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Research Highlights from the Geophysical Fluid Dynamics Laboratory Community

Advancing the Modeling, Understanding, and Prediction of Weather and Climate

Closing the gap — Hurricane Prediction Advances in the US FV3-based Models

Bulletin of the American Meteorological Society *Jan-Huey Chen[1], Timothy Marchok[1], Morris Bender[1], Kun Gao[2], Sundararaman Gopalakrishnan[3], Lucas Harris[1], Andrew Hazelton[3], Bin Liu[4,5], Avichal Mehra[4], Matthew Morin[1,6], Fanglin Yang[4], Xuejin Zhang[3], Zhan Zhang[4], and Linjiong Zhou[2]*

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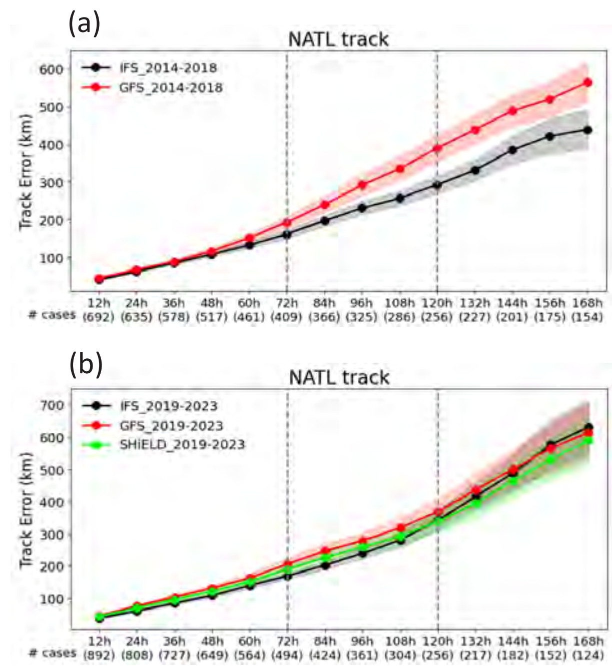
Improving the prediction of hurricane track and intensity in the North Atlantic basin has been a longstanding focus for weather and climate prediction efforts in the United States. For many years, the Integrated Forecasting System (IFS), developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), has served as the benchmark for hurricane track forecast skill, but recent advances have significantly improved the performance of U.S. modeling systems. The performance of U.S. modeling systems in hurricane prediction has advanced substantially. In this study, Chen et al. describe the 10-year progression of North Atlantic hurricane forecasts in various Finite-Volume Cubed-Sphere Dynamical Core (FV3)-based systems, including the operational Global Forecast System (GFS), Hurricane Analysis and Forecast System (HAFS), and the experimental System for High-Resolution Prediction on Earth-to-Local Domains (SHiELD) model, developed at GFDL.

Between 2019 and 2023, significant updates to the Global Forecast System dynamical core, physical parameterizations, and data assimilation contributed to reducing the track forecast skill gap between GFS and ECMWF's Integrated Forecasting System. The FV3-based GFS and SHiELD also demonstrated improvements in hurricane intensity prediction compared to earlier generations of global models. Operational HAFS models matched the high level of intensity forecast skill of NOAA's Hurricane Weather Research and Forecasting (HWRF), which has been the most reliable tool for hurricane intensity prediction to date. From 2020 to 2023, HAFS and the global-nested Tropical System for High-Resolution Prediction on Earth-to-Local Domains (T-SHiELD)—produced track forecasts comparable to non-nested global models while also providing skillful intensity predictions, achieving a combination of strengths that earlier models had not demonstrated. These results highlight progress in NOAA's efforts to enhance global models and regional hurricane forecasting tools.

With increasing demand for improved hurricane prediction and protection of life and property, the authors highlight that future efforts will center on enhancing model components and incorporating machine learning techniques into established forecast modeling systems to advance both accuracy and strengthen operational prediction capabilities.

