SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	**Improvement of the barotropic tide in the 1/12° global ocean NEMO model**
Computer Project Account:	spfrmore
Start Year - End Year :	2019 - 2020
Principal Investigator(s)	Yves Morel, Benoît Tranchant, Loren Carrere
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Other Researchers (Name/Affiliation):	Florent Lyard (LEGOS/CNRS)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The main project objective is the implementation of a new barotropic tide solution in the global 1/12° NEMO ocean model in order to ensure an accurate barotropic tide without disrupting the eddying general circulation. To do so, different solutions have to be tested. The first, classical, one is to modify/improve the tide dynamics in the model (bathymetry, bottom friction, tide loading and tide dissipation via internal tide generation). The second solution is through assimilation of data coming from the “state of the art” tide model FES2014. Providing an accurate global barotropic tide atlas is an essential step before doing realistic simulation of baroclinic tides. The NEMO model (Nucleus for European Modelling of the Ocean (https://www.nemo-ocean.eu) is a platform for ocean modelling developed by a European consortium. This project will use the global configuration at 1/12° named MFC-GLO used in CMEMS that explicitly solve the barotropic tides from an astronomical tide potential.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

As planed in the project, we implemented a new parameterization of the internal wave drag in order to specify the dissipation due to internal waves in the model. This new parameterization generated numerical instabilities that we were only able to kill by using a smaller baroclinic time step (180 s instead 360 s usually).

Smaller time steps lead to a larger computational cost which is the main reasons why we exceeded our SBU quota already and had to ask for additional SBU.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

It was a very positive experience. Everything was very simple and the contacts where rapid, helpful and friendly. Many thanks for all the help and the extra SBU granted, which greatly helped to achieve our project.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

Summary

To improve the quality of the NEMO global barotropic tide solution, several tests and developments have been performed

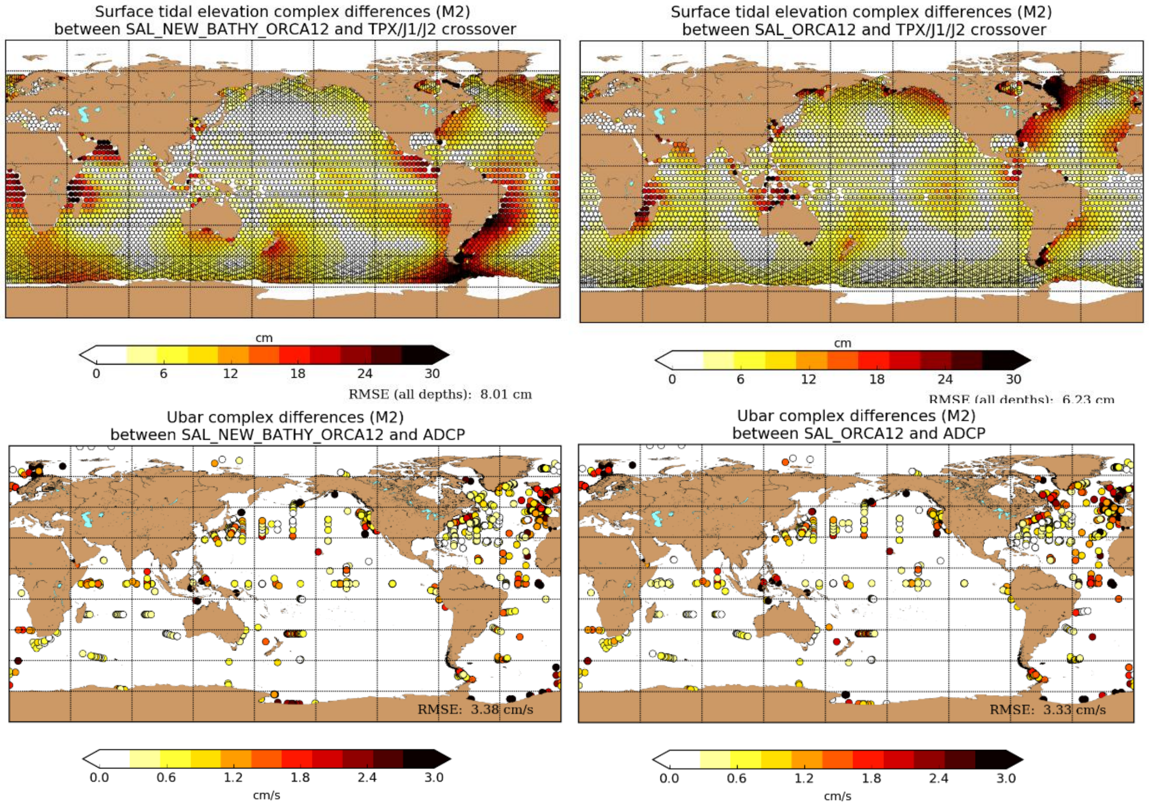
- ORCA12 NEMO solutions have been tested
- Test FES2014 bathymetry and NEMO bathymetry
- Test FES2014 SAL (self attraction and loading) fields and also NEMO SAL fields
- Optimize the bottom friction parameters
- Test different initial conditions (IC) for the simulations: GLORYS2V4, Climatology WOA2013, ORCA12-20 years simulations
- Implement and test the wave-drag dissipation due to internal tides generation/dissipation

At each step of the development several spectral validation diagnostics have been performed to check the efficiency of the parameter tested.

Tests of bathymetry and initial conditions with the ORCA12 configuration

The impact of the new FES2014 bathymetry has been also investigated using the ORCA12 configuration, with the SAL forcing of LEGOS (interpolation of FES2014's SAL on NEMO grid) and the WOA2013 initial condition. As shown on **Figure 1** and **Table 1**, the comparison with all validation databases (altimetry, tidal gauges, ADCP, FES2014) indicates that M2 solution is better when using the SAL_ORCA12 experiment (initial bathymetry); on the other hand, using the new bathymetry allows improving K1 NEMO global solution when comparing to FES2014 and altimetry, but comparison to TG shows a degradation.

A new initial condition named SAL_ORCA12_ORCA12 has been tested, it is the ORCA12 configuration with the SAL forcing of LEGOS (interpolation of FES2014's SAL on NEMO grid) and a long ORCA12 simulation (free run-20 years) as Initial Conditions.
Compared to the last best solution, i.e. SAL_ORCA12 (WOA2013 as initial condition), this new initial condition (free run-20 years) gives the best results, see **Figure 2** and **Figure 3** and **Table 1**
This means that initial conditions are essentials and it should be interesting to look at the initial stratification to go further in this study. Moreover, in regions where topography is crucial for internal wave generation as Indonesian seas, the initial condition seems to play an important role, see **Figure 4**.
Note that for all ORCA12 experiments, a smaller time step was needed, instead to have a usual time step of 360s, we used 180s, which means that the CPU time has increased.



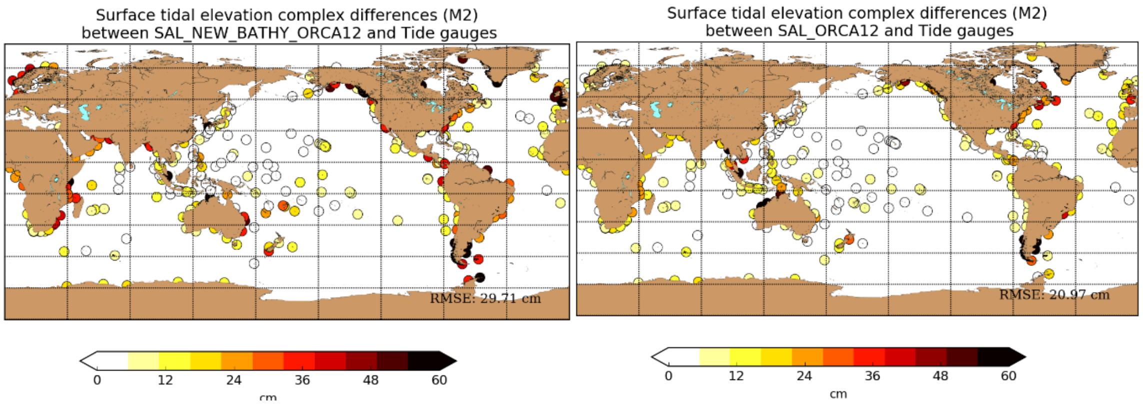


Figure 1: Surface tidal amplitude differences (cm) (M2) between TPX/J1/J crossover, ADCP (U) and Tide gauges and 2 experiments: (left) SAL_NEW_BATHY_ORCA12, (right) SAL_ORCA12 (Init.Cond.: WOA_2013)

