ARTICLE IN PRESS

Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Exploring the synergy between along-track altimetry and tracer fronts to reconstruct surface ocean currents

Francesco Nencioli*, Graham D. Quartly

EOSA, Plymouth Marine Laboratory, United Kingdom

ARTICLE INFO

Keywords:
Satellite synergy
Along-track currents
Ocean Colour CCI
Sea surface temperature
East Madagascar Current

ABSTRACT

High-frequency along-track altimetric data only provide direct information on the geostrophic currents orthogonal to the track. A new approach is proposed that combines these across-track current estimates with directional information from remotely-sensed tracer fields, such as surface chlorophyll concentration and sea surface temperature. The analysis focuses on the South Madagascar region characterised by the strong East Madagascar Current and sharp gradients of surface tracers. The results are compared with in-situ observations from three moorings along the Jason-1 track 196. Accurate information on the total velocity direction is the key factor for obtaining accurate estimates of along-track velocities. Surface tracer fronts can be successfully used to retrieve such information, especially when currents intersect the satellite track at low incidence angles (within ± 60° from the perpendicular direction). Errors in the reconstructed total velocities tend to grow rapidly for higher angles. Best performance is obtained by retaining information from the strongest fronts only. However, this significantly limits the resolution at which total currents can be reconstructed along the altimeter track.

1. Introduction

Surface ocean currents are a key component of the Earth's climate. They regulate the transport and redistribution of heat and dissolved salts, as well as the dispersion of plankton, fish larvae, nutrients and pollutants (e.g. Ganachaud and Wunsch, 2000; Jönsson and Watson, 2016). They also have a significant impact on marine ecosystems since they can define fluid dynamical niches which contribute to the shaping and structuring of population distributions from phytoplankton to top predators (e.g. d'Ovidio et al., 2010; Cotté et al., 2015). As such, they have been included in the list of essential climate variables (Bojinski et al., 2014). Knowledge of their spatial patterns and temporal variability has direct implications on a broad range of socio-economic activities, ranging from fishery and environmental management, to maritime trade and search and rescue operations.

In the last two decades, satellite altimetry has emerged as one of the main sources of observation for the investigation of surface ocean dynamics (Le Traon, 2013). Along-track observations of sea surface height (SSH) from multiple altimeters can be combined together to produce global 2-dimensional fields through interpolation in space and time using optimal interpolation schemes (Le Traon et al., 1998). The gridded maps of SSH can then be used to compute the balanced component of surface ocean currents through the geostrophic balance equations. The 2-dimensional surface velocity fields have an effective resolution of ~150–200 km in space and 5–10 days in time (Chelton et al., 2011). Therefore, while they are capable of resolving processes from basin-scale currents down to the larger mesoscale eddies, they are unable to capture the signature of the smaller scales (100 to 10 km). These include small mesoscale and submesoscale processes, which in recent years have been recognised to be critical for the ocean energy budget (e.g. Capet et al., 2008) and global biogeochemical cycles (e.g. Mahadevan, 2016).

New generation altimeters based on Synthetic Aperture Radar (SAR) technology, such as the European Space Agency Sentinel-3 (https://sentinel.esa.int/web/sentinel/missions/sentinel-3), provide along-track measurements of SSH with a sampling frequency of 20 Hz, resulting in a spatial resolution of ~300 m. Because of the noise affecting the measurements, the smallest scales of currents that can be resolved are in the range of 50 km in highly dynamic areas, but can increase to 100 km in quieter regions (Dufau et al., 2016). Therefore, although these observations are still characterised by a limited spatial (as well as temporal) resolution for the observations of processes of $\mathcal{O}(10)$ km (Chavanne and Klein, 2010), they have the potential to provide information at smaller spatial scales than the gridded fields. Their main limitation is that they can only provide estimates of the velocity component perpendicular to the satellite track.

Approaches based on multi-sensor synergy have the potential to mitigate this limitation and provide the full 2-dimensional velocities

* Corresponding author.
E-mail address: fne@pml.ac.uk (F. Nencioli).

https://doi.org/10.1016/j.rse.2018.04.036
Received 17 September 2017; Received in revised form 10 April 2018; Accepted 19 April 2018

Please cite this article as: Nencioli, F., Remote Sensing of Environment (2018), https://doi.org/10.1016/j.rse.2018.04.036

from along-track observations. Such approaches are particularly attractive in the context of the Sentinel-3 mission, which has the major advantage of having ocean colour, sea surface temperature (SST) and altimeter observations co-localized on the same satellite. Sequential satellite imagery of single surface ocean tracers, such as ocean colour and SST, has been already used in the past to retrieve complementary information about horizontal ocean currents. The various approaches include inverse methods based on heat conservation equation (Chen et al., 2008), neural networks (Côte and Tatnall, 1997), and Maximum Cross Correlation technique (Bowen et al., 2002; Warren et al., 2016). Furthermore, SST has been used within the framework of Surface Quasi-Geostrophy (SQG) to derive the full 3-dimensional velocities within the upper layer (e.g. Lapeyre and Klein, 2006) and, combined with SSH, to reconstruct more accurate horizontal velocity fields (Isern-Fontanet et al., 2014). (Interested readers are encouraged to read Isern-Fontanet et al. (2017) for a detailed overview of these methods.)

