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Improved global surface currents from the merging of altimetry and Sea Surface Temperature data

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ABSTRACT

Six years of surface velocities have been calculated over the global ocean by combining altimeter derived geostrophic velocities and Sea Surface Temperature (SST) data. The method is based on the inversion for the velocity of the heat conservation equation using the altimeter velocities as background. By accurately prescribing the error both on the background velocities and on the forcing term (heat fluxes), the altimeter background velocities are successfully improved in areas characterized by strong SST gradients and remain unchanged in low SST gradient regions, where by construction no additional information may be brought by the SST field. This allows us to provide for the first time a global field of surface velocities from the merging of altimetry and SST. Both the spatial and temporal resolution of the altimeter derived velocities is enhanced by the SST information. Validation is performed through comparison to in-situ drifting buoy velocities. Major improvements (10–20% globally, up to 35% locally) are obtained on the meridional component of the velocity and in the equatorial band. Due to the large uncertainty on the heat fluxes and the spatio-temporal resolution of the input datasets, the high frequency ageostrophic components of the circulation is hardly resolved by the method and, outside the equatorial band, improvements are mainly on the geostrophic component. It is shown that the level of accuracy obtained by combining altimeter velocities based on a two satellite configuration and microwave SST data is equivalent or higher to the one from a four altimeter constellation in western boundary currents. This opens the perspective for a systematic use of the method to improve the altimeter derived surface velocities over the 1993–2001 period, for which only 2 altimeters have been flying simultaneously. Finally, over the recent years, the use of higher resolution SST products based on both microwave and infrared measurements leads to further enhancement of the accuracy of the altimeter velocities on both the zonal and the meridional component in strong SST gradients areas.

1. Introduction

In recent years, improving the accuracy and resolution of ocean surface currents has become a major issue. As no space mission exists at the moment that directly measures ocean currents from space, the only way is to use other types of remotely-sensed or in-situ measured variables and process and combine them to get information about ocean surface currents. A review of the different approaches that can be found in the literature is given in (Rio et al., 2016). In particular, Ekman currents can be estimated from knowledge of the wind field (Rio and Hernandez, 2003; Rio et al., 2014; Lagerloef et al., 1999) and added to the altimeter derived geostrophic currents (Bonjean and Lagerloef, 2002; Sudre et al., 2013; Rio et al., 2014). On the other hand, the combined use of altimetry and Sea Surface Temperature data has been investigated by many authors in the past, using various methods as the Maximum Cross Correlation technique (Emery et al., 1986; Bowen et al., 2002), the Surface Quasi Geostrophic Theory (Isern-Fontanet et al., 2006, 2014), or other approaches (Gaultier et al., 2014). Recently, Rio et al., 2016 (hereafter RIO16) have investigated the feasibility of applying the classical approach of extracting current information from SST images by inverting the heat conservation equation for the velocity field (Kelly, 1989; Vigan and Podesta, 2000; Vigan et al., 2000; Zavialov et al., 1998). Following Piterbarg (2009), altimeter geostrophic velocities are used as background information. An Observing Simulation System Experiment (OSSE) approach was performed, where outputs from a high resolution numerical ocean model were used to simulate the "true" ocean surface velocities together with observations of Sea Surface Temperature and altimeter geostrophic velocities. Considering a perfectly known forcing and error free Sea Surface Temperature observations, the method was shown to be quite

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efficient to improve the altimeter derived geostrophic velocities everywhere in the ocean, with calculated improvements reaching up to 30–35%. Major improvements were obtained on the meridional component compared to the zonal component of the velocity. Also, an important spatial and seasonal variability was observed, governed by a number of different and sometimes opposite factors as the wind seasonal variability, the SST front direction, the SST/SSH correlation. It was shown that the SST observations were able to bring significant information both at short spatial and temporal scales not resolved by the altimeter system and at larger scales by bringing ageostrophic current information as for Ekman and Equatorial currents. Growing forcing errors were shown to decrease the method efficiency, leading to negative improvements (= deterioration) for forcing errors exceeding 30%. Also, two main issues were identified that would limit the efficiency of applying the method on real datasets: the large errors of existing heat fluxes products needed to estimate the forcing term in the heat conservation equation, and the SST products uncertainty. Despite these two issues, the quite positive results obtained in the OSSE study motivated the present attempt of applying for the first time the methodology on real satellite observations of altimeter geostrophic velocities and Sea Surface Temperature. The data used are described in Section 2. Then, Section 3 gives a reminder of the methodology. In the RIO16 paper only the retrieval algorithm based on perfectly known forcing was implemented. In this study, in order to cope for the large uncertainty on heat fluxes, the unknown forcing version of the method from Piterbarg (2009) has been implemented. A specific work, described in Section 4, has been done to estimate the background velocity and forcing errors. The impact on the retrieved optimal velocities of prescribing the forcing error information is assessed in Section 5. The method has then been applied to obtain 6 years of global maps of improved surface currents. Results are described and validated qualitatively (Section 6) and quantitatively (Section 7). Method sensitivity to the accuracy of the input SST products is analysed in Section 8 and the physical content of the corrective term is discussed in Section 9. Main conclusions are drawn in Section 10.

