Comments, replies – sorted by subject – with refs to changes in manuscript

The following pages provide “a detailed point-by-point response” in “a clear and easy to follow sequence” with “(1) comments from Referees, (2) author's response, (3) author's changes in manuscript”. Comments and replies are - of course - available on the GMD web site.

The comments are followed by a latexdiff between the originally submitted and the revised manuscript, as per instructions. It should be noted, that the latexdiff does not show changes to figures and references – nor to data availability or code availability sections. Two figures (Fig 5 and Fig 11) have been updated, one figure (Fig 12) has been added, and a single ref (Büchmann and Söderkvist, 2016) has been added – all in response to referee comments. Also the data availability and code availability sections have been significantly updated.

Request for data from “inner domain” / additional station data

Referee 1:

This paper concerns the use of operationally provided meteorological forcing for ocean models and the resulting discontinuities that arise between subsequent issued forecasts.

This is an interesting topic and the paper is well written with clear explanations.

However, I feel that it needs more work to expand the results and put them in more context as we cannot currently tell whether the proposed ramping solution actually leads to any improvements in the ocean model forecasts.

The paper gives a convincing explanation of the hypothetical basis for introducing spurious waves into the ocean model from the discontinuous forcing, but does not give a feel for how much this is actually a problem in real forecasting.

Has it caused noticeable issues with the operational surge model setup that is discussed?

The only comparison shown of results with and without the ramped forcing is at a single location (Wick) from the outer model NA3. The reasoning is that this is close to the boundary location of the nested NS1C model, but it would also be useful to see what differences are seen throughout the rest of the model domain to provide more information on the impact of the ramping method – is Wick representative of the rest of the region?

Section 2.4 states that as the NA3 model is used to provide boundary conditions for the nested models any spurious waves created by the discontinuty in the NA3 model’s forcing may therefore also enter the inner models through the boundaries. However there are no results shown or discussion of what (if any) differences are actually seen in the inner models when they are forced with boundary data from the two different experiments. Again it is therefore very difficult to judge the impact of the proposed ramping method.

It is acknowledged in the same section (in the footnote) that the inner models will have the same issue as their surface forcing dataset (DMI-HARMONIE-NEA) also contains the discontinuities - is there a reason the ramping experiment was only done for the outer model, where the potential impact is limited only to the effect on the boundary data that is used for the inner models? It would seem more relevant to try ramping the forcing data of the inner models and see the impact that it has there as presumably they are the main focus of the operational system.

With these extra comparisons we would have a much clearer idea of what effect the ramping solution has on the ocean models. It may turn out to be the case that there is actually little impact, but that would still be a useful result since so many institutions run operational models forced by datasets containing these discontinuities.

Author's reply to Referee 1:

We (FCOO) have been using meteo ramping for all our model setups (NA3, NS1C and DK600) for well over a decade. In that period, we have been through several "generations" of DMI-HIRLAM models (E15, T15, S05, S03), before recently (2018) switching to ECMWF-IFS for the outer domain and DMI-HARMONIE-NEA for the inner domains.

As it happens, the ECMWF-IFS model is rather well-behaved, presumably because the results are computed rather late in the 6-hour cycle, such that the first hours show only small change from previous forecast. I have worked with other meteo-datasets, where the problem was much more pronounced (in particular the now-retired DMI-HIRLAM-T15). Even so, ECMWF-IFS is a well-known and widely used model – presumably more so than data from a specific national weather centre, which is why I opted to disseminate this particular case.

For 3D (baroclinic) model setups (eg. NS1C, DK600), there is an additional complication, as even the slightest change of forcing or initial conditions, is likely to trigger a different outcome of the stochastic process, which is the model, see e.g. Büchmann and Söderkvist (2016) [DOI: 10.3402/tellusa.v68.30417]. In essence, the stochastic eddies might be positioned differently in two simulations, even if the changes to input are only at machine precision, and this may cause (small) changes also to the computed elevations. Fortunately, the effect on the elevations in the Kattegat area is rather small – sub-millimeter scale – so in principle it should be feasible to include modelled elevation for one or two positions from the inner domains: Kattegat and/or the south-western Baltic Sea.

I will make sure to note that FCOO operationally use ramping on all received meteo data before the data are used for modelling. I will also add a comment that the ramping length depends on our experience with the data set.

I will add a remark to the point that if the old and new meteo forecasts are very similar, ie. if the discontinuity is small, then the effect of ramping is also small (making a weighted mean of two similar results). In essence, the suggested ramping is not harmful, but "kicks in" in the cases, where the discontinuity is significant.

I will include data (ocean model computed elevation) for one or two stations in shallower water/inner domain, presumably the Kattegat and/or the south-western Baltic Sea. These data will include effects of ramping (or not) of both the outer (ECMWF-IFS) and inner (DMI-HARMONIE-NEA) meteo models. Thus, the results will be less general, but maybe give a better sense for the scale of the problem. For DMI-HARMONIE-NEA we routinely use ramp9, and I will compare to noramp as well as to ramp0 (see reply to reviewer #2) data.

I plan to include the data in the same way as Fig 11, ie. time series of elevations and differences. I do, however, not plan to disseminate statistics on the alternative meteo model (DMI-HARMONIE-NEA).

Referee 2:

A priori, I was very interested in reviewing this paper because it addressed a question I had in mind since a long time and never found the time to analyze: the impact of the discontinuity introduced by the analysis step of the meteorological forcing used to drive operational ocean models and, more specifically, North Sea storm surge models. Unfortunately, the analysis is fairly limited: only a time series of surge elevation at station Wick without ramping and with ramp6 is presented and the difference between both simply indicate that spurious oscillations are generated when the no ramping method is applied. This is by far not enough to demonstrate the added value of the ramping method.

Author's reply to Referee 2:
I have tried to keep the manuscript brief – in the spirit of creating a technical note. It was considered to include more data, but the decision was taken that more data might not necessarily make the manuscript more usable. Adding data for inner domains, such data would (still/also) be selective: the actual choice of meteo and ocean models would be specific to our present setup, and the gauge positions and periods would to some extend be arbitrary. Data from the "inner domains" (NS1C, DK600, see fig 5) might show a stronger response. However, that would introduce one or two extra ocean models as well as at least one extra meteo model, as another forcing (DMI-HARMONIE-NEA) is used for the inner domains.

The present choice of data was taken for the following reasons:

1. ECMWF-IFS is a well-known and widely used model – presumably more so than data from a specific national weather centre.
2. The actual size of the discontinuity varies with the meteo model/setup (as well as with time and space) and – at least to some extent – on the ocean model specifics, i.e. the magnitude of the problem will differ from case to case. Therefore, the choice was made to focus on the principles rather than specific values of the data.
   As it happens, the ECMWF-IFS model is rather well-behaved, presumably because the results are computed rather late in the cycle, such that the first hours show only small change from previous forecast. I have worked with other meteo datasets, where the problem was much more pronounced.
3. It is the goal of the paper to show that "there is a problem", and suggest a simple method to deal with it. The actual choice of ramping length (N) should depend on the application (weather model, update frequency, ocean model etc). In my opinion, "noramp" should never be used, as there is zero computational overhead going from noramp to ramp0. And modellers should at least be aware that there could be a problem – and in many cases N>0 should be considered.