Here we present an exploratory study on the capability of retrieving the full velocity components along an altimeter track by exploiting the synergy between observations from different satellite sensors (i.e. across-track velocities from sea level altimetry and directional information from satellite observations of surface tracers). The study was conducted within the context of GlobCurrent (2014–2017; http://www.globcurrent.org/), an ESA-funded project specifically focussed on "advancing the quantitative estimations of ocean surface currents from satellite sensor synergies". In particular, this study aims at addressing two main questions:

1. Can the synergy between along-track altimetry and surface tracer front direction provide reliable total velocities?
2. As along-track altimetry observations are characterised by higher resolution than the mapped products, can such velocities provide dynamical information at scales currently not resolved in multi-satellite 2D surface velocity fields?

2. Data and methods

2.1. The synergistic approach

As surface tracers are continuously stirred by the ocean circulation, their fields are characterised by fronts predominantly aligned with the direction of the main currents (e.g. Lehahn et al., 2007; d'Ovidio et al., 2009). Therefore, front directions derived from surface maps of chlorophyll and temperature can be combined with the across-track velocities derived from along-track altimetry observations to compute total surface velocities. The method investigated in this study combines the direction of chlorophyll and temperature fronts, α_{front} (here defined as the angle between a front axis and the across-track velocity vector) and the altimetry-based across-track velocities V_{across}, to compute the along-track velocities V_{along} as

$$V_{along} = V_{across} \tan(\alpha_{front}) \quad (1)$$

so that the resulting total velocity vector, ***V***, will have direction parallel to the front and the same across-track component as measured from altimetry (see Fig. 1).

By hypothesising that the fronts are predominantly aligned with horizontal surface currents our approach accepts two main assumptions: a) that surface chlorophyll and temperature act as passive tracers - that is, variations due to local production, in the case of chlorophyll, and surface exchanges with the atmosphere, in the case of temperature, are negligible compared with those due to advection, and b) that tracer advection is mostly 2-dimensional - that is, variations due to vertical motions (e.g. upwelling) are of second order compared with the horizontal ones. The validity of these assumptions will be discussed and assessed in Sections 2.4 and 3.1.

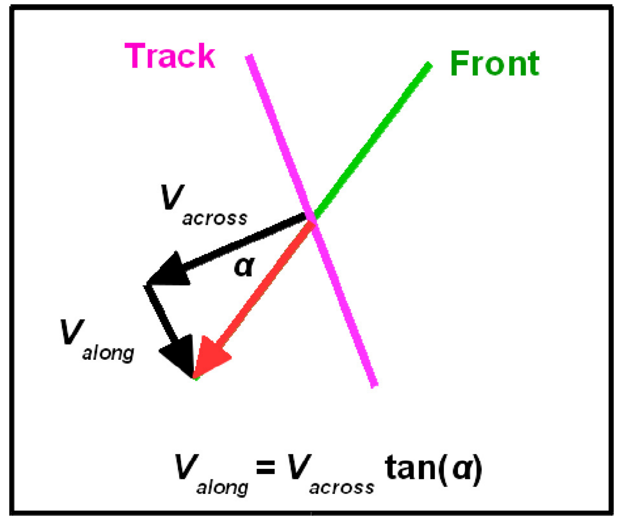

Fig. 1. Diagram illustrating the geometry of the different terms in Eq. (1): front axis and satellite track are shown in green and magenta respectively. The total velocity vector, ***V***, is shown in red. α_{front} varies between −90 and 90°, so that the sign of V_{along} is automatically determined by that of V_{across} (i.e. for a negative α_{front}, V_{along} is positive(southward) when V_{across} is negative(westward), and vice-versa).

2.2. Region of study

The general principles of the method can be applied to any combination of remotely sensed single velocity component and surface tracer front direction. In this study specifically, we applied the method in the South Madagascar region (Fig. 2, top left) combining surface velocities from Jason-1 with front directions from multi-satellite composite observations of surface chlorophyll and sea surface temperature. These particular choices of region and datasets were based on a series of favourable characteristics for testing the proposed approach, which include: a) an intense flow almost perpendicular to the Jason-1 196 satellite track (hereafter J1-196) due to the presence of the East Madagascar Current (EMC); b) strong surface gradients in both temperature and chlorophyll; c) three moorings deployed from February 2005 to April 2006 along the J1-196 track (Quartly, 2006), which provide in-situ velocity observations for validating the results. Although the EMC is a strong western boundary current, the flow field to the south of Madagascar is marked by high mesoscale variability. This has been observed in altimetry, drifters and model output (Quartly et al., 2006), with a good correspondence between features seen in gridded altimetry products and by infra-red and ocean colour sensors (Quartly and Srokosz, 2003). de Ruijter et al. (2004) have shown pairs of large counter-rotating eddies generated by the intense flow and shear within this region. Westward-propagating features are noted in both SST analysis (Quartly and Srokosz, 2002) and in animations of chlorophyll composites (Quartly and Srokosz, 2004). The region is less cloudy than the area of the Agulhas Retroflection to the south of South Africa, so that useful short-period composites of chlorophyll and temperature can usually be achieved for this area.

2.3. Datasets

The analysis is based on the SSALTO/DUACS filtered altimetry data (SSALTO/DUACS User Handbook, 2016) collected along the J1-196 track from February 2005 to April 2006 (Fig. 2, bottom). The data were obtained from AVISO+ (https://www.aviso.altimetry.fr/), but after April 2017, processing and distribution of altimetry products moved to the European Copernicus Marine Environment Monitoring Service (CMEMS; http://marine.copernicus.eu). The data have spatial