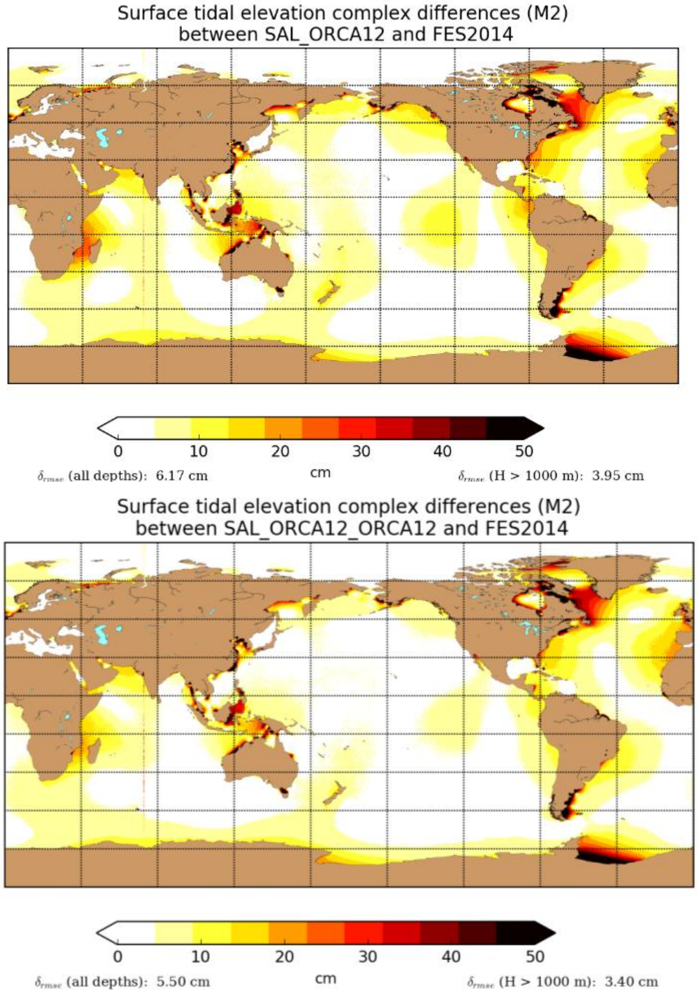
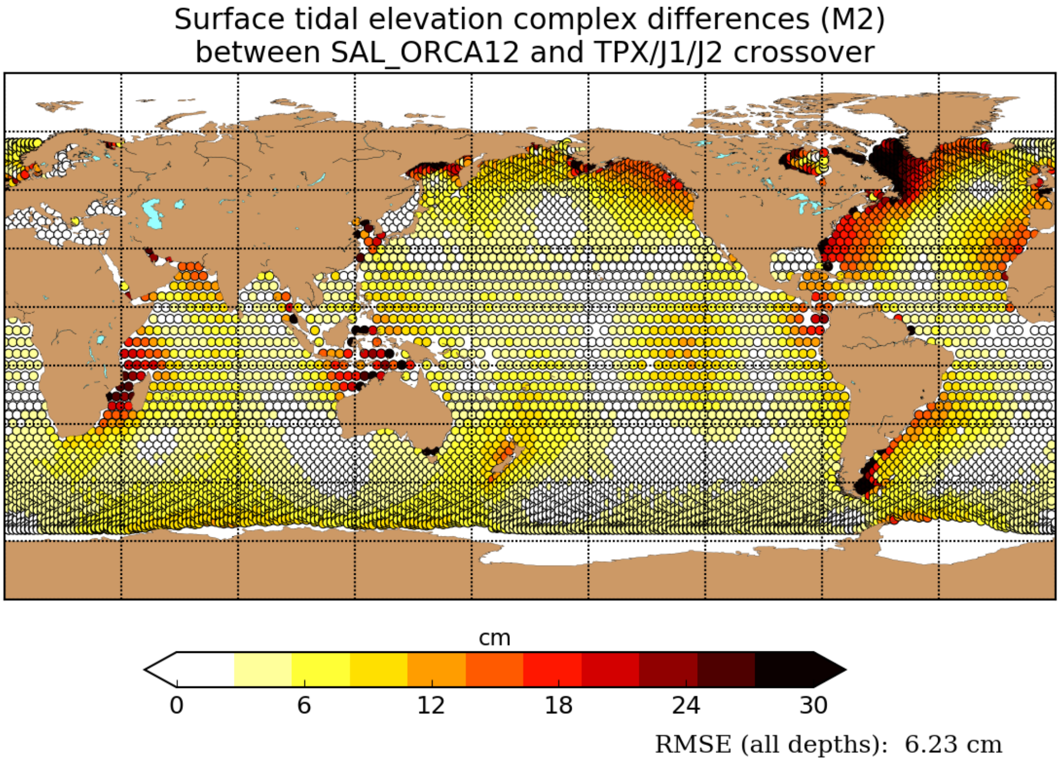


Figure 2: Surface tidal amplitude differences (cm) (M2) between FES2014 and 2 experiments: (top) SAL_ORCA12, (bottom) SAL_ORCA12_ORCA12

Experiment	M2 (cm)				K1 (cm)			
	FES2014	TPX/J1/J2	ADCP	TG	FES2014	TPX/J1/J2	ADCP	TG
SAL_ORCA12	6.17	6.23	3.33	20.9	1.88	2.09	-	4.24
SAL_NEW_BATHY_ORCA12	6.71	8.01	3.38	29.7	1.17	1.18	-	7.12
SAL_ORCA12_GLO	7.47	7.82	3.33	24.01	1.82	1.85	1.94	4.2
SAL_ORCA12_ORCA12	**5.50**	5.69	3.48	19.33	1.84	2.03	1.94	4.15

Table 1: List of different ORCA12 experiments and their associated mean RMSE of M2 and K1 surface tidal elevation complex differences between FES2014, TPX/J1/J2 cross over, ADCP and Tide Gauges and model (cm) over the global domain. RMSE have been calculated for all depths.



