Ocean Surface Current Reconstruction: On the Transfer Function between Infrared SST and along-track altimeter observations

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Abstract—The potentiality of retrieving high spatial resolution velocity fields by exploiting the synergy between nearly simultaneous observations of infrared SST and along-track altimetry is shown here through a case study in the Gulf Stream region. The presented approach relies on the characterization of a transfer function between the SST observations and the streamfunction of the flow and allows to improve the spatial resolution and the effective scales of the retrieved velocity field.

I. INTRODUCTION

Ocean currents are a key component to understanding many oceanic and climatic phenomena and knowledge of them is crucial for both navigation and operational applications. Therefore, a key problem in oceanography is the estimation of the synoptic velocity field. Satellite altimetry is probably the most mature technique for mapping ocean currents and has provided great advances in our understanding of large-scale dynamics (roughly >200 km). However, the separation between passes, and the interpolation performed to produce maps of Sea Surface Height (SSH) limits the minimum observable wavelength of the retrieved currents to 150 km [1], scales for which most of the ocean kinetic energy and its dissipation take place. The approach presented in this work aims at improving the spatial and resolved scales of the ocean surface currents by exploiting the synergy between nearly simultaneous observations of infrared Sea Surface Temperature (IR SST) and along-track altimetry observations.

II. THEORETICAL BACKGROUND

Ocean currents are approximately in geostrophic equilibrium, which means that horizontal pressure gradients in the ocean almost exactly balance the Coriolis force resulting from horizontal currents. Under this assumption, velocity field can be retrieved from the streamfunction of the flow (ψ) as:

\[ \vec{v}(\vec{x}) = \vec{e}_z \times \nabla \psi(\vec{x}) \]  

where \( \vec{e}_z \) is the direction perpendicular to the plane.

The streamfunction can be directly estimated from altimetric measurements as:

\[ \psi(\vec{x}) = \frac{g}{f_0} \eta(\vec{x}) \]  

where \( g \) is the gravity constant, \( f_0 \) the Coriolis frequency and \( \eta \) is SSH.

In addition, and under the appropriate environmental conditions, the surface streamfunction can be derived from SST observations as [2]

\[ \hat{\psi}(\vec{k}) = F_T(\vec{k})\hat{T}_s(\vec{k}), \]  

where \( \hat{\psi}(\vec{k}) \) stands for the Fourier transform, \( \vec{k} \) is the wavevector and \( k = ||\vec{k}|| \) is the modulus of the wavevector, \( F_T(\vec{k}) \) is a transfer function that can be analytically derived by fluid dynamic theory and \( T_s(\vec{k}) \) is the SST. For instance, the Surface Quasi Geostrophy equations [3] for constant stratification predicts \( F_T(\vec{k}) \sim k^{-1} \) [4], [5]. Instead, it can be empirically determined from simultaneous SST and SSH observations, as proposed [2], [6]. This approach combines the phase of SST measurements and the amplitude of SSH measurements, and points to build the transfer function between SST and the streamfunction as:

\[ F_T(k) = \frac{g}{f_0} \frac{\langle|\eta|\rangle_k}{\langle|T_s|\rangle_k}, \]  

where \( \langle \cdot \rangle_k \) indicates that the average is taken over those wavevectors with the same modulus.

III. DATA

To characterize the transfer function between SST and the streamfunction (4), we used nearly simultaneous Infrared SST and along-track SSH observations. Particularly, the infrared SST observations were acquired by the Moderate Resolution Imaging Sensor (MODIS) carried by the AQUA satellite. Due to a sensor radiometric calibration issue, stripe noise exists in brightness temperature used for the production of SST maps. The stripe noise has been here reduced by the algorithm described in [7]. In this study the cloud masking has been done by hand and the MODIS observations of 1 km at nadir has been remapped onto a regular 0.02° grid. Given a SST image, we selected all the available SSH along-track observations for the region within a temporal window of ±3 days, centred on the date of the SST field. Altimeter SSH along-track observations correspond to daily Delayed-Time of filtered Absolute
Dynamic Topography (DT-ADT) produced by Ssalto/Duacs and distributed by AVISO (www.aviso.oceanobs.com), which have a spatial resolution of 14 km along the track [8]. The results presented in this study correspond to a region of the Gulf Stream located latitudes between 35.87°N and 43.61°N and longitudes between 63.37°W and 55.63°W for the 6 May 2010 (see Fig. 1).

