GFDL BULLETIN

SPRING-SUMMER 2024

Research Highlights from the Geophysical Fluid Dynamics Laboratory Community

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

The GFDL variable-resolution global chemistry-climate model for research at the nexus of US climate and air quality extremes

Journal of Advances in Modeling Earth Systems

Meiyun Lin[1], Larry W. Horowitz[1], Ming Zhao[1], Lucas Harris[1], Paul Ginoux[1], John Dunne[1], Sergey Malyshev[1], Elena Shevliakova[1] Hamza Ahsan[2], Steve Garner[1], Fabien Paulot[1], Arman Pouyaei[3], Steven J. Smith[2], Yuanyu Xie[4], Niki Zadeh[1], Linjiong Zhou[3]

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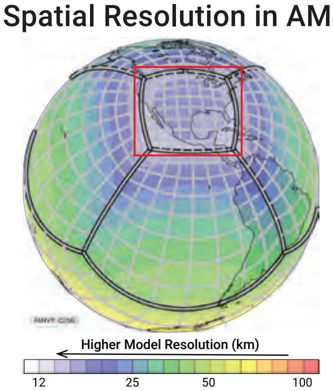
In the United States, air pollution arises from a diverse array of sources—local natural emissions, regional man-made emissions, wildfire smoke from Canada, African dust plumes, and pollution transported across continents from Asia. Addressing these complexities amidst climate change requires a seamless modeling system that not only focuses on specific regions but also incorporates global Earth system dynamics to ensure accurate forecasts. In response, a recent study by Lin et al. introduces a newly developed global chemistry-climate model based on Atmospheric Model version 4 with Variable-Resolution (AM4VR), tailored for researching the complex relationship between U.S. climate fluctuations and air quality extremes. AM4VR stands out by offering more than ten times the spatial resolution over the contiguous U.S. compared to earlier models used in the latest Intergovernmental Panel on Climate Change reports. This allows for a more accurate representation of geographical features and atmospheric phenomena, enhancing the model's ability to simulate extreme weather events like regional rainfall, droughts, haze, and wildfire smoke, which all affect air quality significantly. One of the key improvements with AM4VR is its ability to address the long-standing issue of the central U.S. dry-and-warm bias found in many previous climate models. Correcting this bias is crucial for more precise climate projections, which in turn, helps with understanding the impacts on air quality. The model effectively shows how warmer and drier conditions stress vegetation, limiting its ability to clean the air of pollutants such as ozone. By integrating physical, chemical, and biological aspects, AM4VR offers a comprehensive view of how global climate changes influence U.S. air quality conditions. This capability is essential for improving air quality forecasts, which can inform public safety measures, transportation decisions, and agricultural practices, thereby enhancing the ability to adapt to and mitigate the impacts of climate and air quality extremes. With the development of AM4VR, the authors have created an advance variable-resolution global chemistry-climate model that deepens the understanding of the dynamic relationship between climate change and air quality, thus improving predictions and helping safeguard public health and the environment.

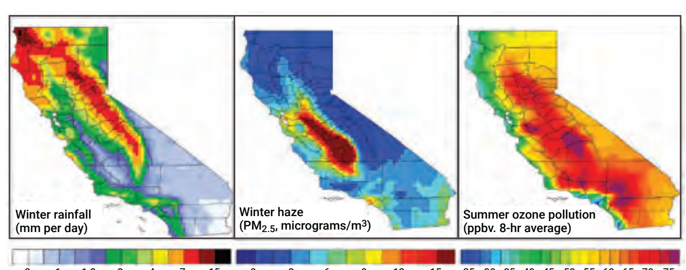
OAR Goals: Make Forecasts Better

Enhanced Spatial Resolution in AM4VR Model



AM4VR model integrates advancements in physics, chemistry and land-atmosphere interactions into a cohesive variable-resolution framework. It achieves a detailed 13-kilometer spatial resolution across the contiguous United States, depicted in blue on the map, facilitating precise regional climate and air quality simulations.

Detailed Climate and Air Quality Modeling for California



The AM4VR model showcases enhanced modeling of rainfall, drought, and pollution extremes across various U.S. air basins, including California illustrated on this figure. This improved representation aids in understanding and predicting localized climate impacts more accurately.

