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Estimating geostrophic and total velocities from CTD and ADCP data: Intercomparison of different methods

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ABSTRACT

Inferring geostrophic velocity fields from CTD data distributions can be handicapped by the impossibility of referring dynamic height to a no-motion level. This is often the case over the continental shelf, but also at open sea, even when velocity measurements (e.g. from a vessel mounted ADCP) are available. In this paper we test and compare four different methods aimed to estimate the geostrophic and total velocity fields from hydrodynamical data. Two of them can either use only CTD data (then relying on the election of a no-motion level) or incorporate ADCP data (through a multivariate interpolation); the other two methods always combine CTD and ADCP data. A 3D primitive equation model is used to reproduce realistic scenarios that provide control velocity fields and typical CTD and ADCP data profiles. The chosen scenarios represent different dynamic situations (in terms of data quality, bathymetric constrictions and dynamical characteristics such as the relative ageostrophic/geostrophic velocity variance) and make possible a broad discussion on the capabilities and limitations of the examined methods. Results show that the performance of the methods is highly dependent on the dynamics to be resolved. The combination of CTD and ADCP data constitutes the best approach for most of the analyzed situations, though special attention has to be paid when dealing with low quality ADCP data and when the circulation is characterized by intense non-divergent ageostrophic velocities.

1. Introduction

Inferring geostrophic velocities from CTD data distributions is reasonably simple. The most important limitation is that dynamic heights have to be referred to a given level surface, the so called “reference level”. In the deep ocean the reference level is often taken as deep as possible, in order to approach a true no-motion level (hereafter NML) and hence to capture the whole baroclinic contribution to the motion field. However, the data availability at deep levels is sometimes constrained by the sampling methodology (e.g. when data is acquired by an undulating CTD) or by the bathymetry (e.g. when the surveyed domain includes the continental shelf). In such cases, the choice of a proper reference level is problematic: errors in the derived geostrophic velocity can be of the order of several cm/s, having a large impact on higher-order derived variables such as vorticity or the vertical component of the velocity.

Several methods have been developed to overcome these problems. A first group includes the methods that assume the existence of a NML. In coastal regions this level often intersects the bathymetry and therefore many CTD profiles may not extend down to the NML. In such cases the simplest approach is to compute dynamic height only at those stations reaching the reference level, but this usually results in large data voids over the continental shelf. Another common approach is to complete the missing lower part of the water column of shallow profiles (i.e., the layer in between the lower limit of the profile and the reference level) with the

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same layer of the nearest offshore station that does reach the NML. In practice this so-called nearest-neighbour approach has been applied in different ways.

Still within the same group of methods, some better founded approaches have been developed. For instance, the one proposed by Csanady (1979), aimed to estimate the along-shore and across-shore pressure gradients on the continental shelf. The theoretical frame of the method assumes that density gradients are parallel to bathymetry gradients and that the surface elevation field is induced by a uniform density along the coastline. These requirements are not fulfilled in regions where the circulation over the shelf shows significant along-shore gradients and eddies; in such cases Csanady's method is not more accurate than the simple methods described above. Another method proposed by Pedder and Gomis (1998), bases on the use of empirical orthogonal functions. The leading modes of the vertical structure are first computed from profiles spanning the whole vertical domain. Then, the amplitudes of these modes are computed for shallow stations under the constraint of reproducing the existing part of the profile. Finally, the missing part of the profile is obtained by using the leading modes in its full vertical extension. The main limitation of this method is the assumed statistical homogeneity between the shelf and offshore domains, an assumption that is not always fulfilled.

A second group of methods are those that do not necessarily assume the existence of a NML, but make use of independent velocity observations (e.g. obtained by a vessel mounted ADCP) to define a “level of known motion”, rather than a NML. The two main methods falling within this group are the one proposed by Chereskin and Trunnell (1996) and the one proposed by Rudnick (1996). Both methods are constrained by the same assumption: that the non-divergent component of the measured velocity field is equivalent to the addition of the geostrophic velocity (due to the baroclinic component relative to a reference level) plus the eventual barotropic component of the flow. That is to say that the ageostrophic non-divergent component of the field is negligible compared with the geostrophic component.