Additionally, in order to validate the quality of the reconstruction, we used the trajectories of drifting buoys available in the region under study within a temporal window of 20 days centred on the date of the IR SST image (6 May 2010). These data were collected and made freely available by the Coriolis project and programmes that contribute to it ( http://www.coriolis.eu.org ). For comparison purposes, we also used the AVISO gridded altimetry product corresponding to the same date as the IR SST image, which has a spatial resolution of 1/4° × 1/4°.

IV. PROCEDURES

The proposed reconstruction of ocean surface currents that exploits the synergy of SSH along-track and SST observations has mainly two parts. In the first place, the characterization of the transfer function between the SST and the streamfunction, and secondly the reconstruction itself, which basically consists in convolving the SST image with the characterized transfer function (3).

Based on previous studies [2], [6], the median transfer function is fit to a model that accounts for a flat response of the lower wavenumber vectors and a steeper response for higher wavenumber vectors. The analytical expression for this model transfer function can be written as the frequency response of a Butterworth filter [10]:

$$F_T(k) = \frac{A}{\sqrt{1 + \left( \frac{k}{k_c} \right)^{2\alpha}},}$$  \hspace{1cm} (5)

where $A$ is the zero frequency component, $k_c$ is the cut-off wavenumber at which the transfer function response changes and $\alpha$ is the spectral slope. These parameters are determined using an optimization procedure to find the minimum mean square error between the model and the observed median transfer function.

Once the transfer function is characterized, the streamfunction can be derived from the SST observations (3) and thus the velocity field (1). Finally, the normal component of the retrieved velocities are compared to the ones retrieved from altimetry along-track observations.

V. RESULTS AND DISCUSSION

We applied the proposed approach to the Infrared SST field provided by MODIS sensor shown in Fig. 1. We found 11 altimeter tracks available for this region within a temporal range of 6 days centred on the 6 May 2010, date of the considered SST field. In order to characterize the transfer function in the mesoscale range (below 400 km) only tracks with a minimum length of 64 points were considered. This left us with only 3 tracks, the rest of tracks were kept for validation purposes.
The transfer function was computed for every of the 3 available individual track combining SST and SSH observations along the track. Then, the median of all the transfer functions was taken over those wavevectors with the same modulus, as indicated in (4) (see Fig. 2). The median transfer function was then adjusted to the model presented in last section (5), for wavelengths ranging between 400-65 km. The minimum wavelength was set to 65 km, because it corresponds to the cut-off frequency for the filtered SSH along-track data (see [8] for further details). The minimization of the error between the observed median transfer function and the model determined the following parameters: $A = 8.2e^{-5}$ m$^2$C, $k_c = 7.42e^{-5}$ rad/m$^{-1}$ and $\alpha = 1.26$. It is worth to note that the spectral slope of the fit transfer function is slightly higher of what the SQG theory predicts.

