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GFDL BULLETIN

Research Highlights from the Geophysical Fluid Dynamics Laboratory Community

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

POLEWARD INTENSIFICATION OF MIDLATITUDE EXTREME WINDS UNDER WARMER CLIMATE

npj Climate and Atmospheric Science *Emanuele Silvio Gentile[1], Ming Zhao[2], Kevin Hodges[3]*

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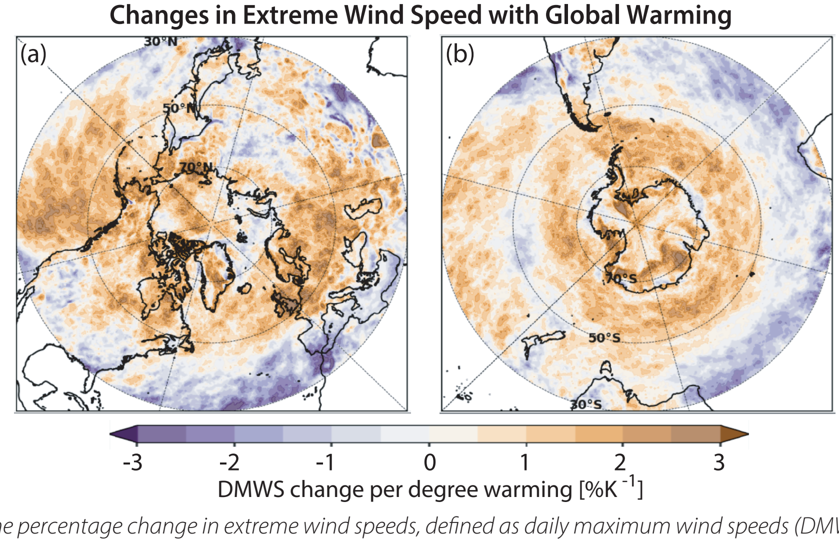
Focusing on climate-induced changes in winds, Gentile et al. investigate how midlatitude cyclones impact the global distribution of extreme wind speed events, defined as those exceeding the climatological 99th percentile, across both hemispheres in a warmer climate. The study uses the state-of-the-art GFDL atmospheric climate model AM4, with a grid spacing of appoximately 50 kilometers, covering the period from 1949 to 2019. The authors analyzed scenarios representing present-day climate conditions and an idealized future projection characterized by global warming conditions with a uniform sea surface temperature (SST) increase of 2K. The findings of the investigation yield several key insights: there is an increase in near-surface extreme wind speeds of up to 3%/K towards the polar regions, while there is a corresponding decrease in the midlatitudes. There is a clear trend of midlatitude cyclones associated with extreme wind speeds migrating towards higher latitudes. One particularly notable finding is the interaction between midlatitude cyclones and extreme wind events. Despite an overall reduction in the number of midlatitude cyclones by approximately 4% in the warmer climate, there is a significant increase in the proportion of cyclone-associated extreme wind speeds by 10%. This highlights the changing nature of extreme wind occurrences in a warmer climate. Additionally, the study identifies specific regions, such as Northwestern Europe, the British Isles, and the West Coast of North America, as areas of heightened concern due to the amplified impacts of cyclone-associated extreme winds in a warmer climate, which in turn has socio-economic consequences.

While the research findings provide critical insights into the complex interplay between midlatitude cyclones, extreme wind events, and climate change, the authors emphasize the importance of understanding the dynamics of midlatitude cyclones amidst human-induced climate change. This understanding is crucial for developing effective climate adaptation strategies and mitigating associated risks. The study also highlights the importance of extreme wind events in vulnerable areas but it acknowledges limitations, including the simplified assumption of uniform SST warming and the overlooked decline in sea-ice cover, which necessitate further exmination of the complexities of cyclonic activity in a warming future.

OAR Goals: Drive Innovative Science

Changes in Extreme Wind Speed with Global Warming



This map illustrates the percentage change in extreme wind speeds, defined as daily maximum wind speeds (DMWS) exceeding the climatological 99th percentile, for each degree of sea surface temperature (SST) warming according to AM4 climate model simulations. The analysis reveals how the median of the 99th-100th percentile daily maximum 10-meter wind speeds, corresponding to the 99.5th percentile (v99.5), shifts per degree of SST warming across both the (a) Northern Hemisphere (NH) and (b) Southern Hemisphere (SH) in an idealized warmer climate scenario.