I will include data (ocean model computed elevation) for one or two stations in shallower water/inner domain, presumably the Kattegat and/or the south-western Baltic Sea, see suggestions from reviewer #1. These data will include effects of ramping (or not) of both the outer (ECMWF-IFS) and inner (DMI-HARMONIE-NEA) meteo models. Thus, the results will be less general, but maybe give a better sense for the scale of the problem. For DMI-HARMONIE-NEA we routinely use ramp9, and I will compare to noramp and ramp0 data.

For all stations I will include the typical RMSE error from our annual statistics, such that a comparison can be made between the size of the spurious waves – and the typical model error on the station.

I do not plan to include observation data in the figures (time series).

Referee 2:
I understand the wish of the author "to keep the manuscript brief in the spirit of creating a technical note". Nevertheless, I do assume that for promoting the use (and getting the right to do it) inside FCOO of the ramping method, the author must have produced a more detailed report. I don't ask for such a detailed report but for something in between the actual version of the paper and something which could convince me I should use the ramp method.

I understand that the "magnitude of the problem differ from case to case", however, we do hope that the tendencies remains valid. For the model results from the inner domains (North Sea, e.g.), I have no problem if they come from the NA3 implementation even if those results are not used in operational mode. If possible, this will avoid the mixture of models/model forcing.

Results at one station in the North Sea will be greatly appreciated as well.

Author’s reply to Referee 2 response:
Unfortunately, there is no recent detailed report, from which I can draw results.

I do not have a problem extracting results from one or two stations, more "central" for the FCOO area-of-interest. However, as NA3 is a simple storm-surge model, tidal data is simply not included. Presenting data from NA3 within the North Sea / Skagerrak area could be misleading, and I would rather not do that. This said, I shall be happy to produce the relevant data for either NS1C or DK600 – including tidal data. I realize, that this will mean mixing models/model forcing, but with a few lines of explanation, I believe that it should be OK. This should give some relevant order-of-magnitude, for differences between respectively noramp and ramp0 – compared to ramp9, which we use operationally for these models.

I will examine a few stations, but expect that data for the inner Danish waters should serve the purpose. I will wait a little longer for further comments from reviewer #1, and then I will prepare an updated version of the manuscript taking into account comments from both reviewers.

Changes to manuscript:

In the end it was decided to use ECMWF-IFS to force the “inner model” NS1C, even though another meteo forcing is used operationally. This decision was made to keep the manuscript as simple and clear as possible – while still accepting the comments and recommendations from the referees.

- Added paragraph at end of §2.3 that at FCOO all meteo data are ramped before use as forcing data
- Data from Hanstholm station added (Fig 12 + updates to §3.2 text)
- Added paragraph on ensemble variability in baroclinic models and reference to Büchmann and Söderkvist (2016).
- Update to Conclusions (§4)
- §3.2: Footnotes that GETM station data are available online

Requests for comparison with observations

Referee 1:

Additionally it would be useful to see how the model results compare with observations at this location as we cannot currently tell if the ramping has led to an improvement. This would also put the differences between the “noramp” and “ramp6” cases in more context as I suspect the difference is small compared with other sources of model error.

Author reply to referee 1:

It has not been my intention to show that ramping alone provides "better" results in term of, say, lowered RMS errors compared to elevation gauge measurements. That is why I have not included measurements – I find them irrelevant for the present discussion, and they could simply muddy the discussion (but see suggestions for changes later).

We routinely compute annual statistics for our models compared to measured elevations. For Wick, the RMSE error on surge (not tide) is typically in the order of 6-7 cm. The spurious waves stemming from the meteo discontinuity are smaller (several centimeters, see Fig 11B), so while they may not be the most important contribution to the model error, they should not be ignored either.

Referee 2: (comment repeated from previous section)

Unfortunately, the analysis is fairly limited: only a time series of surge elevation at station Wick without ramping and with ramp6 is presented and the difference between both simply indicate that spurious oscillations are generated when the no ramping method is applied. This is by far not enough to demonstrate the added value of the ramping method.

Author reply to referee 2:

We (FCOO) routinely compute annual statistics for our models compared to measured elevations. For Wick, the RMSE error on surge (not tide) is typically in the order of 6-7 cm. The spurious waves stemming from the meteo discontinuity are smaller (several centimeters, see Fig 11B), so while they may not be the most important contribution to the model error, they should not be ignored either.

It has not been my intention to show that ramping alone provides “better” results in term of, say, lowered RMS errors compared to elevation gauge measurements, or show improvements on particular time series.

Changes to manuscript:

- §3.2: values given for RMS-errors (model data compared to observations) for stations used
- §3.2+§4: RMS-errors compared to magnitude of the spurious waves induced by pressure jump, noting that the pressure discontinuity may not be a leading error term, but that it is still worth to pursue.

No results are given for “ramp0”

Referee 2:

But, the most disappointing point, from my point of view, is that no results are shown for the method the most commonly used in the operational oceanographic community according to the author himself, i.e., the ramp0 method. I would like to see this paper to be published but with a stronger demonstration of the benefit linked to the ramping method and, in particular with respect to the ramp0 approach.

Author reply to referee 2:

The reviewer writes that "no results are shown for the method the most commonly used in the operational oceanographic community according to the author himself, i.e., the ramp0 method".

Firstly, it is not my intent to claim that ramp0 is "the most commonly used [method]". It is my impression (personal communications), that the ramp0 method is much used in hindcast, as written on p3, l19-20: "This approach [ramp0] corresponds exactly to running a hindcast based on the first six (hourly) fields of each meteo forecast, which seems to be a very common choice among ocean modellers."

However, in operational/forecast mode, even ramp0 would require that the hotstart files are not written at epoch t=0, but at an earlier time (say, t=-1H). And unfortunately, it seems that that t=0 is commonly used for the hotstart files, thus leading to "no-ramp". Thus, it is my best guess (claim) that "noramp" is rather common in operational/forecast mode. For newer operational/forecast setups, where data assimilation of the recent past is included, the hotstart time is presumably "well before epoch". In such cases, even operational /forecast will typically end with a "ramp0" scenario.

As suggested by the reviewer I plan to include "ramp0" data. I suggest to simply include a third panel on Fig 11, depicting difference between ramp0 and ramp6 data. That should indicate also to what extend ramp0 "is enough" compared to ramp6. Also, I will remedy the sentence on p3, l19-20 to stress that the "common choice" also is for hindcast:

This approach [ramp0] corresponds exactly to running a hindcast based on the first six (hourly) fields of each meteo forecast, which – for hindcasts – seems to be a very common choice among ocean modellers.

Referee 2 response:

To be fair, I should say we are using the ramp0 method for years and would like to know if it possible to do a better job.

You know why I have a particular interest for the ramp0 method.

3. Thanks to add ramp0 data.

Author reply to referee 2 response:

However, I shall be happy to produce the required data for ramp0. It is not a problem, except that it takes a little time – in particular the pre-processing of meteo data simply takes some wall time.

