Dear Madam,

We thank the first anonymous reviewer for recommanding to accept the article as is, and the second reviewer for yet again precise and helpful comments. Clearly, she/he spent again a lot of time trying to help us get a very good manuscript.

We answered each of his/her comments, and modified the text and the figures accordingly. The revised version of the manuscript is much more consistent, some new references were again added, all according to the reviewer's comments.

The second reviewer also suggested modifying the « regional » to « nested », as in CMEMS terminology, regional means basin-wide, whereas by regional model, we understood a « local » model. We modified the paper accordingly, but also the title of the paper should now be changed, « regional » becoming « nested ».

We again think the revised paper is much better than the previous version, and submit it to you for consideration for publication in OS.

The replies to the second reviewer are copied below for your convience.

Upscaling of regional models into basin-wide models

Luc Vandenbulcke and Alexander Barth
Research article in Special Issue: The Copernicus Marine Environment Monitoring Service (CMEMS): scientific advances

The paper presents the upscaling technique in a realistic configuration in the Mediterranean Sea domain. A NW-Med model is nested into a Mediterranean model (MED) with a downscaling factor of 5 and the aim is to prove that the upscaling technique is driving the parent model (MED) solution towards the child model one (NW-Med). The upscaling consists in assimilating the 3D temperature and salinity child model fields as pseudo-obs in the parent model. The upscaled model solution is thus closer to the child model when compared to the parent model using 5 different metrics.

General Comment

The paper presents the upscaling technique as a relevant scientific question in the operational model community. After the revision the paper improved but there are things that reveal again a superficial approach of the corresponding author (I am sorry to say), which ignored some suggestions. Some corrections were only partially included. Added material (i.e. Tab.1 and the appendix) has not been described or motivated properly in the text.
I provide further suggestions to improve the paper readability and preciseness, with very detailed indications that required once again a lot of efforts.
However after these corrections the paper could be published.

We thank the reviewer for the constructive comments and the obviously large amount of work that went in the review. We answered each comment in the document below and corrected the article accordingly.

Specific Comments

Abstract

Lines 2-6-20, line 4-5-8-26 page 2,....

I already suggested to revise the following nomenclature to be consistent with CMEMS one. In CMEMS (see Simoncelli et al., 2017!!!!) the **regional** models are considered the basin scale, while you use it to indicate the high resolution model. I seriously recommend to harmonize it in all the paper since you are in a CMEMS special issue.

About the use of the word « regional »… We do not agree with the reviewer that « regional model » should necessarily mean a basin-scale model. Lorente et al, JOO 2016, talks about the IBI model in CMEMS and uses « region » to talk about a specific sub-domain of IBI. In general, a region may refer to both large (e.g. 'Eastern Europe') but also to smaller entities (e.g. the 20 regions of Italy). However, we want to avoid any potential misunderstanding, and it's true that the CMEMS website talks about « regions » for the 7 european seas. To be coherent with CMEMS' choice for the word « region », we do not refer to the NW-Med model as « regional » anymore. We now talk about the « nested model », « child model », « high-resolution model » instead of « regional model », and introduce the « sub-regional » term instead of « regional » when talking about the geographical area.

To be coherent, we also need to modify the title of the paper, which became « upscaling of nested models... » instead of « upscaling of regional model... »

Line 7→ please substitute "forecasts" with simulations, since you are not using the model in forecast mode.

We replaced « forecast » with simulation

Again here you use low-resolution vs high resolution, other time you use parent and child, please harmonize.

It is true that we use both « parent model » and « low-resolution model » when talking about the Med model ; and « child model », « nested model » and « high-resolution model » when talking about the NW-Med model. In our opinion, it is pretty obvious which model is referred to, but to be even more clear, we now explicitely explain this in the introduction. Using only « high-resolution model » (and repeating it over and over again) in the paper would lead to an extremely boring text for a paper that is already kind of « technical ».

Line 10: Being in some sense (not very scientific expression) more realistic means to have better prediction skills from model validation with observations, this should be specified.

Changed «… is, in some sense, more realistic ... » to « … has better prediction skills ... »

Line 12: here you use "stand alone model" instead of introducing the **MED free model** and you could also specify the **MED upscaled model**. However you are stating that you are going to compare **MED**

free model and **MED upscaled model**, but in the text and some figure you refer to NW MED model (i.e. Fig.9 and 10) and the NW upscaled MED model (i.e.Fig.11, Tab.1). This is another point to be harmonized, and that was ignored by the author.
We removed « standalone model » as it was the only place in the article that this was used, and added a note at the bottom of the introduction instead. Also «free model » and « upscaled model » are now introduced in the bottom of the introduction.
Also, in general, we tried to remove the remaining lack of harmony in the figures and table.

Line 13: Looking at Tab. 1 you have improvements, if you consider improvement=decrease of RMSD on your metrics computed among parent-child models, that goes from 14% cross-shelf transp to 0% for SST. After SST Rhone plume metrics presents the smallest improvement. I expect/ed from the author this kind of evaluation which is totally missing in this second version. Tab. 1 has just been inserted without any explanation. I think that the paper should be full revised accordingly.
We added some text in the relevant sub-sections of section 4 (Results) explaining better the results summarized in Table 1. Also in the conclusion a sentence was added.

Intro

Line 19 page 1: I would take out “regional and coastal” referred to the oceanographic centers
Removed

Line 21 page 1: I would take out “increased experience”
OK, removed

Line 21 page 1: now you use “local” models …
Changed to « nested models »

Line 1 page 2: I suggest “high resolution observations of currents”
Changed

line 4 page 2: Again please use either low vs high resolution or parent vs child
changed to « parent and child »

line 7 page 2: Again....please use either low vs high resolution or parent vs child and substitute forecast with simulation.
Changed to « parent and child », and replaced forecast by « model »

line 9 page 2: “This constitutes the baseline hypothesis of the present study: it is desirable to “copy” the results of the nested model into the parent model.”
Your assumption is that the child model performs better than the parent model within the child domain, your objective it to “copy/transfer/mimic?” the child model results in the parent one.
Yes

Line 11 and 17 page 2 à I would substitute “forecasts” with “data”
Line 11 : we changed forecasts to « results »
Line 17 : we changed forecasts to « data »
As a side-note, the « forecasts » of the nested model COULD be extracted, and used as « future pseudo-observations » in a re-run of the parent model. This is the only case where we actually have « future observations » to assimilate in forecast mode.

But this is not considered in the present paper. In the paper, we don't pay attention to the fact that we run in hindcast or forecast. So we agree with the reviewer and remove the word « forecast ».

Line 12 page 3: I suggest to erase "(only the horizontal grid is different). This could influence the conclusion compared to a set-up with 2 different model codes. However, this is not expected to be a fundamental limitation of the method. Concerning the vertical grid, in the usual case of assimilating real observations such as vertical profiles, the observations and 15 model forecasts have different vertical resolutions. Similarly, if the child model were on a different vertical grid than the parent model, it would still contain useful information, worth to be assimilated in the parent model. A limitation could be that some of the observations may be lost, e.g. the lowest child model layer may be out-of-grid in the parent model."
The text is confusing but the content is obvious and does not justify 7 lines of text.
This text was added following a question of the other reviewer, « how would the method behave if the nested model was not NEMO or had a different vertical grid ». It is now replaced with a single sentence : *It is not expected that the conclusions of the study would be fundamentally different if different models and vertical grids are used for parent and child models.*

Line 12 page 3: I would substitute "forecasts" with "data"
Removed, there is not any single « forecast » in the article anymore

Line 18 page 3: "If different model codes were used, the models could represent different processes."

The reviewer considers the text lines 12-29 superficial. Independently from the models' set up, you use child model data as synthetic observations in your data assimilation scheme. As for any other type of observation the assimilation approach is tuned accordingly. Most important would be the model data thinning or weighting as function of child model skill, but the author highly underestimated this aspect, preferring a pure assimilation exercise approach.
Part of the text is removed (see previous comment). The remainder answers a question from the other reviewer, and is (also in our opinion) useful.
Regarding the reviewer's comment on the data thinning and weighting as a function of the nested model skill, this implies to validate the child model with real observations. If real observations are available in sufficient quantity, they would probably be sufficient to constrain the parent model as well, i.e. they could be assimilated directly in the parent model. The exception to this, is the case where very dense (in space) observations are available, that could better be ingested by the nested model than by the parent model (e.g. ultra-high-res SST, or radar surface currents).

Line 1 page 4: I would substitute "forecasts" with "data"
Modified « forecasts » into « simulation »

Line 1 page 4: "*It should be noted that some high-resolution processes, resolved by the nested model but not by the parent model, could have large phase errors in the nested model. In this case, the baseline hypothesis would be violated, and the nested model could actually have higher errors than the former. This aspect is not considered in the paper.*"
Your SST metrics prove that you are in this case thus I would avoid the last phrase and I would ameliorate your results description and Conclusions accordingly.
We do not agree with the reviewer that the SST metric proves that we are in the case of phase errors in the nested model. Typically, phase errors are visible e.g. in inertial oscillations, after a wind burst.
But in the current experiment, for the SST field, if the parent and child models both have small errors (say, smaller than 1°) and at another period, both have large errors (say, 3°C), then I would rather

suspect errors in the atmospheric forcing fields and in the bulk formulae computing the heat fluxes, which are the same in both models. Also the heat propagation towards depth uses the same attenuation parameters in both models.

2.1 Hydrodynamic Model

Line 12 page 4: Please refer to figure 2. I would also use " The region is characterized..."
Added the reference, and changed the text according to the comment

Line 14 page 4: introduce the acronym at line 11 please.
Added

Line 20 page 4: Please specify the resolution of the child model and correct the parent model resolution. 6 or 8 km? (See table in the appendix).
8 km, sorry for the confusion, corrected now
I do not agree on the choice of having an appendix with a table of identical columns. If you want to keep the table just mention it as Tab.1 here. Child and Parent model differences are the horizontal resolution 8km (not 6?), a highest resolution topography and bathymetry of the child model and the Rhone river discharge data.
The reviewer is right, and the appendix with the table has now been removed. The important differences between child and parent models are given around line 20 page 4.