[1]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ; [2]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD
[3]Cooperative Institute for Modeling the Earth System, Princeton University, Princeton, NJ; [4]Princeton School of Public and International Affairs, Princeton University, Princeton, NJ

Greenhouse gas forcing and climate feedback signatures identified in hyperspectral infrared satellite observations

Geophysical Research Letters

[1]Shiv Priyam Raghuraman, [2]David Paynter, [1,2]V. Ramaswamy, [2,3]Raymond Menzel, [4]Xianglei Huang

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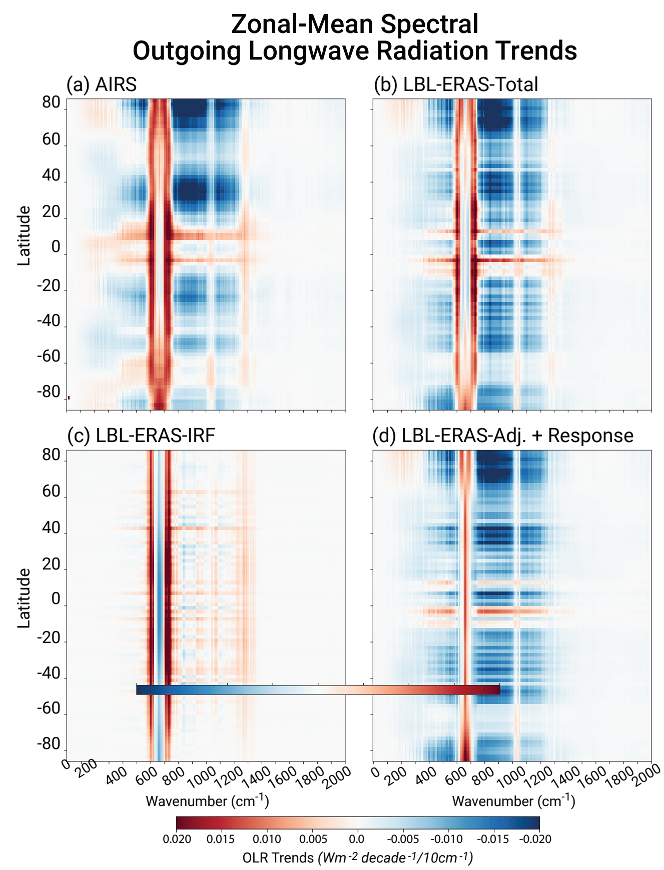
Greenhouse gas forcing from human activities traps heat and drives global warming, a process amplified and damped by various feedback mechanisms within the climate system. Although these factors are primary causes of climate change, direct observations of global greenhouse gas forcing and feedbacks have been limited due to irregular, uncalibrated, or limited measurements. Understanding the thermal spectrum at different wavelengths is important for distinguishing signals from forcings and feedbacks, but this has been challenging. However, the Atmospheric Infrared Sounder (AIRS) instrument on NASA's Aqua Satellite has provided this precise data from 2003 to 2021, offering a breakthrough in the ability to monitor and analyze these critical climate processes. Leveraging this data, Raghuraman et al. have advanced the analysis of the thermal signatures of greenhouse gases to directly observe global greenhouse gas forcing and feedbacks, which are essential components of climate change. GFDL's Line-by-Line Radiative Transfer Code (LBL-GRTCode) is used to calculate the Earth's infrared thermal spectrum resulting from changes in greenhouse gases such as H_2O, CO_2, CH_4, and N_2O. These calculations use data from ECMWF Reanalysis version 5 (ERA5) and climate simulations from GFDL's Atmospheric Model version 3 (AM3) and Atmospheric Model version 4 (AM4). The authors found consistency between the observed data and model predictions. This alignment validates the accuracy of climate models in simulating real-world conditions and reinforces our understanding of climate physics. The key findings include the direct identification of the signature of increased forcing by greenhouse gases and the feedbacks associated with global warming in long-term thermal wavelength satellite measurements. In particular, the research shows that increases in greenhouse gas concentrations have led to observable increases in heat trapped at specific wavelengths associated with these gases. The climate responded with stratospheric cooling, surface and tropospheric warming, as shown by the emission of extra heat to space via wavelengths associated with H_2O absorption bands and transparent sections of the infrared spectrum. Therefore, these spectral trends confirm three fundamental principles of climate change physics: an increasing greenhouse effect, stratospheric cooling, and surface-tropospheric warming. While previous studies have simulated past and future changes in the infrared spectrum due to increases in greenhouse gas forcing, this study demonstrates that observed changes occurring over the 2003-2021 period are highly consistent with the best estimates from climate models and reanalysis data. This framework allows for the determination of global, time-varying, spectrally resolved forcing and feedbacks. The study notes some differences between the trends predicted by AIRS measurements and the calculations, primarily due to issues with ozone in the ERA5 data and discrepancies in cloud observations. Despite these uncertainties, the findings of this research are highly relevant, as observing climate change from space by monitoring changes in the energy entering and leaving Earth provides critical insights that align with theoretical predictions of climate change.