OAR Goals: Make Forecasts Better, Drive Innovative Science

North Atlantic Tropical Cyclone Track Errors



(a) Mean tropical cyclone track errors (km) at 12-hour forecast lead time intervals for the Integrated Forecasting System (IFS, black) and the Global Forecast System (GFS, red) during 2014–2018. The 95% confidence intervals are shown by transparent shading. Homogeneous comparison case counts for each lead time are listed in brackets at the bottom. Vertical gray dotted lines indicate 72- and 120-hour forecast lead times.

(b) Same as (a), but covering 2019-2023 and including System of High-Resolution Prediction on Earth-to-Local Domains (SHiELD, green line).

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Seasonal Forecasts of Tropical Cyclones Using GFDL SPEAR and HiFLOR-S

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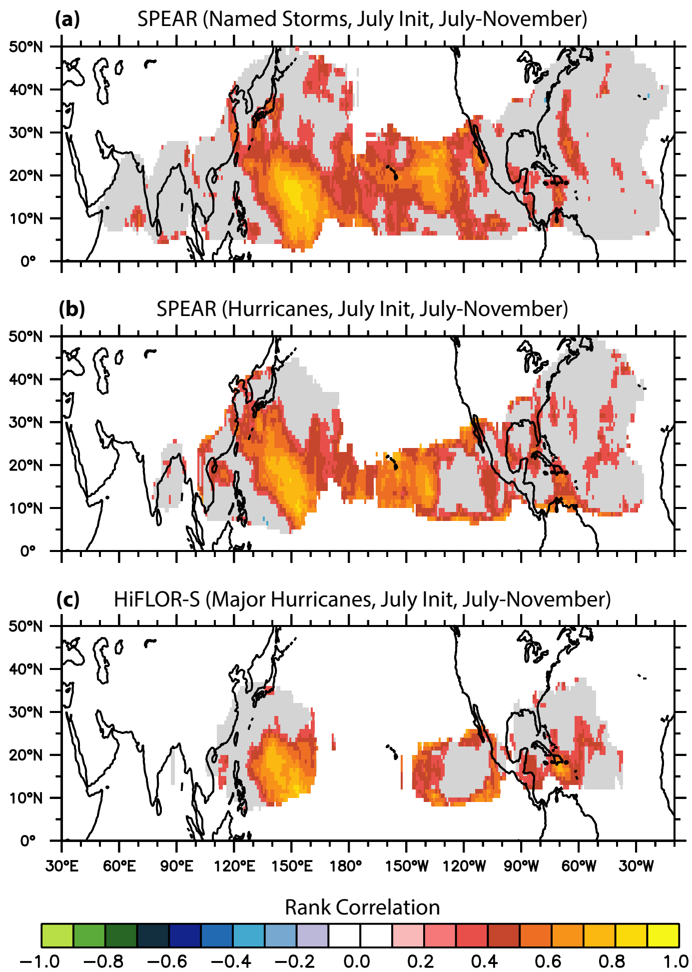
Tropical cyclones (TCs) are among the most impactful weather hazards, with far-reaching consequences for coastal infrastructure, local economies, and public safety. Anticipating TC activity on a seasonal timescale is critical for disaster planning and preparedness. Murakami et al. evaluate how GFDL's state-of-the-art seasonal prediction models—Seamless System for Prediction and Earth System Research (SPEAR) and the High-Resolution Forecast-Oriented Low Ocean Resolution - Seasonal (HiFLOR-S)—are advancing the capabilities to forecast tropical cyclone characteristics across multiple ocean basins in their recent study.

As a seasonal prediction model that provides global forecasts up to 12 months in advance, this study benchmarks SPEAR's ability to predict the frequency of named storms, hurricanes, major hurricanes, and landfall occurrences across the North Atlantic, western North Pacific, and eastern North Pacific basins. HiFLOR-S, a high-resolution atmospheric model, is driven by predicted sea surface temperatures from SPEAR, to produce additional refined forecasts focused on major hurricane activity.