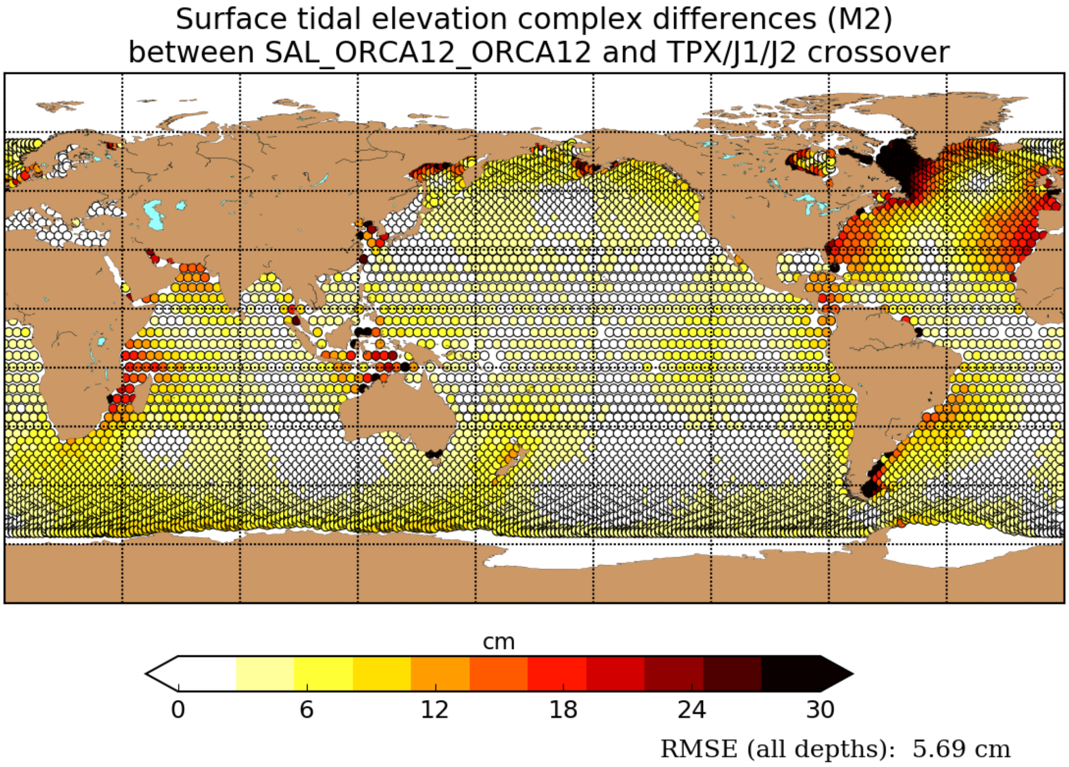
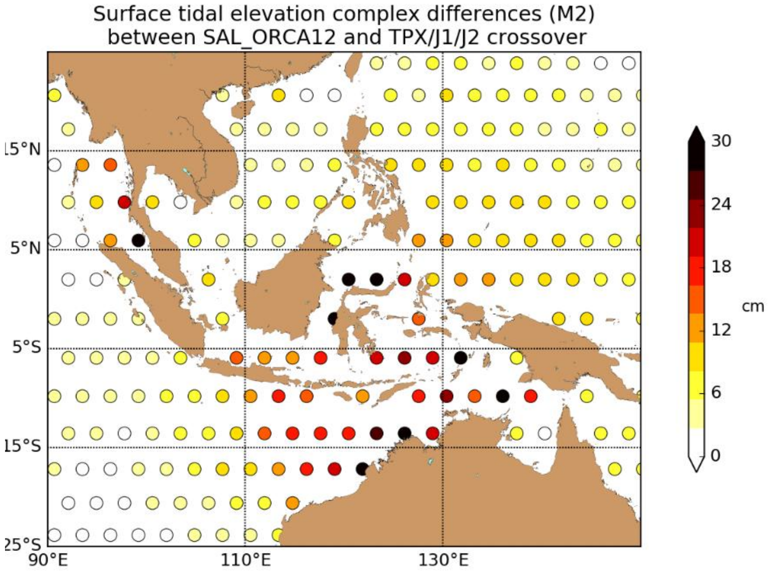


Figure 3: Surface tidal elevation complex differences (cm) at crossing points between TPX/J1/J2 and Model: (top) SAL_ORCA12, (bottom) SAL_ORCA12_ORCA12 over the Indonesian domain.


Surface tidal elevation complex differences (M2) between SAL_ORCA12 and TPX/J1/J2 crossover

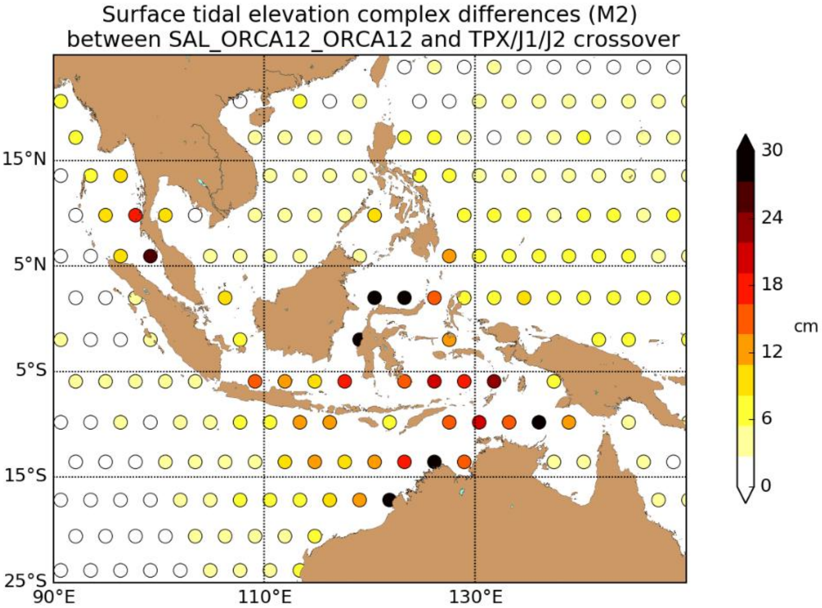

Surface tidal elevation complex differences (M2) between SAL_ORCA12_ORCA12 and TPX/J1/J2 crossover

Figure 4: Surface tidal elevation complex differences (cm) at crossing points between TPX/J1/J2 and Model: (top) SAL_ORCA12, (bottom) SAL_ORCA12_ORCA12 over the Indonesian

Barotropic vs total signal (surface tidal elevation)

NEMO surface tidal elevation contains both the barotropic and baroclinic variability, so to improve the comparison between NEMO and FES2014 barotropic model, a barotropic/baroclinic decomposition has been performed (thanks to Michel Tchilibou) from the entire signal of NEMO SSH. When comparing to FES2014 atlas, the main differences are located where the baroclinic activity is important, see **Figure 5**, but in term of mean rmse, the difference with FES2014 is not significative: 0.4% for SAL_ORCA12_ORCA12 and between 2% (global) and 4% (Indonesian seas) for SAL_NEW_BATHY_GLO.

Experiment	M2 (cm)	
	Total Global/Indo	Barotropic Global/Indo
SAL_ORCA12_ORCA12	**4.95/4.97**	**4.93/4.95 (-0.4%)**
SAL_NEW_BATHY_ORCA_GLO	**6.07/5.43**	**5.93/5.18 (-2.3/-4.5%)**

Table 2: List of different ORCA12 experiments and their associated mean RMSE of M2 surface tidal elevation (total ssh and barotropic part) complex differences between FES2014 and model (cm) over the global domain. RMSE have been calculated for all depths, for global and Indonesian seas vs FES2014.

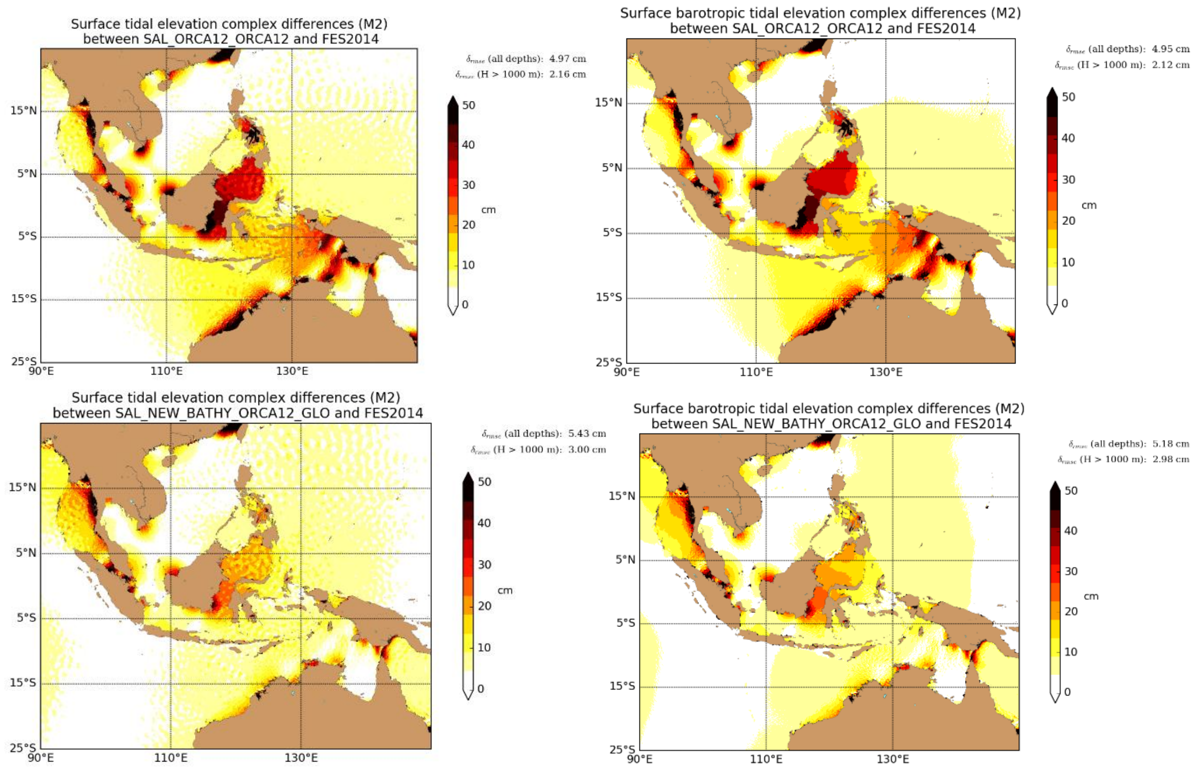


Figure 5: Surface tidal elevation complex differences (cm)) between FES2014 and SAL_ORCA12_ORCA12 (top) and SAL_NEW_BATHY_ORCA12_GLO (bottom) (left) total signal, (right) barotropic part of the signal over the Indonesian domain.