(a) AIRS satellite observations. (b) Simulation using ERA5 atmospheric conditions and GFDL's LBL-GRTCode radiation model.
(c) Simulation showing only the instantaneous radiative forcing.
(d) Simulation showing stratospheric and tropospheric adjustments along with the radiative response.
Note that (c) and (d) together correspond to (b).

OAR Goals: Detect Changes in the Ocean and Atmosphere

[1]Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
[2]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ
[3]University Corporation for Atmospheric Research, Princeton, NJ
[4]Department of Climate & Space Sciences & Engineering, University of Michigan, Ann Arbor, MI

GFDL Study Ranks Among Top 10 Most-Cited Papers by JGR: Ocean

A GFDL study, *"Importance of the Antarctic Slope Current in the Southern Ocean Response to Ice Sheet Melt and Wind Stress Change,"* published in the Journal of Geophysical Research: Oceans, has been honored as one of the top ten most-cited articles last year. Led by a former GFDL Climate and Global Change Postdoctoral Fellow and involving multiple co-authors from GFDL and Princeton University, this research provides important insights into ocean climate dynamics.

Changes in United States summer temperatures revealed by explainable neural networks

Earth's Future

[1]Zachary M. Labe, [2]Nathaniel C. Johnson, [2]Thomas L. Delworth

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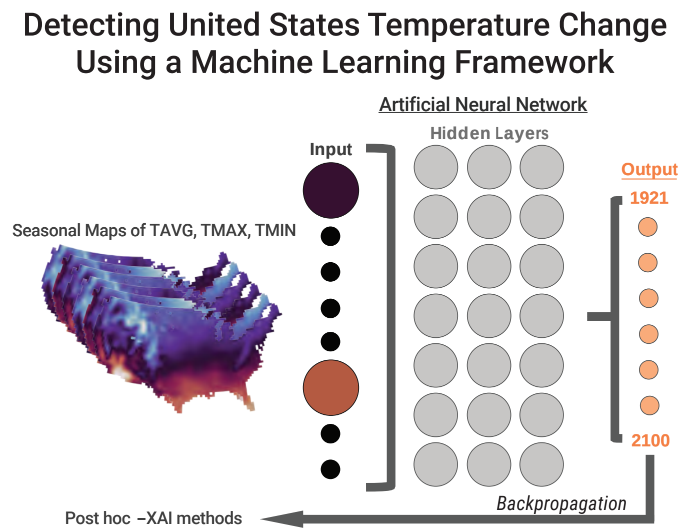
In understanding and preparing for the impacts of extreme weather events like summertime heatwaves, it is essential to account for both natural climate variability and long-term climate warming. However, detecting and attributing changes in summer heat across the United States faces a significant challenge due to the relatively short observational record. To tackle this issue, Labe et al. leveraged an innovative explainable artificial intelligence (XAI) approach, utilizing neural networks to analyze extensive datasets from climate models, including GFDL's Seamless System for Prediction and Earth System Research (SPEAR) and Forecast-Oriented Low Ocean Resolution (FLOR) models. This XAI framework used maps of mean summer minimum, maximum, or average temperatures to estimate the 'timing of emergence' of regional climate change throughout the contiguous U.S. The timing of emergence metric identifies the specific year for when temperature changes exceed historical natural variability, providing valuable insights for decision-makers involved in infrastructure planning, adaptation, and mitigation. Unlike previous methods, this new approach does not rely on point-by-point statistics at an individual location. Instead, the neural networks identify time-evolving climate signals across entire maps, accounting for nonlinear information and variations in background climate conditions. The study also applies explainability techniques to enhance the transparency and reliability of machine learning predictions.



