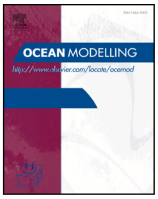
Ocean Modelling 106 (2016) 104–120

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



Optimizing dynamic downscaling in one-way nesting using a regional ocean model

Van Sy Pham, Jin Hwan Hwang*, Hyeyun Ku

Department of Civil & Environmental Engineering, Seoul National University, Seoul 151-744 Republic of Korea

ARTICLE INFO

Article history:
Received 29 March 2016
Revised 14 September 2016
Accepted 16 September 2016
Available online 20 September 2016

Keywords:
Downscaling ability
Error
Ocean regional circulation model
Big-Brother Experiment

ABSTRACT

Dynamical downscaling with nested regional oceanographic models has been demonstrated to be an effective approach for both operationally forecasted sea weather on regional scales and projections of future climate change and its impact on the ocean. However, when nesting procedures are carried out in dynamic downscaling from a larger-scale model or set of observations to a smaller scale, errors are unavoidable due to the differences in grid sizes and updating intervals. The present work assesses the impact of errors produced by nesting procedures on the downscaled results from Ocean Regional Circulation Models (ORCMs). Errors are identified and evaluated based on their sources and characteristics by employing the Big-Brother Experiment (BBE). The BBE uses the same model to produce both nesting and nested simulations; so it addresses those error sources separately (i.e., without combining the contributions of errors from different sources). Here, we focus on discussing errors resulting from the spatial grids' differences, the updating times and the domain sizes. After the BBE was separately run for diverse cases, a Taylor diagram was used to analyze the results and recommend an optimal combination of grid size, updating period and domain sizes. Finally, suggested setups for the downscaling were evaluated by examining the spatial correlations of variables and the relative magnitudes of variances between the nested model and the original data.

1. Introduction

The high-resolution grid of atmospheric and Oceanic Regional Circulation Models (RMCs) allows for the resolution of fine-scale interactions and forcings that are unresolved by coarse-mesh simulations (e.g., Denis et al., 2003). Along with simulating small-scale dynamics by RMCs, one-way nesting schemes help with the representation of large-scale features in RMCs by imposing initial and lateral boundary conditions, which are constructed by downscaling information from global models (Ådlandsvik and Bentsen, 2007; Li et al., 2012; Herbert et al., 2014). However, the procedures employed for such downscaling of large-scale information into small-scale models generate unwanted errors (Warner et al., 1997; Denis et al., 2002a, Denis et al., 2002b). Such errors limit the application of RMCs to short-term forecasts and long-term projections of local weather. Therefore, those errors need to be identified and qualitatively evaluated, to find the optimal temporal and spatial resolutions of the RMCs and to determine whether the RMCs may reasonably forecast the future (e.g., Denis et al., 2002a, Denis et al., 2002b, 2003; Leduc and Laprise, 2008).

ORCMs have modeled coastal seas over several decades in a variety of domains (e.g., Kourafalou and Tsiaras, 2007; Costa et al., 2012) and have operationally forecasted sea weather on regional scales (e.g., Lim et al., 2013; Rowley and Mask, 2014). However, compared with the many "atmospheric climate" studies of downscaling capabilities, the errors produced by the nesting with Ocean Regional Circulation Models (ORCMs) (Spall and Holland. 1991), have not yet been studied well. Many previous studies with ORCMs have focused on optimizing ORCMs to reduce errors from the nesting; but no standard method to identify, assess and reduce those errors has so far been published. As a first step for assessing the oceanic dynamical downscaling feasibility in an ORCM, we investigated the errors produced by one-way nesting on the basis of error evaluation schemes used for assessing downscaling capability in atmospheric climate studies.

According to Warner et al. (1997), Giorgi and Mearns (1999) and Denis et al. (2002a), Denis et al. (2002b), there are several sources of error in atmospheric climate dynamic downscaling. Denis et al. (2002a), Denis et al. (2002b) discussed these error sources for atmospheric models and we modified this approach slightly to suit oceanic circulation studies, as follows:

(1) *Formulations for mitigating inconsistencies*: To reduce the above errors, artificial boundaries are constructed with each

---

* Corresponding author. Fax: +82 2 873 2684.
E-mail address: jinhwang@snu.ac.kr (J.H. Hwang).

http://dx.doi.org/10.1016/j.ocemod.2016.09.009

field from the OGCMs and supplied to each point at the LBCs (McDonald, 1999). However, it is difficult to define a set of formulations to construct boundary conditions that guarantee the existence of a stable and unique solution. Therefore, such over-specified values at the boundaries may differ from the neighboring interior solution and still cause a discontinuity at the boundaries. Such discontinuities, in turn, may result in unstable integration and cause transference of numerical instability to the domain from the lateral boundary, generating unnecessary errors (McDonald, 1999; Marchesiello et al., 2001; Oddo and Pinardi, 2008).

(2) *Spin-up for regenerating smaller scale signals:* Coarse data from Ocean Global Circulation Models (OGCMs) or observations are interpolated to construct finer Initial Conditions (ICs) which are fed into ORCMs. But smooth interpolations cannot generate small-scale perturbations to the ICs and it takes a certain amount of time to regenerate such small-scale features, even with the finer grids of ORCMs (Warner et al., 1997).