Wave-drag implementation – ORCA12 configuration

A specific parametrization of the internal tide generation has been done. It consists of adding a parameterization of the Internal Wave Drag. It is based on the study of Jaynes and St-Laurent (2001) and already used in a NEMO ORCA12 version developed by Kodaira et al. (2016; see equation (5)).

$$C_{IWD} = \frac{\mathrm{K}h'^2}{2h} N_b \sqrt{\frac{\omega^2 - \mathrm{f}^2}{\omega^2}}$$

The Brunt–Väisälä frequency N_b is calculated by the NEMO model.
The bottom roughness h' has been estimated following Gille et al. (2000): (i) we high-pass filtered the GEBCO bathymetry, (ii) we squared this filtered bathymetry and (iii) applied a low-pass filter to obtain a roughness h'.
Different tests have been done in order to define the best parameterization, mainly for K and h'.

- K has been chosen to be 2π/100 km^{-1}
- The roughness *h'* has been calculated from a sub-sampled GEBCO (original GEBCO_2019 is 1' resolution) bathymetry at 1/48° and a gaussian filter with a standard deviation of √3, see Figure 6. As expected, highest values are found where gradients of bottom topography (bathymetry) are highest.
- IWD is applied only for latitude less than 74.5°, i.e, when ω (for M2) = f.
- IWD is not applied in regions shallower than 500m or 1000m

Figure 7 shows an example of internal wave drag coefficient and Figure 8 shows the corresponding E-folding time in days compared to the one calculated by Arbic et al., 2010.

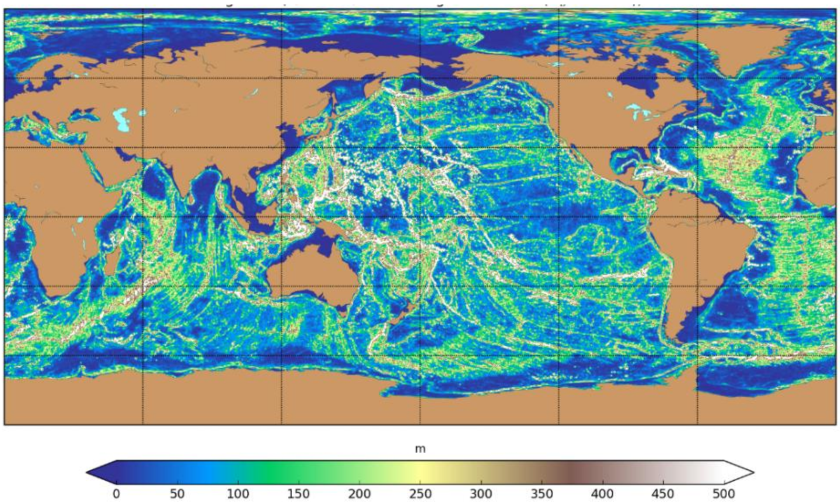


Figure 6: Roughness obtained with a gaussian filer (σ=√3) and the GEBCO bathymetry.

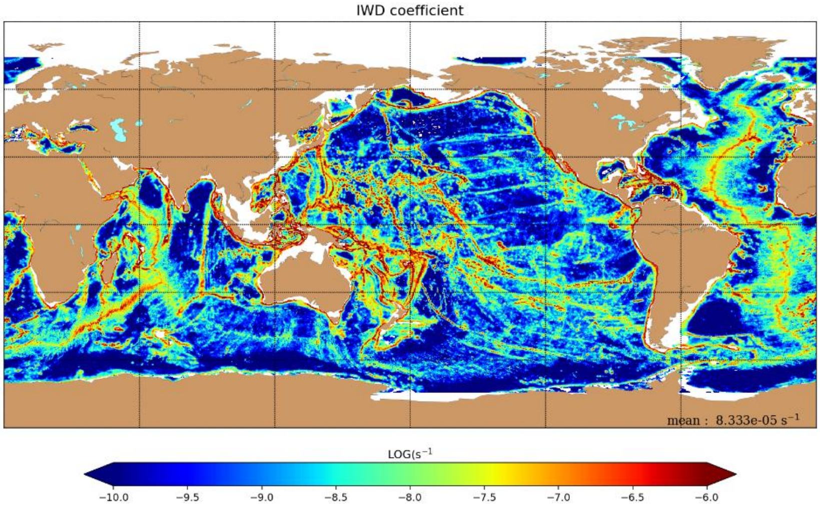


Figure 7: Internal Wave Drag coefficient (C_{IWD}) (s^{-1}) calculated from Kodaira et al., 2016 and implemented in NEMO (ORCA12)

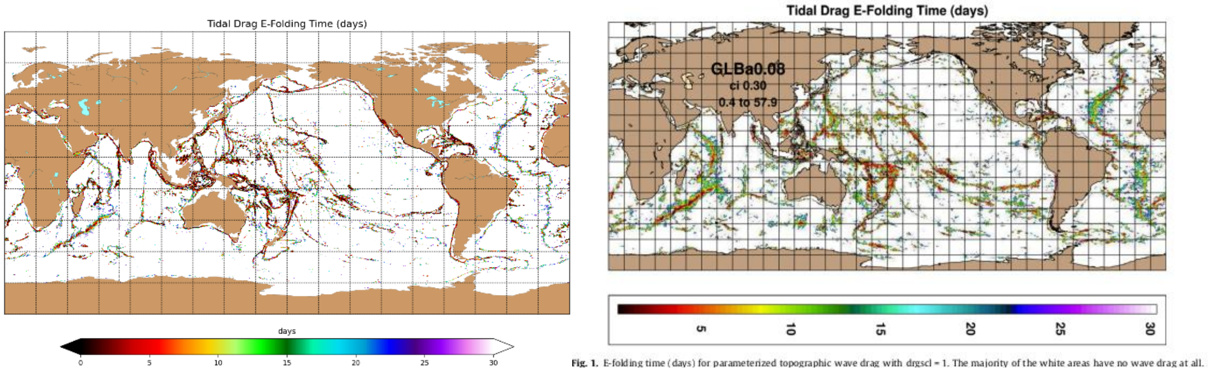


Fig. 1. E-folding time (days) for parameterized topographic wave drag with drgscl = 1. The majority of the white areas have no wave drag at all.

Figure 8 : E-Folding time (days) inferred from the Kodaira parameterization and as implemented in NEMO (ORCA12) (left) and from Arbic et al., 2010 (right)

Validation results when the internal wave drag scheme is applied for all frequencies (SAL_ORCA12_IW simulation)

The results, i.e. RMS differences with FES2014 compared with those found with SAL_ORCA12_ORCA12 (without IWD) are quite equivalent for M2 and K1 over the global domain, and results are slightly better for K1 than for M2. However, more significant differences can be found in the Bay of Biscay, see

Figure 9, where the gain is up to 12.5% for M2 and 5% for K1.

Experiment	M2 (cm)		K1 (cm)	
	FES2014 **Global/BoB**	TPX/J1/J2 global	FES2014 **Global/BoB**	TPX/J1/J2 Global
SAL_ORCA12_ORCA12	**5.50/3.74**	**5.69**	**1.84/2.04**	**2.03**
SAL_ORCA12_IW	**5.92/3.27**	**5.96**	**1.81/1.94**	**1.93**

Table 3: List of different ORCA12 experiments and their associated mean RMSE of M2 and K1 surface tidal elevation complex differences between FES2014 and TPX/J1/J2 cross over and model (cm) over the global domain. RMSE have been calculated for all depths, for global and Bay of Biscay (BoB) vs FES2014.