Line 16 page 4: Please correct the reference in the bibliography to properly cite a specific section in the CMEMS OSR. Simoncelli, S., Pinardi, N., Claudia Fratianni, Dubois, C., Notarstefano, G. 2018. Water mass formation processes in theMediterranean Sea over the past30 years. In: Copernicus Marine Service Ocean State Report, Issue 2, Journal of Operational Oceanography, 11:sup1, s13–s16, DOI: 10.1080/1755876X.2018.1489208
corrected

Line 21 page 4
Please insert the references as suggested previously.
Med analyses at 1/16th
Clementi E., Pistoia J., Fratianni C., Delrosso D., Grandi A., Drudi M., Coppini G., Lecci R., Pinardi N. (2017). Mediterranean Sea Analysis and Forecast (CMEMS MED-Currents 2013-2017). [Data set]. doi:https://doi.org/10.25423/MEDSEA_ANALYSIS_FORECAST_PHYS_006_001.
Added

Paper describing the reanalysis set up
Simoncelli S., Masina S., Axell L., Liu Y., Salon S., Cossarini G., Bertino L., Xie J., Samuelsen A., Levier B., et al. (2017).
MyOcean regional reanalyses: overview of reanalyses systems and main results.
Mercator Ocean J. 54. Special Issue on Main Outcomes of the MyOcean2 and MyOcean Follow-on projects. https://www.mercator-ocean.fr/wp-content/uploads/2017/04/Mercator-Ocean-newsletter-2015_54.pdf

Reanalysis data set
Simoncelli S, Fratianni C, Pinardi N, Grandi A, Drudi M, Oddo P, Dobricic S. 2014. Mediterranean Sea physical reanalysis (MEDREA 1987-2015) [dataset]. Copernicus Monitoring Environment Marine Service (CMEMS). doi:10.25423/medsea_reanalysis_phys_006_004.

Added

Line 24-27 page 4: this is redundant, it's already written in the introduction.
The general idea has been already written, but the particular impact of upscaling on the Corsican currents and the stratification has not been mentionned before

Line 30 page 4: How do you interpolate MED reanalysis data onto your parent and child model grid? Or is it only for the child model? Which kind of extrapolation did you apply where model topographies mismatch? i.e. Coastal strip, or bottom layers deeper than MED reanalysis ones.
Tri-linear interpolation and linear extrapolation, this is now written in the paper

Line 11 page 5: I suggest "...showing the surface salinity difference using climatological or daily data in child model (NW MED model) simulations after 1 month of spin up"
Changed the text as suggested by the reviewer

2.2
Line 24 Page 5: none detail is in the annex about the data assimilation. Modify accordingly.
Modified
Line 25: whole or thinned?
What I meant is : the whole 3D field, but thinned. Rewritten as : the thinned 3D field
Line 26 isn't is a super-obs approach?
I guess so...

You are mixing the description of data assimilation and initial condition, I recommend to start from the upscaling experiment description (absent now), then IC and then DA.
The title of the subsection indicates what will be described : «Upscaling experiment description, Ensemble generation, and Data Assimilation scheme ». This is what the reviewer also suggests. The 3 paragraphs in the subsection are now better separated to reflect that. The first paragraph is a description of the upscaling experiment.

Moreover in Tab 1 you refer to 2 nested systems, thus you should explain both experiments.
This is explained at the very beginning of section 3. This text has been slightly re-written to be more clear.

Are the perturbed IC applied to both child and parent models or only the child, this is not specified.
The perturbed IC (as well as the other perturbations) are applied only to the parent model ; upscaling consists in assimilating into the *parent* model. As a EnKF is used, the parent model thus needs to be transformed into an ensemble. This is now briefly reminded in the description of the upscaling experiment (i.e. at the top of this subsection)

3. Metrics

Please introduce Tab 1 and its interpretation either here or in **4. Results**. Now you mention it in the last line of section 4.5. Insert its reference also in all metrics discussions in 4.*.
We now refer to the Table in each subsection of section 4 (results)

3.4 "This metric is the root mean square (rms) difference between the model and observed SST. For the latter, the L3 images are used. ~~Furthermore, in order to examine the position of features such as fronts and eddies, the rms difference of the norm of the spatial gradient of the SST is also~~

~~computed.”~~
This paragraph could be improved, among which models? What is in Tab.1? How is it computed? I suggest also to remove the second phrase, you are not talking about this afterwards.
Indeed. The second phrase is now removed.
The RMS is computed between the parent model and the L3 SST image (for both the free and upscaled parent model). This is now written in the text.

3.5 I thank the author for the explanation however the text has not been modified. I suggest to do so, without mentioning the tail of the diagram. The reader would thank you.
The text has now been adapted, and the whole issue of the tail of the diagram has been deleted from the text.

4. Results
Figure 4: please increase the size of the red arrow
Done

Figure 5: avoid to use forecast (plot titles), use consistent nomenclature in the caption.
Modified plot titles and changed nomenclature to « MED free », « NW-Med » and « MED upscaled » identical to the other plots

4.2 second line, I would use child instead of nested (same in caption of Figure 3) as in the rest of the paper to harmonize and facilitate the reader. (Already suggested)
Changed

4.3
First Line: Why do you say that? Why don’t you use Tab.1 to argument your statement?
Table 1 shows the RMS for the plume length. The plume direction (offshore or along-shore) is sometimes different in the parent and child model. When upscaling modifies that (succesfully), it is a very significant change, although the RMS does not necessarily reflect that. The text was rephrased to better explain that.

Lines 3-4: The interpretation of Fig.8 is confusing. The upper panel shows the MED free model, please change the title in agreement with figures 6, 7. The bottom panel shows the MED upscaled model, please change the title in the plot accordingly. Why don’t you comment the MED upscaled model instead of the nested model? You do it at line 2 of page 13
The figure titles were changed
The text is changed. In the paper, it now describes the « MED free » plume, then the « NW-MED and MED upscaled» plume.

Moreover the arrows are pointing North-West or South West, is it correct? Could you better explain and interpret the figure for the reader?
The reviewer is absolutely right, I actually meant to say « West » and wrote « East » for both cases. This is now corrected in the text.

I suggest to revise the paragraph and adopt the same nomenclature in figures/captions/text. This suggestion was not handled by the author.
The nomenclature is now changed and consistent with the rest of the paper and the other figures.

Figure 9: This figure presents MED and NW-Med, why not the MED upscaled model? I suggest to

show the three salinity fields. The author just skipped this suggestion, however the reader is confused since you always change approach in presenting the results.
We replaced now the NW-MED plot with the MED upscaled plot (projected on the NW-MED grid), as the reviewer suggests. It's true this is more coherent.

The nomenclature in Fig. 9 is not consistent, please change the titles to match MED free model and MED upscaled model.
Changed according to the reviewer's suggestion

The author replied that the MED upscaled model is indistinguishable from the nested model but the scope here should be to show that the MED upscaled model is close to the nested/child model and not that the nested model is closer to the satellite image. From my point of view the author's answer is very superficial.
The reviewer is right, and we hope the new plots are more convincing. The chlorophyll plot is still left in the paper, as illustration.
Please note that both plots were from Nemo restart files (in the previous version of the submitted paper), and now they are daily means. I don't have anymore the corresponding restart file for the MED upscaled. This does not change anything, but I mention it to explain why very small differences appear also in the MED free plot (compared to the previous version of the paper).

Line 10-13 Page 13: Considering that you do not care about what observations indicate, you say that upscaling is changing in-depth salinity in the ECC and WCC. This phrase should start a new line because not related to the Rhone plume, otherwise please explain what is the connection and motivate why upscaling is behaving in the right direction.
This is indeed unrelated to the Rhone plume. It was moved into a separate paragraph

4.4
Line 3 Page 14: Level 3 images are used for computing the metric→ already said in 3.4
(a level 4 image shown in Fig. 5 is used only for visual comparison) → This should not go here but in the Fig. 5 caption and specified at line 26 page 9.
Moved

Line 4 Page 14: "Results are shown in Fig. 10." What is the plot? What do you want to show? You say it at line 4 Page 15: "Fig. 10 shows the RMS error during the first 2 months of simulation." à of what, which models????
My suggestion is to revise the entire paragraph.
The entire paragraph has been rewritten and figures are clearly described

Line 4 Page 14: I do not agree that the **MED free model** is in very good agreement with SST, at least you do motivate it, including some reference to support it. What is the CMEMS skill in this region/period? http://cmems-resources.cls.fr/documents/QUID/CMEMS-MED-QUID-006-013.pdf
In fact in the paragraph You say that the error is relatively large in some days, that during summer is around 3 degrees C, that all the models are not resolving some coastal processes.
During the first 2 months, the RMS between model and SST is around 0.4 or 0.5°C **without data assimilation**, and in my opinion, this is not bad. During the remainder of the simulation, and especially during summer, the model is less good, and indeed errors go up to 3°C, which is not good.
Rather than make a quality document of the model, which is not our aim, the « very good agreement » has been removed.

Line 5 Page 14: “Usually, the nested model is better still in some areas (e.g. coastal waters), and the upscaling procedure brings back these local improvements to the parent model.” Please rephrase, this statement is vague. You assume that the nested model is performing better in coastal waters, thus your technique should modify the parent model and increase its performance accordingly, right?
The method does not assume geographical criteria (coastal or not, etc). But it so happens that the nested model sometimes performs better at the shelf break or on the shelf. These improvements are indeed brought back to the « MED upscaled » model. When the rest of the domain is essentially unmodified, this improvement at the shelf break almost doesn’t change the overall RMS.
We added a reference to Figure 5, which shows an example for a coastal or shelf-break process improved by upscaling.

Line 5 Page 15: ~~A similar plot for the whole of 2014 shows that~~ The situation worsens during summer when the computed RMS errors are of 3_C, both for parent and child model (not shown).
It goes at the beginning of the paragraph.
We changed the text according to the reviewer’s suggestion, but prefer to keep the description of the 2 first months (and the corresponding figure) separated from the remainder of the year.