Changes in manuscript:

- Added “for hindcasts” in §2.2
- Added station Hanstholm (B) on Fig 5
- Fig 11 updated with “ramp0-ramp6” difference
- Some changes in text to include “ramp0” data, such as refs to figures etc.
- Comments on use of ramp0 vs noramp in §3.2

How is the method actually working

Referee 2:

Note also that this latter [the ramping method] is, from my point of view, insufficiently explained. For instance, Figure 4 is supposed presenting the method for ramp3 and ramp6. If ramp3 seems really to be a linear interpolation between the field at t -1H and that at t + 4H this seems not to be the case for ramp6 (linear interpolation between t -1H and t + 6H). How is the method really working?

Author reply to Referee 2:

The reviewer writes that "Figure 4 is supposed presenting the method for ramp3 and ramp6. If ramp3 seems really to be a linear interpolation between the field at t-1H and that at t+4H this seems not to be the case for ramp6 (linear interpolation between t-1H and t+6H). How is the method really working?"

This seems to be a point of genuine misunderstanding of the method. Obviously, this falls back on the author/manuscript, which means that I need to improve the section describing the method itself (see below).

Basically, there is no interpolation in time taking place. Rather, each meteo-field is recomputed as a "linear combination" (weighted mean) between old forecast and new forecast – each taken for the same time value (hour of the clock). For instance, ramp3 uses 1/4 new value and 3/4 old value (ie 25/75) at t=0H, 50/50 at t=+1H and 75/25 at t=+2H.

The illustration for ramp3 (Fig 4) appears linear only because the two (old and new) forecasts exhibit near-linear behaviour over these few time slices.

Author Suggested changes:

1. As the "ramp3" part of Fig 4 seems to be misleading in the present version, I suggest striking that particular subfigure, such that Fig 4 will depict only ramp6.
2. I will improve the explanation of the method using a simple equation, adding around page 4 line 10:

<LATEX>

If M^i_n denotes the n'th field of forecast no. i, so that M^{i-1}_{n+6} and M^i_n are consecutive forecasts for meteorological fields at the same time (hour on the clock), then the rampN process computes updated fields as

\begin{equation}
\widetilde{M}^{i}_n = \frac{N-n}{N+1} M^{i-1}_{n+6} + \frac{n+1}{N+1} M^i_n \enspace,\enspace \mbox{for\ } n=0, \ldots , N-1
\end{equation}

For $N>6$, it is necessary to make the computation recursive, so that Eq.\ 1 is used for the first ramping ($i=1$), while later epochs use $\widetilde{M}^{i-1}_{n+6}$ in place of M^{i-1}_{n+6}.

It should be noted that the suggested ramping process does not imply interpolation in time.

</LATEX>

Referee 2 response:

A good description of the method (as it is foreseen, see below) will help to understand Figure 4.

1. If the method is well described, there is no need to change Figure 4.
2. The explanation of the method is good.

Changes to manuscript:

Update to §2.3 with explicit description on how method is applied – incl. Eq 1.

Added paragraph at end of §2.3 that method is not harmful in general, but "kicks in" when the discontinuity is significant.

Figures 6+7

Referee 1:

Figures 6 & 7: It might be useful to include the location of the "neatl" box here as well?

Author reply to Referee 1:

I have considered the possibility to add the “neatl-box” on figs 6, 7 and 9. Presently, I tend to think that the additional information “ready at hand” is not worth the increased complexity of the figures. In order to increase the readability, all figures already use exactly the same projection, although Fig 5 is slightly larger, as there is no colour legend. Unless the reviewer really would like to see this, I will not include the "neatl box" on additional plots.

Changes to manuscript:

No further comments have been received on this subject.
No changes made to Fig 6+7.

Figure 10

Referee 1:

Figure 10: As a general point please avoid using red and green colours to distinguish lines, as this is not accessible to people with colourblindness. It would be better with a different pair of colours and/or different symbols on each line.

Author reply to Referee 1:

I will try to find better colour scheme for the lines of Fig 10, replacing green with, say, orange.

Changes to manuscript:

Fig 10 updated – both changing green to orange, and use of different symbols/markers on the coloured lines.

Comments on spelling

Referee 1:

1. The title! discontinuos -> discontinuous
2. Page 7, line 5: apparantly -> apparently
3. Page 10, line 14: have -> has

Author reply to Referee 1:

1. The spelling corrections are duly noted. Thanks so much.
2. A typo in the title is just plainly embarrassing – sorry about that.

Changes to manuscript:

Typos corrected.

Manuscript title

Editor comment:

As per https://www.geoscientific-model-development.net/about/manuscript_types.html, where a development and technical paper relates to a particular model, then the model name and version need to be in the title. This is the case for this manuscript so the title should be adjusted accordingly.

Author reply to editor:

The reviewers have requested inclusion of data from more stations, and this may mean that I will also need to use meteo-data from DMI (Danish weather service) HIRLAM-NEA. These data are (unfortunately, and due to restrictions imposed by DMI) not publicly available, but I will of course describe what is going on. The final title will be updated with "a case study with ECMWF-IFS, DMI-HARMONIE-NEA and GETM (v2.5)".

Changes to manuscript

In the end it was decided to present results of the inner model forced by ECMWF-IFS. Title updated to include "a case study with ECMWF-IFS and GETM (v2.1)"

Code availability

Editor comment:

Simply pointing to the GETM website does not reliably enable the users to identify exactly which code you used and what you ran. Instead, you need to persistently and publicly archive the exact version of the code you used, as well as any input files and pre- or post-processing scripts. Many GMD authors find https://zenodo.org a good platform for this (indeed, since GETM uses git, you can use the Zenodo-github integration to partly automate the process. See: https://guides.github.com/activities/citable-code/).

Author reply to editor:

I will put the exact (GETM) source code (probably in a tarball) alongside all data I am at liberty to give on an open server, such that it can be evaluated along-side the revised manuscript. I find scripts to download, format and convert meteo-data well beyond scope. The actual method suggested to prepare (ramp) the meteo will be included in a revised paper, as per response to reviewer 2.

Changes to manuscript:

- Actual code - which differs slightly between the two operational setups - have been gathered and stored at Zenodo.org, and released with an DOI tag:
- Actual code tags - and link to online code repository (at zeonodo) - are now given in the manuscript code section.

Data availability

Editor comment:

Even though the ECMWF data employed is licence restricted, some of your readers will have the appropriate licences. It is therefore still necessary to precisely identify which ECMWF data was used in which of your runs, so that readers will be able to identify what you did.

Author reply to editor:

I am not sure exactly what is meant by "precisely identify which ECMWF data was used". Is this the actual field names, the horizontal resolution or something else?

The temporal resolution, areas of coverage and the periods are already explicitly mentioned. Running a (semi)operational model is so complex a task, that it is not possible for me to upload all data files, scripts and configurations in a way such that another user will be able to get exactly the same result - or even run them on a different system. I will strive to release as much data as possible - and in particular the raw data necessary for any figure used in the final paper. It is not clear, however, if data such as hotstart files for our particular GETM setups have any relevance for readers - and such files could actually contain data which we are not at liberty to release. This said, I am all in favour of open data, and I will strive to release as much as is possible. However, if GMD will insist on a release of ALL "input files and pre- or post-processing scripts", then I cannot comply, and the paper thus cannot be released in GMD. If that is the case, then I should like to be informed as soon as possible, such that I may consider other publication options.