This is also consistent with the comparisons with tide gauges and TPX/J1/J2 crossover.
There is a small effect on the barotropic to baroclinic energy conversion: a small decrease (~2%) is found when the internal wave drag is added, and mainly for M2. This is not consistent with the results of Timko et al., (2017) who found an increase of the energy conversion with the addition of abyssal hills in the HYCOM model.

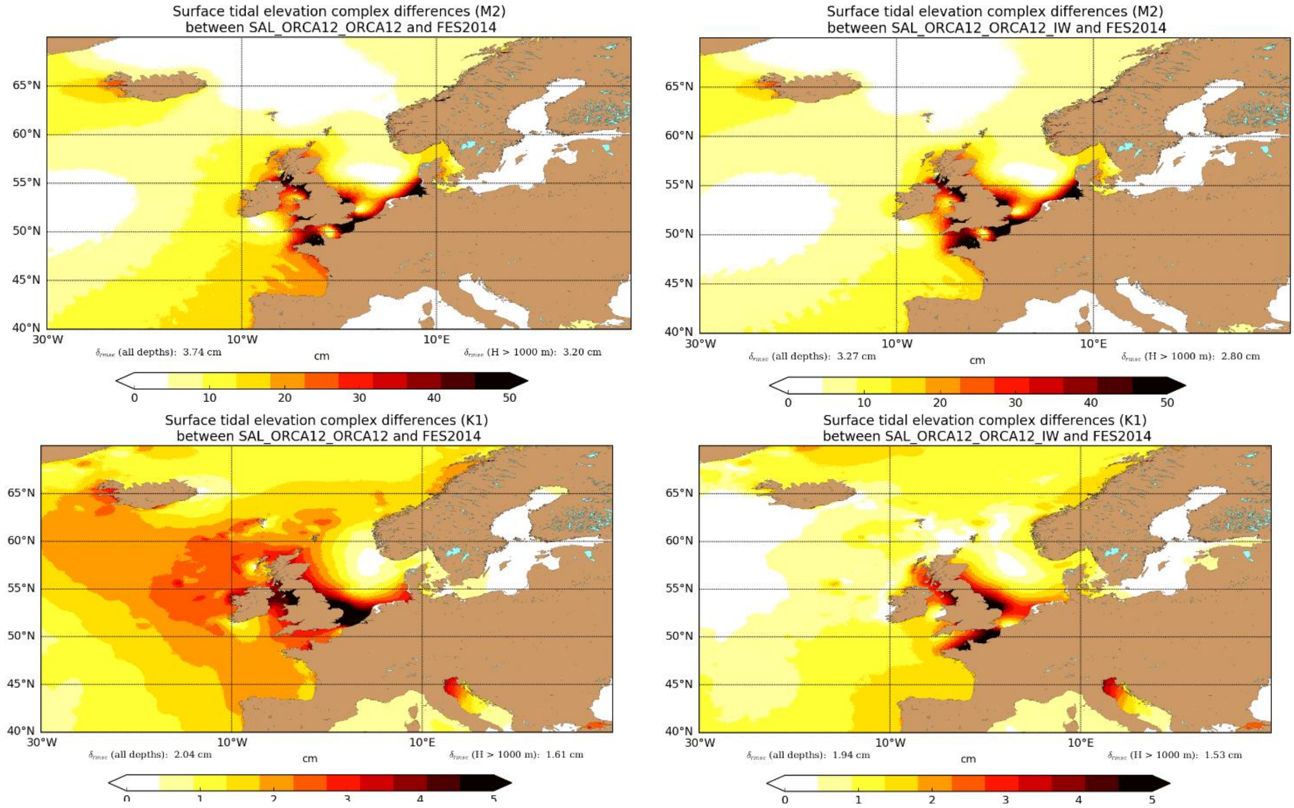


Figure 9: Surface tidal elevation complex differences (cm)) between FES2014 and SAL_ORCA12_ORCA12 (left) and SAL_ORCA12_IW (right), (top) M2 and (bottom) K1 over the Bay of Biscay domain.

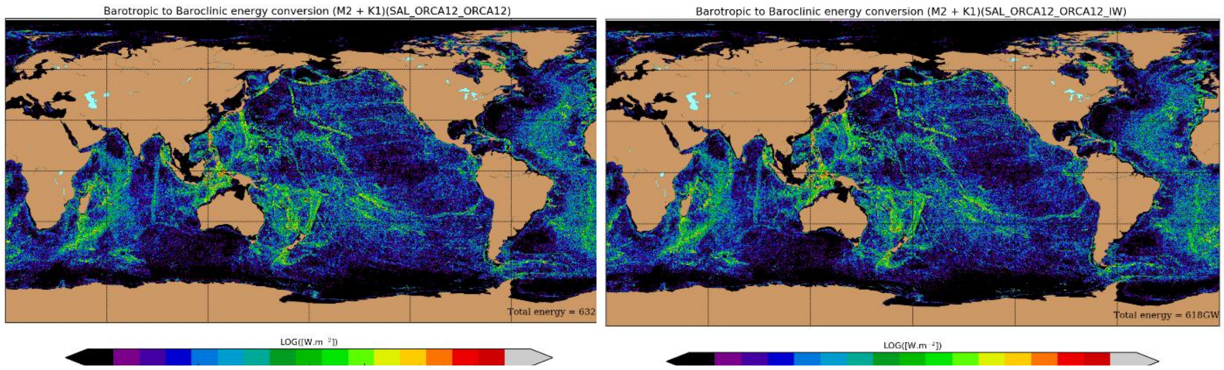


Figure 10: Energy conversion (barotropic to baroclinic) for M2+K1 for SAL_ORCA12_ORCA12 (left) and for SAL_ORCA12_IW (right)

If we plot the barotropic energy due to this internal wave drag for M2, i.e the $C_{IWD}.U_{bar}$, the result seems surprising (e.g. Antarctic) and somehow inconsistent, which means that we need to work further on this parameterization.

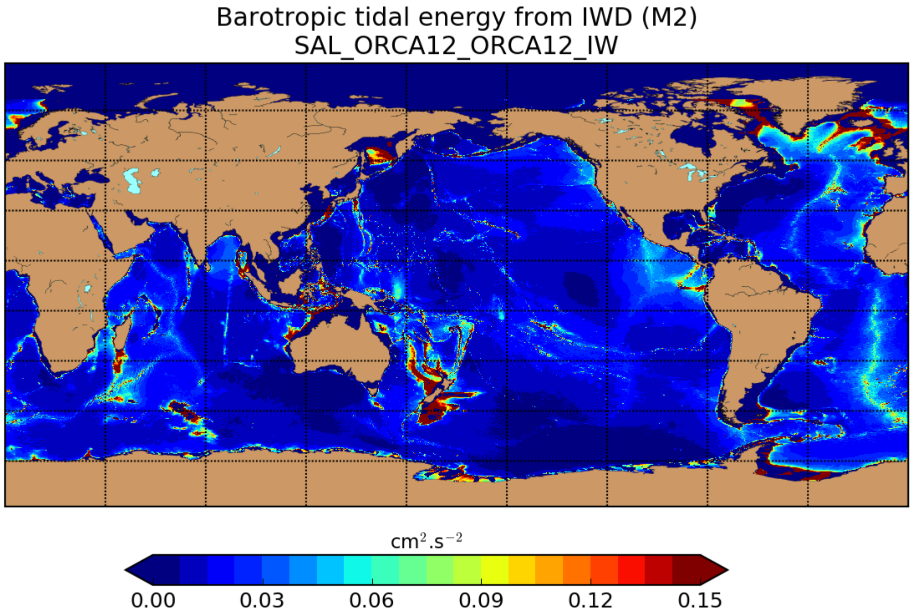
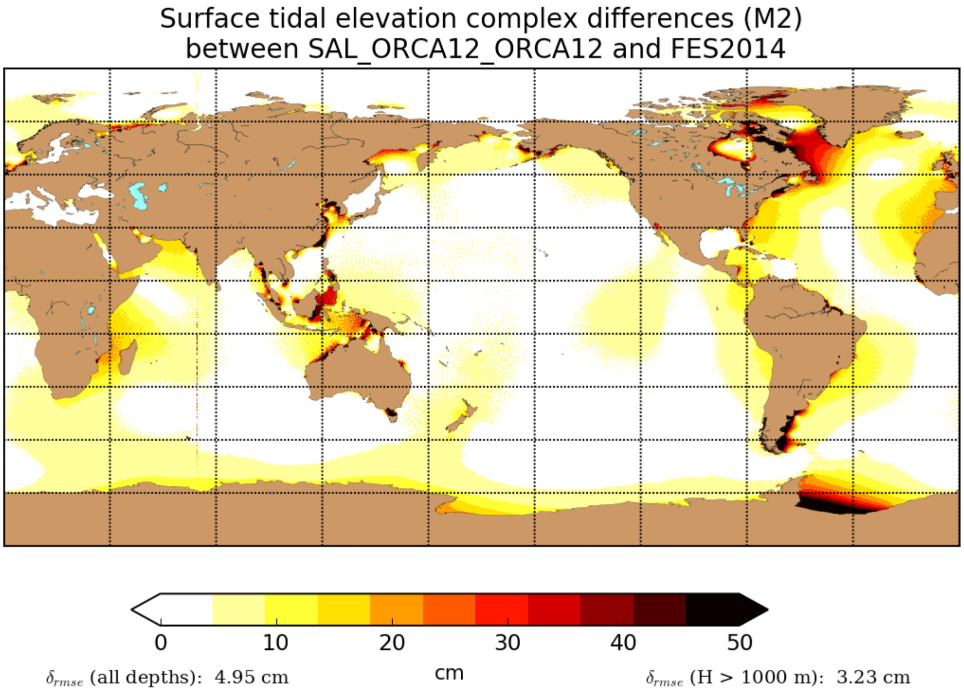


