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The spatial variability of vertical velocity in an Iceland basin eddy dipole

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This paper quantitatively assesses the mesoscale spatial variability in vertical velocity associated with an open ocean eddy dipole. High-resolution, in situ data were collected during a research cruise aboard the NERC research ship *RRS Discovery* to the Iceland Basin in July/August 2007. A quasi-synoptic SeaSoar spatial survey revealed a southeastward flowing jet with counter-rotating eddies on either side. The anti-cyclonic component was identified as a mode water eddy, characterised by a homogenous core ($\sim$35.5 psu and 12 °C) centred at a depth of $\sim$600 m. Vertical velocities were calculated by inverting the quasi-geostrophic (QG) Omega equation at each point in a three-dimensional grid encompassing the dipole. The strongest vertical velocities (up to 5 m day^{-1}) were found primarily in the central jet between the eddies, as fast flowing water was forced over raised isopycnals associated with the large potential vorticity anomaly of the mode water eddy. Weaker upward (downward) vertical velocity was diagnosed ahead of the cyclonic (mode water) eddy in the direction of propagation, reaching 0.5 m day^{-1} (2.5 m day^{-1}) at the depth of maximum potential vorticity (PV) anomaly. The results demonstrate that the mesoscale velocity field cannot be accurately reconstructed from analysis of individual isolated eddy features and that detailed three-dimensional maps of potential vorticity are required to quantify the cumulative effects of their interactions. An examination of potential sources of error associated with the vertical velocity diagnosis is presented, including sampling strategy, quasi-synopticity, sensitivity to interpolation length scale and the unquantified effect of lower boundary conditions. The first three of these errors are quantified as potentially reaching 50%, $\sim$20% and $\sim$25% of the calculated vertical velocity, respectively, indicating a potential margin of error in the vertical velocity diagnosis of order one.

1. Introduction

Vertical transport in the ocean is a key conduit for fluxes of heat, salt, carbon dioxide and nutrients, to name but four. The role of mesoscale oceanic features such as fronts and eddies in this transport is increasingly recognised. The three types of mesoscale eddies that have received the most attention are surface cyclonic, surface anti-cyclonic and mode water eddies (McGillicuddy et al., 1999). In the northern hemisphere, the former type of eddy rotate anti-clockwise and are characterised by upward doming isopycnals within their core, often penetrating several hundreds of metres down into the water column. Conversely, anti-cyclonic eddies are characterised by downward dipping isopycnals in the core and rotate clockwise in the northern hemisphere. In the third type of eddy, mode water eddies, isopycnals dome upwards towards the seasonal thermocline and downwards towards the main thermocline, resulting in a weakly stratified lens-shaped water mass in the core. Geostrophic circulation in mode water eddies is dominated by the greater density gradient associated with the dipping of isopycnals towards the main thermocline and, hence, rotate anti-cyclonically.

The requirement for detailed spatial information in order to characterise mesoscale eddy structures and to determine their impact on upper ocean properties has lead to the development of ship-based in situ mesoscale surveying techniques. The advent of towed CTD vehicles such as SeaSoar (Allen et al., 2002) have enabled mesoscale in situ surveys that are both high spatial resolution (3–4 km along-track) and near synoptic, i.e. completed in a shorter time than that taken for a feature to propagate past a point on its trajectory or to significantly alter its own properties. Several high-resolution surveys of mesoscale eddies and fronts have been carried out to date, from which vertical velocities have been successfully inferred using the quasi-geostrophic (QG)

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Omega equation (Allen et al., 2005; Allen and Smeed, 1996; Legal et al., 2007; Pollard and Regier, 1992; Rudnick, 1996). The QG Omega equation (Hoskins et al., 1978) is a useful method for diagnosing vertical velocity in the atmosphere and ocean (Leach, 1987), where the direct in situ measurement of vertical motion is physically impractical. The method assumes that vertical velocity (w), a component of the ageostrophic velocity field, can be determined from horizontal and vertical gradients in the geostrophic velocity field. Several studies have demonstrated the QG Omega equation to be an appropriate approach to diagnosis of mesoscale vertical velocities in regions of low Rossby number, preferable to approaches such as large-scale temperature and vorticity advection (Fiekas et al., 1994; Strass, 1994).

While Allen and Smeed (1996) and Rudnick (1996) solved the full 3-D Omega equation to calculate vertical velocity at the Iceland Faroes front and Azores front, respectively, the requirement for high-resolution data in both the horizontal and vertical directions has often precluded solution of the full 3-D equation. Pollard and Regier (1992) pioneered the use of high-resolution velocity and density data to calculate absolute geostrophic velocity but inferred vertical velocity from a 2-D version of the QG Omega equation along selected survey lines perpendicular to a strong front. Similarly, Legal et al. (2007) applied a similar 2-D approximation to the QG Omega equation to several survey lines crossing the strain region between two counter-rotating eddies, propagating as a dipole. In both instances, horizontal density gradients were deemed negligible in one direction relative to the other, such that a 2-D approximation was an adequate simplification of the full 3-D form of the equation. Both 2-D and 3-D studies have indicated that strong vertical circulations can be associated with mesoscale fronts and eddies, with diagnosed vertical velocities of up to 10–60 m day^{-1} (Allen and Smeed, 1996; Legal et al., 2007; Naveira-Garabato et al., 2002; Pollard and Regier, 1992; Rudnick, 1996).

