SPRING, 2025

GFDL BULLETIN

Research Highlights from the Geophysical Fluid Dynamics Laboratory Community

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

Western United States wintertime precipitation response to warming: an assessment in a global storm-resolving model

SPRINGER NATURE Link *Tsung-Lin Hsieh[1], Lucas Harris[2], Kai-Yuan Cheng[1], Alexander Kaltenbaugh[2], Linjiong Zhou[1], Liwei Jia[2] & Ming Zhao[2]*

DOI: https://doi.org/10.1007/s00382-025-07651-6

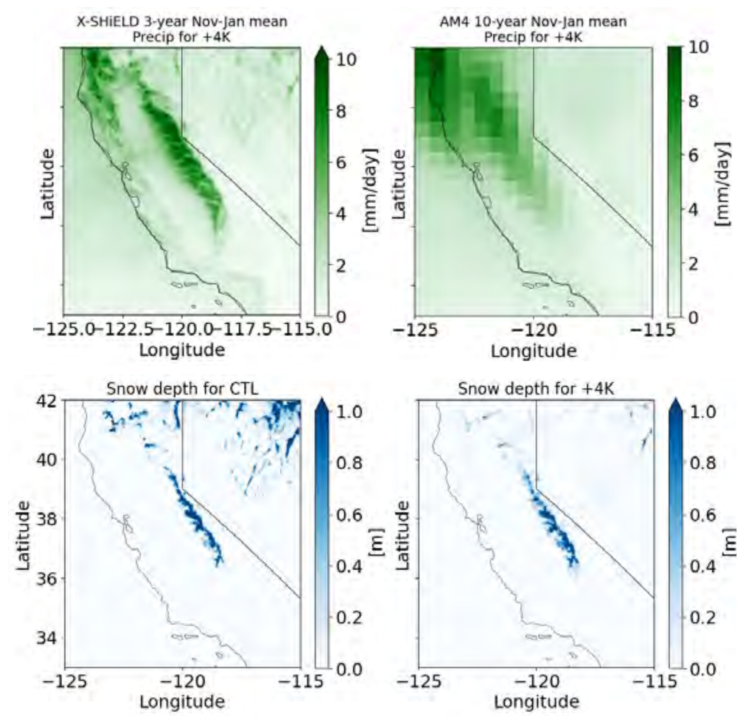
Winter snowpack in high-elevation regions is a primary source of freshwater in the Western United States. However, traditional global climate models, with horizontal grid spacings of 50 to 200 km, have limited ability to represent fine-scale mountain topography and associated precipitation processes. Regional models offer higher spatial resolution but cannot simulate interactions between localized mountain circulations and global-scale weather systems.

This study evaluates simulations from a global storm-resolving model (GSRM), the eXperimental System for High-resolution prediction on Earth-to-Local Domains (X-SHiELD). Developed at GFDL, X-SHiELD operates at global 3 km resolution allowing for the simulation of both broad atmospheric patterns and localized precipitation features. When applied to the Western U.S., the model reproduces observed precipitation distributions over complex terrain more accurately than traditional global models. In addition to present-day simulations, the study includes short-duration experiments under idealized warming conditions. These simulations show that snowpack responses vary with elevation. While mid-elevation regions experience snow loss under warmer conditions, the highest mountain areas in California retain lower temperatures sufficient for snow accumulation. The short simulation period limits the certainty in this conclusion, but results highlight elevation-dependent differences in winter precipitation phase.

The use of X-SHiELD, which uses GFDL's FV3 Dynamical Core, enables direct analysis of precipitation processes across scales within a single modeling framework. While this analysis focuses on the Western U.S., the same approach can be applied to other high-relief regions using the publicly-available X-SHiELD output. This work was supported by the Western U.S. Hydroclimate project and NOAA Research's Global-Nest Initiative.

OAR Goals: Drive Innovative Science, Make Forecasts Better

Resolution is paramount for mountain precipitation



(Top) Multi-year mean winter precipitation from the 3-km X-SHiELD simulation (left) and the 50-km AM4 simulation (right). X-SHiELD more precisely captures orographic precipitation along the Sierra Nevada, with less spillover into the Central Valley compared to AM4.