“The difference in between models is hidden by the temporal variability of the error. In any case, the upscaled model is still very close, and slightly better, than both the (free) parent and the nested models.”
From my point of view, there are not differences among the **MED free model, MED upscaled model and NW-MED model (Tab.1 prove it)**. Please provide the average RMS computed over the considered time period, if you want to say that **MED upscaled model is slightly better than MED free and NW-MED.**
We removed the « slightly better », even though the 1.3°C RMS error is actually very slightly smaller for the upscaled model than the free model (when not rounding the RMS).

Line 8-13: They are about the model temperature in depth and should not go in this paragraph, eventually in the general discussion of results or in the summary.
“The model temperature in depth can be only punctually evaluated against observations (when e.g. drifter observations are available). In any case, the goal of the current study is to check whether upscaling is able to bring the parent model closer to the nested model, under the hypothesis that the latter is “better” in some sense. (not needed here it’s a repetition). Differences between the parent and the nested model are locally important, e.g. on the bottom of the Gulf of Lions, or in the Eastern Corsican and Northern Current cores (with differences of up to 0.3_C), and upscaling is able to push the temperature field in the parent model toward the nested model solution.” (not pertinent here and not shown!).
The reviewer is right, and actually the same thing happens in the previous section, which uses surface salinity to describe the Rhone plume, but then quickly also says a word about in-depth salinity. Both for salinity and temperature, the paragraphs have been moved into a new, separated but un-numbered subsection (after the 5 subsections corresponding to the 5 metrics).
Furthermore, the text was modified according to the reviewer’s suggestions, and generally simplified.

\subsection{Deep temperature and salinity}*
Some metrics considered above used surface salinity and temperature. However, upscaling modifies the 3D variables of temperature and salinity.
Differences between the parent and the nested model temperature are locally important, e.g. on the bottom of the Gulf of Lions, or in the Eastern Corsican and Northern Current cores (with differences of

up to 0.3°C). Similarly, the cores of both Corsican Currents are saltier in the upscaled model, with differences of about 0.15 psu during the first assimilation cycle. For both temperature and salinity, upscaling is able to push the parent model toward the child model solution (not shown).

4.5

Again, what are you showing in Figure 10?

For fig.10 this is now describde in the text. Fig.11 is already described in the text.

I suggest also to modify:

"The total amount of Western Mediterranean Deep Water in the free model (blue curve in Fig. 11) and the nested model (green curve) is periodically important (103 km3), ~~and both~~ but the models do not ~~appear~~ to converge during the simulation. ~~On the contrary, a period of large discrepency~~ , as it appears during most of the second half of the year."

The text has been modified according to the suggestion

Line 4 Page 16: I would use the reference to Tab. 1 here instead of line 9.

Moved the reference to Tab. 1

5. Conclusions

Lines 10 Page 17: You should say that for SST the upscaling did not produce any improvement, as shown also by Tab.1

This paragraph of the conclusion was rewritten, it is now mentioned that the SST RMS is not improved. It is also mentioned that some local improvements (such as seen in Fig. 5) are not contributing significantly to the RMS (as explained already in 4.4).

In fact, you say in 4.4.

"The ~~area-wide~~ spatial RMS error is not influenced very much by upscaling (please refer to Tab.1), as large areas are essentially unmodified (parent and child models use the same atmospheric forcing fields). Some days, some processes ~~appear to be missed~~ are not resolved by the models (both parent and nested), so that the RMS error is relatively large. In this case again (?), upscaling does not influence the RMS error of the parent model ~~very much~~ (the RMS in tab1 is identical), as the nested model is not representing these processes any better than the parent model."

The « area wide » is important to underline that the RMS is computed over the domain, whereas the improvements (when there are any) are only local (e.g. coastal etc, see before). Therefor, the RMS is not improved. This does not imply that there are no changes and that some processes are not modified by upscaling.

Anyway, the reference to Tab. 1 is now added in the sentence as suggested by reviewer 1.

This suggest that without considering the skill of the child model, your upscaling might not improve the parent model solution, but just bring the child solution closer to the parent one blindly.

Yes. Or more exactly, we bring the parent solution closer to the child. This was exactly our aim. After that, it is up to modellers to decide if that's what they actually want. The decision could be based on observations, as the reviewer keeps suggesting, or on other knowledge.

It could also degrade the parent model performance. Obviously if you do not validate the models with observations, you do not know.

Indeed. As mentioned before, when one has lots of observations to validate / improve / assimilate in the parent model, the whole upscaling exercice becomes kind of pointless. But if there are (some) observations, of course it makes sense to validate the child model before considering it as pseudo-observations.

Upscaling of nested models into basin-wide models

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Abstract. Traditionnally, in order for lower-resolution, global- or basin-scale (regional) models to benefit from some of the improvements available in higher-resolution sub-regional or coastal models, two-way nesting has to be used. This implies that the parent and child models have to be run together and there is an online exchange of information between both models. This approach is often impossible in operational systems, where different model codes are run by different institutions, often in different countries. Therefore, in practice, these systems use one-way nesting with data transfer only from the parent model to the child models. In this article, it is examined whether it is possible to replace the missing feedback (coming from the child model) by data assimilation, avoiding the need to run the models simultaneously. Selected variables from the high-resolution simulation will be used as pseudo-observations, and assimilated in the low-resolution models. The method will be called "upscaling".

A realistic test-case is set up with a model covering the Mediterranean Sea, and a nested model covering its North-Western basin. Under the hypothesis that the nested model has better prediction skills than the parent model, the upscaling method is implemented. Two simulations of the parent model are then compared: the case of one-way nesting (or stand-alone model), and a simulation using the upscaling technique on the temperature and salinity variables. It is shown that the representation of some processes, such as the Rhône river plume, are strongly improved in the upscaled model compared to the stand-alone model.

1 Introduction

In the present-day operational oceanography landscape, services are provided at different scales by different expert centers. At the European Union level, the Copernicus Marine Environment Monitoring Service (CMEMS) provides reanalyses, analyses and forecasts at global and basin scales. The models for the different basins are run by different institutes and centers within the regional monitoring and forecasting centers. Various regional and coastal <– suppressed oceanographic centers then use the CMEMS products to provide initial and/or boundary conditions to their respective models. These sub-regional and coastal models benefit from the specific knowledge of the local teams in their particular area of interest. Furthermore, nested models usually run at higher resolution, and may include more accurate data (bathymetry, river discharge data...) and processes of smaller scales, that cannot be easily included into basin-scale models. High resolution observations such as satellite sea surface temperature (SST), and recent ultra-high resolution products (see e.g. Le Traon et al., 2015) have been shown to be best assimilated into nested models, as chances are higher that the observed processes are well represented (Vandenbulcke et al, 2006). Similarly, igh-resolution observations of currents by high-frequency radars are expected to benefit most to models with a similar high resolution (i.e. nested models).

When parent and child models are run together (meaning, concurrently and on the same computing platform), it is possible to use two-way nesting; the benefits mentioned above of using a nested model are then transferred back to the basin-scale model. This has been shown numerous times in the literature, e.g. Barth et al. (2005); Debreu et al. (2012). The beneficial impact of the feedback from nested to the parent model is visible even outside the domain of the nested model. This constitutes the baseline hypothesis of the present study: it is desirable to "copy" the results of the nested model into the parent model.

To emulate this nesting feedback, missing in the operational context, it is analyzed whether results from the sub-regional model can be used as pseudo-observations and assimilated in the basin-scale model. Indeed, data assimilation is not limited to the use of (real) observations by measurement devices. Onken et al. (2005) used data assimilation as a substitute for one-way nesting in a cascade of nested models. Alvarez et al. (2000) used a statistical model to predict SST, which was then assimilated as pseudo-observations in a hydrodynamic model (Barth et al., 2006). In the proposed "upscaling" method, the pseudo-observations come from the nested model. From the point of view of the forecasting centers, a data assimilation scheme is already implemented in the basin-scale model. Hence, implementing the upscaling method requires only to obtain the high-resolution data and assimilate (parts of) it, along with the real observations, during the analysis phase of the system.

When using grid nesting, problems at the open boundary of the child model include stratification mismatches, artificial waves, artificial rim currents; and ultimately instabilities and model blow-up (Mason et al., 2010; Debreu et al., 2012). By upscaling the child model into the parent model, the latter will progressively gain consistency with the child model solution within its domain, being beneficial for the child model over time. Upscaling can potentially reduce the risk of discrepancies at the open sea boundary.

Upscaling can also be seen as using a high-resolution model as a "measurement device" that replaces ever-too-sparse (real) measurements. Guinehut et al. (2002, 2004) showed that a coverage of the North Atlantic with a 3°-resolution grid of Argo floats allows to effectively represent the large scales. Using a 5° array reduces the precision of the estimated fields two times. Currently, some CMEMS areas are largely undersampled.

Upscaling can be understood as a complement to downscaling (initialization) techniques such as presented in Auclair et al. (2000, 2001) (VIFOP) or in Simoncelli et al. (2011). The point of these methods is to combine interpolated fields coming from the large-scale model (the background or first-guess field) and existing high-resolution fields, so that small-scale structures present in coastal models are not lost whenever it is (re)-initialized by fields interpolated from the basin-scale model, and the obtained fields are physically balanced with respect to the coastal physics. If upscaling is used to improve the basin-scale fields and accord them with the coastal model, the “first guess” will be already much better.

Schulz-Stellenfleth and Stanev (2016) is another recent example showing the benefits of two-way nesting, especially in sophisticated modern-day forecasting systems. The study demonstrates that two-way nesting is critical for correct energy transfers between large and small scales (especially in coupled ocean-wave-atmosphere models) for cross-border advection, for the correct use of high-resolution coastal observations that cannot be fed directly into a large-scale model, etc. Ackowledging that operational systems are using only one-way nesting, Schulz-Stellenfleth and Stanev (2016) therefore strongly advocate the research into “upscaling” techniques. The present article tries to develop precisely such a technique.