Figure 11: Example of Barotropic tidal energy due to the internal wave drag for M2.

NEW SAL estimation from SAL_ORCA12_ORCA12 simulation : first iteration

The SAL_ORCA12_ORCA12 configuration is the reference simulation here. A harmonic analysis of the hourly fields allowed extracting the corresponding NEMO oceanic tides atlas; then a new SAL (Self Attraction and Loading) component entirely coherent with the SAL_ORCA12_ORCA12 NEMO simulation has been calculated by LEGOS and using specific LEGOS tools.

This new SAL has been used in a new simulation based on SAL_ORCA12_ORCA12, i.e., an initial condition from ORCA12 and the new SAL solution. This new simulation named SAL_ORCA12_NEW_SAL does not perform as well as the original SAL, see an example in the Figure 12.



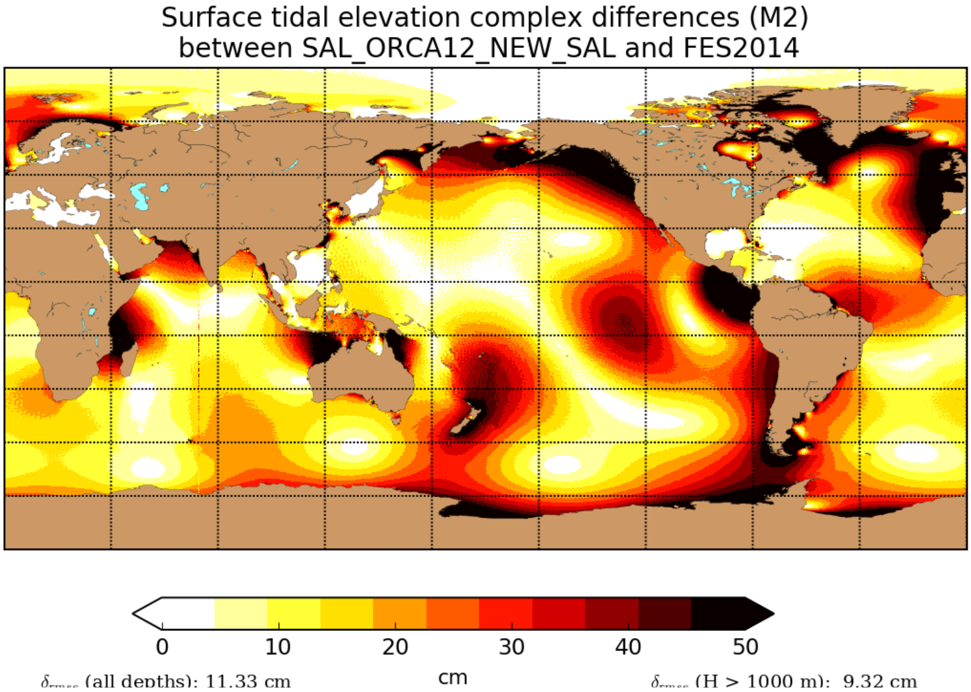


Figure 12: Surface tidal elevation complex differences (cm)) between FES2014 and SAL_ORCA12_ORCA12 (lop) and SAL_ORCA12_NEW_SAL (bottom) over the global domain.

Validation with HFR database and ADCP

The validation of tidal currents is performed on the North-West Atlantic (south of Cape Cod shelf) region using the MARACOOS data, on the IROISE sea using SHOM data, and also globally using current meter database (ADCP) from Timko et al. (2013).

Some validation results are given below. Comparisons of tidal currents from HF radar have been done on the two different areas see Figure 13 and Figure **14**. In both cases and contrary to sea surface elevation, results are better with the new FES2014 bathymetry for the two components M2 and K1. Once again, the initial conditions from ORCA12 (20 years simulation) gives better results.

Figure 15 shows the differences between the global ADCP database and the 2 ORCA12 experiments using either the NEMO bathymetry or the new FES2014 bathymetry. Over the global domain, the differences are not too important and quite neutral, likely due to the localization of ADCP measurements mostly in deep ocean regions where barotropic tide currents are very small. The most important differences between the 2 experiments are located in the North Atlantic where the new bathymetry performs slightly better.