(Bottom) Simulated winter snow depth from X-SHiELD under current climate conditions (left) and in a sensitivity experiment with globally increased sea surface temperatures of +4 K (right, shown as a difference from the control). The warmed simulation indicates a near-elimination in snow accumulation at lower elevations (Nevada, Northern California), but persists in the high Sierra Nevada mountains.

[1]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA; [2]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

Toward transparency and consistency: an open-source optics parameterization for clouds and precipitation

Journal of Advances in Modeling Earth Systems *Jing Feng[1], Raymond Menzel[2], David Paynter[2]*

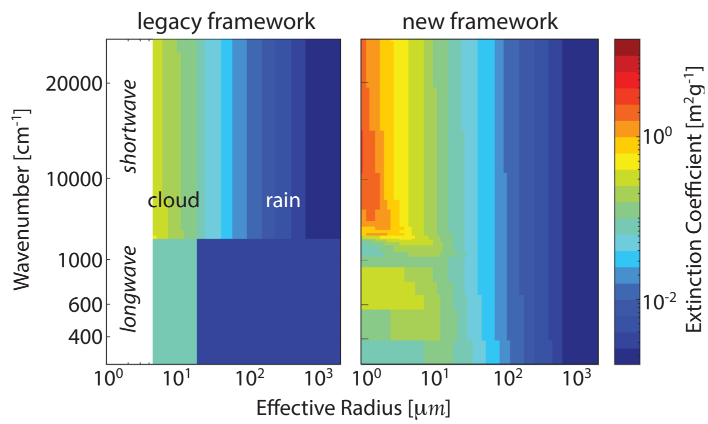
DOI: https://doi.org/10.1029/2024MS004478

Feng et al. present a unified, open-source parameterization framework designed to enhance the representation of cloud and precipitation optical properties in global atmospheric models. Existing parameterization schemes in many of the world's Earth System Models (such as those participating in the World Climate Research Program (WCRP) Coupled Model Intercomparison Project 6 (CMIP6)) were often constrained by limited accuracy and internal inconsistencies, particularly across spectral wavelengths and the broad range of hydrometeor sizes, which can compromise the fidelity of cloud and precipitation simulations in these models.

This new framework addresses these limitations by taking into account physical factors such as spectral variations in optical properties and the vast dimension in hydrometeor size ranges (i.e. from small fog droplets to large snowflakes). The scheme is designed for broad compatibility, generating cloud and precipitation optical properties in formats suitable for use in a broad range of weather, climate and Earth System Models. Its flexibility allows users to tailor optical properties to the specific particle size distributions and spectral bands required by their application. For example, it can compute properties for any desired distribution of cloud or rain droplets and for various mixtures of ice particles across the full range of electromagnetic frequencies.

The parameterization is grounded in Mie scattering computations and incorporates idealized optical properties for non-spherical ice particles. It has been demonstrated to achieve reasonable radiative closure when applied to remote sensing algorithms. It has also been evaluated using NOAA/GFDL's 'benchmark' radiation code to assess the accuracy of the solar and longwave radiation fields at the top and within the atmosphere, and at the surface. Future work is planned to examine its performance in coupled atmosphere-ocean general circulation models for the next CMIP (CMIP7).

Spectral Variation of Mass Extinction Coefficients for Liquid Cloud and Rain: Comparison Between Legacy and New Optical Parameterizations



Shown is a comparison of mass extinction coefficients ($m^2\ g^{-1}$) for liquid cloud and rain as a function of wavelength (x-axis, in microns) and effective radius (y-axis, in microns). The left panel represents a typical legacy optical parameterization used in previous generations of NOAA Earth System Models, with numerous discontinuities, while the right panel shows results from the new unified scheme developed by Feng et al. (2025) that will be used in future NOAA Earth System Models. The new parameterization incorporates a physically consistent treatment across hydrometeor sizes and spectral ranges, allowing for a smoother and more realistic transition between cloud and precipitation regimes. Color shading indicates the magnitude of the mass extinction coefficient in logarithmic scale.