Based on the findings, SPEAR demonstrates prediction skill that matches or surpasses its predecessor models, particularly in the western North Pacific basin, while HiFLOR-S shows skill in forecasting the number of major hurricanes, especially in the North Atlantic. One key result is that improving forecasts of large-scale environmental conditions, such as sea surface temperatures and vertical wind shear—does not necessarily lead to more accurate tropical cyclone predictions. Accurate simulation of how TCs respond to these environmental drivers is also critical for improving forecast skill. These skillful forecasts are produced in real time and were intially sent out monthly, and now quarterly, to the Climate Prediction Center (CPC) and the National Hurricane Center (NHC), where they serve as one of the core inputs for NOAA's Seasonal Hurricane Outlooks. In addition to basin-wide metrics, the models can provide skillful predictions of region-specific hurricane activity, including areas around Hawaii and Guam (see figure). These localized forecasts have the potential to improve public warnings, inform operational planning, and enhance risk assessments across multiple sectors (e.g., emergency management, insurance). Looking ahead, future model development will focus on refining model physics and resolution to further assess and improve forecast performance.

Retrospective prediction skill of the frequency of regional tropical cyclone occurrence from forecasts initialized in July (1992–2020).



Shading indicates the rank correlation between predicted and observed tropical cyclone frequency of occurrence, counted on 1°×1° grids and masked at the 90% confidence level (two-sided). Panels show: (a) Named storms predicted by SPEAR, (b) Hurricanes predicted by SPEAR, and (c) Major hurricanes predicted by HiFLOR-S.

OAR Goals: Make Forecasts Better, Drive Innovative Science

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Implementation of Dynamic Fire Injection Height in GFDL's Atmospheric Model (AM4.0): Impacts on Aerosol Profiles and Radiation

Journal of Advances in Modeling Earth Systems *Arman Pouyaei[1,2], Paul Ginoux[3], Daniel S. Ward[4], Yan Yu[5], and Larry W. Horowitz[3]*

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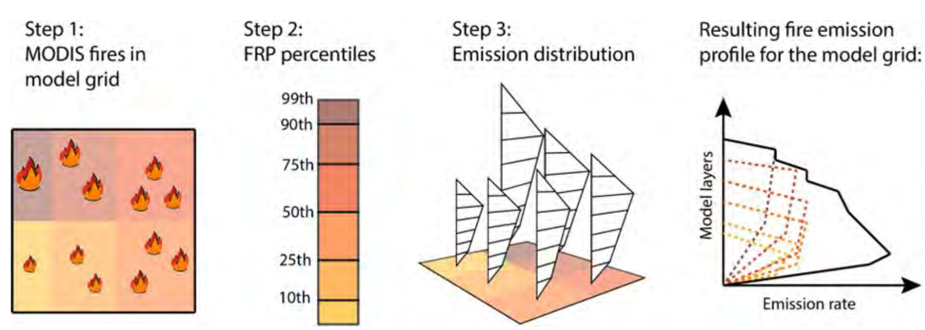
Wildfires emit large amounts of aerosols into the atmosphere that can modify the Earth's radiation balance by scattering and absorbing sunlight. Currently, many Earth System Models (ESMs) rely on fixed-height aerosol injection schemes, limiting their ability to simulate the spatial and temporal variability of wildfire emissions. In this study, Pouyaei et al. implemented a mechanistic plume injection approach into GFDL's Atmospheric Model version 4.0 (AM4.0) to improve the representation of wildfire aerosol distributions and their radiative impacts.

