How many altimeters are needed to map the ocean mesoscale circulation ?

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Abstract :

The contribution of merging multiple satellite altimeter missions to the mesoscale mapping of Sea Level Anomaly (H) is analyzed from a North Atlantic high resolution (1/10°) numerical simulation (Smith et al., 1999). The model is known to represent the mesoscale variability quite well and offers a unique opportunity for assessing the mapping capability of multiple altimeter missions.

Several existing or planned orbits (TOPEX/POSEIDON, Jason-1, ERS-1/2-ENVISAT, GEOSAT-GFO) are analyzed and Jason-1 and T/P orbits are assumed to be interleaved. The model sea level anomaly fields are first subsampled along T/P, ERS, GFO and Jason-1 tracks and a random noise of 3 cm rms is added to the simulated altimeter data.

A sub-optimal mapping method is then used to reconstruct the 2D sea level anomaly from along-track data and the reconstructed fields are compared with the reference model fields. Comparisons are performed over the full North Atlantic domain and over a complete year.

1. Introduction

The usually agreed main requirement for future altimeter missions is that at least two (and preferably three) altimeter missions with one very precise long-term altimeter system are needed. The long-term altimeter system is supposed to provide the low frequency and large scale climatic signals and to provide a reference for the other altimeter missions. It requires a series of very precise and inter-calibrated missions (TOPEX/POSEIDON and later on the Jason series). The role of the other missions is to provide the higher wavenumbers and frequencies and, in particular, the mesoscale signal, which cannot be well observed with a single altimeter mission.

Such a requirement for future altimeter missions is partly based on several studies on the sampling characteristics of single and multiple altimeter missions (e.g. Wunsch, 1989; Chassignet et al., 1992; Greenslade et al., 1997; Le Traon and Dibarboure, 1999) although these studies do not always provide quantitative and consistent estimations of the merging contribution.

Le Traon and Dibarboure (1999) (hereafter LD99) have analyzed, in particular, the mesoscale mapping capabilities of multiple altimeter missions (Figure 1). Their main conclusions were that existing and future two-satellite configurations (T/P and ERS and later on Jason-1 and ENVISAT) will provide a rather good mapping of SLA mesoscale variability (mapping error below 10% of the signal variance).

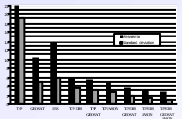


Figure 1 : Mean and standard deviation of sea level mapping error (in percentage of signal variance) derived from a formal error analysis of different single and multiple altimeter missions (Le Traon and Dibarboure, 1999).

The mapping capability of single and multiple altimeter missions is thus still an open and important issue. This paper provides an extension of LD99 study using Los Alamos North Atlantic model simulation (herefater LAM) (Smith et al., 1999). The LAM is a 1/10° primitive equation model forced with realistic winds. It is one of the first basin-scale models with a mesoscale variability in quantitative agreement with T/P and ERS-1/2 altimeter data (Smith et al., 1999) (Figures 2a and 2b).

The model thus offers a unique opportunity for assessing the mapping capabilities of single and multiple altimeter missions.

2. Methods

The model sea level outputs were first transformed into Sea Level Anomaly data by removing a three-year mean (1993-1995). They were then sub-sampled to obtain simulated along-track altimeter data sets for T/P, Jason-1, ERS (or ENVISAT) and GFO. A random noise of 3 cm rms was added to the simulated along-track SLA data. Those simulated data sets were then used to reconstruct the Sea Level Anomaly gridded fields using a space-time sub-optimal interpolation method.

The method is described in detail in Le Traon et al. (1998). The space correlation scales (zero crossing of correlation function) vary with latitude from 250 km at 20°N to 100 km at 60°N and the time correlation (e-folding time) is set at 15 days. These scales are the ones used for mapping real T/P and ERS-1/2 altimeter data (Ducet et al., 1999). These covariance functions are thus only approximations of the actual (i.e. here derived from model fields) covariance functions which is more representative of an actual mapping exercise.

The estimations are performed on a regular grid of 1/10° x 1/10°. We chose to analyze the following configurations :

- one altimeter : T/P, ERS/ENVISAT, GFO
- two altimeters : T/P +ERS, T/P + Jason-1 (interleaved)
- three altimeters : T/P + ERS + GFO
- four altimeters : T/P + Jason-1 + ERS + GFO, 4 interleaved T/P (or Jason-1).

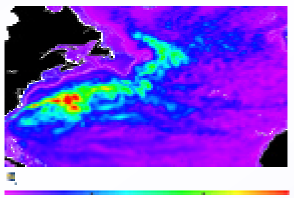


Figure 2a : Los Alamos Model rms sea level variability for the year 1993 (Smith et al., 1999).