By improving the accuracy and consistency of radiative transfer in the global models, this framework directly supports NOAA's objectives in enhancing forecasting capabilities and environmental modeling and monitoring across timescales. Its open-source nature facilitates the incorporation and integration into various modeling systems, promoting transparency and reproducibility in atmospheric and climate research, and Earth System science.

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

[1]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA; [2]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

John Dunne Co-Authors Highly Cited JAMES Paper

John Dunne, Supervisory Research Oceanographer and Head of GFDL's Earth System Processes and Interactions Division, co-authored a paper listed among the top 10 most cited in 2023 by the Journal of Advances in Modeling Earth Systems (JAMES), a publication of the American Geophysical Union. The paper, "*Global surface ocean acidification indicators from 1750 to 2100*," presents a framework for tracking changes in surface ocean chemistry over time, using a set of standardized indicators. The work provides data relevant to long-term observations and projections of ocean conditions. This recognition reflects ongoing contributions from GFDL scientists to peer-reviewed research across Earth system modeling and observation.

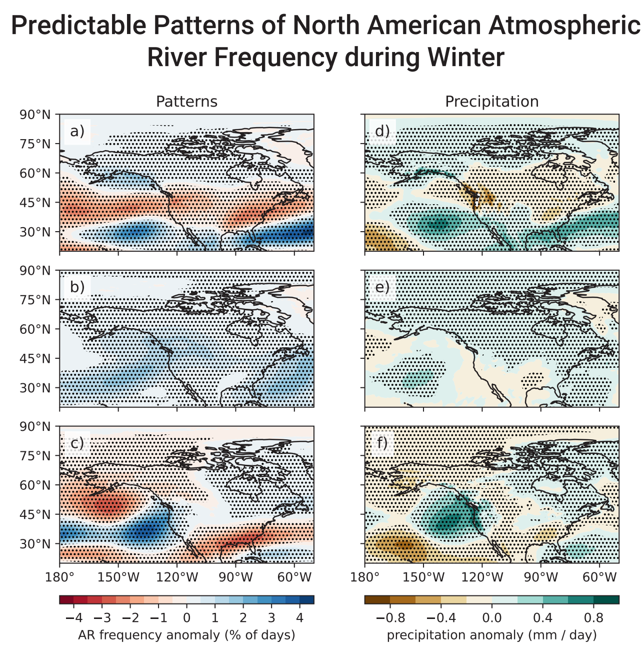
Predictable patterns of seasonal atmospheric river variability over North America during winter

Geophysical Research Letters *Joseph P. Clark[1], Nathaniel C. Johnson[2], Mingyu Park[1], Miguel Bernardez[2,3], Thomas L. Delworth[2]*

DOI: https://doi.org/10.1029/2024GL112411

Seasonal precipitation forecasts over North America remain limited in many regions, in part due to challenges in simulating and predicting key atmospheric processes. One such process is the occurrence of Atmospheric Rivers (ARs), which are narrow bands of enhanced water vapor transport that frequently contribute to winter precipitation across the midlatitudes. ARs can lead to both beneficial impacts, such as snowpack accumulation, and adverse outcomes, including flooding and landslides. As a result, understanding the drivers of AR variability and its potential predictability is relevant for improving seasonal forecast systems.

In this study, Clark et al. examine the predictability of winter AR frequency using ensemble hindcasts from GFDL's Seamless System for Prediction and Earth System Research (SPEAR) model. Previous studies have shown that SPEAR demonstrates skill in forecasting AR frequency at seasonal timescales, but the physical mechanisms underlying this skill had not been clearly established. To identify the sources of predictability, the authors apply Average Predictability Time (APT) analysis to AR frequency hindcasts. APT analysis is a statistical method for isolating patterns in a dataset that contribute most to predictability. The research reveals that three primary sources account for nearly all of the seasonal AR frequency skill in SPEAR: the El Niño–Southern Oscillation (ENSO) (figures a, d), a long-term trend component (figures b, e), and variability in convection over the western equatorial Pacific (figures c, f). These three sources are also found to contribute to seasonal precipitation skill, indicating a shared set of drivers between AR frequency and precipitation variability. The results suggest that the ability to predict AR activity may enhance precipitation outlooks over North America, particularly in regions where ARs are a dominant source of winter precipitation.



