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“A dynamical downscaling approach for the improved representation of sub-annual coastal sea level variability: the importance of shelf and slope ocean dynamics”

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Response to Reviewers - RC2 - Referee #2

1. Summary and Overall Assessment

This manuscript evaluates a 100-member ensemble of one-year dynamical downscaling hindcasts for the period 1999–2018 along the U.S. East and Gulf Coasts. The hindcasts are produced using the high-resolution, $1/12^\circ$ Northwest Atlantic regional ocean model (NWA12), driven by retrospective seasonal forecasts from the global coupled SPEAR model, which has an atmospheric resolution of 0.5° and an ocean resolution of 1° .

The authors investigate how increased ocean-model horizontal resolution and improved representation of continental-shelf and slope bathymetry affect subannual coastal sea-level variability and short-term daily extremes.

Overall, this is a well-designed, timely, and insightful study that addresses an important gap in coastal sea-level forecasting: the need to connect global climate and seasonal prediction systems with fine-scale ocean dynamics over the continental shelf and slope. The methodology is robust and makes effective use of a comprehensive 100-member ensemble dataset. The manuscript is logically organized, and the figures are generally clear and of high quality.

The physical interpretations linking model resolution, shelf hypsometry and bathymetry, coastal-trapped waves, and western boundary-current behavior are physically sound and well supported by the results. The study also provides useful and actionable insights for regional coastal-risk assessment and the prediction of extreme water levels.

Recommendation: Minor Revision. The manuscript is suitable for publication after the authors address several methodological clarifications, expand the discussion of certain physical mechanisms, and correct a small number of technical and typographical issues.

2. Major Comments

2.1 Uncoupled Air–Sea Interaction and Surface-Stress Formulation

The authors acknowledge in Section 2.1, Lines 97–104, that NWA12 is an ocean-only model forced by atmospheric fields from SPEAR. Consequently, regional ocean sea-surface temperatures and currents do not feed back onto the atmospheric circulation or surface winds. Please clarify whether the wind-stress calculation in NWA12 accounts for relative air–sea velocity, that is, whether the stress is calculated using surface wind velocity minus ocean surface-current velocity. In regions of strong horizontal shear, particularly near the Gulf Stream, current–wind stress feedback can substantially influence upper-ocean energetics and shelf–slope exchange.

A brief statement indicating whether absolute winds or relative winds are used in the NWA12 bulk-flux formulation would strengthen the methodological description in Section 2.1.

The NWA12 regional model configuration used here calculates the relative wind to determine the stress to apply to the ocean; in other words, the NWA12 ocean surface current was subtracted from the SPEAR winds being applied. We acknowledge that the use of relative wind forcing in a high resolution uncoupled ocean model can often have an overly strong eddy killing effect (e.g., Renault et al. 2020). In recent experiments with a different atmospheric forcing

product, we found that using a correction similar to Renault et al. 2016 to make the wind forcing closer to absolute rather than relative to the current increased the eddy kinetic energy in the model. Therefore, we expect that the increased sea level variance in NWA12 would be boosted even further if this correction was included. To address this comment, we have inserted a description of how the wind forcing was applied into the methods (L91-93).

“While surface ocean conditions do not feed back onto the atmosphere, wind stress calculations in NWA12 account for relative air-sea velocity, with NWA12 surface currents subtracted from the SPEAR surface winds.”

2.2 Treatment of Tides and Nonlinear Tide–Surge Interactions

NWA12 includes tidal constituents, which are removed offline using UTide before the model output is averaged to daily resolution. In contrast, SPEAR does not explicitly resolve tides. Nonlinear tide–surge interactions, including the modulation of bottom friction by tidal currents, can influence non-tidal residual sea level in shallow coastal regions. The authors should briefly discuss whether some portion of the enhanced coastal variance in NWA12 relative to SPEAR could arise from nonlinear tidal interactions represented in NWA12, rather than solely from improved bathymetric resolution, shelf dynamics, and wind-driven Ekman transport. The authors do not necessarily need to quantify this contribution but acknowledging it as a possible source of difference between the two models would provide a more complete interpretation of the results.