This diagram outlines the artificial neural network (ANN) framework utilized to analyze maps of June to August surface air temperatures over the contiguous United States. The ANN processes these inputs to determine the likelihood that a map is classified as a single year from 1921-2100, yielding the final output. To associate each mean summer average temperature (TAVG), mean minimum temperature (TMIN), and mean maximum temperature (TMAX) map with its correct year, the ANN needs to learn time-evolving patterns of climate change amidst the noise of internal variability. The ANN architecture adapts with the horizontal resolution of the training data, incorporating various combinations of hidden layers and nodes optimized for accuracy. Afterward, explainable artificial intelligence (XAI) methods are applied to identify the key locations of climate change signals that are influencing each of the ANN's predictions by backpropagating the output through the ANN.

The findings reveal a clear shift in average minimum temperatures across the U.S., surpassing the known range of natural variability in observational records since the early 2000s. The SPEAR model forecasts an even earlier emergence of this signal, particularly in regions with higher terrain and notable land surface changes. Furthermore, the study highlights that higher resolution climate model data improves the accuracy of neural network predictions, emphasizing the importance of data size and resolution in future climate research. The authors suggest that future research which applies machine learning to climate data should carefully consider the sensitivity of their results to the size and resolution of their training data. Overall, this framework demonstrates the potential of machine learning to integrate insights from models and observations, setting a path for future advancements in climate model development and evaluation.

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

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

Cindy Wang Receives AGU and AMS Awards

Cindy Wang, a graduate student in the Atmospheric and Oceanic Sciences (AOS) program at Princeton University, which is part of the Cooperative Institute for Modeling the Earth System (CIMES) in collaboration with GFDL, has been honored with two prestigious awards for her outstanding contributions to research in Earth Science and for her ability to effectively communicate it. She received the Outstanding Student Presentation Award (OSPA) at the American Geophysical Union (AGU) 2023 Meeting and the Best Student Presentation and Poster Award from the American Meteorological Society in the 16th Symposium on Aerosol Cloud Climate Interactions for her research on "The Nonlocal Effects and Radiative Feedbacks of Sea Salt Aerosol Engineering in the GFDL Coupled Model." This work has been part of Cindy's academic pursuit of understanding aerosol-climate interactions.

Improvements in September Arctic sea ice predictions via assimilation of summer CryoSat-2 sea ice thickness observations

Geophysical Nature Letters

[1,2]Yong-Fei Zhang, [2]Mitchell Bushuk, [2]Michael Winton, [2]Bill Hurlin, [1,2]William Gregory, [3]Jack Landy, [2,4]Liwei Jia