The new mechanistic scheme, based on the Sofiev et al. (2012) parameterization, uses satellite-derived fire radiative power and simulated atmospheric stability to estimate injection heights dynamically. This approach incorporates subgrid-scale variability by accounting for differences in fire intensity observed at 1-kilometer resolution within each model grid cell (approximately 100 kilometers). Compared to the model's earlier fixed injection method, the dynamic scheme improved agreement with observations of aerosol vertical profiles and significantly reduced biases in aerosol optical depth during major wildfire seasons, especially over boreal forests. In particular, it provided a more accurate representation of the vertical profile of the aerosol extinction coefficient below 4 kilometers altitude, where the largest discrepancies were previously observed. Simulations indicate that dynamic injection affects clear-sky radiative fluxes both regionally and globally. The model showed a global mean reduction in net surface shortwave radiation of approximately 0.38 watts per square meter relative to a baseline simulation without fire emissions and a regional increase of up to 1.5 watts per square meter at the top of the atmosphere. Changes in aerosol distributions also influenced atmospheric temperature gradients and circulation patterns.

While the mechanistic injection approach reduced biases compared to observations, uncertainties remain due to limitations in emission inventories and the coarse spatial resolution of the model. This study advances NOAA/OAR/GFDL's ongoing efforts to improve the efficiency and accuracy of ESMs by delivering science-based insights that support public safety, resource planning, and risk management across U.S. communities.

OAR Goals: Make Forecasts Better, Drive Innovative Science

Scale-Aware Treatment of Aerosol Injection from Wildfires



Scale-aware emission distribution: Step 1: All MODIS-detected fires within a model grid cell are identified, Step 2: Fire Radiative Power values are sorted, and the 10th, 25th, 50th, 75th, 90th, and 99th percentiles are used to calculate plume-top heights for each group. Step 3: Emissions are vertically distributed according to the estimated injection heights, and contributions are allocated to each percentile group. The resulting fire emission profile for the grid cell is shown by the integrated emission rate across model layers (black line).

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LM4-SHARC v1.0: resolving the catchment-scale soil–hillslope aquifer–river continuum for the GFDL Earth system modeling framework

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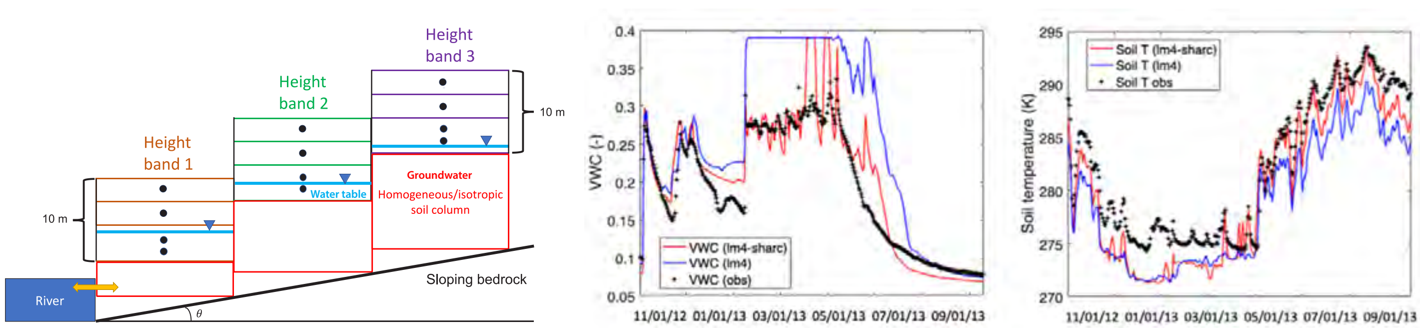
Predicting water in weather and Earth System Models (ESMs), including variables such as soil moisture, runoff, and streamflow, presents numerous challenges due to the complex interactions between the atmosphere, land, human systems, and water bodies (e.g. rivers, lakes, wetlands). A key limitation is the mismatch in spatial and temporal scales. Hydrological processes like infiltration and runoff occur at fine spatial scales, e.g. below one kilometer. In contrast, weather models and ESMs operate on a coarser resolution of tens of kilometers, ignoring surface orography in land components. In addition, groundwater, streams, and upper soil water interactions are often poorly represented despite their critical role in water storage, flow, and floods. To address these challenges, GFDL land modelers, in collaboration with hydrologists from Princeton and Duke University, developed a new parameterization (Hong et al., 2025) to better capture the effects of hillslopes, orography, groundwater interactions, and stream water levels, known as the Soil–Hillslope Aquifer–River Continuum (SHARC) model. SHARC was implemented in GFDL's fourth-generation Land Model version 4 (LM4) for use with weather and EMS. Incorporating these catchment-scale processes at the resolution of weather models allows the bridging of gaps between local hydrologic dynamics and continental-scale and weather patterns, a critical step towards developing a coupled atmosphere-land-ocean hydrologic extremes system within global weather and ESMs. A machine-learning-based method - a hierarchical multivariate clustering – is used to characterize the sub-grid spatial heterogeneity. This approach utilizes high-resolution topography and geomorphology data to derive the distribution of sub-grid tiles and their connectivity. The study demonstrates improved agreement with observations of streamflow, baseflow, near-surface soil moisture, and temperature compared to previous GFDL land models that lack groundwater and dynamic river stage. For example, the model reduced baseflow bias during snowmelt periods and more accurately captured the seasonal variability in runoff timing. LM4-SHARC was further tested in additional headwater catchments with diverse climatic and topographic conditions, demonstrating robust performance across different environments.