Changes to manuscript:

- Reference to data availability added to manuscript: DOI:10.5281/zenodo.3243187
- Updated information on ECMWF-IFS data sue and availability.
- Data for all stations from the two GETM setups released (at zenodo) for all ramping cases, in high temporal resolution covering 25 months of simulation. Data are available as one NetCDF file per station per month, and collected in one tarball (tgz-file) per ramping case.
- Processed data for all figures released on Zenodo

Dealing with ~~discontinuos~~ discontinuous meteorological forcing in operational ocean modelling: a case study using ECMWF-IFS and GETM (v2.5)

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Abstract. Meteorological data providers release updated forecasts several times per day – at the forecast epochs. The first time step ($t = 0$) of each forecast, the so-called analysis step, is updated by a data-assimilation process, so that the meteorological fields at this time in general do not match the fields from the previous forecast. Seen from the perspective of oceanographic modelling, the analysis step represents a possible discontinuity in the model forcing. Unless care is taken, this "meteorological discontinuity" may generate spurious waves in the ocean model. The problem is examined and quantified for a single meteorological model: the European Centre for Medium-range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). A simple straight-forward solution is suggested to overcome the forcing discontinuity, and the effect on a particular ocean model is examined: the FCOO NA3 (North Atlantic 3nm) storm surge model.

1 Introduction

Numerical ocean models are in operational use at many institutions around the world. In the present paper, a particular issue related to an inherent discontinuity of operational meteorological forcing data will be examined. It will be shown that a naïve implementation of an operational forecast process may lead to discontinuous forcing data, which excite spurious waves in the oceanographic model. Further, unless care is taken, there could be a difference in the forcing data applied in, respectively, forecast/nowcast and hindcast modes. This difference may result in under-prediction of forecast/nowcast errors of ocean models.

The discontinuity problem is examined, and a straight-forward solution is proposed. The effects of the discontinuity on a particular ocean model are quantified, and results with and without use of the outlined solution are examined.

2 Background

2.1 Operational forecast in meteorology

Since the early days of numerical weather prediction (see *e.g.* Richardson, 1922), observations have played a major role: to accurately forecast the weather systems, an understanding of the near past is necessary. Operational weather forecasts run

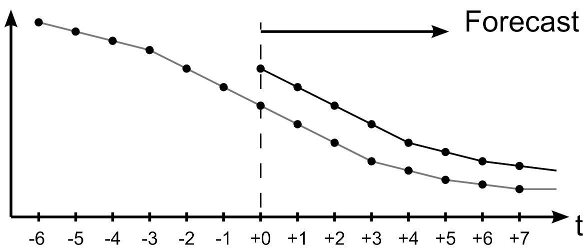

Figure 1. Conceptual time series of meteo data in a particular point for two consecutive forecasts: new (black line) and old (grey). Dots denote times, where data fields are available. The actual variable could be e.g. pressure, temperature or wind. The dashed line denotes the start of the meteorological forecast: +0H, *i.e.* the analysis time.

several times per day, using data assimilation schemes to update the initial field in a so-called "analysis step", see *e.g.* Lynch (2008). The specific methods used during the analysis is beyond the scope of the present work, but see *e.g.* Buizza et al. (2005) for a comparison between several weather centres. As we shall see, the data provided for the downstream users are significantly impacted by the assimilation and the analysis step, so ocean modellers should be aware of the consequences and take appropriate actions to deal with possible adverse effects.

As part of the optional boundaries programme, the European Centre for Medium-range Weather Forecasts (ECMWF) provides forecasts every six hours, at times which in the following will be denoted the "epoch" (time zero) of each forecast. Each forecast consists of a number of hourly "fields" (time steps), delivered in GRIB format to the member countries. For each forecast, the simulated time may be denoted by the number of hours from the epoch. Thus, +6H corresponds to the time of the following epoch (the base time of the next/coming forecast), while -6H is the previous epoch. As each forecast is significantly longer than six hours, the initial fields of a forecast coincides in time with fields from several previous forecasts. The meteorological update cycle of hourly fields provided every six hours is used in illustrations and discussions in the present work. Even so, the results of the present work should be applicable to other update cycles as well.

In Figure 1, it is illustrated how a meteorological forecast differs from the previous forecast at a specific point. The difference is caused by the afforementioned data assimilation procedure in the meteorological forecasting system which adjusts the forecasts according to observations, and updates *e.g.* the location of low pressure areas. In the present work, the change from previous to new forcast at $t = 0$ will be denoted "the meteorological discontinuity" or simply "the jump". Some atmospheric models are adjusted within a short time window while others (*e.g.* 4DVAR) provide a smooth transition from the previous forecast to the current forecast in an assimilation window prior to the analysis time/epoch. It is however common practice to only disseminate forecasts from the analysis time and forward in time as illustrated in the figure. The dots shown on Figure 1 thus represents the data actually available for downstream use *e.g.* as forcing in oceanographic forecasting models.

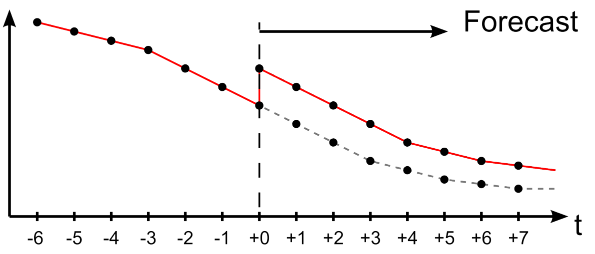

Figure 2. Conceptual example of meteorological forcing for ocean model with hotstart coinciding with the epoch. It is assumed that the meteorological model uses linear interpolation between the available meteorological fields.

2.2 Operational oceanographic forecasting

Operational ocean models are forced with meteorological forecast data received at each epoch. The ocean models typically run when the meteorological forecasts are available. However, the method for providing initial conditions to the subsequent forecast is rarely documented. It does however seem common to keep so-called "hotstart files" with the model state exactly at the analysis time, and then at time +6H save new hotstart files needed for the next epoch. At a first glance this choise of hotstart time may seem natural. However, as discussed, the meteorological data from two consecutive forecasts are discontinuous exactly at the epoch – the analysis time. Therefore, even though there is a high correlation between the current and previous forecasts, each meteorological forecast should be seen as an entirely new forcing function for the ocean model rather than an extension of the previous forcing function, see Figure 2.

If the ocean model hotstart time is chosen to coincide with the analysis time, then effectively the ocean model is forced by meteorological fields from the previous forecast (gray line in Figure 1) up until the epoch and by new/updated fields after the epoch (black line in Figure 1). Even though the ocean model may interpolate (linearly) in time between the available meteorological fields, the forcing is discontinuous exactly at the epoch. This discontinuity in the meteorological forcing, which could include instantaneous repositioning of pressure minima, may generate non-physical waves, as the ocean model adapts to the sudden changes in forcing. Since this process is repeated every six hours (every epoch), the ocean model is in effect forced by discontinuous data every six hours back in time, and these discontinuities may generate spurious non-physical waves that propagate around the model domain.