In this article, the upscaling procedure is tried out in a realistic, nested model configuration covering the Mediterranean Sea and the North-Western basin and simulating the year 2014. The same model, NEMO 3.6 (Madec, 2008), and the same vertical resolution, are used for both configurations (only the horizontal grid is different). It is not expected that the conclusions of the study would be fundamentally different if different models and vertical grids are used for parent and child models. If different model codes were used, they could represent different processes. Hence, this should be taken into account by modifying the (representativity part of the) observation error covariance matrix when performing the data assimilation of the pseudo-observations. Examples of such contributions to the representativity error could be

- different vertical coordinates (see above)
- different implementations of the ocean surface: rigid lid or free surface; for the latter, linear or non-linear representation
- hydrostatic model or not
- different atmospheric forcing fields
- different turbulent closure schemes
- different numerical schemes for advection, horizontal diffusion etc.

The most striking difference between the parent and child models however, remains the horizontal resolution, and therefore, the general conclusions of the paper are expected to be valid, and upscaling should not be limited to the case of parent and child models being identical.

In this study, it is not the aim to verify that the nested model is indeed more realistic, according to some metrics, than the parent model. Rather, this consistutes the baseline hypothesis, and thus it is always considered beneficial to bring the parent model simulation closer to the child model simulation. It should be noted that some high-resolution processes, resolved by the nested model but not by the parent model, could have large phase errors in the nested model. In this case, the baseline hypothesis would be violated, and the nested model could actually have higher errors than the former. This aspect is not considered in the paper.

The parent model (also called “low-resolution” model), and the child (or “nested” or “high-resolution”) model, and the data assimilation scheme are described in section 2. The parentmodel will be run both in “free” mode, and “upscaled” mode (i.e. assimilating pseudo-observations from the child model). The “free model” is equivalent to a stand-alone model, i.e. even if there are nested models, it is not influenced by them. Section 3 proposes some metrics to evaluate the system, related to the Rhône river plume, the cross-shelf exchanges, the large-scale current, SST, and the formation of Western Mediterranean Deep Water. Results are given in section 4 and a conclusion in presented in section 5.

2 Model and data assimilation configuration

2.1 Hydrodynamic model

The upscaling technique has been implemented in the North-Western Mediterranean Sea (NW-Med), including the Gulf of Lions and the Ligurian Sea (see Fig. 2). The region is characterized by large-scale currents (the Northern Current also called Liguro-Provencal Current, created by the junction of the Eastern and Western Corsican Currents, see e.g. Pinardi et al. (2015)), by intense meso-scale activity and by inertial oscillations. Furthermore, the NW-Med is the siege of formation of Western Mediterranean Deep Water (WMDW), important to the circulation in the whole Mediterranean Sea (e.g. Millot, 1999; Pinardi et al., 2015; Bosse et al., 2015; Somot et al., 2018; Simoncelli et al., 2018).

A realistic, one-way nested configuration was implemented using the NEMO 3.6 model and the AGRIF nesting tool (Debreu et al., 2008), covering respectively the Mediterranean Sea (MED) with a 8 km horizontal resolution, and the North-Western Mediterranean basin (NW-Med). The parent model resolution is similar to the previous version of the CMEMS Mediterranean Sea analysis-forecasting system (up to October 2017) (Clementi et al., 2017) and to the present reanalysis (1/16°) (Simoncelli et al., 2014). The child model horizontal resolution is 1.6 km.
When implementing the upscaling method, it is expected that after some time, the feedback from the NW-Med model will modify the Northern Current position and intensity in the parent model, which will in turn influence the NW-Med model through its open-sea boundary. The boundary condition provided by the MED model also influences the stratification of the water column, which is important for the pre-conditionning of the convection (S. Somot, private communication).

Both model bathymetries are interpolated from the GEBCO bathymetry. Thanks to its higher resolution, the bathymetry of the nested model (1/80°) is more realistic than in the parent model, at the coastline and more importantly, at the different canyons at the Gulf of Lions shelf break. The temperature and salinity initial condition is interpolated from the CMEMS Mediterranean reanalysis (1/16°) for 01/01/2014 (see https://doi.org/10.25423/medsea_reanalysis_phys_006_004), using tri-linear interpolation and linear extrapolation where needed. The model starts from rest. Atmospheric fluxes are computed using the bulk formula from the Nemo MFS module; the atmospheric forcing fields are obtained from ECMWF ERA Interim with a temporal resolution of 3 hours and a horizontal resolution of 0.75° reinterpolated by the ECMWF server to 0.125° (Dee et al., 2011). In the MED model, the flow between the Black Sea and the Mediterranean Sea, through the Marmara Sea and the Dardanelles Strait, is modelized as a river, using climatological flow, temperature and salinity values. The salinity of the incoming water has a minimum and maximum of 22.5 psu and 27.5 psu reached in July and March respectively. Five other rivers (Rhône, Po, Ebro, Nile, Drin) are also represented, and monthly climatologic values for the flow and temperature are used, whereas the salinity is put to 5 psu, except for the Drin river where is it put at 2 psu. Using climatologic monthly values is coherent with the operational set-up in the CMEMS Mediterranean system, although the latter represents many more small rivers.

Daily Rhone river discharge measurements at the Beaucaire station were obtained from the Compagnie du Rhône, in order to be used in the nested NW-Med model. Interestingly, the total annual flow computed from the climatology and from the measured values for 2014-2015 are very similar (1% difference). However seasonal and daily values can be very different (see Fig. 1a). In particular, during the considered period, the climatology underestimates the winter discharge, but overestimates the summer discharge. Hence, depending on the dataset used, it is expected that the modelled river plume will also be significantly different. This is illustrated in Fig 1b, showing the surface salinity difference using climatological or daily discharge data in the child model (NW-Med) after 1 month of spin-up. The plume obtained using real river discharge extends much further offshore, almost completely across the Gulf of Lions, whereas the plume obtained with the climatological river discharge is essentially staying at the coast close to the river mouth. This is consistent with the much larger (almost double) discharge values observed in the real river data during January 2014.

2.2 Upscaling experiment description, Ensemble generation, and Data Assimilation scheme

In order to assimile pseudo-observations into the basin-scale models, different setups could be implemented, regarding the choice of the pseudo-observations, the frequency of assimilation, the data assimilation scheme itself, etc. The choices described below are consistent with current-day practices in the CMEMS operational systems. In particular, none of them currently assimilates velocity fields, and all of them use parameterized model state vector error covariances. Only one system (the Arctic system) currently uses an Ensemble Kalman filter, but the other systems are planning to evolve toward ensemble simulations in the future.

The following settings were chosen for the current experiment. The filter will be an Ensemble Kalman filter (the parent model is thus transformed into an ensemble of models). Assimilation will be performed daily. Only temperature and salinity will be used as pseudo-observations; the thinned 3D fields will be used. Velocity and surface elevation are not updated by the data assimilation procedure. Thinning is realized by taking the average of 5x5 cells of the nested model. The thinned pseudo-observations coming from the nested model are then considered independent, i.e. their error covariance matrix is diagonal. This is still a strong assumption which should be taken into account when determining the (diagonal) part of the observation error covariance matrix.

The members of the ensemble have perturbed initial conditions, atmospheric forcing fields and Rhône river discharge, similar to Auclair et al. (2003). The initial condition is the randomly weighted sum of the real initial condition (01/01/2014), and 6

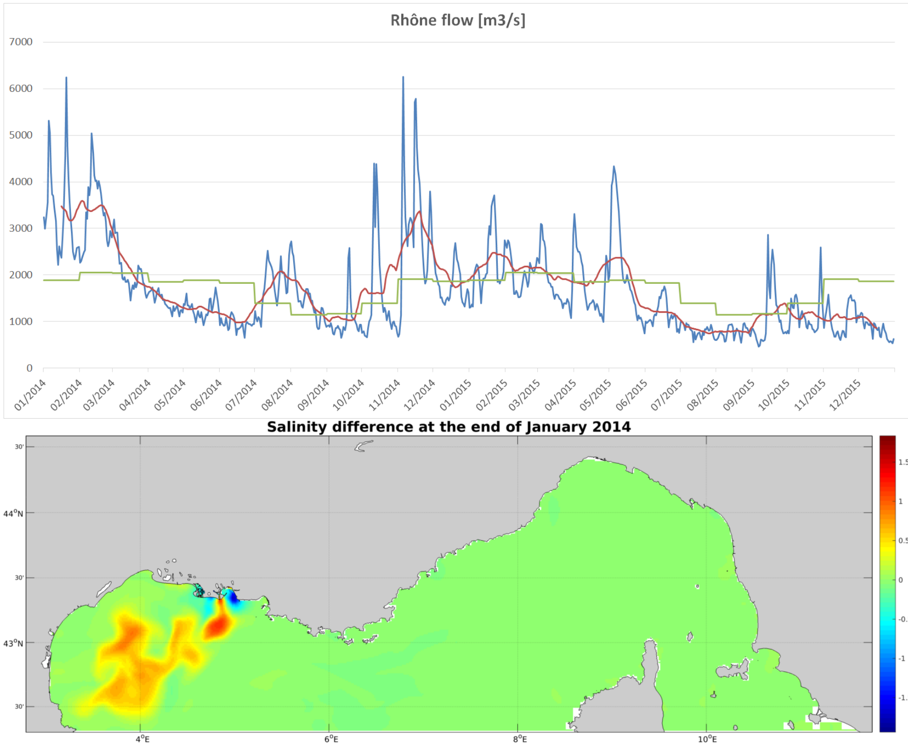

Figure 1. (above) Rhône river discharge from (green) the climatology, (blue) the measurements by the Compagnie du Rhone at the Beaucaire station, (red) the 1-month moving average of the measurements. (below) Difference of surface salinity in 2 different model runs of the nested grid on 28/Jan/2014, when using climatological or measured Rhône discharge values (i.e. using the green or blue curve in the upper panel)

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other initial conditions (1 year, 20 days and 10 days earlier, and 10 days, 20 days and 1 year later). The weight of the real initial condition is a random-normal number chosen in the Gaussian distribution with mean 0.5 and standard deviation 0.2; if necessary, the random number is then limited back into [0.2 0.8], whereas the 6 remaining weights are random numbers chosen uniformly in [0 1], and normalized so that the sum of all 7 weights is 1. This procedure ensures that the stability of each member is not modified (for example, the linear combination of 7 stable water columns is still a stable water column).

