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A window on the deep ocean: The special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation

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ABSTRACT

We show how, by focusing on bottom pressure measurements particularly on the global continental slope, it is possible to avoid the "fog" of mesoscale variability which dominates most observables in the deep ocean. This makes it possible to monitor those aspects of the ocean circulation which are most important for global scale ocean variability and climate. We therefore argue that such measurements should be considered an important future component of the Global Ocean Observing System, to complement the present open-ocean and coastal elements. Our conclusions are founded on both theoretical arguments, and diagnostics from a fine-resolution ocean model that has realistic amplitudes and spectra of mesoscale variability. These show that boundary pressure variations are coherent over along-slope distances of tens of thousands of kilometres, for several vertical modes. We illustrate the value of this in the model Atlantic, by determining the time for boundary and equatorial waves to complete a circuit of the northern basin (115 and 205 days for the first and second vertical modes), showing how the boundary features compare with basin-scale theoretical models, and demonstrating the ability to monitor the meridional overturning circulation using these boundary measurements. Finally, we discuss applicability to the real ocean and make recommendations on how to make such measurements without contamination from instrumental drift.

1. Introduction

In monitoring the global ocean circulation we are faced with a major challenge in the form of the wide disparity in length scales involved. A recent review (Wunsch, 2016) highlighted how this challenge limits what can be said about large-scale, integral properties of the ocean. In essence, the issue is that ocean currents are dominated by mesoscale variability (Ferrari and Wunsch, 2009), with natural length scales of order 10–100 km, so that any one in situ measurement is only representative of a very small region of the ocean. Quantification of mapping accuracy requires a knowledge of the frequency-wavenumber spectrum of ocean variability. To this end, Wortham and Wunsch (2014) have made an effort to characterise this spectrum as seen in the primary physical variables of pressure (and sea level), velocity and density (or temperature and salinity). Their spectrum varies regionally, and most of this variation is designed to reflect the varying characteristics of mesoscale eddies around the world.

One method of obtaining large-scale information is to use a variable which intrinsically integrates some property. Earth rotation measurements are one such variable, but can be difficult to interpret because the integral involves the entire Earth system, not just the ocean. Somewhat more focused is the Earth's gravity field as measured by the GRACE satellite mission. This has provided extremely valuable information about variations in total ocean mass and the sources of water responsible for these changes (Dieng et al., 2015) and is a crucial element of the ocean and Earth observation system, although it does suffer from some of the same ambiguities as Earth rotation, the influence on long time scales of long term plastic deformation of the earth, particularly with respect to the pole tide, remains contentious (Wahr et al., 2015), and it is limited to providing relatively coarse resolution information on ocean bottom pressure variations.

A second way to obtain large-scale information is to have good sampling over the entire ocean. In this respect, satellite altimetry is a particularly powerful system, with sufficient sampling to average out most of the mesoscale variability. Once the trend and seasonal cycle has been removed, the measured variability in global mean sea level has a standard deviation of only 2.5 mm, a level of noise which allows for detection of a trend of 1 $\mathrm{mm\,yr^{-1}}$ from only 2 years of data, compared

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to a typical requirement for local sea level which is measured in decades (Hughes and Williams, 2010).

The Argo float program sampling is now sufficiently dense that a similar noise reduction is apparent in estimates of upper ocean heat content (Wunsch, 2016), although the sampling is significantly poorer than altimetry, and even altimetry leaves significant room for improvement with the present nadir-sampling systems only measuring thin lines along the ocean surface. These systems are providing very important inventory information; how much water there is in the ocean and in different density classes. What they cannot generally do is provide useful transport estimates.

To the extent that the ocean is in geostrophic balance, pressure and sea level represent naturally integrating variables, pressure difference at a particular latitude and depth being proportional to the integrated horizontal current perpendicular to the section. Unfortunately, to obtain a useful integral it must be from boundary to boundary, otherwise the end points are likely to be in regions of strong mesoscale variability and the integral will still be dominated by the mesoscale (Wunsch, 2008). For sea level this is a problem because the boundaries are in shallow water where locally-driven dynamics can dominate, as the direct effect of wind stress on sea level is inversely proportional to the depth. Viscous processes also become important in shallow water, so geostrophic balance does not hold. Furthermore, the boundaries are the most troublesome region for satellite altimetry. Here, special measures must be taken to apply the standard path-length corrections to altimetry, tidal variability is typically larger and more complicated than in the open ocean, and temporal aliasing is more important (Vignudelli et al., 2011).

To give an idea of the size of the signals we are interested in, a good rule of thumb is that, at mid-latitudes where the Coriolis parameter f is about $10^{-4}\,s^{-1}$, a sea level difference of 1 cm (or a pressure difference of 1 mbar = 1 hPa) reflects a transport of 1 Sv (Sv stands for sverdrup, a unit of $10^6\,m^3\,s^{-1}$), on the assumption that the associated geostrophic flow penetrates to 1000 m depth. This is the transport associated with about a 5% change in the Atlantic meridional overturning circulation (AMOC), for example, and is the size of change we might aspire to monitor if changes in global ocean circulation are considered.