The three leading sources of predictability for seasonal wintertime atmospheric river (AR) frequency in SPEAR, identified using Average Predictability Time (APT) analysis. Panels (a–c) show the spatial patterns of anomalous AR frequency associated with each source: (a) El Niño–Southern Oscillation (ENSO), (b) a long-term trend component, and (c) convection variability over the western equatorial Pacific. Panels (d–f) show the corresponding precipitation anomalies associated with each AR pattern. Stippling indicates regions statistically significant at the 10% level, adjusted for false discovery rate. The average predictability times for these patterns—363 days (a,d), 236 days (b,e), and 183 days (c,f)—represent abstract metrics that scale with the lead times for skillful seasonal prediction.

This study provides a clearer understanding of the large-scale climate signals that underpin seasonal AR variability in SPEAR. By identifying specific sources of model skill, the work supports efforts to evaluate, interpret, and refine prediction systems at seasonal lead times. The approach may be applied in future studies to assess the role of tropical and extratropical variability in shaping winter precipitation and related extremes.

OAR Goals: Make Forecasts Better, Drive Innovative Science

[1]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA; [2]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA
[3]University Corporation for Atmospheric Research, Boulder, CO, USA

Exploring multiyear-to-decadal North Atlantic sea level predictability and prediction using machine learning

npj Climate and Atmospheric Science *Qinxue Gu[3], Liping Zhang[1,2], Liwei Jia[1], Thomas L. Delworth[1], Xiaosong Yang[1], Fanrong Zeng[1], William F. Cooke[1], Shouwei Li[3]*

DOI: https://doi.org/10.1038/s41612-024-00802-2

Understanding sea level variability on multiyear-to-decadal timescales is crucial for regions like the North Atlantic and U.S. East Coast, which have been identified as hotspots of accelerated sea level rise under present and future climates. However, the limited spatial coverage of tide gauges and the short duration of satellite observations pose challenges to capturing the full range of sea level variability at these timescales.

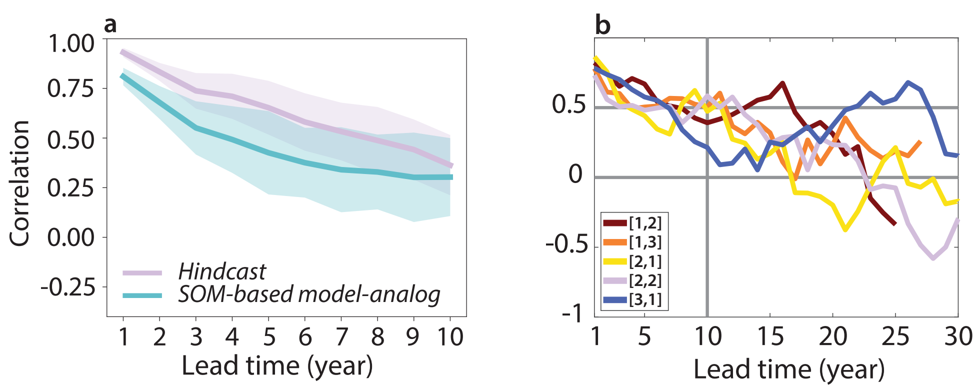
In this study, Gu et al. apply a machine learning method—self-organizing maps (SOMs)—to examine multiyear-to-decadal sea level anomaly (SLA) variability and predictability, and to conduct decadal prediction of large-scale North Atlantic SLA patterns and low-frequency coastal SLA variations. Utilizing two 5,000-year preindustrial control simulations from the Seamless System for Prediction and Earth System Research (SPEAR) model, the authors identify recurring SLA patterns and preferred transitions among them. These transitions are linked to internal climate variability, notably phases of the Atlantic Meridional Overturning Circulation (AMOC), suggesting potential for long-term predictability.