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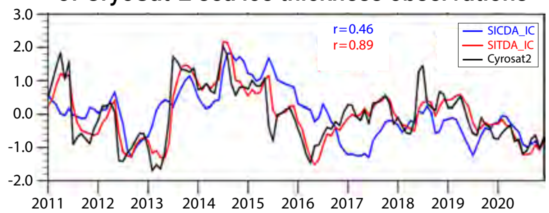
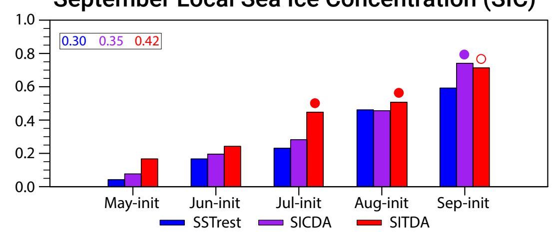
The rapid decline of Arctic Sea ice, particularly during summer months, remains a critical concern in climate research. Accurate predictions are essential for protecting local communities, preserving ecosystems, and managing economic activities in the Arctic. However, forecasting summer sea ice has been historically challenging, especially due to the spring predictability barrier. This barrier significantly reduces prediction accuracy for summer Arctic Sea ice initialized before June 1st, highlighting the need to integrate post-June initial conditions with sea ice thickness (SIT) observations. The scarcity of SIT observations during the melt season has long hindered efforts to establish more realistic sea ice initial conditions. Addressing this challenge, Zhang et al. utilized CryoSat-2's year-round sea ice thickness (SIT) observations spanning from 2011 to 2020. These observations provide crucial data to enhance initial conditions in sea ice models, especially during the historically data-limited melt season. By assimilating CryoSat-2 SIT data into GFDL's ocean-sea ice model, the authors significantly improved the model's representation of sea ice thickness anomalies, particularly in the Central Arctic. This improvement played a key role in refining summer sea ice predictions. Reforecast experiments using initial conditions with and without SIT data assimilation demonstrated notable improvements in September sea ice concentration (SIC) and extent forecasts. The impact was comparable to assimilating sea ice concentration data alone. While most regional forecasts benefited from SIT assimilation, the Chukchi Sea region saw degraded forecasts. This was attributed to negative correlations introduced between September SIC and earlier SIT, contrasting with increased correlations observed in other regions. These findings show the critical role of SIT observations in advancing seasonal Arctic Sea ice predictions. Integrating year-round SIT data enhances forecast accuracy, which is essential as the Arctic faces profound climatic shifts. However, the regional variability in forecast improvements highlights the complexity of sea ice dynamics, warranting further investigation. By integrating advanced observational data with dynamic climate models, the authors continue to establish more reliable predictions of Arctic Sea ice. This progress is vital in mitigating climate change impacts on vulnerable Arctic environments.

The pan-Arctic sea ice volume anomalies are improved by the data assimilation of CryoSat-2 sea ice thickness observations



The time series of sea ice volume anomalies (units: 10^3 km^3): the blue line represents the DA experiment assimilating sea ice concentration (SIC) observations only (SICDA_IC), the red line represents the DA experiment assimilating both SIC and sea ice thickness (SIT) observations (SITDA_IC), and the black line represents CryoSat-2 observations. The symbol "ρ" in the figure denotes the correlation coefficient between the model (colored lines) and the observations (black line).

Impact of May–August SIT Assimilation on September Local Sea Ice Concentration (SIC)



The September-mean pan-Arctic averaged Arctic Climate Change (ACC) of local sea ice concentration (SIC) from May–August initialized reforecast experiments. Blue bars represent the SSTrest experiment without any sea ice observations assimilated, purple bars represent SICDA with only SIC assimilated, and red bars represent SITDA with both SIC and SIT assimilated. The numbers indicate the mean ACC across all initialization months for SSTrest (blue),SICDA purple), and SITDA (red). The purple dot indicates that SICDA is significantly better than SSTrest, while the red dot/circle indicates that SITDA is significantly better/worse than SICDA. The ACC of SIC does not have a unit.

OAR Goals: Make Forecasts Better

[1]Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
[2]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ
[3]Centre for Integrated Remote Sensing and Forecasting for Arctic Operations, Department of Physics and Technology, UiT The Arctic University of Norway, Tromsø, Norway
[4]University Corporation for Atmospheric Research, Boulder, CO

Chris Milly Elected to National Academy of Engineering

Dr. P.C.D. (Chris) Milly, who served as a Research Hydrologist at GFDL since 1988 through a NOAA-United States Geological Survey (USGS) Memorandum of Understanding and currently a Scientist Emeritus with the U.S. Geological Survey (USGS), has been elected to the National Academy of Engineering (NAE) for "advances in the understanding of global and continental hydrology and their interactions with a changing climate." This prestigious recognition places Dr. Milly among 114 new members elected this year for their contributions to engineering research, practice, or education.

Dr. Milly's seminal work in hydrology and climate science, particularly his research on the impacts of climate change on freshwater availability, has significantly advanced the integration of hydrological processes into global climate models, improving predictions of droughts and floods. His leadership in developing the land hydrology component of GFDL's climate models has been vital to the contributions being made to the Inter-governmental Panel on Climate Change Assessment Reports and have helped in shaping global water resource management policies.

