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Assessing the impact of SAR altimetry for global ocean analysis and forecasting

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Abstract :

Satellite altimetry provides essential sea level observations to constrain ocean analysis and forecasting systems. New generation of nadir altimeters now provides enhanced capability thanks to a SAR mode that allows reducing the 1 Hz (7 km) measurement noise level from about 3 to 1 cm RMS. A first assessment of the impact of SAR altimetry for global ocean analysis and forecasting is carried out using Observing System Simulation Experiments (OSSEs) with the global Mercator Ocean high resolution 1/12° system. OSSEs are used to quantify the impact of assimilating multiple altimeter missions with and without a SAR mode. A simple twin experiment set up that only takes into account initialisation errors and impact of altimeter random noise is used. Results are analysed in high eddy energy regions where initialisation errors are the most important ones. Both sea surface height and surface velocity analyses and 7-day forecasts are improved. Compared to conventional altimetry, SAR altimetry sea surface height variance errors for both analyses and forecasts are typically reduced by 20% in western boundary currents. This suggests that use of SAR multiple altimeter missions with high-resolution models will significantly improve the capability of the ocean analysis and forecasting systems in the near future.

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Introduction

Satellite altimetry is an essential remote sensing technique for operational oceanography (see Le Traon et al., 2015 and Le Traon et al., 2017 for a recent review). Multiple altimeter missions provide all weather, global and high resolution sea level observations that are critical to constrain ocean analysis and forecasting systems (e.g. Lellouche et al., 2013; Oke et al., 2015). New generation of nadir altimeters now provides enhanced capability thanks to a SAR mode (also known as Delay-Doppler processing mode) that allows reducing significantly the measurement noise level compared to conventional pulse limited altimeters (Dibarboure et al., 2014; Boy et al., 2017). Noise level for 1 Hz sampling (about 7 km) is thus about 1 cm rms for SAR altimeters compared to about 3 cm rms for conventional pulse limited altimeters (hereafter referred as CONV altimeters).

Cryosat-2 launched in 2010 was the first altimeter mission with a SAR mode. Although Cryosat-2 is a mission dedicated to ice studies, its data have been extensively analyzed to assess the value of altimeter SAR mode over the ocean (e.g. Boy et al., 2017). Sentinel 3 is a constellation of two ocean missions (S3A and S3B) from the European Union Copernicus programme. S3-A was launched in early 2016 and S3-B was launched in Spring 2018. They are both equipped with SAR altimetry. By 2020, Sentinel-6 (Jason CS) that will ensure the long term continuity of the Jason series will also feature a SAR altimetry mode. It is thus expected that in the years to come at least three altimeters with a SAR mode will be flying simultaneously.

A reduced noise level allows a better effective resolution of mesoscale variability along the altimeter tracks (e.g. Dufau et al., 2016). It should also lead to improved ocean analyses and forecasts but this effect has not yet been quantified. Note, however, that a better effective 1D resolution along the altimeter tracks will not necessarily translate into a better 2D resolution as the latter is also mainly dependent on the space/time sampling characteristics of the altimeter constellation.

A first assessment of the impact of SAR altimetry for ocean analysis and forecasting is performed as part of this study. An Observing System Simulation Experiment (OSSE) is carried out with the Mercator Ocean global 1/12° ocean analysis and forecasting system to quantify the impact of SAR versus CONV altimetry. The note is organized as follows. The OSSE design is presented in section 2. Results are discussed in section 3 and main conclusions are summarized in section 4.

Observing System Simulation Experiments

OSSEs use two models (see Hoffman and Atlas, 2016 for a recent review). One model is used to perform a "nature" run. The "nature" run (NR) is sampled to yield synthetic altimeter observations and a noise of 1 cm RMS and 3 cm RMS is added to simulate respectively SAR and CONV altimeter observations. These synthetic observations are assimilated into the second model (Assimilated Run or AR) and the model performance is evaluated by comparison to the NR. In this study, both the NR and the AR are based on the global NEMO model at 1/12° horizontal resolution and 50 vertical levels (identical twin experiment). The AR uses the SAM2 (*Système d'Assimilation Mercator version 2*) data assimilation system (see Lellouche et al., 2013). It is the same data assimilation system used by Mercator Ocean for the Copernicus Marine Environment Monitoring Service (CMEMS). A Free Run (FR) without assimilation is also used to quantify the relative improvement of altimeter data assimilation.

The OSSEs were started from January 7, 2009 over a one-year time period. Two different initial conditions (i.e. January 7, 2009) for the NR and for the AR are required so that we can quantify the impact of assimilating pseudo observations of the NR in the AR. This was achieved by running the two free run NEMO configurations initialized from climatology but at different times. The NR simulation was started in 2003 and the AR was initialized from a 1/12° free run started from 2006. Both NR and AR are forced with ECMWF (European Centre of Medium Weather Forecasting) operational 3-h atmospheric data.