The SOM framework is combined with a model-analog method to conduct decadal predictions. This approach yields skillful predictions of large-scale SLA patterns and low-frequency coastal sea level variations, with performance comparable to that of initialized hindcasts, but achieved at a much lower computational cost. Shorter-term predictability is also identified after removing low-frequency variability. These signals arise from delayed oceanic responses to atmospheric variability, particularly those associated with the North Atlantic Oscillation (NAO), indicating the role of coupled ocean-atmosphere dynamics in modulating sea level across multiple timescales. The analysis is based on simulations with a nominal 1° ocean resolution, which limits the representation of fine-scale coastal processes. Future work with higher-resolution, long-duration simulations could further assess the sensitivity of sea level variability and predictability to model resolution.

Multiyear-to-decadal sea level variations establish a background state that modulates the impacts of shorter-term events such as tides and storm surges. The SOM-based approach provides a framework for identifying and predicting these longer-term changes, offering a data-driven, computationally efficient complement to existing modeling systems. Results contribute to broader efforts to improve sea level information on timescales relevant to coastal planning and risk management.

OAR Goals: Make Forecasts Better, Drive Innovative Science

Prediction skill assessment for North Atlantic sea level anomalies



(a) Pattern correlation between North Atlantic sea level anomaly (SLA) fields from an ocean reanalysis and those predicted using initialized decadal hindcasts and the self-organizing map (SOM)-based model-analog method, over 1–10-year lead times. The SOM method classifies SLA patterns from the model simulations into a 2D array of representative patterns, referred to as "SOM nodes" (e.g., [1,2] denotes row 1, column 2 of the SOM array). Each node corresponds to a distinct SLA pattern used to identify historical model-analogs, whose subsequent evolution is then tracked to generate the prediction. Thick solid lines represent the mean correlation across all SOM nodes; shaded areas denote one standard deviation above and below the mean, indicating notable long-lead skill of the model-analog prediction for certain initial conditions. (b) Same as (a) but for initial SOM nodes whose pattern correlation exceeds 0.5 at lead times beyond 10 years, illustrating the method's potential for extended-range prediction under favorable initial conditions, beyond the 10-year window typically covered by initialized dynamical predictions.

[1]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA; [2]University Corporation for Atmospheric Research, Boulder, CO, USA
[3]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA.

A link between U.S. East Coast sea level and North Atlantic subtropical ocean heat content

Journal of Geophysical Research: Oceans *Jacob M. Steinberg[1], Stephen M. Griffies[1,2], John P. Krasting[1], Christopher G. Piecuch[3], Andrew C. Ross[1]*

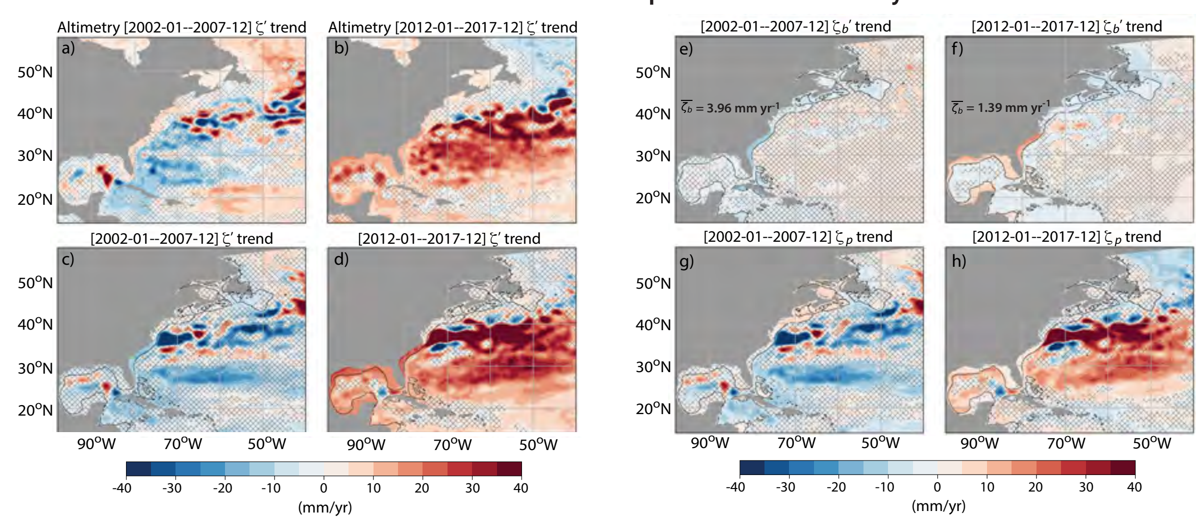
DOI: https://doi.org/10.1029/2024JC021425