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ANTHROPOGENIC FORCING CHANGES COASTAL TROPICAL CYCLONE FREQUENCY

npj Climate and Atmospheric Science *Shuai Wang[1,2,3], Hiroyuki Murakami[2], William F. Cooke[2]*

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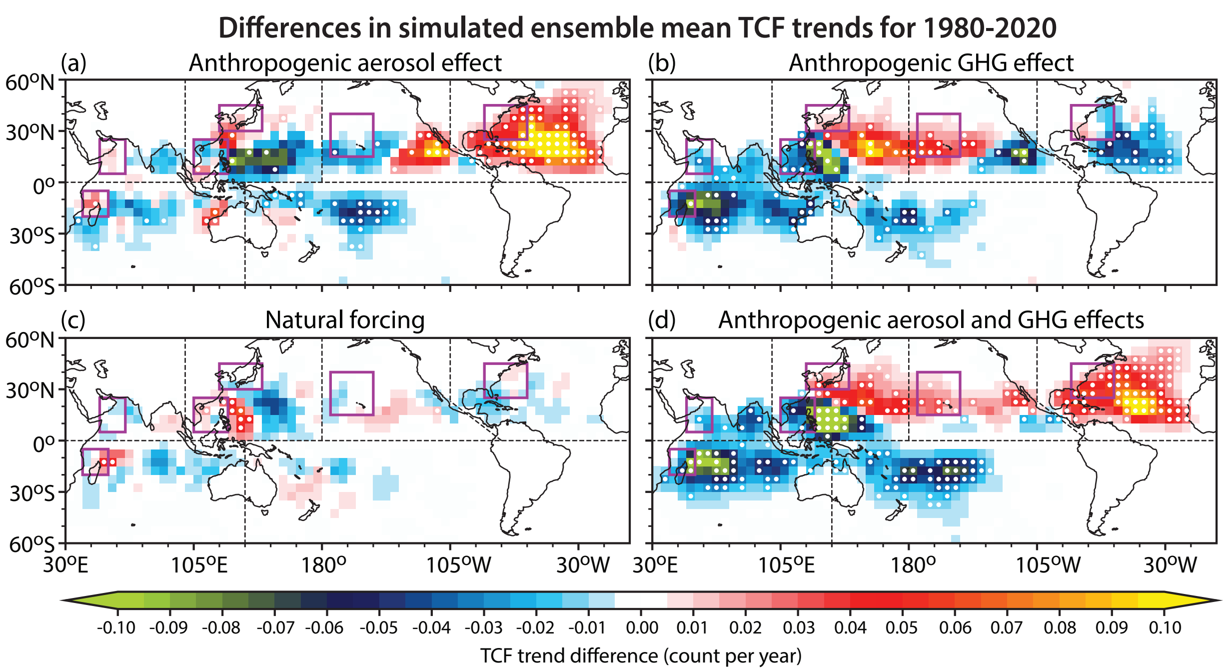
Human activities have been impacting the climate since the Industrial Revolution, with the influence on tropical cyclones (TCs) being a major concern due to its devasting impact upon landfall and relatively high frequency. However, attributing localized changes in tropical cyclone frequency (TCF) to human-induced climate change is extemely challenging for two main reasons: first, the natural variability of the climate can significantly affect regional TC activities, and second, dependable observations of TCs only exist from the satellite era onwards, providing a limited timeframe for analysis. Even so, advancements in high-performance computing have led to significant improvements in climate modeling, offering new ways to address these challenges. Large-ensemble climate simulations, which utilize multiple runs of a climate model with slightly different initial conditions, allow researchers to quantify the natural variability of the climate. This approach helps to isolate the signal of human-induced climate change from the noise due to natural variability. Wang et al. used GFDL's Seamless System for Pre-diction and EArth System Research (SPEAR) model to investigate the connection between human activities and observed changes in coastal TCF around the world. The findings suggest a dominant role of human-induced emissions, such as aerosols and greenhouse gases (GHGs), in influencing TCF changes in several regions, including the US Atlantic coast, the Hawaii region, the Northeast Asian coast near Japan and Korea, and the South China Sea. The study also showed that, since 1980, increases in TCF observed in these areas can be linked to the effects of aerosols and GHGs, with different impacts depending on the region. For example, aerosols and GHGs together are associated with TCF increases near Japan and Korea, while GHG emissions alone relate to the observed decrease in the South China Sea. Additionally, the research highlights how human-induced climate change can alter large-scale environmental conditions, leading to changes in coastal TC frequency. This suggests that human activities may have a substantial impact on TCF, especially in densely populated coastal regions. It's important to note, however, that this study is based on a single climate model, and the results might vary with different models. Despite the potential model dependency, the findings provide compelling evidence that the observed changes in TCF in various coastal regions over the last 40 years can be largely attributed to human-induced climate change. The process is mainly through the mechanism of regional warming and its influence on atmospheric circulation patterns that, in turn, affect TC genesis and steering conditions. The research highlights the importance of understanding and quantifying climate change effects on the occurrence of coastal TCs.