It can be seen from Figure 2 that time -1H is the last meteo field, which is not changed by the new forecast. Thus, to avoid the discontinuity, the ocean model should really employ temporal interpolation from -1H (using data from the previous forecast) to +0H of the new forecast. However, as the new data for +0H is not available at the time of the previous ocean forecast, the new ocean forecast must start at -1H, see Figure 3. As a consequence, the hotstart files for the next forecast must be written at +5H; six hours of simulated time into the forecast. This approach corresponds exactly to running a hindcast based on the first six (hourly) fields of each meteo forecast, which – for hindcasts – seems to be a very common choice among ocean modellers. Modellers running hindcast according to this model (Figure 3) and operational/forecasts according to the previous (Figure 2)

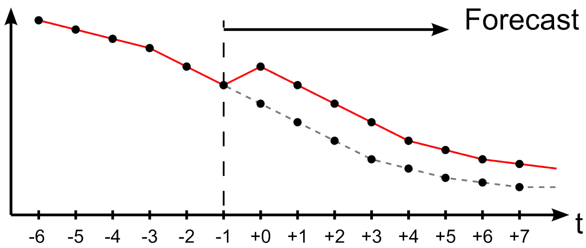

Figure 3. Conceptual example of meteorological forcing for ocean model with hotstart at -1H.

should be aware of the difference. In such cases, the hindcasts could under-predict the errors in the model leading to too high confidence in an operational model, when compared to the model in a hindcast scenario.

At the Joint GeoMETOC Support Center (FCOO), the ocean forecast always starts at -1H to avoid discontinuities of the meteorological forcing. The extra simulated hour is only a small overhead to pay for the increased model accuracy, which follows. Also, for hindcast simulations, FCOO use the same meteorological forcing principles as the operational model (excepting the forecast period itself), such that the hindcast performance may be used as a solid base for operational performance of at least the first 5-6 hours of the forecast.

2.3 Ramping

Even if hotstarts are positioned at -1H, it is not ensured that the meteorological forcing is smooth, see Figure 3. Although the severe discontinuity is avoided, the epoch can still represent an hour with larger changes of meteorology than a typical hour of the simulation. As a result there may still be generated unphysical waves in the ocean model – although hopefully at a smaller scale. To increase the uniformity of the meteorological forcing, it is possible to perform a so-called ramping process, in which a linear combination between old and new meteorological forecast fields are used to change smoothly from the old to the new forecasts~~, see Figure 4~~. If M_n^i denots the n'th field of forecast no. i, so that M_{n+6}^{i-1} and M_n^i are consecutive forecasts for meteorological fields at the same time (hour on the clock), then the rampN process computes updated fields as

$$\widetilde{M}_n^i = \frac{N-n}{N+1} M_{n+6}^{i-1} + \frac{n+1}{N+1} M_n^i \;, \quad \text{for } n = 0, \ldots, N-1 \tag{1}$$

For $N > 6$, *i.e.* if the ramping is longer then the number of time fields between consequtive forecasts, then it is necessary to make the computation recursive, so that Eq. 1 is used for the first ramping ($i = 1$), while later epochs later epochs use $\widetilde{M}_{n+6}^{i-1}$ in place of M_{n+6}^{i-1}. The method is outlined in Figure 4 for different values of the ramping length. It should be noted that the suggested ramping process does not imply interpolation in time.

The obvious disadvantage is that the ramping process sacrifices the accuracy of the first fields of the meteorological forecast, by replacing a significant part of the data with older and probably less accurate data from the previous forecast. Thus, the ramping is a delicate balance between smoothness and (local) accuracy. As is the case in many other aspects of (ocean)

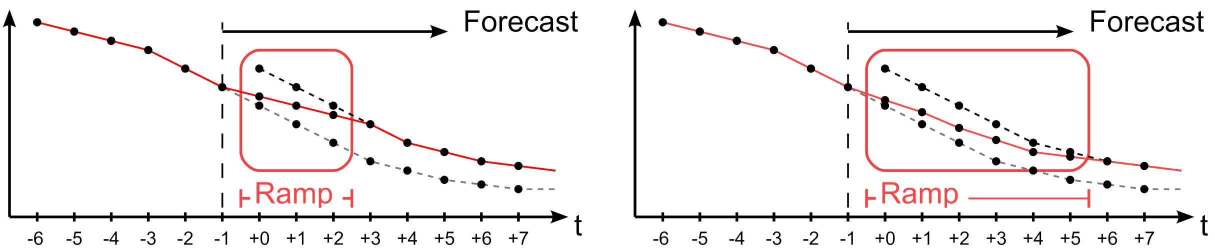

Figure 4. Conceptual examples of meteorological forcing for ocean model with hotstart at -1H and three or six hours of meteorological ramping. Longer ramping yields smoother transition between old and new forecast data.

modelling, such as the bathymetry, the use of the most accurate (unfiltered) data does not implicitly ensure the most accurate results.

While the ramping processing of meteorological forcing data requires some pre-processing overhead, there is no computational penalty involved for the actual model forecasting. It should be noted that it is entirely possible to use a ramp longer than the time between epochs.

Note that the initial shifting of the hotstart time shown in Figure 3 may be considered as a special case of the ramping procedure. If "rampN" denotes ramping over N meteo fields, such that Figure 4 shows ramp3 and ramp6, then Figure 3 shows ramp0, i.e. a linear interpolation between old and new forecasts, but with no intermediate interpolated fields. The discontinuous process shown in Figure 2 could then be dubbed “no ramping” (noramp).

It should be noted, that if two consecutive meteorological forecasts provide very similar results, *i.e.* if the discontinuity is small, then the effect of ramping is also small. In essence, the suggested ramping process is not harmful in general, but “kicks in”, when the discontinuity is significant.

At the Joint GeoMETOC Support Center (FCOO) all meteorological forcing data is ramped before used as forcing for oceanographic models. The ramping length depends on the experience with the particular meteorological dataset. For the ECMWF-IFS data, ramp6 is used operationally at FCOO.

If the weather centers would provide updated information for previous fields ($t < 0$) to present a smooth update from some prior known state to the present analysis time, then that would be preferable to using the presented ramping method. In such a scenario, the hotstart time of the oceanographic model should simply be pushed back in time to the latest unchanged field, in a procedure totally equivalent to what is presented in Figure 3.

2.4 Operational ocean model setup

During each FCOO forecast cycle, three nested setups (Büchmann et al., 2011) of the General Estuarine Transport Model (GETM, see Burchard and Bolding, 2002) are run in sequence, see Figure 5. The outer-most setup (NA3) is a barotropic storm-surge model setup, and it feeds inwards to two nested 3D baroclinic setups (NS1C, DK600).

