We'd like to thank the referee (S. Losa) for her useful comments and suggestions, which helps to greatly improve the quality of our manuscript. Our responses are in blue.

Interactive comment on "Assimilating High-resolution Sea Surface Temperature Data Improves the Ocean Forecast in the Baltic Sea" by Ye Liu and Weiwei Fu

S. Losa (Referee)

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This paper describes an experience in assimilating a high-resolution satellite sea surface temperature (SST) product into a NEMO-based numerical model of the Baltic Sea. There is no doubt that the Baltic Community urgently requires a good quality forecast of the Baltic Sea hydrography. And there is no doubt that any forecasting system would definitely benefit from assimilating observational information. These circumstances provide a strong motivation for the study discussed. I am, however, not sure that this data assimilation experience is sufficient enough to be documented in a peer-reviewed publication (at least with respect to improving forecast, as stated). In its present form, I cannot recommend the manuscript for publication. Below I list my comments the authors might want to consider.

We thank the referee for reviewing our manuscript, acknowledging the importance of our topic, and for her suggestions on how to improve the manuscript.

General comments

The Title does not correctly reflect the subject/results of the paper. My concern is the statement "Improves the Ocean Forecast": 1) because of the use of atmospheric reanalysis (not the forecast) as the forcing; and 2) since it is not clear from the text whether the authors evaluate the system state after the LSEIK analysis or in the forecast phase (just before the analysis). Same is to the statements in lines 20 – 21, 86, 278, 440. “the Ocean Forecast in the Baltic Sea” sounds a bit odd.

1) We changed the title a bit to “Assimilating High-resolution Sea Surface Temperature Data Improves the Ocean Forecast Potential in the Baltic Sea”. We think the new title more correctly reflect the subject as our main focus is to demonstrate the potential impact of SST assimilation on the model predictions of the NEMO-Nordic, which aims for operational forecast. We believe that the reanalysis forcing will not impair this objective of our paper. In this study, we intended to showcase how useful the DA method and SST dataset are within the framework of NEMO-Nordic. One advantage of the reanalysis forcing is to reduce the uncertainty/bias of results arising from NWP forcing. We chose the atmospheric reanalysis to force the model, which, we thought, may reduce the intervention of the atmospheric errors regarding the analysis of the experiment results.

2) In the revision, we clarified this issue by pointing out that the system evaluation was done in the forecast phase after the LSEIK filter analysis (Fig.2). In this study, we firstly verified the system with two cases in two different seasons. Then we assess the impact of the SST data assimilation on Baltic forecast based on 48-hours forecast.

In the first paragraph of section 5, we added

“*We considered the evolution of SST based on 48-hourly local analysis from 1 January 2010 to 31 December 2010. The 48-hourly forecast of SST from two runs was assessed with observations from different dataset (see Fig. 2 for details).*”

There is a lack of detailed information on the data assimilation set up: whether the ensemble error statistics (or ensemble of model trajectories) dynamically evolve(s) in time or there is just one model trajectory and at the analysis step (every 48 hours) a constant (as it looks like given the expression “a stationary ensemble sample” in line 465, the suggestion on “a flow-dependent background error covariance” in line 472) covariance matrix represents the model error statistics: The SEIK and LSEIK are normally considered as ensemble-based data assimilation methods. It would be nice if the authors clearly emphasize what is different/distinct in their application and why they use (L)SEIK for the analysis while they do not use any ensemble at all. Why do the authors not use the flow-dependent background error covariance? Do the authors really "use a localized Singular Evolutive Interpolated Kalman (SEIK) filter" just only "to characterize correlation scales in the coastal regions"? Please describe the model variables used to construct the multivariate error covariance matrix and included in the state vector.

According the reviewer's comment, we added more details to clarify these points. we used a stationary ensemble to statistically estimate the background error covariance. We did not use time-varying ensemble based on a couple of considerations: 1) firstly, the stationary ensemble is computationally efficient as we don't need to integrated many model states like the EnKF. Secondly, the time-invariant ensemble was shown to be able to mimic the signature of circulation in the background error covariance (Fu et al., 2011; Liu et al., 2013). Time-varying vs time-invariant ensemble is an interesting topic with respect to approximating the background error covariance (Korre et al. 2004). However, the major objective of this study is to validate the assimilation of high resolution SST data. Given the number of ensemble samples used in this study and our previous study, we are confident that the stationary ensemble can produce robust analysis (Liu et al. 2013).