The objectives of the present paper are two-fold: (i) to diagnose the vertical circulation associated with a mesoscale eddy dipole by solving the full 3-D QG Omega equation with high-resolution, in situ density and velocity data and (ii) to assess the mechanisms driving the spatial variability in vertical velocity. Section 2 describes the collection of physical data and the application of the QG Omega equation. The interpretation of the vertical velocity field takes place in Section 3, followed by a discussion and full examination of potential errors associated with the vertical velocity diagnosis in Section 4. Final conclusions are presented in Section 5.

2. Methods

2.1. Survey design

Data were collected as part of a research cruise to the Iceland Basin (Fig. 1a) carried out between 24 July and 23 August 2007 (Allen, 2008). Daily, near real-time satellite altimetry and ocean colour images for the northeast North Atlantic were used early in (and prior to) the cruise period, alongside current vector data from the vessel mounted Acoustic Doppler Current Profilers (VM-ADCPs), to identify an eddy dipole near the study location (Fig. 1b, image from 17th July 2007). A high-resolution in situ spatial survey of the dipole was carried out using the SeaSoar vehicle (hereafter referred to as S1) within a $\sim$130 km $\times$ $\sim$130 km box consisting of nine closely spaced parallel tracks, approximately 14 km apart and orientated in an east–west direction (Fig. 1c). SeaSoar was successfully towed along 4.5 of the survey lines, but had to be suspended on the remaining survey lines due to adverse weather and/or mechanical issues; see D321 cruise report for more details (Allen, 2008). During the suspension of SeaSoar activity, lowered CTD casts were carried out along the survey lines with $\sim$25 km along-track spacing. The total survey time for S1 was 5.3 days.

A second survey was carried out eight days after the termination of S1, using a traditional CTD rosette as a platform for in situ data collection. Due to limited spatial resolution, the CTD survey was not used in the diagnosis of vertical velocity but is referred to in the discussion of the physical structure of the dipole in Section 3 and so is described briefly here. The survey (hereafter referred to as C2) consisted of seven survey lines orientated in a north–south direction. The survey track, locations of CTD casts and sections where sampling had to be suspended due to bad weather are indicated in Fig. 1d. Horizontal along-track resolution in C2 was $\sim$18 km between CTDs (north–south direction) and $\sim$20 km cross-track between survey lines (east–west direction). The total survey time for C2 was 5.8 days.

2.2. Density and velocity data

SeaSoar carried a Chelsea Technologies Group (CTG) Minipack conductivity, temperature, depth, fluorescence (CTDF) instrument. The lowered CTD vehicle carried a Seabird 9/11plus CTD. Average ship speed during SeaSoar deployments was 8.5 knots, corresponding to an average SeaSoar vertical descent/ascent rate of $\sim$1.3 m s^{-1} and a vertical data resolution of 1.3 m. This tow speed and surface to 450 dbar profiling gave a horizontal resolution of $\sim$3.5 km at the surface and $\sim$2 km at mid-depth. During SeaSoar deployments, data from each sensor were output in real time to an external Linux data acquisition system on SeaSoar (Allen et al., 2002).

A total of 50 CTD casts were carried out; 19 as part of S1 and 31 as part of C2. The maximum depths of CTD profiles, approximated by measured pressure, were 800 dbar in S1 and 1000 dbar in C2. Water samples were taken from all CTD casts at depths (approximated by pressure) of 5, 10, 20, 27, 32, 47, 75, 125, 200, 400, 600 and 800 dbar. Horizontal water velocity data were collected continuously throughout the survey periods using a 75 kHz VM-ADCP, configured to sample over 60 bins of 16 m depth (960 m) and averaged over 5 min intervals.

It is important that considerable care is taken to obtain a reliable basic density field from in situ measurements, in light of the sequence of calculations applied to derive vertical velocity. The initial processing steps for each instrument and full calibration of the in situ temperature and salinity data obtained from SeaSoar and the lowered CTD against independent, coincident data sets (continuous underway surface thermosalinograph (TSG), continuous CTD temperature and conductivity sensor data and discrete bottle samples) are described in full in Pidcock (2011).

2.3. Deriving the geostrophic velocity field

2.3.1. Reference level of known motion

Obtaining vertical velocities from the Omega equation requires a detailed and accurate knowledge of small-scale horizontal gradients in geostrophic velocity. Following the method of Allen and Smeed (1996) and Pollard and Regier (1992), the geostrophic component of the in situ flow at a chosen reference level obtained from the ADCP data was combined with the geostrophic shear calculated from the hydrographic SeaSoar/CTD data relative to the ADCP reference depth to derive absolute geostrophic velocity.

The first step in this process was to determine a depth level in the ADCP data at which the velocity was primarily geostrophic. To do this, 5-km averaged across-track geostrophic velocity calculated from the east–west SeaSoar legs from S1 was compared with the in situ cross-track velocity from the corresponding