OAR Goals: Detecting Changes in the Ocean and Atmosphere



The trends are calculated based on annual TCF numbers, due to (a) the anthropogenic aerosol effect, (b) the anthropogenic greenhouse gas (GHG) effect, (c) natural forcing and (d) the combined effect of anthropogenic aerosol and GHG effects. The white dot shows the grid where the ensemble mean tropical cyclone frequency (TFC) trends in two experiment suites are statistically different at a 90% confidence interval based on a two-sided t-test approach. The magenta boxes highlight the coastal regions where statistically signigficant increases or decreases in TCF since 1980 are observed in TC best tracks.

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GFDL BULLETIN

IMPLEMENTATION AND EVALUATION OF A MACHINE LEARNED MESOSCALE EDDY PARAMETERIZATION INTO A NUMERICAL OCEAN CIRCULATION MODEL

JAMES/AGU *Cheng Zhang[1], Pavel Perezhogin[2], Cem Gultekin[2], Alistair Adcroft[1], Carlos Fernandez-Granda[2,3], Laure Zanna[2,3]*

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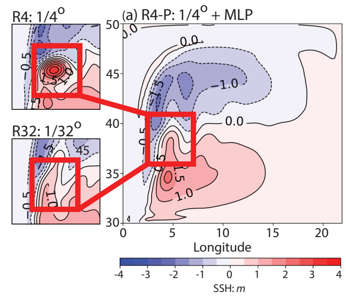
The study examines the integration of a machine-learned parameterization into a general circulation model, with a comprehensive assessment of its computational and physical performance. The focal point is a specific machine-learned parameterization (***Guillaumin and Zanna, 2021***), which undergoes evaluation within a distinct model, differing from its original testing environment. This parameterization uses a complex machine learning model, convolutional neural network (CNN), trained to improve its accuracy, allowing it to predict average values and their spread within a certain range. This specifically targets forcing by mesoscale eddies in the oceans.

Once implemented into the numerical global model MOM6, the ocean circulation model used at GFDL, the parameterization is treated comparably to a traditional one. This involves subjecting it to various flow conditions distinct from its training context, diverse spatial resolutions, and other variations, all aimed at assessing its adaptability and generalization. The findings reveal the parameterization's stability, coupled with diminishing impacts as spatial resolution increases. Nevertheless, several implementation limitations are identified. Firstly, online performance falls short of optimal; however, it is showcased that scaling the forcing from the CNN model can enhance specific metrics. *Figure 1* offers a visual comparison, presenting a five-year averaged sea surface height (SSH) and kinetic energy (KE) spectra for upper-layer flow. This spans the fine resolution model, the coarse resolution model R4, and the latter with optimal scaling of momentum forcing. Secondly, it is observed that challenges emerge concerning the parameterization's ability to predict forcing near boundaries, particularly in contrast to its performance in open ocean regions. Lastly, the computational demands of this parameterization on Central Processing Units (CPUs) for realistic global simulations are prohibitively high. Nevertheless, the transition of CNN inference to Graphics Processing Units (GPUs) proves to be a successful solution, rendering the network more computationally efficient *(Figure 2)*. The study not only identifies these limitations but also offers potential strategies to overcome them.

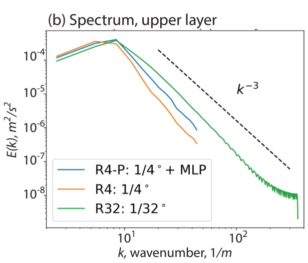
In conclusion, while this specific machine-learned parameterization successfully achieves its goals of increasing energy input and improving energy distribution, it may still benefit from further refinement before becoming a practical addition to contemporary climate models in production mode. Furthermore, this research underscores the potential of machine learning in advancing climate predictions, and highlights the importance of harnessing emerging technologies' capabilities in climate modeling and science.