Comparison of the reconstructed fields with the reference model fields allows an estimation of the mapping error. The main interest of such a simulation is that it allows us to visualize the mapping errors. In practice, the comparison was made over a one year period (1993) with maps calculated every 9 days, i.e. we compared a total of 40 maps. The calculations were done on a large area from 20°N to 60°N and 80°W to 5°W, i.e. covering the full North Atlantic.

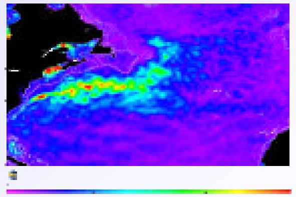


Figure 2b : Rms sea level variability for the year 1993 from the combination of T/P and ERS-1 data (Ducet et al., 1999).

3. A few illustrative results

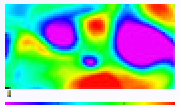


Figure 3: Los Alamos Model sea level anomaly in the Gulf Stream area in jj/m/ 93. Units are cm.

As an illustration, figure 3 shows the Los Alamos Model (LAM) sea level anomaly for a particular day in the year in an area centered on the Gulf Stream. The LAM signal ranges from –100 cm to + 100 cm and corresponds to meanders, rings or eddies of the Gulf Stream and its extension. The same field was reconstructed from T/P, T/P+ERS, T/P+ERS+GFO and T/P+Jason-1+ERS+GFO simulated along-track data (figures 4a to 4d). The mapping errors, i.e. the differences with the reference LAM field, are shown on figures 5a to 5d for the different orbit configurations.

The signal is qualitatively well recovered with all configurations except for the T/P case which shows large differences with the reference field. The other configurations also more and less miss the small space (and time) scales of the model. The rms difference is xx cm, xx cm, xx cm and xx cm for T/P, T/P +ERS, T/P+ERS+GFO and T/P+Jason-1+ERS+GFO respectively. The signal variance is about xx cm^2 which means that the relative mapping errors (in percentage of signal variance) are all below 10% except for T/P.

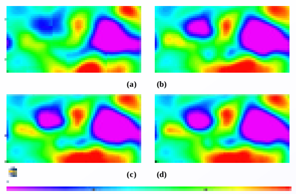


Figure 4 : Same as figure 3 but reconstructed from simulated along-track altimeter data for T/P (a), T/P+ERS (b), T/P+ERS+GFO ©, T/P+JASON+ERS+GFO. Units are cm.

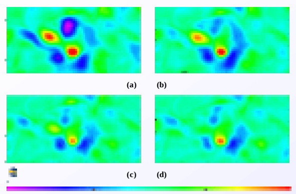


Figure 5: Sea level mapping error (difference between the figure 1 reference field and the fields reconstructed from simulated along-track altimeter data in figure 2) for T/P (a), ERS (b), GFO (c), T/P+ERS (d), T/P+Jason-1 (e), T/P+ERS+GFO (f), T/P+Jason-1+ERS+GFO (e). Contour interval is 2 cm.

Figure 6: Evolution in time of the sea level mapping error at 34.8°N – 70°W for T/P, T/P+ERS, T/P+ERS+GFO, T/P+Jason-1+ERS+GFO. The model sea level anomaly is also shown. Units are cm.

The mapping capability varies in space and time. Some configurations have a mapping error very stable in time (e.g. T/P, T/P+Jason-1) while others have complex space/time variations of mapping errors (GFO, ERS). To complement the previous illustration, we show the evolution in time of mapping error at a given location for the different satellite configurations (figure 6).

The point location is situated between two T/P crossovers in the center of the figure 3 (34.8°N – 70°W). T/P error is, of course, large (10.79 cm rms). T/P+ERS is smaller (10.02 cm rms); the combination of T/P+Jason-1+ERS+GFO has the smallest error, of course, (8.04 cm rms) but the gain relative to the T/P+ERS+GFO configuration is small.

The two and three satellite combinations have thus rms errors below x cm with maximum errors generally below x cm. Such mapping errors are much lower than the signal which has an rms of xx cm. Thus, the variations in time of the mapping errors will not be a problem for interpreting the reconstructed ocean signal. These variations are actually more representative of very short time scale events in the model fields rather than time inhomogeneity of the mapping error.

This is clearly observed near day 250 which corresponds to a very rapid evolution of a Gulf Stream meander.

This event is not well captured even with the four satellite configuration because it has a typical time scale of a few days and spatial scale of a few tens km (figure 7). If these events are representative of the real ocean, they will be very difficult to map from altimetry.

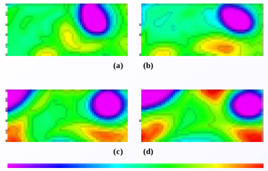


Figure 7 : Los Alamos Model sea level anomaly in the Gulf Stream area for days 247 (a), 250 (b), 253 (c) and 256 (d) in year 1993. They show the rapid evolution of the Gulf Stream meanders and eddies with sea level variations of up to 30 cm in 3 days. Units are cm.

