zonal flow may make them converge in some regions [26].

5. CONCLUSIONS

In this paper we have briefly reviewed the state of the art of the research on planetary wave effects on phytoplankton. It is an established fact that planetary waves are visible in ocean colour, and there is consensus that horizontal advection of meridional gradients of phytoplankton is responsible for at least part of the signal.

However, a key question still remains open on whether vertical mechanisms are important, and if planetary waves can therefore significantly affect primary production and the global carbon cycle. An additional complication to this study stems from recent research [27] suggesting that large part of the westward-propagating energy at latitudes polewards of 25° is in the form of non-linear eddies; this would undoubtedly result in a biological response via mechanisms different from those modelled for planetary waves, mechanisms that need further modelling studies.

In situ observations can certainly help to shed some light on this intriguing problem, as demonstrated for instance by [21], but the time has now come for a global satellite-based SSH/SST/chlorophyll study of westward-propagating features at multiple scales, either with classic statistical/spectral techniques or with feature-tracking techniques [28], which would hopefully help answering the questions outlined above

We conclude by noting that the study of the signature of planetary waves in ocean colour is emerging as a convincing proof of the remarkable insight that can be gained from the synergy of different Earth Observation techniques and from the cross-fertilization of ideas between physicists, biologists and the altimetric, SST, and ocean colour communities.

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