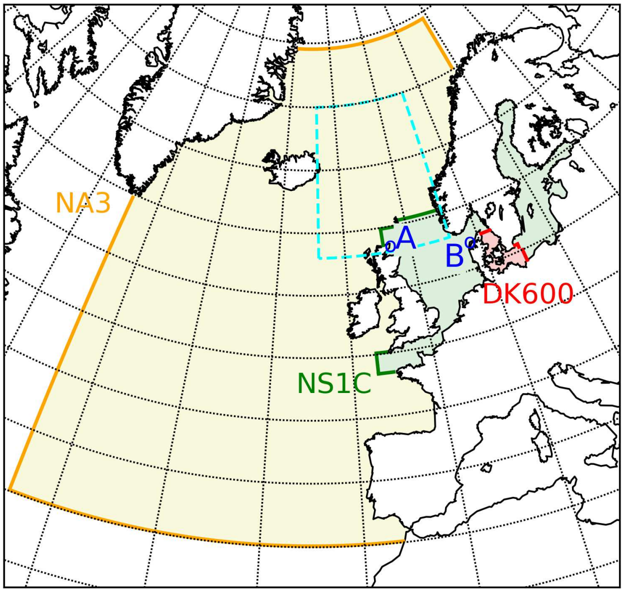

Figure 5. FCOO nested GETM ocean model setup: NA3, NS1C, and DK600. Station Wick (A) is used as proxy for effect on boundary conditions for the NS1C model, while station Hanstholm (B) is used to gauge the actual effect on the NS1C model. For later reference the north-east atlantic area "neatl" (lon=[-14:6] lat=[58:70]) is marked with a cyan dashed box.

The NA3 setup is a 2D storm surge model with no tidal wave components included. The lateral boundary conditions are forced by Flather-style boundary conditions (Carter and Merrifield, 2007) driven by inverse barometric effect (Ponte et al., 1991) derived from the meteorological forecast from the ECMWF-IFS (Integrated Forecasting System) model. The meteorological wind (stress) and pressure components of the ECMWF-IFS forecast data also act directly on the ocean free surface.

The NS1C and DK600 setups are 3D baroclinic setups and include tides, which are added to the boundaries of NS1C, where OSU tidal data inversion (Egbert and Erofeeva, 2002) data are combined with surface elevations and depth-integrated velocities from the NA3 setup to get elevation and velocity boundary conditions. Data from DMI-HARMONIE-NEA (Bengtsson et al., 2017) are used to force the surface of the NS1C and DK600 setups. As the NA3 setup is used for boundary conditions (nesting), there is an impact from the ECMWF-IFS model on the "inner" NS1C and DK600 models. Any discontinuities in the meteorological pressure – especially in the "neatl" area shown in Figure 5 – may propagate to the boundaries of the NS1C setup, and thus create non-physical waves in the NS1C and DK600 setups.[1]

Presently, FCOO makes 54 hour forecasts, i.e. to time +54H, of the entire model complex (NA3-NS1C-DK600) four times per day at epochs 00, 06, 12 and 18 UTC. The timing is based on data availability of the meteorological models used for forcing the ocean models.

[1] As NS1C and DK600 use DMI-HARMONIE-NEA data as forcing, the meteorological discontinuity of this model must be considered as well.

3 Experiments and analysis

In this section, the meteorological pressure discontinuity will be examined in detail (§3.1). Subsequently, the effect on the ocean model will be examined (§3.2).

3.1 Meteorological forcing

In order to quantify the difference in sea level pressure (SLP) caused by the discontinuity between two meteorological forecasts, the typical SLP change during one hour of a forecast is computed, see Figure 6. For each of the four daily IFS-forecasts in 2016–2018, the absolute pressure difference between each forecast field and the previous field is computed for each of the first 18 fields (+01H to +18H). Subsequently, the values are averaged over each forecast (18 fields) and over all 4384 forecasts in the three-year period. For the "neatl" area near the northern boundary of the NS1C model (see Figure 5), the average hourly change is computed to 42 Pa.

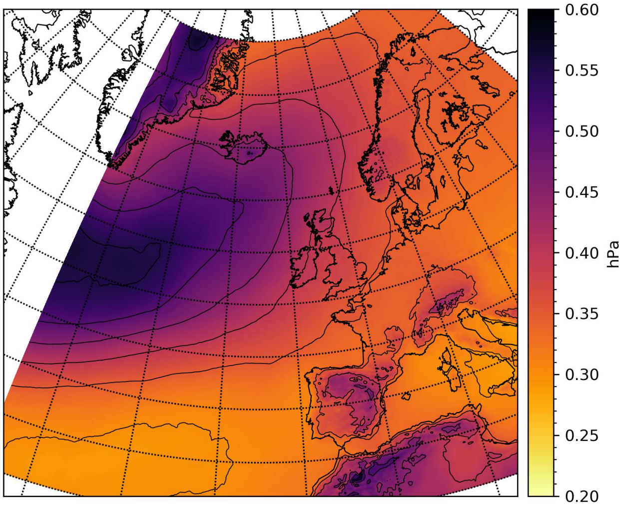

Figure 6. ECMWF-IFS absolute hourly pressure-change for the first 18 hours (+0H through +18H) forecast - averaged over all 4384 (four daily) forecasts in 2016–2018. The spatial average over the "neatl" area (Fig 5) is 0.42 hPa.

The temporal average of the absolute value of the pressure jump has been computed, see Figure 7. For the open ocean, the magnitude is significantly lower than the average hourly pressure change shown in Figure 6: for the "neatl" area, the average "pressure jump" is computed to 0.22 hPa, or 54% of the average hourly change in the same area. In words, the update to the analysis field corresponds – on average – to about half the typical hourly change. However, the average pressure-change of Fig. 7 hides a rather large variability in both time and space. To examine the temporal variation, the spatial average (over the "neatl" area) of the absolute pressure jump has been computed as a function of time for the three-year period 2016–2018, see Figure 8. As written previously, the temporal average is 0.22 hPA, but this covers a variation exceeding an order of magnitude: from 0.068 hPa to 0.81 hPa, the latter occuring at 2016-12-24 00:00.

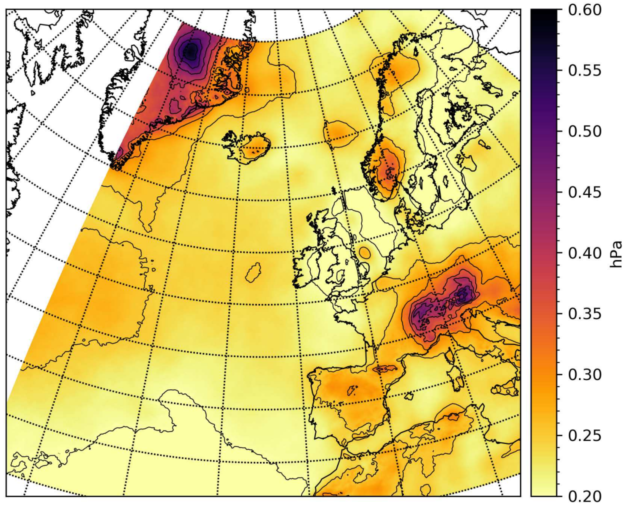

Figure 7. ECMWF-IFS absolute pressure disontinuity (jump) averaged over all forecasts in 2016–2018. The spatial average over the "neatl" area (Fig 5) is 0.22 hPa.

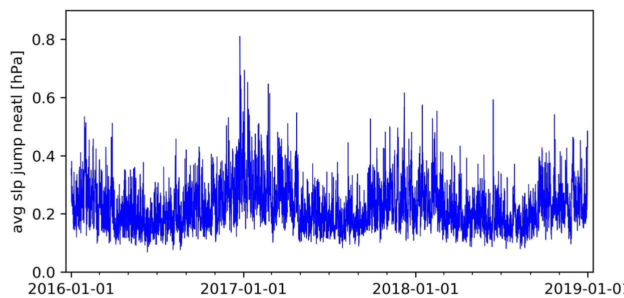

Figure 8. Spatial average over the "neatl" area (Fig 5) of ECMWF-IFS absolute pressure-jump for each forecast in 2016–2018.