OAR Goals: Make Forecasts Better and Drive Innovative Science

Model results with or without the machine-learned parameterization

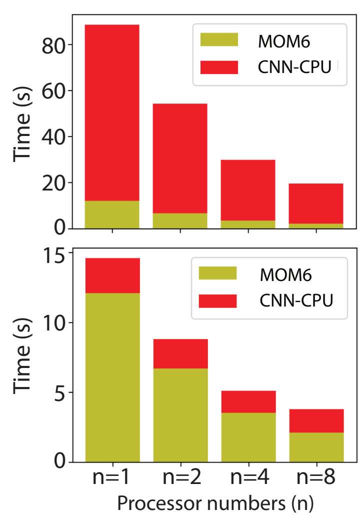


a) illustrates the comparison of five-year averaged sea surface height (SSH) around the region of the separated boundary current, as indicated by the red box.



b) displays the kinetic energy (KE) spectra for upper layer flow among different models, including the fine resolution model R32 (green line), the coarse resolution model R4 (orange line), and the coarse resolution model with optimized scaling of momentum forcing R4-P (blue line).

Cost of CNN Inference on CPU vs. GPU



Cumulative processing time of the CNN inference on CPU (upper panel) and GPU (lower panel) alongside MOM6 simulations at the coarse grid resolution with various parallel processor counts.

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SKILLFUL MULTIYEAR TO DECADAL PREDICTIONS OF SEA LEVEL IN THE NORTH ATLANTIC OCEAN AND U.S. EAST COAST

Communications Earth & Environment, a Nature journal

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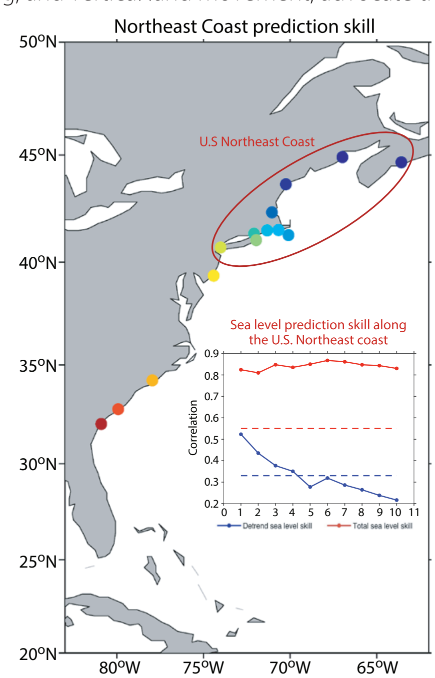
Rising sea levels, marked by long-term trends and multiyear to decadal variations, pose significant risks of flooding and erosion to coastal communities worldwide. The socioeconomic implications are especially pronounced along the densely populated U.S. East Coast, where the urgency to accurately forecast sea-level changes from seasonal to decadal scales is crucial for mitigating adverse impacts effectively. Traditionally, the focus has been on short-term predictions; however, the growing need for forecasts that extend beyond seasonal scales is evident, as it may benefit strategic planning and investment in coastal infrastructure. Building on previous research that has shown the probability of decadal predictions by leveraging insights from the Atlantic Meridional Overturning Circulation (AMOC) and the heat content of the North Atlantic's upper ocean – critical elements affecting sea-level changes – the Zhang et al. study deepens the understanding by utilizing diagnostic analysis and initiating decadal hindcasts with GFDL's Seamless System for Prediction and EArth System Research (SPEAR) model. This approach explores the predictability and projection of sea-level changes over time spans ranging from several years to decades across the North Atlantic and the U.S. East Coast. The findings reveal a basin-scale upward trend in sea level across the North Atlantic Ocean as the most predictable component, with a predictability lead time of up to a decade, primarily due to external radiative forcing. It also points to the multidecadal variability of the AMOC as another significant source of sea-level predictability. While perfect model simulations suggest a potential predictable window of 5-7 years, the realized predicitve skill is somewhat reduced to 3-5 years because of model biases and initialization uncertainties, with variations depending on the specific location. Despite these challenges, the relationship between radiative forcing and the variability of the AMOC leads to long prediction skills for sea-level changes along the U.S. East Coast. These predictive capabilities could provide substantial societal benefits for informed planning and adaptation strategies. Yet, the limitations of the SPEAR model, including its low ocean resolution and its inablilty to simulate key dynamics such as tides, land ice melting, and vertical land movement, advocate the need for further advances in prediction models that integrate these critical factors. While the primary goal of this research is to highlight the sources of predictability rather than to quantify the predictive skill, the authors strongly recommend ongoing model development. Addressing the identified gaps will lead to more accurate sea-level predicitons, which is essential for informed decision-making and effective socioeconomic management amid rising sea levels under climate change.