We added the text in the revision:" We used a time-invariant sample ensemble to approximate the background error covariance during the experimental period (Korres et al, 2004, Liu et al. 2013, 2017). This stationary ensemble affords a good approximation of the ocean's background error covariance. Meanwhile, it is computationally efficient for our objective."

We described the LSEIK in more details in the revised manuscript.

Similar to other ensemble data assimilation EnOI or EnKF, the SEIK filter method includes both the global and local analysis based on different consideration. We used local analysis version of SEIK (LSEIK) with domain localization in this study (Neger et al. 2007). We used a localization scale of 70km for the Baltic and North Sea. Now we moved the following text from Section 4 to Section 2.2:

"*Localization was used to remove the unrealistic long-range correlation with a quasi-Gaussian function and a uniform horizontal correlation scale (Liu et al. 2013). It was performed by neglecting observations that were beyond correlation distance from an analyzed grid point. In other words, only data located in the "neighborhood" of an analyzed grid point contribute to the analysis at this point.*"

We stated that the state vector includes the sea level, temperature and salinity. The same model variables (sea level, temperature and salinity) were also used in the multivariable EOF analysis.

To further clarify the DA setup, we also added the text about the observation error and forget factor: "To define the forgetting factor, a one-month simulation experiment with varying the factor ρ was done in January 2010. At last, a factor $\rho = 0.3$ resulted in the best assimilation performance. Further, we define a two-day assimilation window in assimilation experiment. As a result, the observations in the two days before the assimilation time were used to calculate the innovation with observation operator. When we calculated the innovation we also changed the observation error according to the observation time by

$\varepsilon = 0.4 \times \exp(-0.15\Delta t)$ (9),

here Δt is the absolute time difference between observation time and DA time. "

In the present form the conclusions include only general statements on the impact of SST DA, which does not, however, add anything new to what was drawn from previous studies, and there is nothing specific with respect to assimilating the OSISAF SST. More emphasize could be made on benefits due to the resolution of the OSISAF SST product, then a comparison against similar experiments but assimilating satellite SST data with coarser resolution are required.

The major objective of this study is to demonstrate the potential impact of assimilating OSISAF SST product on the forecast of the Baltic Sea. We showed in detail the potential of SST data assimilation for the forecast of temperature, salinity, sea level, mixed layer depth and sea ice. This study provides a clear and informative image to the Baltic Sea community for improving the forecast of different fields in the future. It is also the first time that OSISAF SST was assimilated into NEMO-Nordic model, which will replace the old operational forecasting system and serve the operational purposes at SMHI.

We summarized some new results in this study:

1. We demonstrated the potential of SST assimilation for the Baltic Sea forecast with the OSISAF Level 2 product, which is not contaminated by hind-cast information.
2. We provided overall validations of the potential impact of SST assimilation for the forecast in the whole Baltic Sea (both shallow basins and much deeper regions such as the Gotland Basin).
3. We found that the assimilation of SST could generally improve the forecasts of sea level from late spring to summer.
4. We showed an in-depth evaluation of the impact of SST assimilation on sea ice forecast by comparing the model with the observations of sea ice concentration (SIC) and sea ice extent (SIE). We found that the impact of SST assimilation on sea ice forecast is time-dependent, more important during the phase of sea ice formation than sea ice melting (March-April).

The assimilation of coarser resolution of the OSISAF product into the same model is interesting, but we would respectfully think it is beyond the scope of this study. Actually, previous studies showed that proper 'observation-thinning' schemes were very helpful to assimilate high-density remote sensing data. For instance, Li et al (2009) assimilated 0.3ºx0.3º satellite SST observation in the Chinese shelf-coastal seas. With an ensemble-based observation-thinning scheme, the assimilation of coarser resolution SST (0.5ºx0.5º) can yield an Analysis Error variance (AEV) of 0.1ºC. In the Baltic Sea, we expect that the impact of coarsening SST data on the forecast is weakened to some degree, depending on the actual thinning scheme.

Li XC, Zhu J, Xiao YG, Wang RW (2010) A Model-Based Observation-Thinning Scheme for the Assimilation of High-Resolution SST in the Shelf and Coastal Seas around China Journal of Atmospheric and Oceanic Technology 27:1044-1058 doi:10.1175/2010jtecho709.1

Specific comments

Lines 12-13: overall the sentence sounds misleading; moreover, for the localised SEIK you can use the LSEIK abbreviation. Missing reference to Nerger et al. (2006).

Thank you. We now used the LSEIK for the data assimilation method.The Nerger et al. (2006) was added as a reference in Section 2.2.