Observational records of sea level along the U.S. East Coast reveal varied patterns of variability across regional and temporal scales. Recent analyses by Steinberg et al. explore the connection between these coastal sea level changes and subsurface ocean heat content within the North Atlantic subtropical gyre (a large, clockwise ocean current system in the North Atlantic). Using the high-resolution (1/12°) regional ocean model MOM6-COBALT-NWA12, a configuration of the Modular Ocean Model version 6 (MOM6) coupled with the COBALT ocean biogeochemistry model, developed by GFDL for the Northwest Atlantic (NWA) region, the authors investigate distinct patterns of variability north and south of Cape Hatteras. South of Cape Hatteras, coastal sea level variability is found to be strongly influenced by changes in the strength and structure of the subtropical gyre (large-scale ocean circulation), particularly with respect to the Gulf Stream's intensity and the latitude at which it separates from the coast. These oceanographic conditions significantly affect how heat is stored and distributed with depth in the ocean.

To better understand the connection between coastal sea level and offshore circulation features, the study uses a framework that quantifies the exchange of water between shallow coastal areas and deeper offshore regions. This analysis suggests that coastal sea level changes south of Cape Hatteras are primarily driven by a movement of water from deeper regions towards the coast, rather than by local changes in ocean density. The underlying driver of this water movement is identified as warming in the North Atlantic mode water; a relatively uniform water mass located a few hundred meters below the ocean surface. The predicted sea level changes from this simplified model align closely with both simulated and observed coastal sea level data. The relationship between offshore subsurface density variations and coastal sea level changes holds consistently across seasonal to interannual (year-to-year) timescales. Importantly, this study demonstrates that nearly half of coastal sea level variability can be explained by offshore density changes occurring below the continental shelf break. This finding highlights a stable, equilibrium-like response of the coastal ocean to changes farther offshore. Moreover, this connection extends beyond the U.S. East Coast to the Gulf of America and Caribbean Sea, linking widespread coastal regions to changes in subtropical North Atlantic heat content. By leveraging GFDL's regional and global models, the authors explore the potential to predict coastal sea levels well in advance, emphasizing the importance of ocean memory or how the persistence of subsurface ocean conditions can influence future sea level trends in understanding and forecasting coastal sea level variability.

OAR Goals: Detect Changes in the Ocean and Atmosphere, Drive Innovative Science

Six-Year North Atlantic Sea Level Trends and Decomposition from Density and Mass Contributions



The figure compares observed (a–b) and simulated (c–d) sea level trends for two recent 6-year periods: 2002–2007 (left column) and 2012–2017 (right column). These trends are further decomposed into contributions from local mass changes (e–f) and local density-driven changes (g–h), the latter primarily reflecting subsurface ocean warming (the trend values in (e–f) denote the mean rate of sea level change throughout the model domain). Comparisons highlight regional variability, including a decrease in coastal sea level south of Cape Hatteras during the early period, followed by a substantial increase during the later period. These near-coast and shelf changes align with offshore density changes, particularly in North Atlantic mode waters. The spatial patterns shown here support the mechanistic link between subsurface density variations and coastal sea level variability, as confirmed using a simplified mass redistribution model. South of Cape Hatteras, coastal sea level increases coincide with offshore subsurface ocean warming, demonstrating a non-local link to coastal impacts.

[1]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA; [2]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA
[3]Woods Hole Oceanographic Institution, Woods Hole, MA, USA.