While the framework enhances the representation of coupled land surface, stream, and groundwater processes, some uncertainties persist, particularly regarding groundwater parameter estimation in regions lacking extensive observations. Ongoing and future efforts aim to extend this modeling capability to the global scale, with fully coupled sub-grid hillslopes, streams, and river networks. By integrating a more mechanistic treatment of soils, groundwater, and streams in complex topography, GFDL's LM4 modeling system provides new tools to support planning, resource allocation management, and aids in reducing risk from hydrological extremes for communities across the United States.

OAR Goals: Make Forecasts Better, Drive Innovative Science

LM4-SHARC representation of complex terrain for the weather/ESM applications and land surface state simulations



(Left) The LM4-SHARC representation of height-band tiling, river, and groundwater interactions. The water table is predicted to be either below or above the bottom of the soil water column. The bedrock depth is parameterized based on geomorphological data and could be located within the soil column. (Right) Comparison of observations with LM4-HydroBlocks (hillslopes but no groundwater) and LM4-SHARC time-series of soil moisture and temperature, for the 2012 water year at the 1km² headwater catchment in the Sierra National Forest, Nevada.

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Skillful multiyear prediction of flood frequency along the US Northeast Coast using a high-resolution modeling system

Science Advances *Liping Zhang[1,2], Thomas L. Delworth[1], Vimal Koul[3], Andrew Ross[1], Charles Stock[1], Xiaosong Yang[1], Fanrong Zeng[1], Andrew Wittenberg[1], Jian Zhao[4], Qinxue Gu[3], Shouwei Li[3]*

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Long-term changes in coastal sea level are a critical factor influencing flood risk along the U.S. Northeast Coast. Tide Gauge (TG) observations reveal pronounced multidecadal variability in sea level across this region, superimposed on a broader rising trend. To investigate the physical drivers of this variability and assess its predictability, Zhang et al. applied the Seamless System for Prediction and Earth System Research (SPEAR) global high-resolution Climate Model version 2.6 (CM2.6) modeling system, coupled with a downscaled 1/12° Modular Ocean Model version 6 (MOM6), within an initialized decadal prediction framework.