2. Data

As background information for the velocity field calculation we used daily, ¼ gridded altimeter maps of geostrophic currents calculated at CLS in the framework of the Ssalto-Duacs project and distributed by the Copernicus Marine Environment Monitoring Service (CMEMS) Sea Level Thematic Assembly Center (TAC). Two different products were used, the “twosat” product calculated using information from only two altimeter satellites, and the “allsat” product obtained using all altimeter data available at a given time (Pujol et al., 2016). The spatial resolution of the calculated geostrophic current maps increases with the number of available altimeters (Pujol et al., 2012), typically from 150 to 200 km (2 satellites) to 100 km (4 satellites). Six years of data have been used, spanned over two time periods: 2003–2005 and 2014–2016. Both periods are characterized by a very favorable altimeter constellation: 4 satellites (resp. 5) have been flying simultaneously from 2003 to 2005 (resp. from 2014 to 2016). This allows using the “allsat” altimeter velocities as benchmark for checking the efficiency of the method to improve the “two satellite” altimeter velocity maps. (Section 7).

Sea Surface Temperature maps over the same time periods were downloaded from the Remote Sensing System (REMSS) website. Two products are available, at a daily temporal resolution: a low resolution product (25 km) based on microwave SST observations (TMI, AMSR-E, AMSR2 and WindSat and GMI after 2014), hereafter the MW SST product, and a higher resolution product (9 km) based on the combination of microwave and infrared (Terra MODIS, Aqua MODIS) data, hereafter the MWIR SST product. SST observations are first corrected using a diurnal model to create a foundation (i.e. 10 m) SST that represents a 12 noon temperature. Then both the MW and the MWIR products are calculated using an Optimal Interpolation scheme with 100 km and 4 days correlation scales (Reynolds and Smith, 1994). Both products come with SST error information issued from the optimal interpolation processing. MWIR SST products also include for each grid point a flag indicating if infrared SST measurements were available for the estimation or if the analysed SST is based only on microwave measurements. The most recent Version 5 of the MW SST products is used for both time periods. Version 5 of the MWIR SST product is available only for the 2014–2016 period. Therefore, version 4 of the MWIR SST product is used over the 2003–2005 period. The main changes between Version 4 and Version 5 for the MWIR SST product are the integration of GMI (microwave) and VIIRS-NPP (infrared) measurements, the update of the diurnal warming model and the sensor correlation model, improvements of the rain and cloud quality control and of the sea ice masking.

In-situ surface temperature and the 15 m depth velocities measured by SVP-type drifting buoys were used for validation. Quality-controlled, 6 hourly sampled data were downloaded from the Surface Drifter Data Assembly Center (SD-DAC). The 15 m depth velocities were also used for estimating the error on the background velocities. Buoy temperature measurements were used to assess the error of surface forcing fields.

3. Method

3.1. Optimal merging method

The method applied to improve the altimeter derived geostrophic surface currents using SST information is fully described in the (Piterbarg, 2009) paper. It consists in inverting the heat conservation equation (Eq. (1)) for the velocity (u,v) by using the altimeter derived geostrophic velocities as background information (u_{bck}, v_{bck}):

$$\frac{\partial SST}{\partial t} + u\frac{\partial SST}{\partial x} + v\frac{\partial SST}{\partial y} = F \tag{1}$$

As discussed in RIO16, the forcing term F in Eq. (1) includes the heat fluxes, vertical advection, entrainment velocity and diffusion. All these components are very challenging to measure accurately.

We define a background forcing term F_{bck} and a forcing error term h such as $|F\text{-}F_{bck}| < h$.

In RIO16, the solution obtained considering a perfectly known forcing term has been implemented ($h = 0$). In that ideal case, the optimized velocities (u_{opt},v_{opt}) are obtained (Eqs. (2), (3)) as a function of the background velocities, the forcing term $F_{bck} = F$ and the spatial and temporal derivatives of the SST.

$$u_{opt} = u_{bck} - \frac{A*(A*u_{bck} + B*v_{bck} + E)}{A^2 + B^2} \tag{2}$$

$$v_{opt} = v_{bck} - \frac{B*(A*u_{bck} + B*v_{bck} + E)}{A^2 + B^2} \tag{3}$$

where

$$A = \frac{\partial SST}{\partial x} \quad B = \frac{\partial SST}{\partial y} \quad E = \frac{\partial SST}{\partial t} - F_{bck}$$

The background forcing term F_{bck} is estimated assuming that atmospheric and ocean forcing fields affecting the SST variability are characterized by different spatial and temporal scales. Based on ocean model outputs, RIO16 suggests that the larger spatial scales of the SST temporal variations are mostly due to air-sea forcing and heat while the shorter scales are due to advection. Following this approach, a first order estimate of the heat fluxes is obtained by extracting the large scale component of temporal SST gradients. Further neglecting the contribution of the vertical advection, entrainment velocity and diffusion terms, F is thus approximated by keeping only the largest scales of the SST temporal derivatives (Eq. (4)).