The atmospheric forcing fields of air temperature at 2m height and wind speed at 10m height are perturbed following the same procedure as in Barth et al. (2011); Vandenbulcke et al. (2017). Point-wise, the forcing fields are decomposed in Fourier series (from 3 hours to 1 year). For each member, a random field is generated, using these Fourier modes and random coefficients which have a temporal correlation length corresponding to the respective mode. This random field is added to the original field.

The Rhône river discharge is perturbed using a random walk approach, with the expected perturbation after one year set as 20%. The other rivers are outside the observed part of the domain, and their discharge is not perturbed. With all 3 perturbations, an ensemble of 100 members is then spun up for 1 month.

Data assimilation is performed by the Ocean Assimilation Kit (OAK) package (Barth et al., 2008) implementing different filters such as SEEK and the Ensemble Kalman filter (EnKF). Different variants of the EnKF exist, and are classified in stochastic and deterministic methods. The former require to perturb the observations, adding sampling noise. The latter, also called Ensemble Square Root Filters, do not present this requirement; the perturbation approach is only applied in the model to obtain model errors. Different variants are compared in Tippett et al. (2003). One variant, called the Ensemble Transform Kalman Filter (Bishop et al., 2001; Wang et al., 2004), is used in this study. The filter equations are listed in Barth and Vandenbulcke (2017).

Nerger et al. (2012) summarizes how the spurious long-range correlations can be suppressed using so-called covariance localization, or domain localization and its addition observation localization. OAK uses the latter variant introduced in Hunt et al. (2007). In essence, the state vector is split into subdomains (water columns). In every water column, the analysis is performed independently (domain localization). In addition, for every water column, only nearby observations are used and the inverse of their error variance is multiplied by a localization function (observation localization). In the current setup, the localization function is a radial Gaussian function with an e-folding distance of 30 km.

The observation errors for temperature and salinity are set respectively at 0.3°C and 0.09 psu. These values were determined after a sensitivity experiment with observation errors of (0.5°C, 0.15 psu), (0.3°, 0.09 psu), (0.2°C, 0.05 psu) or (0.1°C, 0.03 psu); as a trade-off between generating a close emulation of two-way nesting (hence very small observation errors), and generating fields as balanced as possible, that will not cause adjustment shocks into the model (hence larger observation errors). With the latter 2 choices for the observation error, the obtained assimilation increment was not much larger than with the final choice of (0.3°, 0.09 psu), but qualitatively, unrealistic small scale variations started to appear.

From a technical point of view, OAK allows to use a multi-variate multi-grid state vector. As the Mediterranean model is parallized in 64 tiles, the multi-grid feature allows to update directly the tiles from the Mediterranean model restart files, influenced by the nested model, without including the other tiles in the state vector. The procedure thus allows to skip the reconstruction of the complete Mediterranean restart files. It should be noted that the tiles of the parent model, considered in the data assimilation procedure, are the ones covering the nested-model area, but also the neighbouring ones which are influenced by the data assimilation.

3 Metrics

To assess the upscaling method, five metrics were defined, that allow to compare the nested model and the parent model, in both cases without upscaling (MED free model) and with upscaling (MED upscaled model). If upscaling is succesfull, the parent model with upscaling will be closer to its nested model, than its counterpart without upscaling.

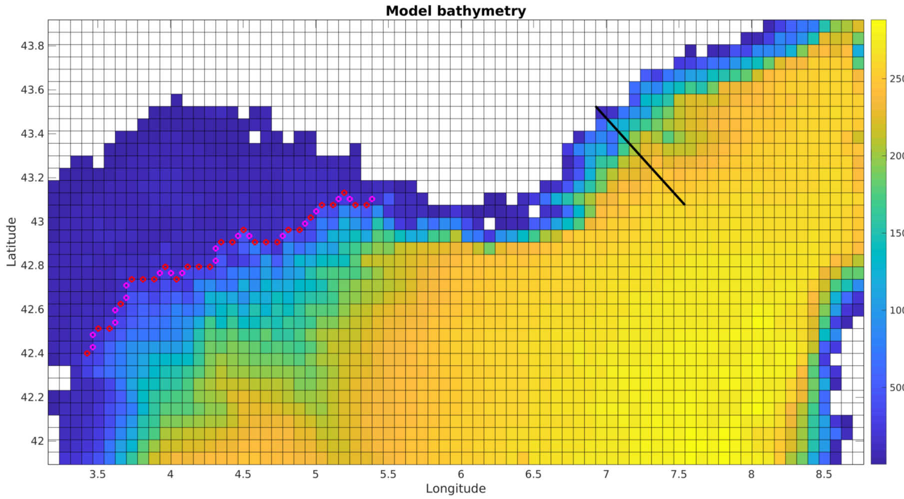

Figure 2. Zoom of the MED model grid, with the positions for computing the Northern Current metric (black line) and the cross-shelf transport metric (magenta and red dots)

3.1 Cross-shelf transport

The penetration of off-shore water on the GoL (or inversely when negative transport values are obtained), is critical for the circulation on the shelf, for the shelf-open sea exchanges, etc. It is obtained by integrating the current over the boundary shown in Fig. 2. This metric is useful to compare basin-scale models (free and upscaled) and check whether the upscaling procedure is able to drive the solution toward the nested model solution. The intensity of the cross-shelf transport cannot, however, be compared to real measurements (by lack of them).

3.2 Northern Current intensity

The Northern Current (NC) is the most important large-scale feature of the region of interest. It is considered to have a width of 40-50km during summer and 20-30km during winter; but the most offshore currents do not modify the transport much. Similarly, the NC is considered to be 100-200m deep in summer and 250-400m in winter. Following Alberola et al. (1995), its intensity is obtained by integrating the currents normal to a line from Nice to the location (43.0756°N, 7.5415°E), 214 km to the South-East, indicated in Fig. 2. As for the previous one, this metric only allows to inter-compare different models.

3.3 Rhône river plume

The plume of the Rhône River is measured by selecting all points around the river mouth with a salinity smaller than 37psu, and then choosing the most distant one from the river mouth. This provides the plume length and direction, although it may be an approximation: the plume can be curved, in which case its real length is larger than the estimation, or it can cover a large area, in which case the algorithm still obtains an azimuth although in reality it is not well defined.

This metric can be used quantitatively to compare models. Furthermore, it can be used to compare model results to real measurements. Indeed, although the real Rhône river plume length and direction are not measured directly, they can be estimated from satellite chlorophyll-a images. The model-observations comparison is then qualitative.

3.4 Sea surface temperature

This metric is the root mean square (RMS) difference between the parent model and the observed SST. For the latter, the L3 images are used.

3.5 Western Mediterranean Deep Water formation

Following Bosse et al. (2015) and references herein, the formation zone of Western Mediterranean Deep Water (WMDW) is comprised in 41-43°N, 4-6°E. WMDW forms an easily identifiable water mass: it has a temperature between 12.86~12.89°C, a salinity of 38.48~38.50 psu, and its depth is larger than 1000 m. The nested model (NW-Med) southern boundary is at 42.3°N, and hence only a part of the formation area is included in the area of MED covered by pseudo-observations. The WMDW metric measures the total volume [m^3] of WMDW in the domain covered by the NW-Med model, and is used to compare the different models.

4 Results

The temperature difference between the (unperturbed) parent and child models at the end of the spinup (31 January 2014) is represented in Fig. 3 on the child model grid. There are large temperature differences at the shelf break of the Gulf of Lions (the canyons are much better represented in the nested model); which extend all the way from the surface to the bottom of the Gulf of Lions. Other large differences appear in the Eastern and Western Corsican Currents, and their junction resulting in the Northern Current, as well as at the southern open boundary. The difference in salinity (not shown) has large values around the Rhône river plume (over 1 psu), and in a lesser extent in the Eastern Corsican Current. It appears that after a month, the differences are already significant, and if one trusts the nested model more, then it would be beneficial to bring these differences back to the basin-scale model.

At the end of the spin-up, the spread of the ensemble of models (Fig. 4) is very visible over the basin, at all river mouths, but also in other areas (Alboran Sea, Tunesian coastal zone...) as all 3 perturbations are applied at once. The ensemble spread is also visible in depth (i.e. deeper than when only the river discharge is modified).

As an example, the first data assimilation cycle is shown in Fig. 5 depicting SST. The L4 SST image is shown only for visual comparison. Qualitatively, it appears that upscaling changes important features: the Rhône river plume is oriented offshore instead of being mostly along-shore; fronts seem to be more well-defined; and the Northern Current flows along the shelf break instead of covering a large part of the shelf. The nested model, and the “upscaled” model, seem to be in closer agreement with the satellite image, than the free model.

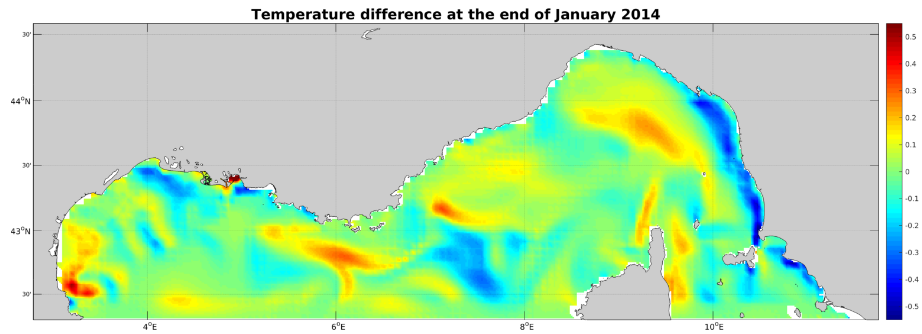

Figure 3. Temperature difference between the parent and nested models at 31/01/2014, projected on the nested model grid.