Thank you for this comment, we now acknowledge non-tidal interactions as a possible source of SPEAR-NWA12 differences (L110-113).

“We also acknowledge that additional factors, for example, non-linear tide-current interactions, may contribute to enhanced NWA12 near-coast variance, but we expect these impacts to be smaller as NWA12 does not include a dynamic land/sea interface where these effects may become large.”

2.3 Temporal Resolution of the Inverted Barometer Correction

The inverted barometer effect is added offline using daily averaged atmospheric surface pressure from SPEAR.

Because synoptic storms and coastal-flooding events often involve substantial pressure changes on hourly to six-hourly timescales, the use of daily averaged pressure may smooth short-lived pressure minima. Could this procedure lead to an underestimation of the upper tails of the daily sea-level distributions, particularly in Figures 10 and 12 and at higher-latitude stations such as Boston and Portland?

Please clarify whether higher-frequency pressure fields were available and, if so, why daily averaged pressure was selected. At minimum, the manuscript should acknowledge the potential effect of temporal averaging on the representation of extreme sea-level events.

Yes, upper tails of the distributions in both SPEAR and NWA12 may be underestimated. This will not impact SPEAR-NWA12 comparisons in Figures 11 and 12 (left columns), but will impact comparison to observations in Figures 11-13. Despite this, comparison between models and observations at northern stations are favorable. Higher-frequency pressure fields were not saved. See added text (L147-150, 262-263).

“In using daily mean surface pressures, referenced to global ocean mean, higher frequency variability associated with synoptic scale storms may result in an underestimation of extremes and distribution tails.”

“At all stations, model extremes, and distribution tails, are expected to be under-represented as daily mean surface pressures miss a higher-frequency component of coastal flooding and surge associated with synoptic storms.”

2.4 Coastal-Waveguide “Choke Point” Near Cape Hatteras

The manuscript identifies Cape Hatteras as a critical geographic transition where the continental shelf narrows, and the Gulf Stream separates from the coast. The discussion in Section 3.3 would benefit from a more explicit physical explanation of why SPEAR performs poorly south of Cape Hatteras.

Please discuss whether the 1° SPEAR ocean grid is too coarse to resolve either the relevant coastal Rossby radius of deformation or the physical width and bathymetric structure of the narrow continental-shelf waveguide. Such a discussion would help clarify the spatial-resolution threshold required to represent coastal-trapped-wave propagation and related shelf dynamics in this region.

It would also strengthen the broader interpretation of why dynamical downscaling provides substantially greater benefits in some coastal regions than in others.

SPEAR is unable to resolve the physical width and bathymetric structure of the narrow continental shelf in this region (shelf widths decrease to less than 1 degree latitude/longitude). The relevant coastal Rossby radius of deformation is too small for even NWA12 to properly resolve ($O[2-10\text{km}]$). Discussion is added (L245-250).

“While SPEAR horizontal resolution is too coarse to resolve the first baroclinic Rossby radius of deformation over the continental shelf ($\mathcal{O}$ 2-10 km), and NWA12 may at best resolve this radius with one grid cell, model resolutions relative to the shelf width are quite different. SPEAR may resolve the average US east coast shelf width of 100-150 km with one grid cell while NWA12 will have over twelve. Where the shelf narrows, coastal grid cells in SPEAR will generally be too deep as they are generated by averaging over shelf and slope depths. This difference impacts shelf process and coastal trapped wave representation significantly and reveals where dynamical downscaling will improve model coastal sea level. “

See new Figure 7 (included here), left column.

3. Minor Comments and Technical Corrections

Line 248: “...after removal a monthly seasonal climatology...” to: “...after removal of a monthly seasonal climatology....”

Corrected.

Line 411, References: In the citation for Wise et al. (2020), “oddshore-forced” should be corrected to “offshore-forced.”

Corrected.