To assess the impact of the number of altimeter data, three satellites (Jason-1, Jason-2 and Envisat) have been considered. Jason-1 and Jason-2 have a 10-day repeat cycle and Envisat a 35-day repeat cycle. Jason-1 was in its interleaved orbit with its ground tracks just in between Jason-2 tracks. Jason-1, Jason-2 and Envisat simulated observations were derived from the NR with an along-track resolution of 7 km (1 Hz) (real Envisat, Jason-1 and Jason-2 tracks were used to simulate the observations). A first OSSE (CONV altimetry) uses an observation white noise of 3 cm RMS that was simulated and added to these pseudo observations. A second OSSE (SAR altimetry) uses an observation noise of 1 cm RMS. Note that as we use the same model resolution for the assimilated run and nature run, we do not have to take into account representativity errors. The observation error covariance matrix is reduced to a diagonal matrix with 9 cm^2 for CONV altimeters and 1 cm^2 for SAR ones.

This study is a first attempt only to assess the sensitivity of ocean analyses and forecasts to the level of random noise in altimeter data. We only assimilate altimeter data and, apart from random noise, we do not consider other sources of errors and, in particular, systematic errors related to the use of external Mean Dynamic Topography (see Le Traon et al., 2017).

Our OSSE design is also a simplified one. We use an identical twin experiment (the same model is used for the AR and the NR) and do not include model and forcing errors in the OSSEs but only initialization errors (see discussion in Halliwell et al., 2014 and Hoffman and Atlas, 2016). This simplified design can result in an overestimation of the impact of altimeter data assimilation. Initialization errors are, however, the most important ones in high eddy energy regions. This was checked by comparing our OSSE innovations (i.e. observations minus model forecasts) statistics in high eddy energy regions with those derived from the global Mercator Ocean operational system that uses the same 1/12° model and data assimilation method. Innovation variances relative to the total signal variance from our OSSEs are consistent with the ones derived from the global Mercator Ocean model. Our OSSEs are thus able to simulate a large part of the error growth between reality and a model assimilating real observations. We also checked that there is not a convergence of the AR towards the NR over time. Our innovations statistics remain stable over time after an initial spin up of about 2 months.

Main results

The two assimilation experiments (SAR and CONV) start the 7th of January 2009 and end the 30th of December 2009. The difference between a given simulation and the NR are used to derive statistics of errors on analyses and 7-day forecasts over the last 7 months (June-December 2009).

Impact of assimilation of altimeter data is analysed on sea surface height (SSH) and surface zonal and meridional velocities (U, V). Errors on temperature and salinity at depths are also analysed to quantify the sensitivity of the results for the deep ocean fields. Analyses are focused on regions with high mesocale variability, notably Gulf Stream (GS), Agulhas Current (AC) and Kuroshio (KU).

Fig. 1 shows the Mean Squared Error (MSE) in the SSH for the free run (FR), i.e. the difference between the FR and NR. As expected, the FR shows large differences with the NR as they provide two uncorrelated mesoscale variability fields.

Fig. 2 shows the MSEs in the SSH for the analyses and forecasts of the two different assimilation runs (SAR and CONV altimetry) as estimated from the difference with the NR. Both SAR and CONV assimilation runs strongly reduce analysis and forecast errors. SAR results are globally better than CONV results.

To summarize results shown on the different maps and to focus on regions with high mesoscale variability, error variances for three Western Boundary Current (WBC) regions (Gulf Stream, Agulhas, Kuroshio) are given in Table 1. Relative error variance reduction of SAR versus CONV altimetry is given in Table 2.

Compared to the FR error variance, SSH analysis errors for SAR and CONV altimetry are of about 10%. This shows the strong contribution of multiple altimeter data assimilation to constrain mesoscale variability in the global 1/12° data assimilation system. 7-day SSH forecast errors are about twice as large as SSH analysis errors (about 20% of the FR error variance). Velocity analysis and forecast errors are, as expected, larger and are respectively about 30% and 50% of the FR error variance for analysis and forecast errors. Note that there are significant differences between the three regions. Largest errors are generally found in the Gulf Stream and the smallest ones in the Kuroshio. We do not have a clear explanation for this result but note that this is consistent with what we observe with real observations in our operational system.

SAR altimetry provides better results for the three different WBC regions both for SSH analyses and forecasts. Although the improvements with respect to the FR error variance are small, the relative improvement with respect to the CONV error variance is quite significant and is on average of about 20%. The largest impact is obtained in the Kuroshio where the relative improvement is almost 40%. Comparable results are obtained for the surface zonal and meridional velocity but the relative impact of SAR versus CONV altimetry is smaller and is on average of about 10%.

Similar calculations were done for temperature and salinity fields. Assimilation of multiple altimeters has a significant impact on the upper ocean temperature fields. Use of SAR altimetry versus CONV altimetry showed slightly improved results but not as large as for SSH and surface velocity.

Conclusion

Observing System Simulation Experiments (OSSEs) carried out with a global analysis and forecasting system at 1/12° have been used to assess for the first time the impact of future multiple altimeter missions in SAR mode. A simple twin experiment set up that only takes into account initialization errors and impact of altimeter random noise is used. Results show a positive impact. In high eddy energy regions where initialization errors are the most important ones, SSH analysis and forecast errors are typically reduced by about 20% with respect to conventional altimeter missions. This suggests that the future altimeter missions developed as part of the EU Copernicus programme should improve the quality of CMEMS analyses and forecasts. This should now be checked with more comprehensive OSSEs and real data. Sensitivity of the results to the data assimilation scheme and its evolutions should also be carried out.