The findings indicate multidecadal fluctuations in the buoyancy-driven Atlantic Meridional Overturning Circulation (AMOC), influenced by the North Atlantic Oscillation, play a primary role in modulating sea level and flood frequency. Since 2005, periods of weakened AMOC conditions have contributed to elevated background sea levels, accounting for approximately 20% to 50% of observed flooding events across TG stations. It also revealed shifts in AMOC strength substantially affect the frequency of coastal flooding. Meaning a higher background sea level significantly increase the likelihood that storm surge and high tides will result in flooding, while lower background levels reduce that risk. The model results show that the long-term upward trend in flood frequency—primarily linked to rising greenhouse gas concentrations—can be projected up to a decade in advance. Variations in detrended flood frequency also demonstrate predictive skill on timescales of up to three years, reflecting the model's ability to capture AMOC-driven multidecadal variability.

Rather than focusing on attribution to external forcing or internal variability alone, the study emphasizes identifying the underlying physical drivers and sources of predictability. The authors also acknowledge limitations, including the omission of land ice contributions, non-climatic influences, and relatively low atmospheric resolution. Future model development and inter-model comparisons are expected to address these gaps and further improve flood risk predictions that support planning and risk management efforts in coastal communities.

OAR Goals: Make Forecasts Better, Detect Changes in the Ocean & Atmosphere

Influence of the Atlantic Meridional Overturning Circulation (AMOC) on U.S. Northeast Coast Flood Days in Tide Gauge (TG) Observations

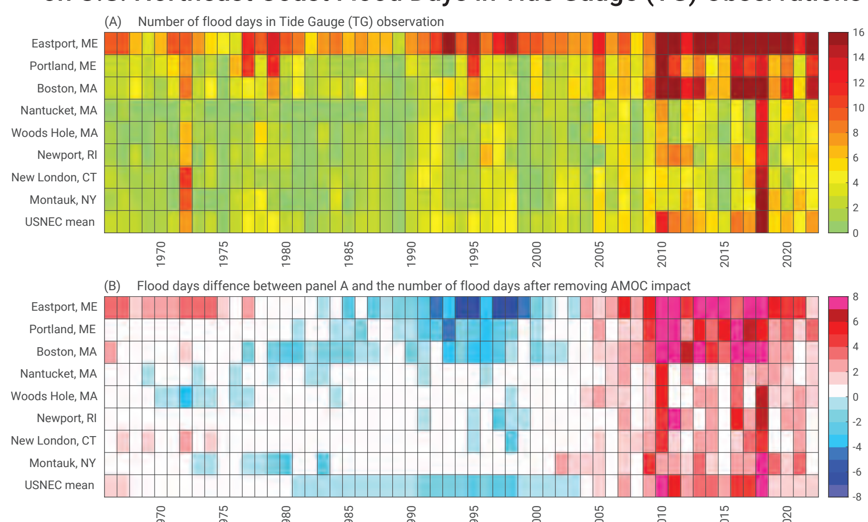

Fig. A shows the annual number of flood days (days per year) at each TG station along the USNEC as a function of time. A day is defined as a flood day when hourly water levels exceed the minor flood threshold at least once within a 24-hour period. Fig. B shows the flood day difference between the total number of flood days (from Fig. A) and the number remaining after removing the AMOC-related sea level variability from the records. The relative contribution of buoyancy-driven AMOC variability to flood frequency is estimated by calculating the annual number of exceedances after subtracting these components from the total water level records. To obtain the AMOC-related sea level fluctuations at each station, TG records were regressed onto the first principal component time series of North Atlantic Sea level variability, which serves as a representative fingerprint of the AMOC.

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Dynamically downscaled seasonal ocean forecasts for North American East Coast ecosystems

Ocean Sciences *Andrew C. Ross[1], Charles A. Stock[1], Vimal Koul[2], Thomas L. Delworth[1], Feiyu Lu[1], Andrew Wittenberg[1], and Michael A. Alexander[3]*