Please ensure that the terms “non-tidal residual” and “sea-level anomaly,” as well as the abbreviations NTR and SLA, are used consistently throughout the text, figure legends, and captions. In particular, the terminology appears to differ between Figure 3 and Figures 10–11. If the terms refer to distinct quantities, the distinction should be clearly defined; otherwise, consistent terminology should be adopted throughout the manuscript.

We have reviewed and revised usage of NTR and SLA for improved consistency. As all comparisons are between daily means we remove NTR time series in Figure 3.

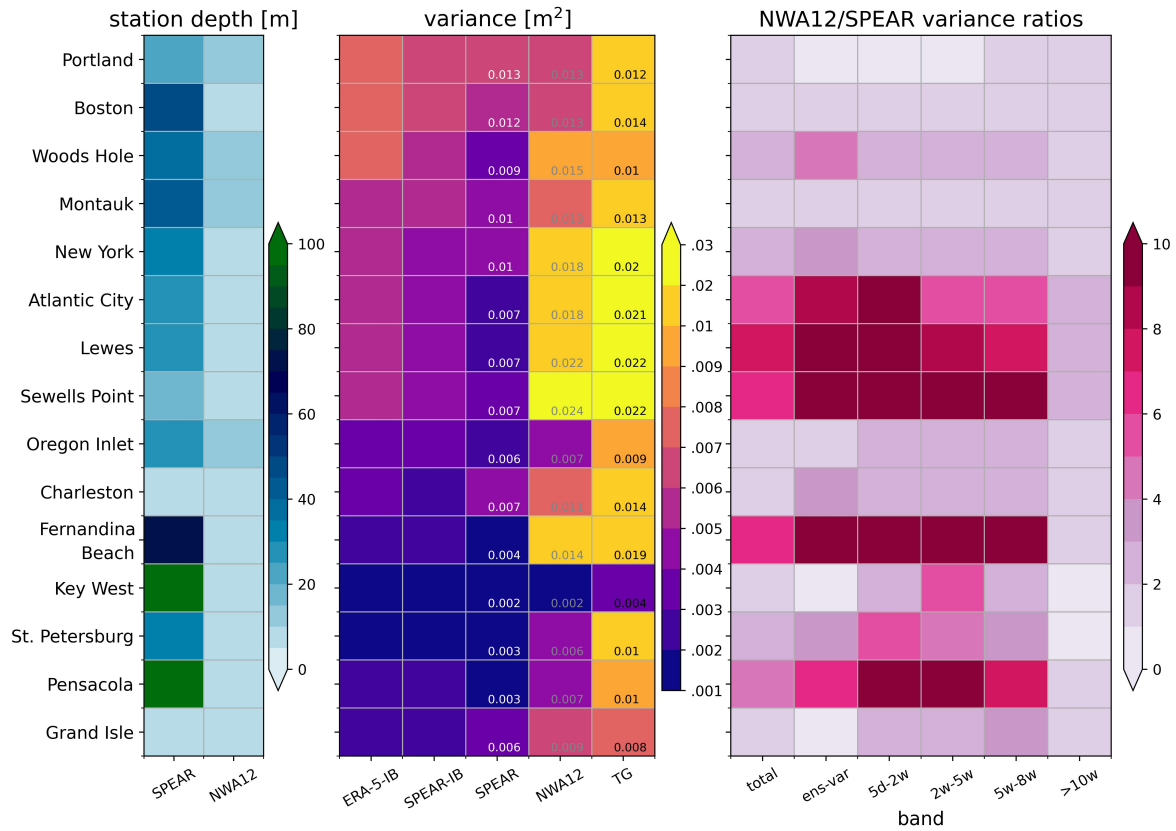


Figure 7 - left) SPEAR and NWA12 ocean depth at 15 tide gauge stations. middle) Coastal sea level variance: ERA-5 inverted barometer contribution (ERA-5-IB), SPEAR inverted barometer contribution (SPEAR-IB), SPEAR, NWA12, tide gauge observations (TG). Text reports model sea level variance with the IB contribution included and observed sea level variance. Note colormap and colorbar are on a log scale. right) NWA12/SPEAR variance ratios: total, ensemble spread (ens-var), and for each frequency bands.