4. Statistical results

For each of the analyzed configurations, the sea level mapping errors were calculated over one year (1993) over the full domain coverage. Results for T/P, T/P+ERS, T/P+ERS+GFO, T/P+ERS+Jason-1+GFO are shown on figures 8a to 8d. They can be compared with Figure 3 which represents the model rms sea level variability. The improvement of mapping capability when going from one satellite to two satellites is plain to see. With the T/P and ERS combination, the error is much reduced (by a mean factor of about 4). The error decreases with three and four satellites by xx% and xx% respectively.

The decrease is not as much as was expected. Even with four satellites, the errors are about 15 cm rms in the Gulf Stream area which is to be compared with the signal itself which reaches 50 cm rms there. This is mainly due to the high frequency and high wavenumber variability of the model fields (see figure 5). In the Gulf Stream area, the rms of signals with periods of less than 20 days and wavelengths of less than 200 km (which are not resolved even along T/P tracks) is more than 10 cm. These signals can only be captured with a very dense spatial and temporal sampling (at least four "optimized" altimeter missions).
Table below gives the mean (in space and time) and standard deviation of the mapping error in the Gulf Stream area (34°N-39°N – 70°W-60°W). Errors in percentage of signal variance are also given. For the table, we also included results of ERS, GFO, T/P+Jason-1 and of the four interleaved T/P.

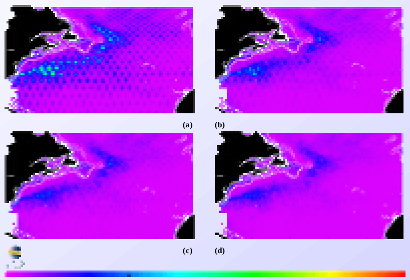


Figure 8 : Rms sea level mapping error for T/P (a), T/P+ERS (b), T/P+ERS+GFO (c), T/P+Jason-1+ERS+GFO (d). Units are cm.

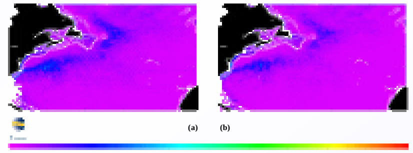
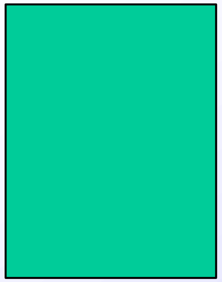


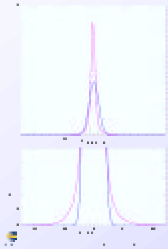
Figure 8b : Rms sea level mapping error for optimized configurations T/P+JASON (a), Four interleaved T/P (b). Units are cm.

Table below gives the mean (in space and time) and standard deviation of the mapping error in the Gulf Stream area (34°N-39°N – 70°W-60°W). Errors in percentage of signal variance are also given. For the table, we also included results of ERS, GFO, T/P+Jason-1 and of the four interleaved T/P.

	Mean mapping error (in cm)	Mean mapping error (in percentage of signal variance)
T/P	[illegible]	[illegible]
ERS	[illegible]	[illegible]
GFO	[illegible]	[illegible]
T/P + ERS	[illegible]	[illegible]
T/P + Jason-1	[illegible]	[illegible]
T/P + ERS + GFO	[illegible]	[illegible]
T/P + Jason-1 + ERS + GFO	[illegible]	[illegible]
4 interleaved T/P	[illegible]	[illegible]

Table 1 : Mean mapping error in cm and in percentage of signal variance in the Gulf Stream area for all the analyzed configurations.





5. Conclusions

The availability of high resolution primitive equation models with realistic mesoscale variability has opened up new scope for analyzing the contribution of single and multiple altimeter missions. These new results confirm the main conclusions of the LD99 study based on formal error analysis and analysis of lower resolution model (POCM). There is a large improvement in mapping capability when going from one satellites to two satellites and the gain for an optimized (e.g. T/P and Jason-1) and non-optimized two satellite configuration (e.g. T/P and ERS) is small. Mapping errors (in percentage of the signal variance) are, however, larger than the ones derived from lower resolution model (by a factor of almost 10) and LD99 formal error analysis (by a factor of 2). This is due to the high frequency and high wavenumber signals of the model. The small space and time scale of the model (< 20 days and <200 km) have a variance of about 10% of the total sea level variance. The mapping of such signals demands a resolution better than 10 days and 100 km which can only be obtained with at least four satellite configurations.

The study is now extended to the analysis of the velocity field mapping capability and to quantify the contribution of new altimetric missions (e.g. WSOA, Alti-Ka).

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