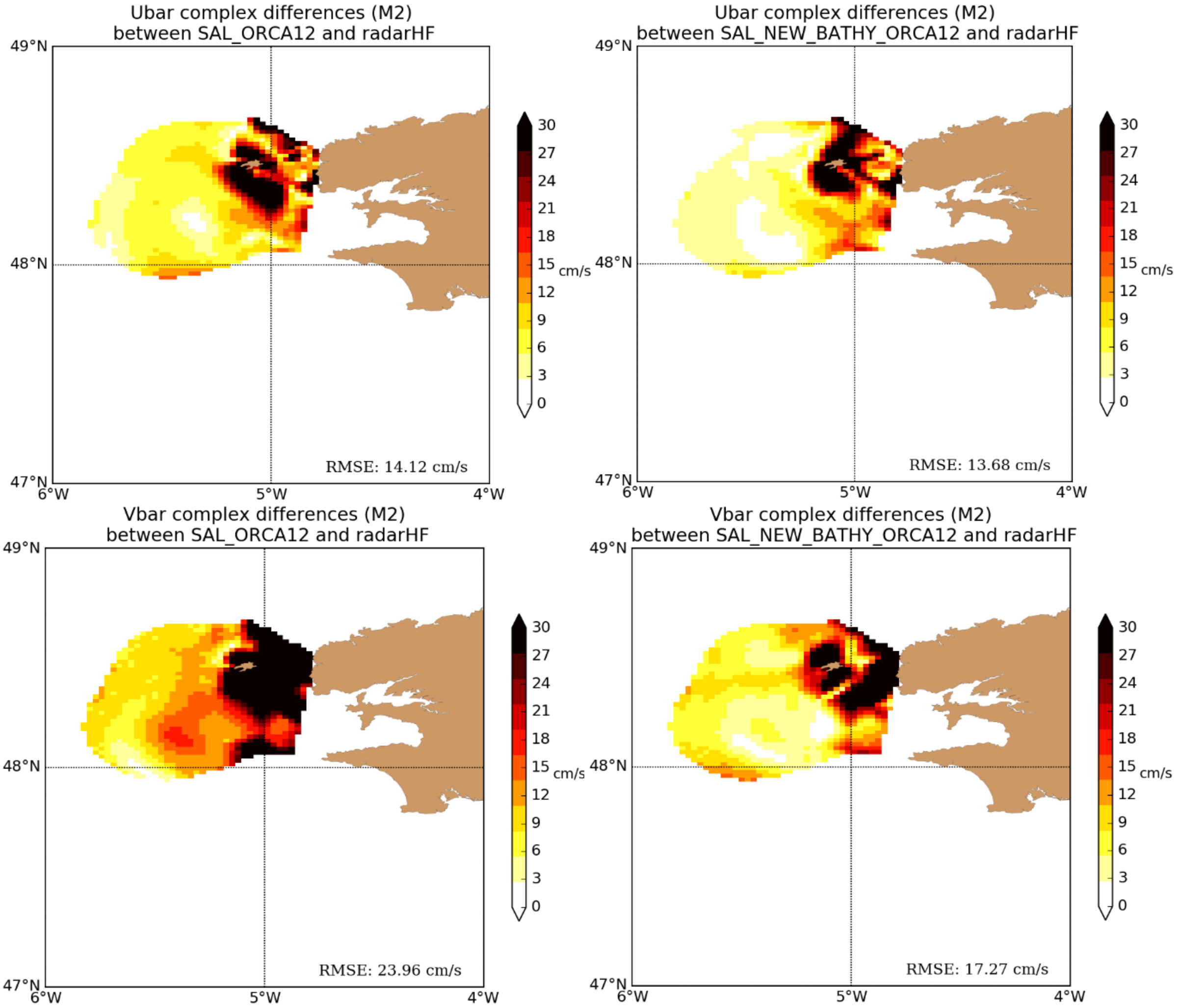
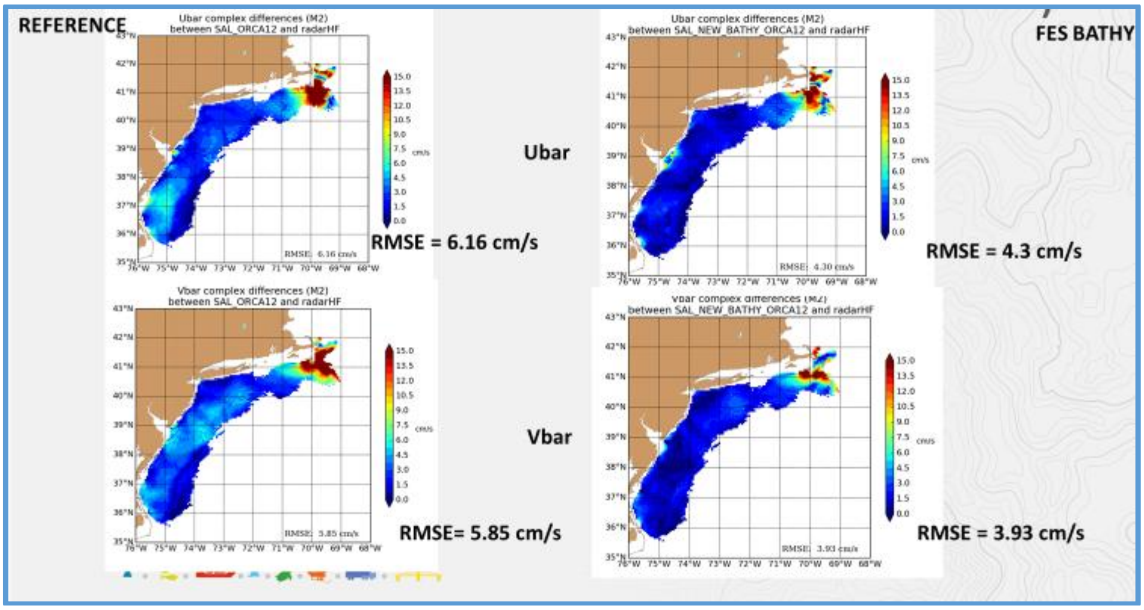


Figure 13: Tidal current Ubar (top) and Vbar (bottom) complex differences (cm/s) for M2 between HFradar (Iroise) and 2 experiments with ORCA12: (left) REF_WITH_SAL, (right) SAL_WITH_NEWBATHY. RMS of errors are indicated.



SAL_ORCA12_ORCA12

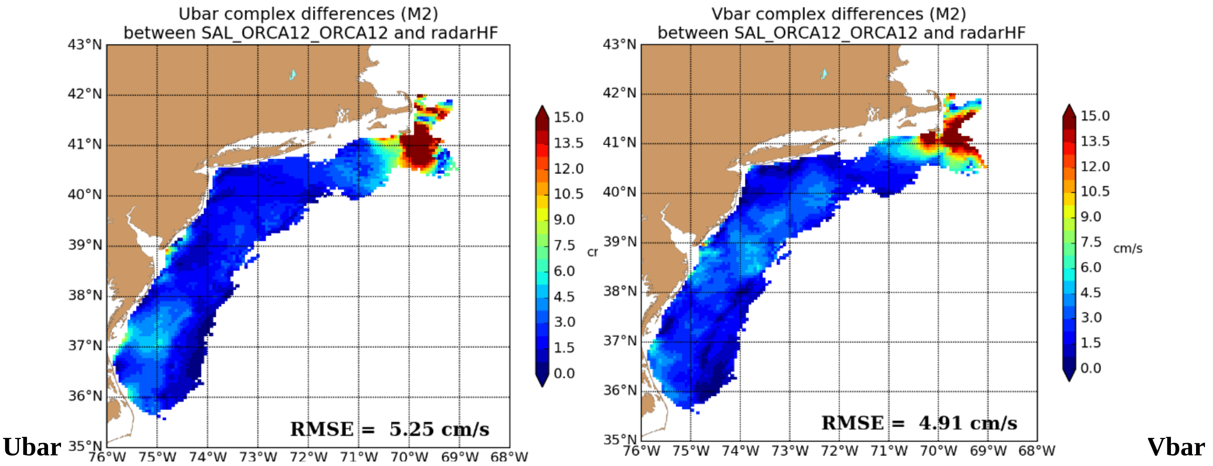


Figure 14: Upper panel : tidal current Ubar (top) and Vbar (bottom) complex differences (cm/s) for M2 between HFRadar (Maracoos database) and 2 experiments with ORCA12: (left) REF_WITH_SAL, (right) SAL_WITH_NEWBATHY. The complex differences with SAL_ORCA12_ORCA12 experiment is given on the bottom panel. Mean RMS of errors are indicated.