(3) *Spatial and temporal inconsistencies between Lateral Boundary Conditions (LBCs) of the nesting and nested models:* As with the ICs, the OGCMs' data should be spatially and temporally interpolated and then supplied as LBCs to the ORCMs (Warner et al., 1997; Denis et al., 2002a, Denis et al., 2002b). In the vicinity of the boundaries, however, significant discontinuities occur when data are updated with new LBC information interpolated from OGCMs. For example, velocities at the boundaries before and after updating have neither the same direction nor the same magnitude; in particular newly interpolated LBCs do not have enough small-scale features. Such inconsistencies occur at every updating with new LBCs.

(4) *Sizes of nested domains:* Once the aforementioned perturbations develop at the boundaries, they propagate toward the center of the domain along with the cross-boundary flow (Warner et al., 1997). If the domain of interest is located far enough away from the lateral boundaries, then errors can be prevented from quickly propagating into the domain of interest. This buffering distance may help reduce the effects of errors at the boundary on the central domain of interest.

(5) *Sub-grid scale parameterization:* ORCMs usually consider more complicated sub-grid parameterization schemes or different coefficients from those of OGCMs (Samelson et al., 2008). In particular, the performance of sub-grid-scale turbulence closure models could differ depending on their grid sizes. Thus, inconsistent physical parameterizations between driving and driven models could cause non-physical forcing gradients, which can generate unavoidable errors, near boundaries in particular (Warner et al., 1997; Denis et al., 2002a, Denis et al., 2002b).

(6) *Addition of local forcing:* Atmospheric weather data, such as pressure, wind stress, precipitation and surface flux, are interpolated from the Global Climate Model or from the NCEP analyses (NCEP, 2016). But, the atmospheric forcing obtained from the global models has poor spatial and temporal resolutions as do the oceanic variables from the OGCMs. Therefore, errors from interpolation of the local atmospheric forcing could also cause large gradients and accelerations, in particular near boundaries (Warner et al., 1997).

Among all these error sources, the present work focuses on error sources 1, 2, 3 and 4, namely, formulations for mitigating inconsistencies, spatial resolution of initial conditions, spatial resolution and temporal updating of LBCs, and domain sizes. Error source number 5 should be related to sources 2 and 3, but too much depends on the numerical scheme of a certain model, so it is beyond the scope of this discussion. To focus attention on the ORCM itself, the effects and variations due to source 6 are also neglected here.

Once the sources of errors were identified, we assessed whether the ORCM itself has skill in downscaling from the OGCMs. Even under optimal conditions, the ORCM cannot avoid having some errors due to downscaling. Therefore, we evaluated how well patterns were reproduced and how well the magnitudes of signals were regenerated. The main objectives of this research can be summarized by the following questions:

1. How do errors associated with the downscaling technique affect the results of the ORCM?
2. How well does the ORCM downscale coarser data into finer simulations?

In order to answer the above questions, we employed the Big-Brother Experiment (BBE), which enables us to separate each source from the others and to quantitatively assess the individual effects on the results of the ORCMs.

2. Methodology

2.1. The Big-Brother experimental scheme and evaluations

The BBE was used to examine the downscaling ability of a nested ORCM, similar to the work conducted by Denis et al. (2002a), Denis et al. (2002b) in the field of atmospheric research. Fig. 1 shows a schematic diagram of the present BBE scheme. First the BBE was used to simulate a large area with high resolution and these results were named Big-Brother. Such highly resolved data were taken as real values, to be used as reference data in later steps. Big-Brother data were then intentionally degraded by removing high-wave number signals with a low-pass filter. By filtering out high wave number-signals, the data can be taken as if produced by a coarser-grid global model. Since the ICs and BCs had lost small-scale signals and were underspecified, the filtered data needed to be interpolated again to fill the IC and BC grids in the nested model. With these interpolated ICs and BCs, our simulations produced data for the Little-Brother, which has a finer resolution and shorter updating intervals. Now, the Little-Brother results have the same resolution as the original Big-Brother results before filtering. Note that the Little-Brother uses the filtered Big-Brother results to construct ICs and BCs that mimic the coarser OGCM results. The Little-Brother results can be compared directly to those of the original Big-Brother results before filtering. Such a comparison can evaluate the difference between the nested modeling results.

This experimental method has the advantage of separating the numerical error from other error sources in the nesting and downscaling. Furthermore, this method is free of limitations associated with observational methods, such as coarse resolution at the deep layers and the possible lack of observational variables. Moreover, the simulated variables of the Little-Brother can easily be compared with the Big-Brother results, as they have exactly the same resolution. The differences between the results of Big-Brother and Little-Brother can be regarded as errors resulting from the nesting and downscaling, and are not attributable to model errors or observational errors.

The appropriateness of the downscaling procedures was evaluated in two steps. First, a Taylor diagram was used to find an optimized combination of each setup condition to simulate with the dynamic downscaling. A 2-D Taylor diagram can summarize and help with comparing two sets of results, as Taylor (2001) suggested; so this diagram was used to assess the overall error during downscaling. Similarity among results was quantified in terms of three statistics: the Standard Deviations (SDS), the correlation coefficient (COR) and the Center Root-Mean-Squared Difference