If the SLP discontinuity at 2016-12-24 00:00 is examined in detail, see Figure 9, then it may be seen that the local (in space) pressure-jump at that time exceeds 5 hPa. The largest pressure-jump appears on the east side of a low-pressure system (results not shown), where the meteorology analysis step ~~apparantly~~ apparently has adjusted the size and speed of the system slightly. Overall, however, the two pressure-fields (weather maps) do look vary similar, so there has not been any large error in the pressure-forecast.

Time series of SLP for three consecutive forecasts in a single point are depicted in Figure 10. For comparison, the time series for "noramp" and "ramp6" are also shown. It should be noted that without ramping, the SLP forcing used for a hydrodynamic model does include significant pressure discontinuities. The introduction of ramping (see §2.3) decreases the spurious pressure jumps significantly. Further, if the pressure-jump is small, *ie.* if the present and previous forecasts agree, then there is no large impacts from the ramping procedure, and thus the noramp and ramp6 methods give essential the same result. Basically, the adverse effects of the ramping method seem to be small. Even though the impact of "best" first fields of each forecasts are

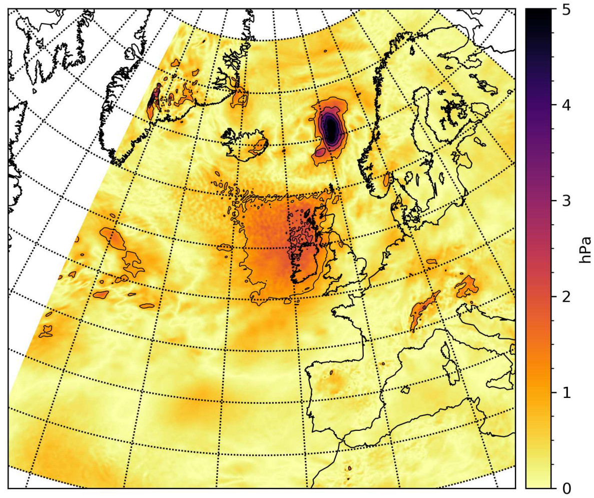

Figure 9. ECMWF-IFS absolute pressure-jump at 2016-12-24 00:00, ie absolute pressure difference between 2016122400+0H (analysis step) and 2016122318+6H. The spatial average over the "neatl" area (Fig 5) is 0.81 hPa. Note the changed color-scale: the maximum pressure-difference is 5.7 hPa, occurring at (lon,lat)=(0.773,64.793).

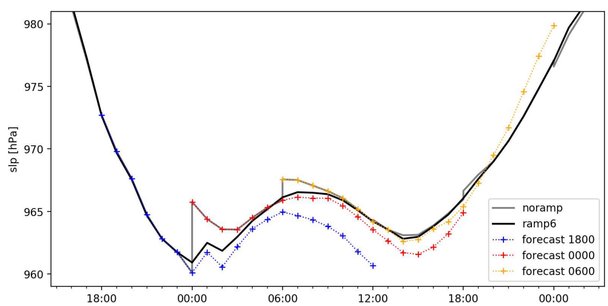

Figure 10. First 18 hours of ECMWF-IFS surface pressure (slp) forecasts at point (lon,lat)=(0.773,64.793), for epochs 2019-12-23 18:00, 2019-12-24 00:00, and 2019-12-24 06:00. Also shown are the resulting forcing without use of ramping ("noramp") and for a 6-hour ramping ("ramp6").

reduced, the change is small unless there are large updates in the analysis step, which is exactly the time where ramping is necessary to alleviate discontinuities in the forcing.

3.2 Impact on ocean model

To investigate how the discontinuity affect the ocean elevation, the ocean ~~model~~ models NA3 and NS1C have been run in hindcast mode with different preprocessing (ramping) of the meteorological forcing: noramp, ramp0 and ramp6, see figures 2~~and 4. In both~~ , 3 and 4 for the period 2016-12-01 through 2018-12-31. In all cases, the ocean model has been forced by the ECMWF-IFS data set, only the ramping method is varied. In operational mode, the NS1C model is forced with meteo data from the Danish Meteorological Institute (DMI-HARMONIE-NEA), but for simplicity the ECMWF-IFS data is used in the present work.

As seen in the previous section, the pressure discontinuity may in certain situations exceed 5 hPa. As a single hecto-Pascal corresponds roughly to one centimeter of water column, spurious waves in the order of several centimeters might be expected. As the discontinuous forcing could excite gravity waves over a range of frequencies, it may be difficult to *a priori* estimate the spectral content of the spurious waves.

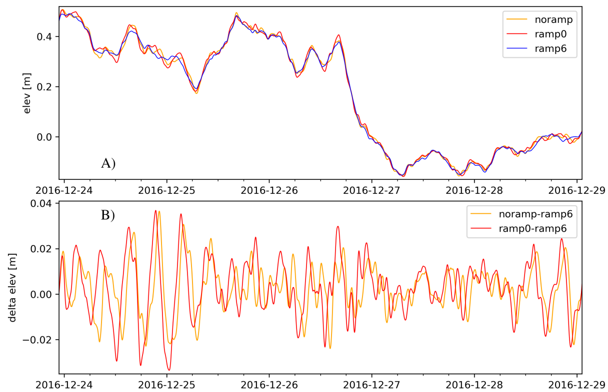

Figure 11. NA3 surge elevation at Wick station during Dec 23rd and 24th December 2016 forced by ECMWF-IFS data. A: Results for models forced by the discontinous “noramp” method (discontinuous), “ramp0”, and forced by “ramp6” smothed datamethods, and B: difference differences between “short” ramps and the tworecommended “ramp6”.

As a proxy for the impact on the NS1C north boundary, the computed surge elevation at Wick station (see Fig. 5) is examined.[2] The time step (Δt) of the NA3 model is 8 s, and to ensure that high-frequency components are resolved and to avoid data aliasing, station data has been saved every 40 s, *ie.* every 5 time steps. In Figure 11, the Wick elevation is depicted for the two cases examined. Also the difference between the two surge time series is shown in the figure. With respect to the overall features – on the scale of several hours to days – the time series of the two methods agree. However, there is significant difference in the higher-frequency components: the elevation difference (Figure 11B) has significant energy components in the range of one to two hours (results not shown). For the chosen station and period, however, it is not clear if the “ramp0” method is significantly better than no ramping. Further, it It may be noted that the magnitude of the differences is in the order of several centimeters, consistent with the magnitudes of the pressure discontinuities found in the previous section. At FCOO, the modelled data (elevations, in this case) are routinely compared to observations in order to gauge the performance of the model. For the present setup and station, the RMS-error – comparing model elevation to observed surge (low-pass filtered elevation) – has been computed to 6.8 cm for 2016 and 5.1 cm for 2017. In comparison, the pressure discontinuity – inducing changes of up to 3–4 cm for the present station – is by no means the leading error term, but it is not negligible either.