OAR Goals: Make Forecasts Better



Multiyear prediction skill of sea level along the U.S. Northeast

Shown are the anomaly correlations between the total (internal) U.S. Northeast Coast sea-level composite timeseries in the initialized decadal hindcasts and Tide Gauge (TG) observations as a function of lead times (years) denoted by the red (blue) line. The red and blue dash lines denote the 90% confidence level using a Monte Carlo method. To remove the effect of external radiative forcing and obtain the internal variabilities, the linear trend at each TG station is removed before analysis. In the model, the forced signal was removed from the initialized decadal hindcasts at each lead time, where the external forcing is obtained from SPEAR_LO large ensemble simulations using the signal-to-noise maximizing EOF analysis. The color dots overlapping the map denote the different locations of tide gauge stations along the U.S. East Coast. The Northeast regime comprises stations north of the New York (Halifax to Montauk stations, green and blue dots). The Mid-Atlantic regime includes the New York and Atlantic City (two stations). The Southeast regime comprises stations south of Cape Hatteras (Wilmington to Fort Pulaski stations, red and orange dots).

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GFDL's New Data DOI Policy Puts Data Producers in the Spotlight

NOAA's commitment to open data sharing has led to a significant advancement with the introduction of GFDL's policy for Digital Object Identifiers (DOIs) for GFDL data, published in late 2023. This initiative, propelled forward by leadership efforts of Lauren Koellermeier, GFDL, and Aparna Radhakrishnan, Princeton University/CIMES, aims to enhance data creditorship and accessibility by aligning with the FAIR principles—Findability, Accessibility, Interoperability, and Reusability—and adopting data citations as a key strategy. This marks a significant advancement in recognizing data producers and effectively navigating the evolving data landscape. Leveraging the GFDL data portal and partnering with the Princeton University Library, GFDL utilizes a novel framework to expeditiously assign data DOIs wherein the metadata and data are linked together, though decoupled physically. By adopting Data DOIs and embodying the FAIR principles, this initiative reflects the NOAA/GFDL dedication to actively engaging with and making meaningful contributions to the broader research and societal landscape, showcasing the collaborative spirit and exemplary efforts of the cross-divisional teams at NOAA/GFDL.

THE IMPORTANCE OF DYNAMIC IRON DEPOSITION IN PROJECTING CLIMATE CHANGE IMPACTS ON PACIFIC OCEAN BIOGEOCHEMISTRY

Geophysical Research Letters

Liz Drenkard[1], Jasmin John[2], Charlie Stock[1], Hyung-Gyu Lim[3,4], John Dunne[1], Paul Ginoux[1], Jessica Luo[1]