To put these numbers into context with the mesoscale variability, Fig. 1 (top) shows the standard deviation of sea level from 20 years of satellite altimetry (trend, annual and semiannual cycle removed). This is deliberately plotted using a saturated colour scale, in order to show how few regions approach variability of only a few centimetres.

It is not just the amount of variability that matters, but also its spectrum in both space and time. For the frequency spectrum, given a certain standard deviation, it is helpful for climate monitoring if the variability is dominated by the highest frequencies, since high frequencies can be averaged out more effectively if sampling frequency is high enough. Fig. 1 (bottom), updated from Hughes and Williams (2010), illustrates the variability in the shape of the spectrum in a relatively intuitive way: it simply shows the colours which would be perceived if the spectrum of sea level variability was translated to a light spectrum, with periods 2–24 weeks mapped on to the visible range, corresponding to wavelengths of 380–760 nm.

More detailed explanation of these colour plots and their scale bars is given in the appendix, but they should not be interpreted in a very quantitative way. For present purposes, the value of these colour spectrum plots is as a qualitative condensation of a combination of information about amplitude of variability (brightness) and spectral shape (colour), which we can also exploit when looking at model diagnostics. Blue colours tend to represent relatively higher variability at high frequencies, and similar colours are often representative of similar processes, but more detailed analysis is needed to confirm this. We will not attempt similar diagnostics for the spatial spectrum because, as we will find, bottom pressure is strongly influenced by topography, so the along-slope and across-slope variations can be very different, something which is difficult to account for with wavenumber spectra in the presence of complex topography.

Our purpose in this paper is to illustrate the value of ocean bottom pressure measurements, and to make the case that such measurements, in particular regions, should be a major part of a global ocean observing system. In the following sections, we will see that bottom pressure is quieter than sea level, and has a "whiter" characteristic spectrum (meaning that it will appear more blue in the spectral colour plots). We will also find that mesoscale variability is strongly damped by steep topography, and give a theoretical reason why that should be expected. Focusing on the steep topography of the continental slope, we will show how this allows us to see global scale ocean processes and to access diagnostics which test simple theoretical representations of the global ocean circulation, particularly the AMOC.

We will make these arguments based on diagnostics from a fine resolution global ocean model. While we will only illustrate these arguments with one model, we have investigated a number of different models with a range of resolutions and architectures, and the general findings we present are robust.

Section 2 describes the model runs, and general aspects of the data analysis, Section 3 discusses the variability and spectra of model sea level and bottom pressure, demonstrating how different bottom pressure is and describing some general features. Section 4 presents a theoretical argument explaining why the mesoscale signal is so strongly suppressed in bottom pressure, particularly over steep topography. Section 5 focuses on the Atlantic continental slope, illustrating the striking coherence of dynamical signals over large distances, and making some links to theoretical ideas and simple models, particularly in the context of the AMOC. Finally, in Section 6 we discuss how this can be applied in the real ocean, highlighting the capabilities and deficiencies of present technology and some possibilities for the future.

2. Model descriptions

The model diagnostics are mainly from the National Oceanography Centre run N006 of the 1/12° global NEMO model. This is a single integration of NEMO v3.6 encompassing years 1958–2012 (inclusive), though it has more recently been extended to 2015. The model is forced by the Drakkar Surface Forcing data set version 5.2, which supplies surface air temperature, winds, humidity, surface radiative heat fluxes and precipitation (Dussin et al., 2014; Brodeau et al., 2010). To prevent excessive drifts in global salinity due to deficiencies in the fresh water forcing, sea surface salinity is relaxed toward climatology with a piston velocity of $33.33\,mm\,day^{-1}\,psu^{-1}$. Sea ice is represented by the Louvain-la-Neuve Ice Model version 2 (LIM2) sea-ice model (Timmerman et al., 2005). Bottom topography is represented as partial steps and bathymetry is derived from ETOPO2 (U.S. Department of Commerce, 2006). Climatological initial conditions for temperature and salinity were taken in January from PHC2.1 (Steele et al., 2001) at high latitudes, MEDATLAS (Jourdan et al., 1998) in the Mediterranean, and Levitus et al. (1998) elsewhere. More details of the model and validation of its representation of the AMOC can be found in Moat et al. (2016).

There is no atmospheric pressure forcing, so the sea level can be considered to be equivalent to the inverse barometer-corrected dynamic topography provided in the satellite data. The output data are averaged over 5-day periods which start at the beginning of each year, giving 73 × 5-day means per year (the last day of leap years is thus not saved). The model is volume conserving (Boussinesq), so we calculate bottom pressure from sea level (multiplied by acceleration due to gravity and surface density) plus an integral of gravity times density using hydrostatic balance exactly as implemented in the model, then subtract off the global area-averaged pressure at each time to enforce mass conservation. The corresponding adjustment to global area-averaged sea level was also made, as described by Greatbatch (1994).

The nominal 1/12° resolution is on the tripolar ORCA12 grid, which is regular in longitude south of 20°N, with Mercator latitude spacing

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