[2]Time series of 40 stations for each of the three ramp settings are available online

The pressure discontinuity affects the nested model (NS1C) both directly on the free surface and through the boundary conditions computed from the NA3 results. For the NS1C setup, elevation data have been saved every 90 sec at more than 250 stations[3] hroughout the domain. The Hanstholm station in the Western Skagerrak on the Danish peninsula of Jutland (see Fig. 5) is examined to gauge the effect on a station in the NS1C model setup. While the event in Dec 2016 results in differences of up to 4–5 cm at the Hanstholm station (results not shown, but data available on-line), a year later, the differences exceed 6 cm, corresponding to nearly 5% of the monthly elevation range, see Figure 12. From the figure, it may be noted that the

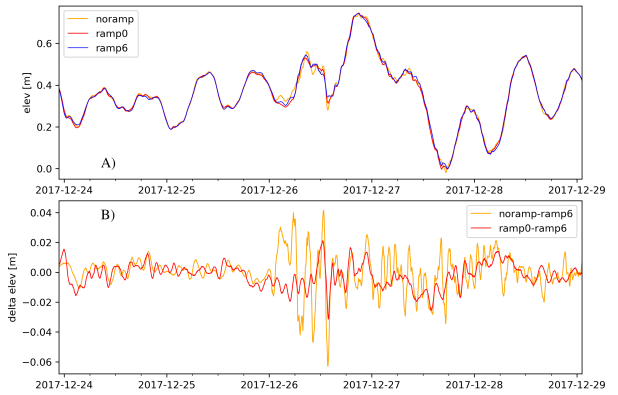

Figure 12. NS1C elevation at Hanstholm station during December 2017 forced by ECMWF-IFS data. A: Results for models forced by the "noramp", "ramp0" and "ramp6" methods, and B: differences between "short" ramps and the recommended "ramp6".

"noramp" method results in high-frequency components in the elevation signal, especially on 2017-12-26. In the present case, the "ramp0" method suppresses the major part of the high-frequency components. It is also observed that most of the time, the difference between the three methods is small. Compared to observed elevation, the statistics for the Hanstholm station (forced with ECWMF-IFS ramp6) shows an RMS-error of 6.9 cm for 2016 and 6.4 cm for 2017. Again, the pressure discontinuity is not a leading error term, but it should be worth to address.

For completeness, it should be mentioned that even the slightest change in forcing or initial conditions may induce a change the location of baroclinic eddies in the 3D circulation model. Büchmann and Söderkvist (2016) found the related salinity ensemble variability to be less than about 1PSU in Skagerrak. At any particular time the exact eddy location may differ between the three simulations (noramp, ramp0 and ramp6), and this introduces a small elevation difference, which is unrelated to the pressure jumps. The elevation difference was not examined explicitly for Skagerrak by Büchmann and Söderkvist (2016) , but for a station in Kattegat the difference was found to be in the order of 0.1 mm – about two orders of magnitude smaller than the effects from the meteorological pressure discontinuities examined in the present work. Thus, the differences shown in Figure 12B, do originate from the pressure discontinuities rather than from repositioning of baroclinic eddies.

[3] Time series for 266 stations are available online

4 Conclusions

Data assimilation in meteorological models – implemented at the so-called “analysis step” – results in updated data fields at this and later time steps. It appears to be common practice, that weather centers, such as European Centre for Medium-range Weather Forecasts (ECMWF), disseminate updated forecast only from the forecast epoch ($t = 0$) and forward ($t > 0$). It has been shown that direct use of such meteorlogical forcing - in combination with saving hotstart files exactly at the epoch - results in the use of a meteorological forcing with a discontinuity at every model epoch back in time.

As a side-note it is observed that the discontinuity may not be present in hindcast mode, and thus the forecast-error of an oceanographical model could be under-estimated unless care is taken.

The size of the pressure discontinuity ~~have~~ has been examined for a single model: the ECMWF-IFS model in a particular area in the North-East Atlantic. It was found that although the discontinuity on average is only about 0.2 hPa, it may exceed 5 hPa at specific incidents. A simple, straight-forward and easy-to-implement solution to the problem has been suggested, namely to slowly “ramp” the new forecast data, *ie.* to use a linear combination of old and new forecast for a few time steps.

The effect of the discontinuity on a particular operational storm-surge model has been examined, and spurious waves of the magnitude of several centimeters was observed in an area, where the storm-surge model data are used as boundary conditions for a higher-resolution operational circulation model. Additionlly, it has been shown that high-frequency spurious waves may also be seen directly in the circulation model. For the two particular stations examined, the magnitude of the spurious waves was in the same order of magnitude as the annual RMS-error of the model elevation compared to in-situ observations. Although the pressure discontinuity – for the present model setups – is not the leading error term, it is considered well worth the effort to eliminate the possible spurious waves in the models.

It is recommended that operational ocean modellers take steps to ensure that the meteorological forcing fields are smooth in time. Preferrably, meteorological forcing providers may provide updated forcing fields also before the forecast epoch, *ie.* for $t < 0$, thus to provide every field, which has been updated by the data assimilation procedure. In this case, the ocean model hotstart time should be moved to the time of the latest meteorological field, which is not updated by the process. As an alternative, the discontinuity may be alleviated by the ramping procedure suggested in the present work.

Data availability. Data used in this manuscript is available on-line at Zenodo.org, DOI:10.5281/zenodo.3243187. The raw data for each of the Figures 6–12 is available as indidual tar balls of NetCDF data files. Model elevation data are available in NetCDF data for 40 station in the NA3-domain and 266 stations in the NS1C-domain for the three examined ramp settings for the period 2016-12-01 through 2018-12-31.

ECMWF-IFS data are available through the MARS system, but access is limited to member countries. For the present paper, the first 19 hourly fields of each of four daily operational weather forecasts 2016-01-01 – 2018-12-31 have been used.

Code availability. GETM (Burchard and Bolding, 2002, https://getm.eu/) is open source, and builds on GOTM (Umlauf and Burchard, 2005, https://gotm.net/) and FABM (Bruggeman and Bolding, 2014, https://github.com/fabm-model/fabm). The source code versions used in the present work reflects the executables in operational use at FCOO at the time of writing. As a consequence, the source codes differ between the NA3 and NS1C model setups. The exact git commit hashes and dates for the code used is given in the following table:

Model		branch	date	git commit
NA3	GETM	iow_master	2017-04-21	b23ad75
	GOTM	iow_master	2017-04-30	7fe7b19
	FABM	master	2016-12-01	d5c7fbe
NS1C	GETM	iow_master	2017-06-07	25dabf7*
	GOTM	iow_master	2017-05-30	a3fa955
	FABM	master	2016-12-01	d5c7fbe

For operational purposes the GETM code for NS1C was modified slightly to improve the initializations of particular arrays. The modifications does not impact on the results of the present paper. The exact source code – including changes – used in this study is available on-line at DOI:10.5281/zenodo.3243187. The actual changes compared to GETM-25dabf7 are given also as a diff-file.

Author contributions. BB identified the possible discontinuity, suggested the solution, examined the effects, implemented the solution operationally at FCOO, and wrote the paper.

Competing interests. The author declare that there is no conflict of interest

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