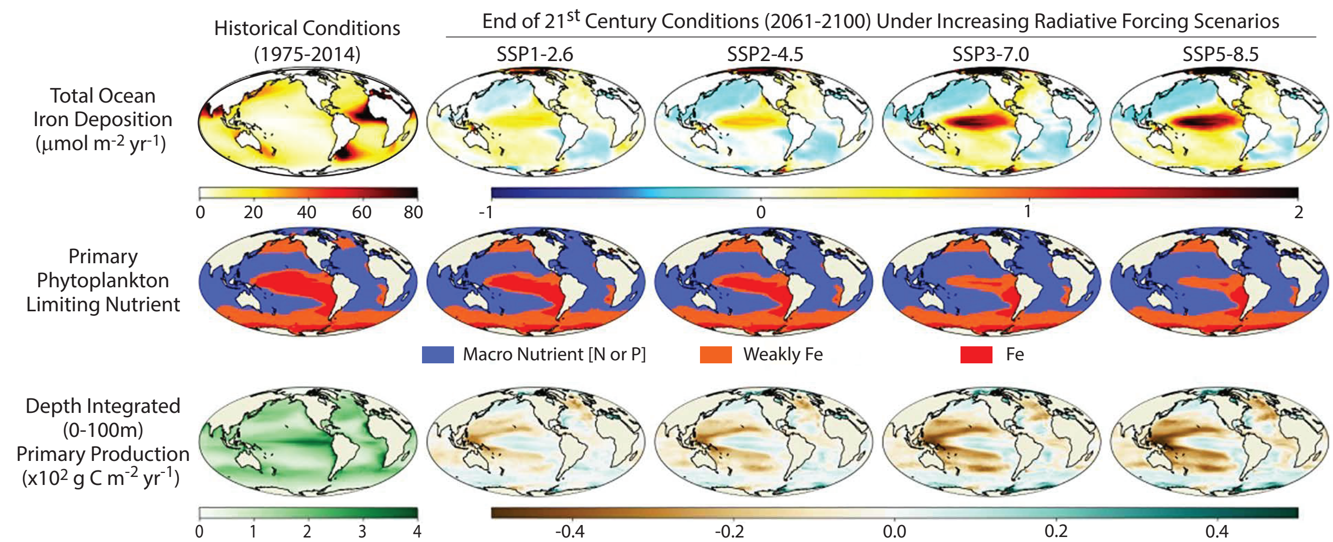
DOI: 10.1029/2022GL102058

The study of future nutrient limitations and primary production carries significant ramifications for fisheries management. By investigating a range of climate change scenarios, Drenkard et al. delve into the future of marine ecosystems, focusing on the climate-driven alterations in atmospheric dust and iron deposition to the ocean. This research aims to understand the distribution and availability of “fish food” across the oceans and to unravel the underlying drivers behind these transformations. The study employed GFDL’s Earth System Model (ESM4.1), which utilizes a dynamic approach to model iron depositon, and accounts for variations in atmospheric dust loads influenced by factors such as wind and precipitation. These elements play a crucial role in transferring dust and iron from the atmosphere to the ocean. With the progression of climate change, the model anticipates drier soil conditions, an increase in atmospheric dust and heightened precipitation over the Pacific Ocean by the end of the century. Such changes are expected to enhance iron delivery to the ocean, thereby mitigating iron limitation for phytoplankton growth in the central Pacific. However, the subsequent surge in phytoplankton production in the central and equatorial Pacific presents a double-edged sword, leading to depleted levels in the western and off-equatorial Pacific. This phenomenon stems from the depletion of other vital nutrients, a result of reduced upwelling and escalated production in the eastern Pacific. This spatial distribution also mirrors changes in carbon sinking from the surface ocean to the depths, illustrating the comprehensive impact of climate change on marine ecosystems.

The study’s findings reveal that projected increases in dust and iron depositon in the central tropical Pacific, aligned with increasing emissions and radiative forcing, correspond with decreases in soil moisture in adjacent land areas and increases in precipitation over the equatorial Pacific. The dynamic versus static dust deposition scenarios highlights the potential for enhanced primary production and particulate organic carbon flux in the central-to-eastern equatorial Pacific, contrasting with reductions off the equatorial Pacific. Such insights are crucial for forecasting and managing the future health and productivity of marine ecosystems, and emphasize the role of advanced modeling techniques in addressing the complexities of climate change impacts.

OAR Goals: Make Forecasts Better and Drive Innovative Science

Historical and Relative Changes in Dust Deposition Drivers and Ocean Biogeochemical Response Under Different Climate Change Scenarios



This image contrasts the historical mean (left) and relative change (right four columns) in ESM4.1 dynamic iron deposition scenario simulations. End-of-21st-century-plots for iron deposition and primary production show the relative change calculated as (future-historical)/historical, where a value of 0, 1, and 2 indicates no change, a doubling, and tripling of historical conditions, respectively. Conversely, −½ indicates a halving of historical conditions and −1 indicates where future conditions have gone to 0; values lower than −1 are not physically possible for these diagnostics. The future plots for primary phytoplankton limiting nutrient show the climatological (2061–2100) mean distribution of nutrient limitations.