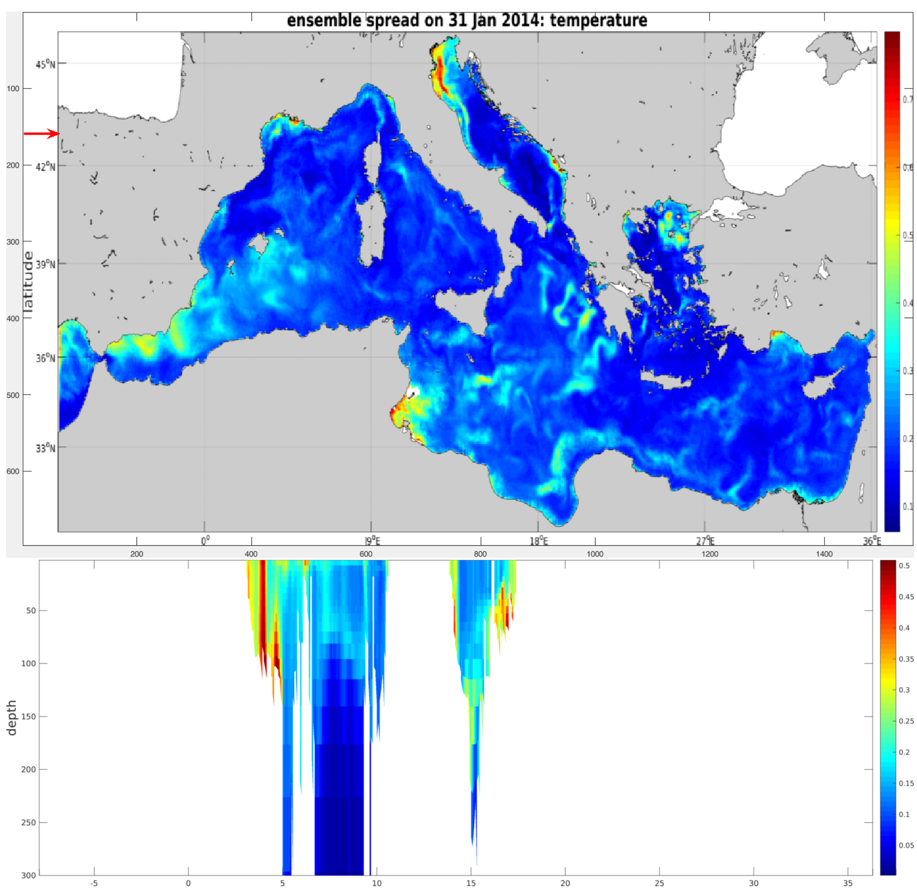

Figure 4. Spread of the ensemble of MED models at 31/01/2014: (upper panel) surface temperature, (lower panel) section at 43°N, indicated by a red arrow on the upper panel

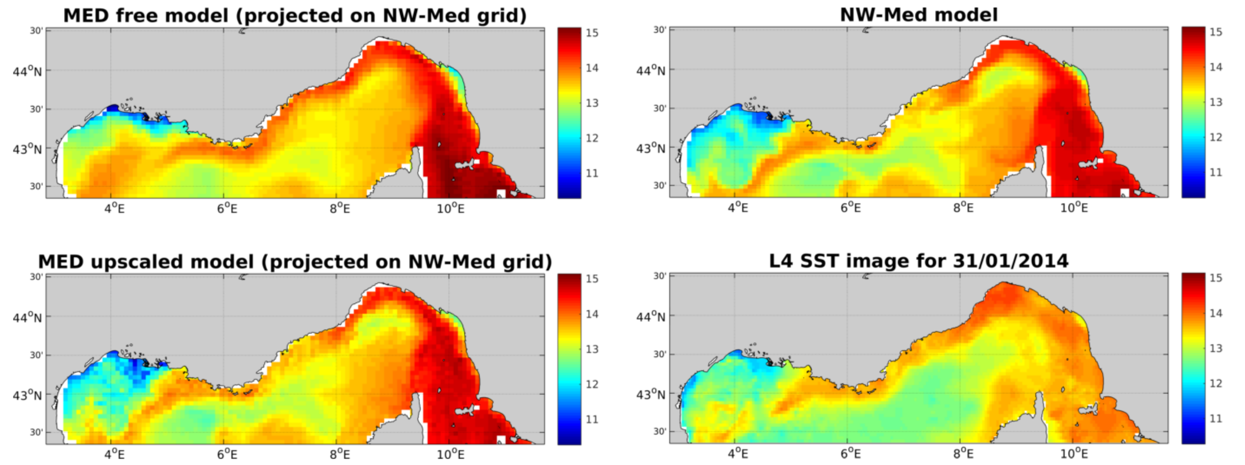

Figure 5. Sea surface temperature after the first upscaling step (31/01/2014), in the free model (upper left), nested model (upper right), upscaled model (lower left) and L4 satellite observation (lower right)

4.1 Cross-shelf transport

The flow accross the shelf break is represented in Fig. 6, for the basin-scale model in the free and upscaled cases. Although alternating periods of inflow and outflow appear, the transport seems to show a chaotic behavior. Yet it can be seen that while both models are generally similar, some periods exist where the simulated transport is very different. During the first month (February 2014), the free model predicts a net outflow during the first 2 weeks, followed by a net inflow during the last 2 weeks. The nested model (not shown) and hence also the upscaled model actually predicts the exact opposite. The reasons for the nested model to behave differently than the parent model may be an effect of wind interaction with the (different) bathymetries, or related to the different resolution. The actual transport is not measured or available; but the result of interest here is that the upscaling method is able to align the (parent model) currents with the ones from the nested model, and hence emulate two-way nesting, although only temperature and salinity pseudo-observations are used.
During the remainder of the year, the upscaled model predicts somewhat larger transports (both inward and outward). Generally speaking however, the two transport curves are closer than in February (or at least they are not of opposite signs anymore). Noticeably, in August-September, the upscaled model predicts a period of large inflow on the Gulf of Lions. The free model also predicts this inflow, but delayed by about 2 weeks.
The RMS difference between the parent and child models is shown in Table 1, for the MED free model and the MED upscaled model.

4.2 Northern Current

The transport by the Northern Current off Nice is represented in Fig. 7. Over the whole period, the root mean square difference between parent and child models is 0.22 Sv for the free model, and 0.19 Sv for the upscaled model. The same qualitative ob-

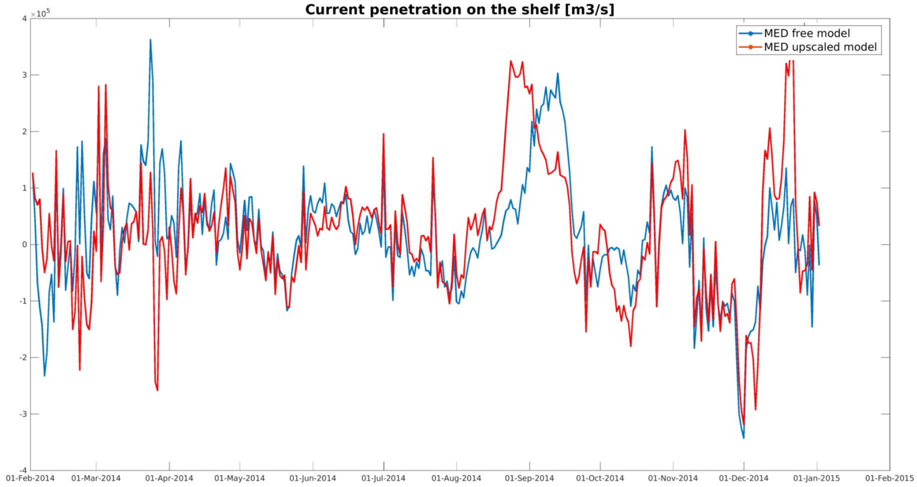

Figure 6. Water transport accross the shelf break during 2014, as obtained by the free (blue curve) and upscaled (red curve) parent models. Positive values indicate a net on-shelf transport.

servations can be made as for the cross-shelf transport. Both models generally agree, but periods exist with relatively important differences. Interestingly, a large difference appears in August-September, when the free model predicts a larger transport than the upscaled model. This is also the period when the transport accross the shelf break presents a temporal shift in between models.

For the purpose of our study, this metric cannot be used to validate the model since real measurements of the Northern Current transport are not available; but (as for the previous metric), it can be used to compare models, and to show that our goal is reached and upscaling of scalar fields is able to modify the velocity field of the parent model although only temperature and salinity are observed. The RMS differences between parent and child models are again given in Tab. 1.

4.3 River plume

The Rhône plume is perhaps the feature most significantly altered by upscaling. During the first month of the upscaled simulation, the free parent model usually places the plume along-shore, to the North-West, whereas the child model (and the upscaled parent model) usually orient the plume off-shore to the South-West (see Fig. 8). On top of the resolution-related differences between parent and nested models (in particular the bathymetry and the interaction of the water masses with the wind), both models have different freshwater discharge values, which is usually much higher and has also a much larger variability in the nested model during February 2014. The upscaling method is clearly able to make the parent model ingest the different plume dynamic coming from the nested model. During another period (late August - early September), the opposite case occurs: the free model plume is oriented off-shore, but the nested (and upscaled) model predicts an along-shore plume. Apart from these 2 periods, differences between parent and child models are smaller; therefore, the time-average of RMS difference between the parent model and the nested model length is reduced only from 95.1 to 88.0 km (see Tab. 1).

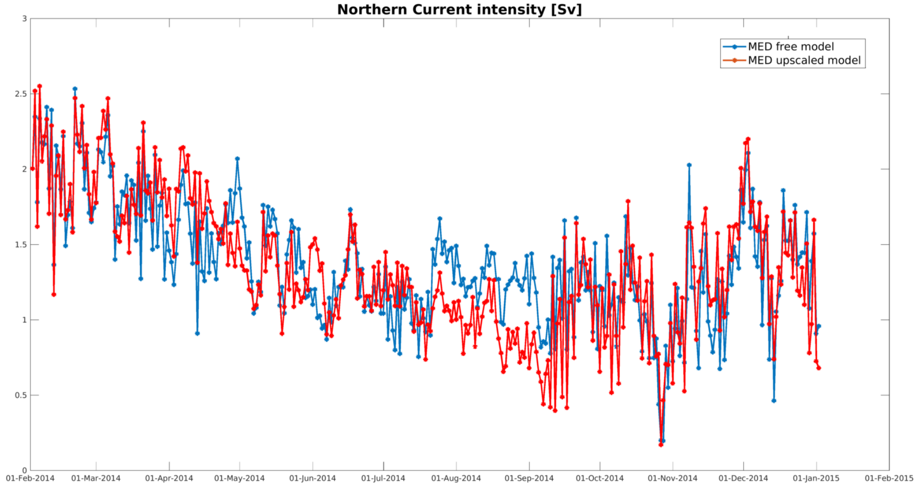

Figure 7. Water transport by the Northern current off Nice (France) during 2014, as obtained by the free (blue curve) and upscaled (red curve) parent models.