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Sea Level	Gulf Stream		Algulhas		Kuroshio	
	Analysis	***Forecast***	***Analysis***	***Forecast***	***Analysis***	***Forecast***
CONV	37	83	21	48	27	59
SAR	33	75	16	38	17	38
Free12	360	360	366	366	341	341
U	**Gulf Stream**		**Algulhas**		**Kuroshio**	
	Analysis	***Forecast***	***Analysis***	***Forecast***	***Analysis***	***Forecast***
CONV	280	454	198	301	279	412
SAR	257	431	182	278	214	316
Free12	1027	1027	891	891	874	874
V	**Gulf Stream**		**Algulhas**		**Kuroshio**	
	Analysis	***Forecast***	***Analysis***	***Forecast***	***Analysis***	***Forecast***
CONV	271	427	210	321	243	337
SAR	251	405	191	289	207	290
Free12	855	855	970	970	826	826

Table 1: Mean Squared Errors in the analysis and 7-day forecast of the sea surface height and the zonal (U) and meridional (V) velocities for the Gulf Stream, the Agulhas Current and the Kuroshio regions (as defined by Jcommops, see www.jcommops.org). Units in cm^2 for SL and cm^2s^{-2} for U and V.

Error reduction (in %) SAR versus CONV	Gulf Stream		Algulhas		Kuroshio	
	Analysis	***Forecast***	***Analysis***	***Forecast***	***Analysis***	***Forecast***
Sea Level	13	9	22	22	37	35
U	8	5	8	7	23	23
V	7	5	9	10	15	14

Table 2: Reduction (in percentage) of Mean Squared Errors (MSEs) between SAR and CONV for Sea Level (SL), zonal (U) and meridional (V) velocity analysis forecast errors. Statistics are given for three WBC regions: Gulf Stream (GS), Kurohio (KU) and Agulhas Current (AC).

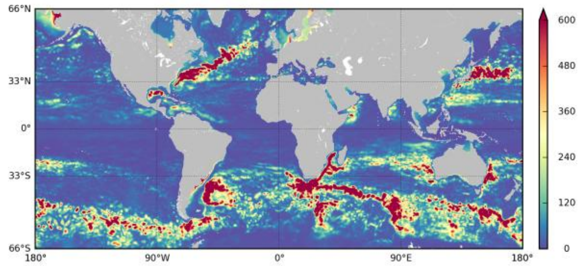
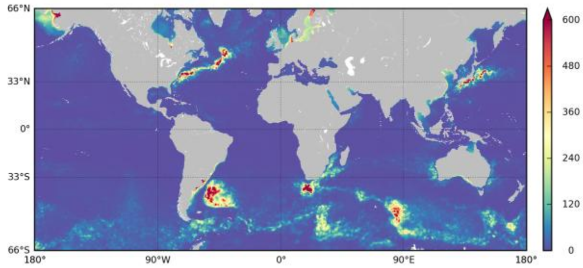
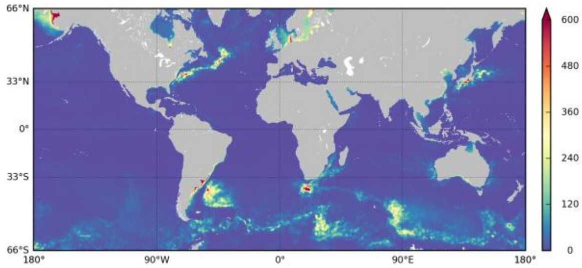


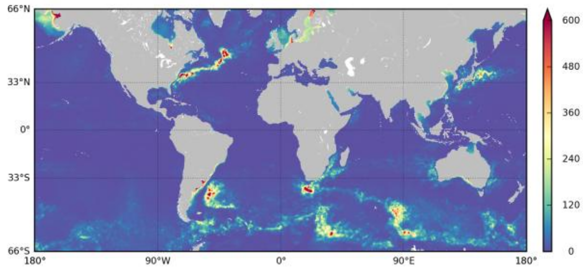
Figure 1: Mean Squared Error for the Free Run. Units in cm^2.



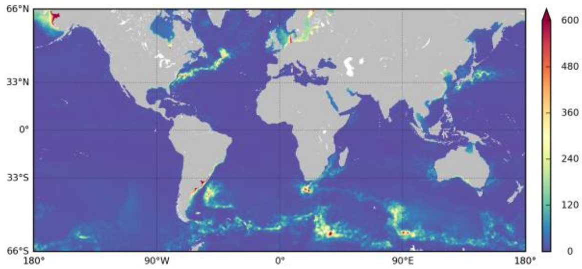
MSE Forecast CONV (c)



MSE Ana CONV (a)



MSE Forecast SAR (d)



MSE Ana SAR (b)

Figure 2: Mean Squared Error for the CONV (a) and SAR (b) analyses and CONV (c) and SAR (d) forecasts for the global high resolution 1/12° Mercator Ocean system. Units in cm^2.