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A HIGH-RESOLUTION PHYSICAL-BIOGEOCHEMICAL MODEL FOR MARINE RESOURCE APPLICATIONS IN THE NORTHWEST ATLANTIC (MOM6-COBALT-NWA12v1.0)

Geoscientific Model Development

A.C. Ross[1], C.A. Stock[1], A. Adcroft[5], E. Curchitser[2], R. Hallberg[1], M.J. Harrison[1], K. Hedstrom[3], N. Zadeh[1], M. Alexander[4], W. Chen[5], E.J. Drenkard[1], H. du Pontavice[5], R. Dussin[1,6], F. Gomez[7,8], J.G. John[8], D. Kang[9,2], D. Lavoie[10], L. Resplandy[11,12], A. Roobaert[13], V. Saba[14,1], S. Shin[4], S. Siedlecki[15], J. Simkins[2]

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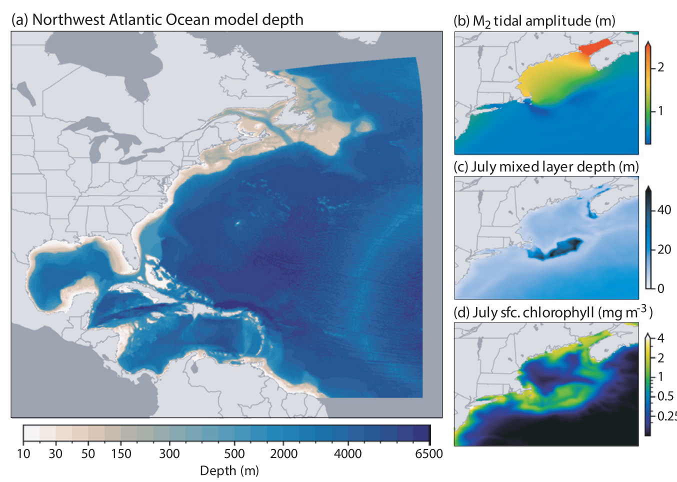
Decisions crucial for the management of marine resources hinge on accurate information about ocean and ecosystem conditions, particularly along coastlines and continental shelves. While global ocean models play a significant role in understanding these dynamics, they frequently struggle to capture fine-scale features due to their coarse horizontal resolution – a limitation necessary to use computational resources efficiently. To bridge this gap and provide more accurate and efficient insights into coastal marine ecosystems, GFDL authors, in collaboration with other NOAA laboratories and academic partners, have developed the first high resolution regional ocean model using the Modular Ocean Model version 6 (MOM6). This model boasts an impressive 1/12° resolution, equivalent to approximately 7 km, enabling detailed simulations of the ocean, sea ice and biogeochemistry across a substantial portion of the Northwest Atlantic Ocean (Figure a). The authors made substantial enhancements to the model, particularly in its ability to simulate nearshore environments. These improvements include highly accurate tide modeling and the inclusion of a specific phytoplankton group designed for better ecosystem representation. As a result, the model excels in reproducing vital ecosystem processes, such as tidally induced mixing on the shallow Georges Bank, which sustains year-round productivity (Figures b-d). The model's accuracy was rigorously evaluated by comparing a 27-year historical simulation with observations, covering various metrics essential for regional marine resource applications. The model demonstrated the capacity to simulate key regional features, including mean ocean temperature, salinity, chlorophyll, nutrient patterns, and recent temperature trends and variability in the Northeast U.S. While certain challenges persisted, particularly concerning the Gulf Stream's path – a common complexity in many ocean models – the model's overall performance is impressive. This regional model, a collaborative effort led by GFDL scientists, serves as the cornerstone of NOAA's Climate, Ecosystems, and Fisheries Initiative within the Northwest Atlantic. Ongoing endeavors involve harnessing the model's capabilities to develop high-resolution seasonal to decadal ocean ecosystem predictions and century-scale climate projections. Furthermore, the authors are leveraging this model to gain insights into and predict extreme sea level events along the U.S. East Coast, ultimately contributing to a deeper understanding of the societal impact of ocean dynamics.

OAR Goals: Make Forecasts Better, Drive Innovative Science



Investigating Tides, Mixing, and Chlorophyll in the Regional Model

(a) Ocean model depth over the full Northwest Atlantic model domain.

(b) Closeup of tidal amplitude simulated by the model along the coast from New Jersey to Maine.

(c) Closeup of average model mixed layer depth during July. Strong tides and shallow bathymetry produce deep mixing and push nutrients onto Georges Bank in the center of the figure.

(d) Closeup of July average surface chlorophyll in the model. Mixing sustains a phytoplankton bloom throughout the summer on Georges Bank.

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