As a side note, the river plume can qualitatively be compared to real observations by using satellite observations of chlorophyll. During the first month of simulation, where the most significant differences appear, only a few level-3 satellite images are not almost entirely obscured by clouds. An example is given in Fig. 9 for 12 February 2014. One can clearly see the off-shore plume from the chlorophyll observations, whereas the free model plume is mostly along-shore. The nested (not shown) and upscaled models correctly place the plume off-shore.

4.4 SST

The sea surface temperature metric allows to quantify the model error by comparison with satellite images. Level 3 images are used for computing the metric. The RMS difference between the different models and the L3 image are shown in Fig. 10 for the first 2 months of simulation. It appears that the RMS difference is around 0.4-0.5°C, even though no data assimilation is performed. Usually, the nested model is better still in some areas (e.g. coastal waters), and the upscaling procedure brings back these local improvements to the parent model (see Fig. 5 for an example). However, the area-wide RMS error is not influenced very much by upscaling (see Tab. 1), as large areas are essentially unmodified (parent and child models use the same atmospheric forcing fields and the same bulk formulae).

Some days, some processes appear to be missed by the models (both parent and nested), so that the RMS error is relatively large. In this case again, upscaling does not influence the RMS error of the parent model very much, as the nested model is not representing these processes any better than the parent model.

In both cases, this does not imply that the upscaling method is flawed, but rather that, in the current setup, the nested model is not able to generate an RMS error significantly lower than the parent model; hence upscaling does not have much to feed on.

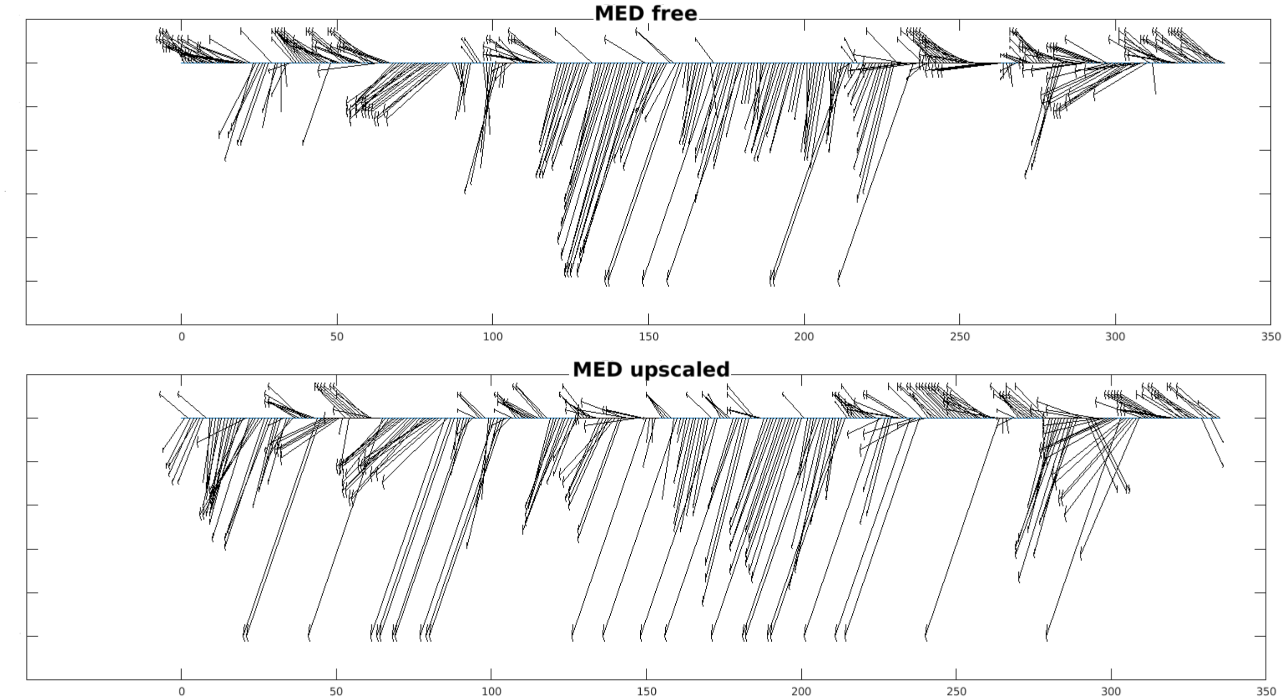

Figure 8. Rhône river plume direction and length (upper panel) for the free and (lower panel) upscaled MED models. The horizontal scale represents the days after the start of the upscaling experiment (Feb/2014).

Fig. 10 shows the RMS error during the first 2 months of simulation. The situation worsens during summer when the computed RMS errors are of 3°C) both for parent and child model; the difference in between models is hidden by the temporal variability of the error (not shown). In any case, the upscaled model is still very close to both the (free) parent and the nested models.

4.5 WMDW

The total amount of Western Mediterranean Deep Water in the free model (blue curve in Fig. 11) and the nested model (green curve) is periodically important ($10^3 km^3$), but models do not converge during the simulation, as it appears during most of the second half of the year. Upscaling largely modifies the parent model, which in turns provides modified boundary conditions to the nested model, so that after a while, the upscaled model and its child model significantly diverge from the free models. Without measurements and due to the choice of the model domain, it is not possible to assert which pair of models is more realistic. However, as for other metrics, the discrepency between parent and child model is reduced in the upscaled pair of models, which is certainly a desirable characteristic (see Tab. 1). This can be explained by the fact that the data assimilation also modifies the parent model solution outside the nested area (in the limit of the localization radius used in the data assimilation procedure). Therefore, the water immediately outside the nested domain is modified and made more coherent with the nested

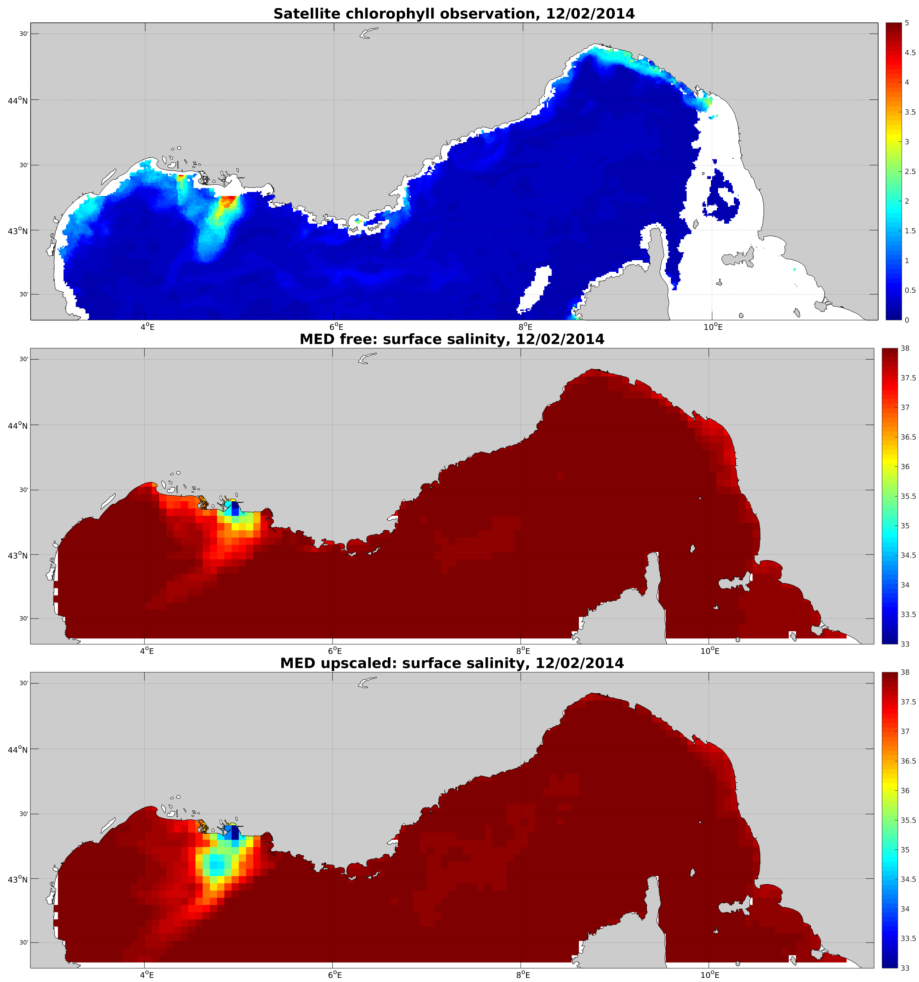

Figure 9. Comparison of the Rhône river plume on 12/Feb/2014 (upper panel) satellite chlorophyll image (middle panel) free parent model salinity (lower panel) and upscaled parent model salinity

solution. East and West of Corsica, the Corsican currents will reintroduce this water into the domain, and one can see how this repeated procedure will ultimately reduce discrepencies between parent and nested models.

Deep temperature and salinity

Some metrics considered above used surface salinity and temperature. However, upscaling modifies the 3D variables of temperature and salinity.