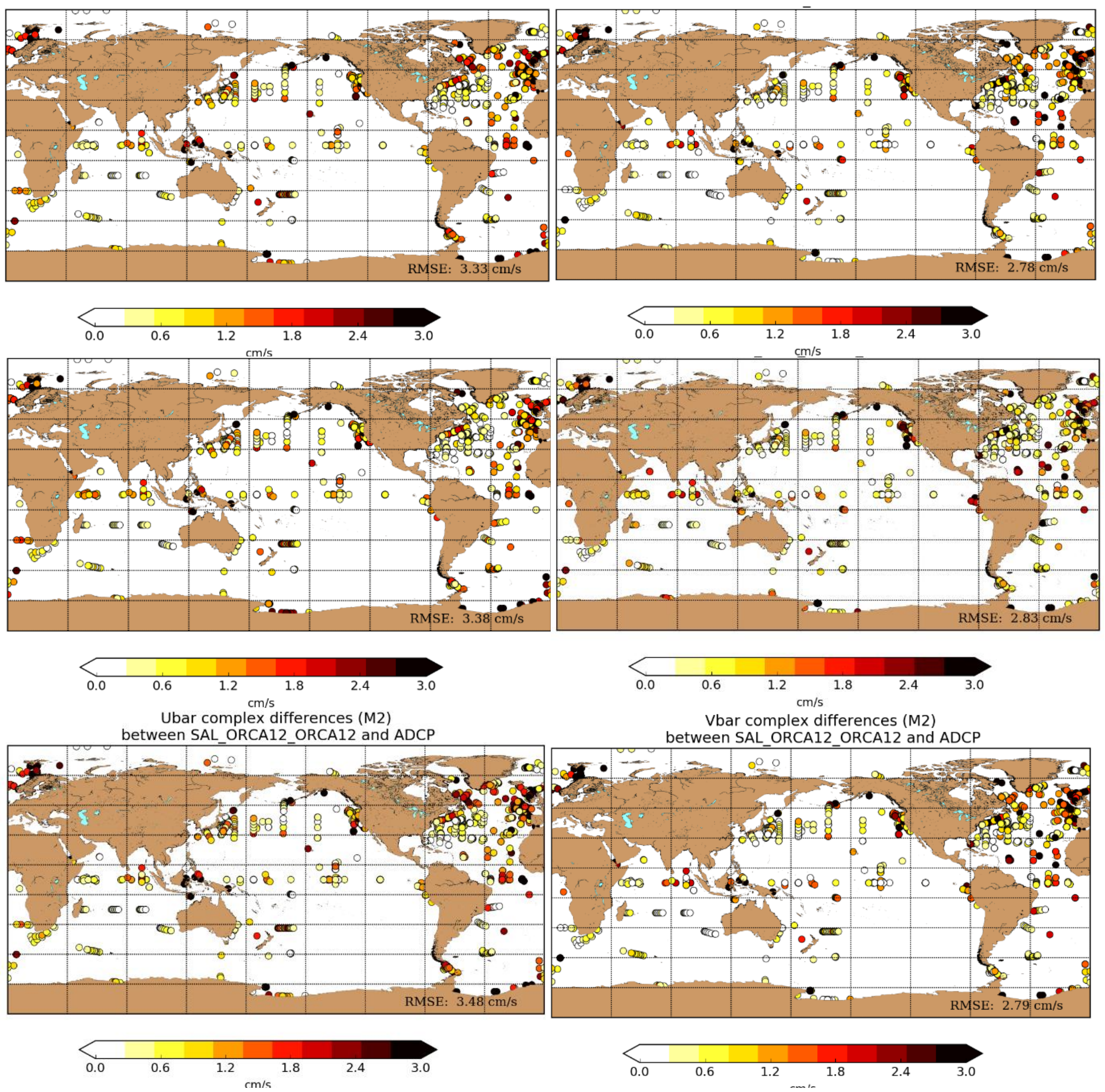


Figure 15: Tidal current Ubar (left) and Vbar (right) complex differences (cm/s) for M2 between ADCP database (Timko et al., 2013) and 3 experiments with ORCA12: (top) REF_WITH_SAL, (middle) SAL_WITH_NEWBATHY, (bottom) SAL_ORCA12_ORCA12. Mean RMS of errors are indicated.

Conclusion

The project has demonstrated several strong points and left some others as opened questions or perspectives. The present accuracy of the NEMO tidal simulations has been strongly improved compared to the initial state of the art. It remains still high (~5cm for the M2 tide) compared to dedicated hydrodynamic, shallow water tidal configuration such as the one of FES2014 (~1.3 cm before data assimilation). The NEMO configuration suffers from the non-inclusion of the two major austral ice-shelf seas (Weddell Sea and Ross Sea), which play a major role in the global ocean tides (Weddell Sea is resonant for the semi-diurnal tides, and the Ross Sea is resonant for the diurnal tides). This is probably a show-blocker in future NEMO tidal configurations performances. As the tidal dynamics has basin-scale correlations, this issue can result in significant errors in some far-remote regions, and mix-up with others more regional sources of errors.

1. The implementation of the realistic tidal loading/self-attraction (derived from FES2014b atlas) has proven to be essential to improve the accuracy of the tidal simulations, for any considered tidal constituent. The activation of the SAL forcing for NEMO simulation is therefore a strong recommendation from the project.

2. The NEMO simulation initialization has a major impact on the tidal solutions. The configuration Initialized from a long ORCA12 free run performs much better than the configuration from a climatology database (WOA). This is likely related to the change in barotropic to baroclinic tidal energy conversion (estimated to be 30 to 40% of total barotropic tides dissipation) associated with the resulting stratification differences between the 2 configurations (climatologic initialization could result in a smoother stratification, hence a weaker internal tides generation). However, additional investigations would be necessary to clarify this point. So far, it is recommended to use preliminary long free run to initialize the global ocean tidal simulations.

3. The configuration bathymetry is of course a major parameter for tidal configurations. The differences between the tidal solutions obtained from the original bathymetry and the one derived from the FES2014 hydrodynamic configuration (that includes patches from the best available regional databases and was carefully edited and checked) are mitigated. The FES2014 bathymetry is beneficial to K1 tide accuracy but not to M2 tide accuracy, as one could expect. It could be the effects of other errors compensating effects, such as ice-shelf seas non-inclusion. Locally it seems that using a specific regional bathymetry could help also (cf bathymetry proposed by D. Nugroho (2017) on the Indonesian seas).

4. The implementation of the IWD parametrization is beneficial, but call for some additional comments:
    a. The formulation is normally related to bottom roughness at scale less than a few kilometers, but is fed with topography oscillations at 100 km. A more rigorous parametrization should be tried (typically linked with topography gradients).
    b. Some tests are necessary to better separate the high-frequency and the low frequency parts of the model velocity as the wave-drag shall be applied only on the high-frequency part but a continuous HF operational filtering is not trivial.
    c. In the internal (3D) mode, it normally should only compensate for non-resolved internal tide generation, in proportions dependent upon the NEMO grid resolution. This point needs some additional investigations to properly calibrate the parametrization effects.

5. The on-line extended harmonic analysis, barotropic/baroclinic separation and energy budget computations have demonstrated to be very useful to analyze and diagnose the NEMO simulations. It is strongly recommended to continue the effort of implementing further those functionalities in the NEMO code and companion tools.

6. A new optimization methodology for the barotropic tide has been developed and tested within the project and results obtained are very promising. A scientific paper describing the method is currently being written and will be terminated in 2021. This new method is very promising and its implementation and operational use is relatively straightforward. So we need to finalize the test of this optimization methodology:
    a. We need to use a more conservative interpolation of the FES barotropic transports.
    b. The FES resolution should be refined locally (at the Poles) to avoid the discontinuities when interpolating on the NEMO grids.
    c. More generally speaking, data assimilation of tide signal must also be handled with care. For instance, to deal with the new methodology developed in WP5, the link between the SSH evolution and the divergence of the transport must be ensured in FES. Otherwise there will exist discrepancies between the FES SSH and the SSH reproduced by the NEMO model.

7. Some new tools have also been developed to validate the global barotropic tide and developers will be able to use them.

8. It is also strongly recommended to add the ice-shelf seas in the future NEMO global grids, as their non-inclusion puts a lot of incertitude in analyzing the other dynamical sources of errors, making any further progress quite uncertain.

Despite still far from dedicated tidal models accuracy, the new NEMO configuration built in the project shows considerable progresses compared to the initial one, and we have listed several recommendations that should lead to further improvements. This project is definitely a great step toward realistic barotropic and baroclinic tides simulation with the NEMO model.

List of publications/reports from the project with complete references

- Evolution and optimization of NEMO code used in CMEMS-MFC-GLO: global barotropic tide simulations - Quarterly report – Q1, February 2019, CLS-ENV-RP-19-0050
- Evolution and optimization of NEMO code used in CMEMS-MFC-GLO: global barotropic tide simulations - Quarterly report – Q2 May 2019, CLS-ENV-NT-19-0177.
- Evolution and optimization of NEMO code used in CMEMS-MFC-GLO: global barotropic tide simulations - Quarterly report – Q3, July 2019, CLS-ENV-RP-19-0306
- Evolution and optimization of NEMO code used in CMEMS-MFC-GLO: global barotropic tidesimulations documentation on tide validation diagnostics, –TIDE-REP-02: CLS-ENV-RP-19-0302.
- Evolution and optimization of NEMO code used in CMEMS-MFC-GLO: global barotropic tide simulations - Quarterly report – Q4, February 2020, CLS-ENV-RP-20-0060
- Evolution and optimization of NEMO code used in CMEMS-MFC-GLO: global barotropic tide simulations - Quarterly report – Q5, May 2020, CLS-ENV-RP-20-0203

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We are workin on a new method for the implementation of tide in NEMO. This method is currently developed and tested on a “light” configuration (at ¼°). It will be necessary to test it on the 1/12° model, a “heavy” configuration for which we may ask for a new special project.