Finally, another option to estimate the geostrophic velocity over the entire domain is the use of inverse models such as the beta-spiral method (Stommel and Schott, 1977; Schott and Stommel, 1978), the Wunsch method (Wunsch, 1978) or the Bernoulli method (Killworth, 1986). All of them rely on constraining the recovered hydrodynamical fields to obey some balance equations, typically geostrophy, hydrostatic balance and mass conservation (Davis, 1978). They are especially useful at open sea, typically for large-scale domains enclosed by observation transects but poorly sampled inside (Wunsch and Grant, 1982); in such cases, the constraints are reasonable and help to recover the poorly sampled field. However, in the case of small, well sampled coastal regions, the methods described above are more suitable, since some of the constraints used by inverse models (the mass conservation, for instance) may not apply.

In this work, we test the capabilities and limitations of four of the methods described above: two methods based on the election of a NML [The methods proposed by Csanady (1979) and by Pedder and Gomis (1998) are not considered because their assumptions do not fit with the dynamics of the selected scenarios] and the methods proposed by Chereskin and Trunnell (1996) and Rudnick (1996) that combine CTD and ADCP data to infer geostrophic velocities. The methods are applied to synthetic data extracted from different realistic scenarios produced by a numerical model that intend to simulate different coastal and open sea regions of the western Mediterranean Sea. Density and velocity pseudo-observations are extracted simulating a real surveying strategy in terms of spatial sampling and observational errors.

Except for one of the examples, the pseudo-observations are not time dependent and thus they do not account for an eventual lack of synopticity of the data set. The lack of synopticity is recognized as a key error source (Gomis et al., 2005), but the magnitude of the associated errors is highly dependent of the dynamics of the region and on the survey strategy. Here we give some estimation of the magnitude of these errors relative to the errors associated with the different diagnostic methods, but the nucleus of the work focuses on the intercomparison between the methods themselves. The application of all the methods to these pseudo-observations implies the use of an interpolation scheme, which is also recognized as an error source (Gomis and Pedder, 2005). In this work the interpolation scheme is common to all the methods, in order to avoid interfering with the test results. The errors associated with the different methods are computed as the differences between the dynamical fields produced by the methods and the geostrophic and total (geostrophic plus ageostrophic) velocity “control” fields given by the numerical model.

The paper is organized as follows. The main methodological aspects are presented in Section 2: first, the different analysis methods and the interpolation scheme; next, the extraction of data from the numerical model; and last, the scenarios and test cases constituting the core of this work. In Section 3 we present the results, dedicating a subsection to each test case. They are all discussed in Section 4 and conclusions are outlined in Section 5.

2. Methodology

2.1. Analysis methods

Within the group of methods that assume a NML, the approach of computing dynamic height only for the profiles extending down to the reference level is referred to as ‘standard NML’; this is the first of the four methods considered in this work. In this approach, stations not reaching the reference level are simply not considered in the computations, so that in the regions covered by shallow profiles dynamic heights are extrapolated from deeper nearby stations during the spatial objective analysis that precedes the computation of geostrophic magnitudes.

The second method is a version of the nearest-neighbour method: at shallow stations dynamic height is computed at each level relative to the next (in the sense of the vertical spacing of the output grid) and not relative to a common reference level. After station dynamic height data have been interpolated onto the grid, all levels are referred to the lowest one by adding the contributions of all the levels below. The *a priori* advantage of this method with respect to the standard NML method is that profiles obtained at shallow stations take part in the recovery of the dynamic height field (only the missing part of the water column is interpolated from nearby stations). This method will be referred to as ‘stepped NML.’