The surface streamfunction was derived from the SST field observations and the previously characterized transfer function, using expression (3). The streamfunction allows the retrieval of the two components of the velocity field with the same spatial resolution as the original SST field. Fig. 3 aims to illustrate the limitations we are currently facing to when measuring ocean surface currents from the space and the synergy between different kind of observations. On one side, it shows that altimetric along-track observations can be temporal and spatially sparse, when compared to a single snapshot of SST observations. Secondly, that in those cases where the altimetric observations are sparse, the gridded product of SSH may not properly allocate oceanic structures as already unveiled by [12]. In the case study shown in Fig.3, it can be seen that whereas the eddy centred at around latitude 48°N, longitude 56°W is well sampled by the altimeter track and, in turn, it has a good signature in the SSH gridded product, which is also coherence with the trajectory of a drifting buoy, it is not the case for the signature of an eddy present in the gridded product at longitude 58°W latitude 37°N, which is not sampled by any altimeter track. The trajectory of the buoy, in that case, is indeed partially coherent at the southern part of the eddy present in the southern part of the region considered in Fig.3. However, it does not complete an entire loop like the eddy placed northwards. We checked the quality flags of the buoy data that may indicate a drogue loss, and it was apparently not the case. On the other side, the reconstruction from the SST observations by the characterized transfer function gives a better spatial resolution, and despite it is in general in agreement with the altimetric velocity field and the in-situ data, there are a few exceptions. More specifically, in the region southern 38°N which corresponds to the region that revealed discrepancies between the in-situ and the altimetric observations. Here the discrepancies with in-situ data may be due to the presence of cloud coverage and the quality of the SST field. Another relevant observed discrepancy between our reconstruction and the velocity field obtained from the
Fig. 4. Scatter plot of the velocity component normal to the track retrieved from altimetry (horizontal axis) and from the SST observations and the characterized transfer function (vertical axis).

grid SSH product, is the eastwards velocity observed in the southern part of the main branch of the Gulf stream (i.e: 37°N in Fig.3) in the reconstruction from SST. Nevertheless, this eastward component is in agreement with the altimetric velocity component normal to the track, as shown in Fig. 1 and 3.

In order to further assess the capability of the reconstruction from SST observations, the components of the retrieved velocity field normal to the altimeter tracks were compared to the ones retrieved directly from altimetric observations. Results shown in Fig. 4 indicate a moderate performance of the reconstruction when all tracks are considered with a correlation of 0.3. The computation of the correlation for each individual track allowed us to identify in which cases the reconstruction is better. We had 3 tracks with high correlations, between 0.75-0.85, 7 tracks with correlation between 0.3-0.5 and the rest of tracks presented lower correlations. To get insight on the possible reasons of this moderate performance, the normal components to the track were plotted as a function of latitude. Fig. 5 shows an example of one track with a moderate correlation of 0.41. It can be seen that the in some parts of the track both velocities may appear shifted between one or two positions of the track. This shift could be due to the fact that we are combining observations that are not completely simultaneous. In that sense, it is foreseen to test this approach using ENVISAT observations which provide simultaneous IR SST and along-track, and to further study its temporal and spatial validity. In addition, Sentinels 3, the new ESA operational mission launch last February, will ensure the continuity of the simultaneous SST and along-track observations.

VI. SUMMARY AND FURTHER WORK

In this study, we present the potentiality of retrieving high spatial resolution velocity fields by exploiting the synergy between nearly simultaneous observations of infrared SST and along-track altimetry. The presented approach relies on the characterization of a transfer function between the SST observations and the streamfunction of the flow. Despite the good overall performance of the proposed approach to retrieve high spatial resolution of ocean surface currents shown in this work, a number of important technical challenges remain. Despite the spatial resolution of the retrieved velocity field is the one of the SST field (0.02° in this case), the effective scales resolved are constrained to 65 km, due to the filtering of the along-track data. Nevertheless, it is lower than the scales resolved when using the gridded SSH product (∼150 km [1]). In that regard, Sentinels 3 data could improve the resolved scales, since it will provide higher spatial resolution altimetric observations.

In this case study the transfer function has been characterized using only 3 different tracks, which might be insufficient to properly reconstruct the dynamics of the region. Other data driven approaches, like the analog method, could be used to create pseudo observations of along-track SSH from SST observations, in order to increase the available track data and the characterization of the transfer function.

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