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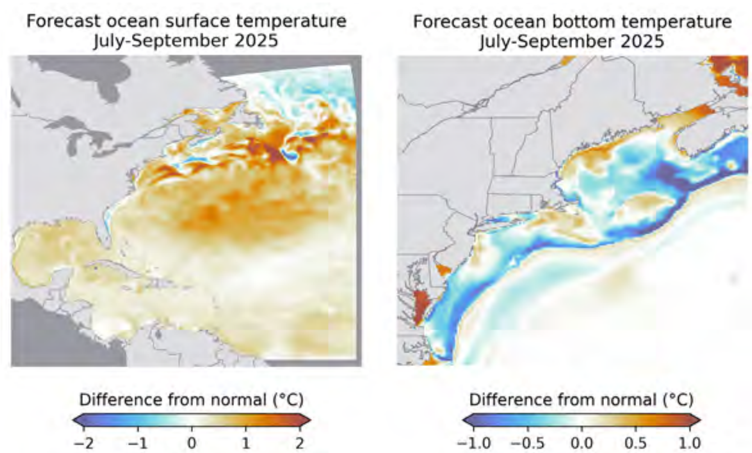
Understanding how ocean conditions may evolve over the coming months is increasingly important for those managing and relying on marine ecosystems. Seasonal forecasts—ranging from one month to a year in advance—offer a valuable tool for anticipating changes affecting fisheries, habitat conditions, and broader ecosystem dynamics. However, producing accurate seasonal forecasts along the U.S. East Coast has been particularly challenging due to the region's complex oceanography, including the influence of the Gulf Stream and its interactions with coastal waters.

Forecast Ocean Temperature July – September 2025



Forecast departures from average ocean temperatures (anomalies) for July through September 2025 from the forecast initialized July 1. Left: forecast sea surface temperature anomalies across the full Northwest Atlantic regional MOM6 model domain. Right: closeup of forecast bottom temperature anomalies along the Northeast U.S. shelf portion of the regional MOM6 model.

Ross et al. examine the performance of seasonal ocean forecasts generated using a high-resolution ocean model for the Northwest Atlantic, configured using the Modular Ocean Model version 6 (MOM6). This regional model, referred to as MOM6-NWA12 and developed at GFDL, features a 1/12° ocean resolution and its accuracy has been tested using an extensive set of retrospective forecast simulations. In these simulations, the regional MOM6-NWA12 model was driven by atmospheric conditions from the Seamless System for Prediction and Earth System Research (SPEAR), a global coupled climate model also developed at GFDL, with a 1° ocean and 0.5° atmosphere configuration. The study evaluates the skill of both models in predicting sea surface temperature, bottom temperature, and surface salinity across key regions along the U.S. East Coast including the Gulf of Maine and the Mid-Atlantic Bight. The findings show the high-resolution regional MOM6 model improves forecast skill across several variables and lead times, particularly within the Northeast U.S. Large Marine Ecosystem. These improvements are attributed to the regional model's enhanced ability to represent coastal processes such as the advection of ocean anomalies along the shelf, seasonal re-emergence of subsurface temperature anomalies, and variability in the Gulf Stream's strength and position.

Since April 2025, the MOM6-NWA12 model has served as an operational prototype under NOAA's Changing Ecosystems and Fisheries Initiative (CEFI), with GFDL providing quarterly forecasts that deliver seasonal ocean outlooks up to 12 months in advance. These forecasts are publicly available through the CEFI data portal and are shared with NOAA Fisheries, the fishing industry, and other partners to support seasonal planning, ecosystem monitoring, and public communication. The first 2025 outlook, for example, indicated warmer-than-average surface temperatures during late summer and early fall across much of the region. It also projected cooler-than-average bottom temperatures in deeper parts of the Gulf of Maine—a departure from recent trends that has drawn interest from resource users and local observers. The most recent forecast for July through September (see figures) reflects a similar pattern.

High-resolution regional models like MOM6-NWA12 offer an efficient, science-based approach to improving seasonal ocean forecasts, supporting NOAA's mission to deliver actionable information for U.S. coastal communities and marine resource stewardship.

OAR Goals: Explore the Marine Environment, Make Forecasts Better

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