Line 20 (also line 453): I am just wondering whether 0.4% difference is a statistically significant in this particular application.

The model SLA was highly correlate with observation. The improvement of SLA varies considerably with stations. The 0.4% difference is the overall impact of the SST assimilation on the SLA. Since it is difficult to test the significance of the overall impact, we removed this sentence.

Line 119: please provide a reference to the used "runoff database".

We added the reference for the river runoff data:

Donnelly, C., Andersson, J. C., and Arheimer, B.: Using flow signatures and catchment similarities to evaluate the E-HYPE multi-basin model across Europe, Hydrological Sciences Journal, 61, 255–273, 2016.

Lines 205, 206: the discussed is the representation error (Janji´c et al. 2017, https://doi.org/10.1002/qj.3130).

There is different definition of the components of observation error in different consideration and theory. For clarify, we removed the discussion "The observation error mainly comes from the observation instrument itself, the observation representativeness, the temporary reading error and imperfect retrieval algorithm."

Part 4, Lines 224-225, 228: Please explicitly determine the state vector – which particular model variables it includes.

In the reversion, we added one sentence to clarify:

The sate vector includes sea level, temperature and salinity.

Lines 227-228: editing is required for the sentence "There does not exist uniform nature of error covariance for the variables of the model state vector and for the coastal zones "

Thank you. We rephrased the sentence as : "In the North Sea and Baltic Sea, error covariances of different variables are not uniform and strongly dependent on whether the variable resides in the open sea or coastal zone."

Line 233: "a forgetting factor" or "the so-called forgetting factor"

Thank you. we use "the forgetting factor" as the same using in Nerger et al. (2006).

Liner 236: missing references to Janji´c0 et al. 2011

We added this reference Janjić et al. (2011)

Lines 247-248: The sentence "The correlation length scale : : :." is a copy-paste from

Losa et al. 2012; please rephrase and provide the references, including the references to the original studies by reporting on the estimates of the Rossby radius of deformation (Alenius et al., 2003; Fennel et al., 1991).

we rephrased this sentence and added the Losa et al., (2012) as a reference.

"The correlation length scale is to some extent dependent on the Rossby radius of deformation (Losa et al., 2012), which varies from ~ 200 km in the barotropic mode to ~ 10 km or even less in the baroclinic mode (Fennel et al., 1991; Alenius et al, 2003)."

Lines 271-276: the discussion on the bias seasonality: while, in general, the statement (l. 271) is true and was also discussed in Losa et al. 2014, it is difficult (if ever necessary) to conclude anything in this respect given just 2 snapshots for the increments (Figure 2).

Thanks for good comment. We removed the seasonally bias discussion related to Figure 2.

Line 457: "significantly improved" – this is not obvious.

we removed "significantly".

Line 14: should it be "improvements of" instead of "improvements on"?

we revised it to "improvements".

Lines 33-35: please provide references;

we added a reference Omstedt et al. 2014:

Omstedt, A., Elken, J., Lehmann,A., Leppäranta, M., Meier, H.E.M., Myrberg, K., and Rutgersson, A.: Progress in physical oceanography of the Baltic Sea during the 2003–2014 period. Progress in Oceanography, 128, 139-171, 2014.

Line 38: "a numerical model" instead of "a numeric model";

It was fixed.

Line 46: "joint effort" instead of "joints effort";

It was fixed.

Line 49: "used for the operational" instead of "used to the operational"?

It was fixed.

Line 85: “sea level anomaly” instead of “sea level Anomaly”;

It was fixed.

Line 271: “model forecast possibility” – please remove “possibility”;

In revision, we don’t want to discuss the season variation of model SST. Therefore, we deleted the sentence “The SST bias of model forecast **possibility** has seasonal variability because of the errors in the forcing and/or heat flux parameterization used in the ocean model (Fu et al. 2012).”

Line 308, 333, 335: “Arkona” instead of “Arokna”;

It was fixed.

Line 329: “The possible reason” not “The possibility reason”;

It was fixed.

Line 470: “strongly”, however the sentence in the lines 470-471 sounds misleading.

We removed “around the observation position.”

References

Janji´c0, T., Nerger, L., Albertella, A., Schröter, J., Skachko, S., 2011. On domain localization

in ensemble based Kalman filter algorithms. Monthly Weather Review 136 (7),

2046–2060.

Nerger, L., Danilov, S., Hiller, W., Schröter, J., 2006. Using sea level data to constrain

a finite-element primitive-equation model with a local SEIK filter. Ocean Dynamics 56,634–649.