Differences between the parent and the nested model temperature are locally important, e.g. on the bottom of the Gulf of Lions, or in the Eastern Corsican and Northern Current cores (with differences of up to 0.3°C). Similarly, the cores of both

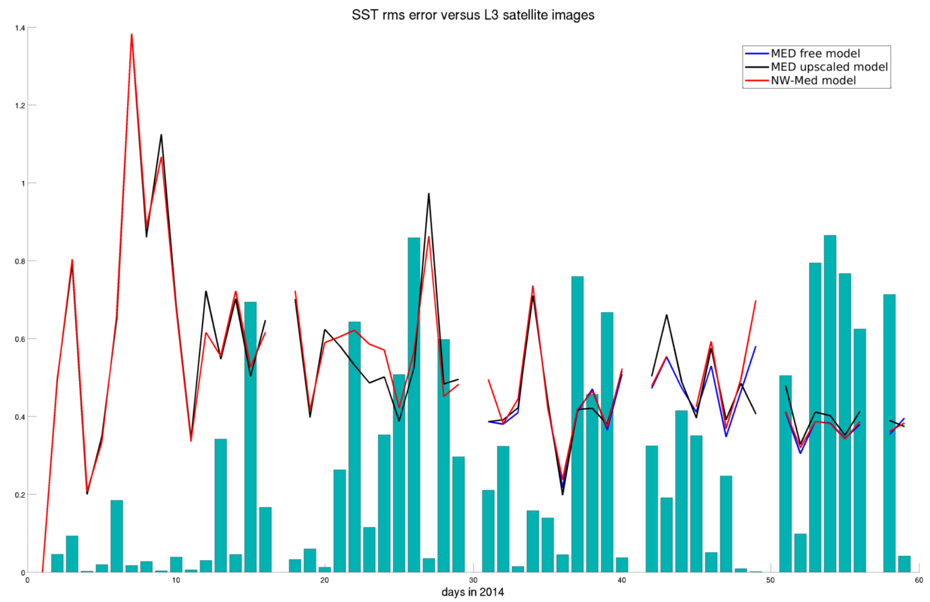

Figure 10. SST RMS error in the free model (black curve), nested model (red curve), upscaled model (blue curve) during the first 2 months of simulation. The bars represent the proportion of unclouded points in the L3 satellite image.

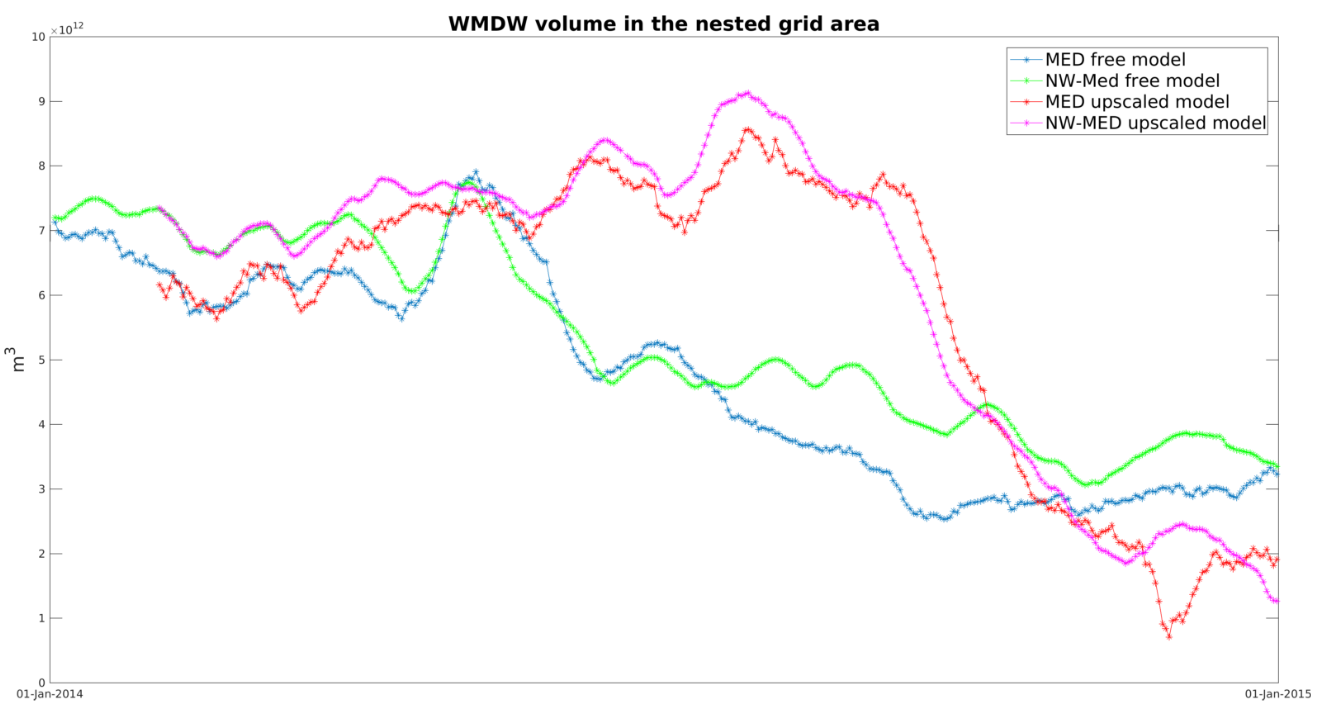

Figure 11. Time serie of total amount of WMDW in the area covered by the nested model: (blue) free parent model (green) nested model in the free model (red) parent model with upscaling (magenta) nested model in the upscaled model

Metric	MED Free model	MED Upscaled model
Cross-shelf transport [m^3/s]	99.6 10^3	85.2 10^3
N.C. intensity [Sv]	0.22	0.19
Rhône Plume [km]	95.1	88.0
SST [°C]	1.3	1.3
WMDW [km^3]	1563	1422

Table 1. Root Mean Square difference between parent and child model for the case of the free parent model and the upscaled parent model, for the defined metrics

Corsican Currents are saltier in the upscaled model, with differences of about 0.15 psu during the first assimilation cycle. For both temperature and salinity, upscaling is able to push the parent model toward the child model solution (not shown).

5 Conclusions

When a nested model is available, it usually benefits from higher resolution, and improved representation of some relevant processes. However often, and particularly so in the operational oceanography context, there is no feedback from the nested model to the parent model. Data exchanges are limited to the parent model providing initial and/or boundary conditions to the nested model. Thus, the benefit of having a nested model is lost to the parent model.

The upscaling method consists in assimilating results from a sub-regional model into a regional (basin-wide) model, in order to emulate the feedback of two-way nesting. The underlying hypothesis is that the nested model is more realistic than the parent model.

The method was tried out using a nested model configuration of the Mediterranean Sea and the North-Western basin, with a resolution ratio of 5. Data assimilation was performed using a localized ensemble Kalman Transform filter; as pseudo-observations, thinned 3D fields of temperature and salinity were used. The aim of this study is limited to verifying whether nesting feedback could be emulated by data assimilation; without trying to verify whether the nested model is indeed more realistic than the parent one.

Whether upscaling was able to emulate two-way nesting, was measured using 5 metrics related to processes relevant in the study domain: the intensity of the Northern Current, the cross-shelf transport, the position of the Rhône river plume, sea surface temperature, and the quantity of Western Mediterranean Deep Water. These metrics show that the upscaling method is indeed able to emulate two-way nesting and bring the parent model closer to the child model. Only for sea surface temperature, the RMS does not indicate an improvement, probably because this variable is essentially determined by atmospheric fluxes which are mostly identical (in our experiment) in the parent and child model. Some local improvements to sea surface temperature were observed, but are averaged out in the domain-wide RMS error.

By assimilating only temperature and salinity, velocity and transport metrics were also improved in the parent model. The ability to constrain the cross-shelf transport by T/S assimilation is also an indication that the data from a high-resolution glider fleet would be beneficial to constrain the model. Finally, concerning the Rhône river plume, upscaling was able to strongly modify the plume direction when it was different in the parent and child models; the length of the plume was also modified. Qualitatively, when real chlorophyll observations were available, the nested and upscaled parent model seemed to be more realistic than the free parent model.

Advantages of using upscaling include the following. Most importantly of course, the parent model takes advantage of improvements in the nested model. In the current study, these improvements may be due to higher resolution, better representation of local processes, and the use of more realistic river discharges. In general, they may also have other causes, such as assimilation of local and/or very high resolution measurements (e.g. HF radar observations), atmospheric fields from a regional weather forecasting model, or other more realistic boundary conditions. Another advantage is that over time, discrepencies between parent and nested model are attenuated. The parent model then provides more consistent boundary conditions to the nested model, and artefacts such as wave reflexion at the boundary may be avoided.
In the operational context, a supplementary advantage may appear. If a user is interested in a particular are not entirely covered by a nested model, it may be difficult for him to merge 2 products (the large-scale model, and the finer model not entirely covering the area of interest). By default, the user may then use only the coarser model. If the nested model is upscaled into the large-scale model, this is the only product the user needs to consider.

The most important limitation of the method is that the child model should be more realistic than the parent model. Furthermore, the coupling with upscaling is not as strong as with real two-way nesting. Other limitations are linked to data assimilation methods and are not different from the assimilation of real observations: (i) the data assimilation procedure itself uses approximations, and this could degrade the analysis; (ii) if the parent and child models are very different, the parent model could be unable to ingest the pseudo-observations. These limitations are investigated in the litterature in the context of assimilation of real observations, and potential solutions include (i) anamorphosis techniques (when a non-linear relation exists between model variables and observations), particle filters (when the error distribution cannot be considered Gaussian), etc; and (ii) carefull specification of the observation error covariance matrix (and more specifically the contribution of the representativity error) to filter out processes of the nested model that cannot be represented in the parent model.

Appendix A: Model configuration

NEMO model parameters for the parent and nested models are given in Table A1.

Competing interests. No competing interests are present.

parameter	parent model	child model
horizontal resolution	8km	1.6km
vertical resolution	31 levels	31 levels
bathymetry	interpolated from GEBCO	interpolated from GEBCO, smoothed at the commen open-sea boundary
surface module	Nemo MFS bulk formula	Nemo MFS bulk formula
surface forcing data	ECMWF Era Interim	ECMWF Era Interim
nudging (damping)	/	/
advection scheme	TVD	TVD
horizontal diffusion	bilaplacian	bilaplacian
vertical diffusion scheme	TKE	TKE
rivers	6 (climatological discharge)	Rhône (daily measured discharge)

Table A1. Model parameters for the parent and child models

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