GFDL SCIENTISTS IN THE SPOTLIGHT

NOAA/OAR/GFDL Director V. Ramaswamy Elected to National Academy of Sciences

Venkatachalam "Ram" Ramaswamy, Director of NOAA/OAR/GFDL and Lecturer with the rank of Professor in Princeton University's Department of Geosciences and Program in Atmospheric and Oceanic Sciences, has been elected to the National Academy of Sciences (NAS). He is the sixth NOAA federal employee, the fifth from OAR and the third from GFDL, to be elected to the NAS, and is currently the only NAS member within NOAA.

This honor recognizes Ramaswamy's distinguished contributions to weather and climate science and his leadership in advancing Earth System Modeling. As the Director of GFDL since 2008, he has led the development of advanced weather and climate models that have significantly enhanced the understanding of atmospheric processes and improved predictive capabilities of the Earth System across timescales. His research has provided fundamental insights into radiative interactions involving greenhouse gases, aerosols, and clouds, their effects on weather and climate processes, the heat balance of the Earth System, and the hydrological cycle.

"I am deeply honored to be elected to the National Academy of Sciences," said Ramaswamy. "I look upon this recognition as a reflection of the collaborative teamwork at GFDL, our multiple partnerships, and our shared focus on advancing the scientific knowledge of the Earth's weather and climate. I am grateful to have contributed to research that supports the understanding and prediction of the Earth System, delivering science-based developments for planning in service of the public." His election highlights a career marked by foundational research, scientific leadership, interdisciplinary collaborations, and the advancement of computational Earth System models, producing practical benefits for society and trustworthy information for real-world decision-making.

Ramaswamy holds a Bachelor's and a Master's degree in Physics and Astrophysics from the University of Delhi (India), and a Ph.D. in Atmospheric Science from the State University of New York at Albany. He was a postdoctoral Fellow in the Advanced Study Program at the National Center for Atmospheric Research, Boulder, CO, before joining NOAA/OAR/GFDL and Princeton University, Princeton, NJ.

NAS is a private, nonprofit institution established in 1863 by an Act of Congress, signed by President Abraham Lincoln. Election to membership is a recognition of distinguished and continuing achievements in original research. The NAS membership is a widely accepted mark of excellence in science and is one of the highest honors that a scientist can receive.

GFDL Scientists Contribute to One of JGR: Atmospheres' Top 10% Most-Viewed Papers in 2023

Jing Feng (Princeton University, Program in Atmospheric and Oceanic Sciences), David J. Paynter (GFDL), and Raymond Menzel (formerly GFDL) were recognized for authoring one of the Top 10% Most-Viewed Papers in Journal of Geophysical Research: Atmospheres in 2023. Their paper, "*How a Stable Greenhouse Effect on Earth Is Maintained Under Global Warming*," examines how Earth maintains energy balance as surface temperatures rise. Using a combination of global climate model diagnostics and physical theory, the study explores how radiative feedbacks and relative humidity help regulate outgoing longwave radiation. The results contribute to a deeper understanding of key processes in the Earth system and provide useful benchmarks for evaluating weather and climate model behavior over time.

Research on Greenhouse Gas Signatures Earns 2023 Top Viewed Article Recognition in GRL

Shiv P. Raghuraman (Princeton University, Program in Atmospheric and Oceanic Science), David J. Paynter (GFDL), Venkatachalam "Ram" Ramaswamy (GFDL), Raymond Menzel (formerly GFDL), and Xianglei Huang (University of Michigan, Department of Climate and Space Sciences and Engineering) have been recognized for authoring one of the Top Viewed Articles in Geophysical Research Letters for 2023. Their paper, "*Greenhouse Gas Forcing and Climate Feedback Signatures Identified in Hyperspectral Infrared Satellite Observations*," analyzes nearly two decades of data from NASA's Atmospheric Infrared Sounder (AIRS) to identify spectral signals of greenhouse gas-induced radiative forcing and climate feedbacks. The study connects observed changes in infrared radiation to increases in atmospheric greenhouse gases, providing direct observational evidence consistent with established radiative transfer theory and Earth system response. These findings offer important benchmarks for evaluating weather and climate models and contribute to efforts aimed at improving the observational foundations for long-term environmental prediction.