Enhanced future vegetation growth with elevated carbon dioxide concentrations could increase fire activity

Communication *Earth & Environment*

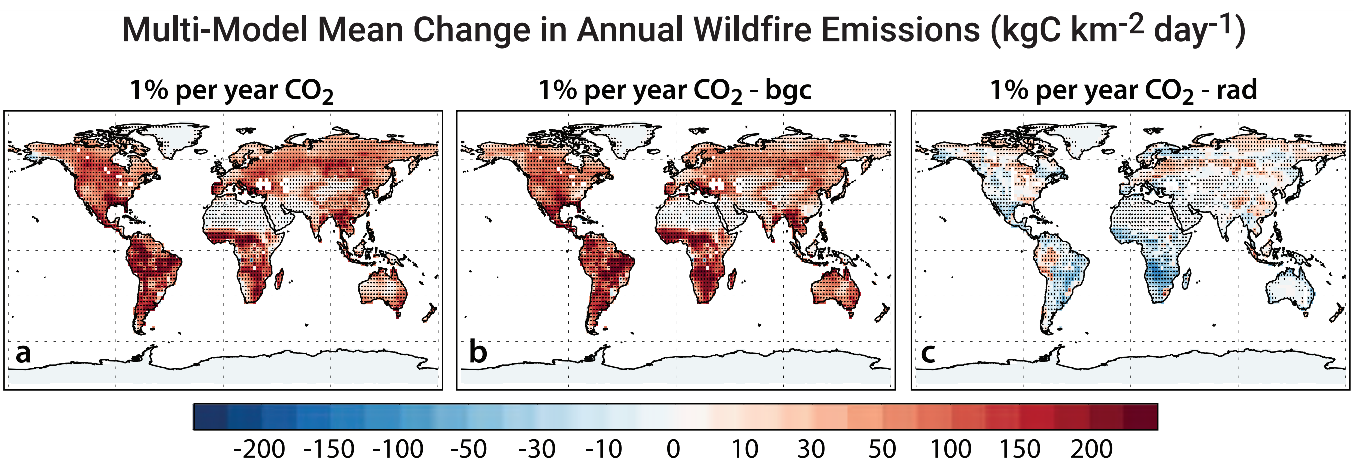
[1]Robert J. Allen, [1]James Gomez, [2]Larry W. Horowitz and [2]Elena Shevliakova

DOI:10.1038/s43247-024-01228-7

Recent decades have seen a significant increase in wildfire activity worldwide. Traditionally, this surge has been attributed to the hotter, drier conditions brought on by climate change. However, a study by Allen et al. finds that the fertilizing effect of rising carbon dioxide (CO_2) levels on plants may play a more substantial role in driving this trend. The authors used GFDL's Earth System Model and six other global Earth system models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). By simulating an idealized 1% annual increase in atmospheric CO_2 concentrations from pre-industrial levels, the study isolated the effects of CO_2 on wildfire activity, excluding other climate change drivers and wildfire influences such as land use. This approach allowed the authors to focus on how CO_2 specifically impacts fire activity through two pathways: its warming effect on climate and its fertilizing effect on plant growth. The study found that while climate warming contributes to more frequent and severe heat waves and droughts, the CO_2 fertilization effect, which enhances plant growth and net primary productivity, provides additional biomass fuel for wildfires. This increase in fuel load, rather than the hot, dry, and windy conditions often associated with wildfires, is the primary driver of the rise in fire occurrences. Additional findings revealed that a doubling of CO_2 concentrations results in an average increase in fire carbon emissions by 66.4%, with most of this increase (+60.1%) attributed to enhanced vegetation growth due to CO_2 biogeochemical effects. In contrast, CO_2 radiative effects, including warming and drying, contributed only to a negligible +1.7% increase in fire carbon emissions.

This research brings to light the importance of considering both ecological and human factors in policy efforts to mitigate fire risks. However, the authors caution that proposed "natural climate solutions," such as initiatives to enhance carbon sequestration in forests, must account for the potential counteracting effects of increased wildfire activity. These efforts aim to bolster the world's carbon sinks but must not overlook the risk of releasing stored carbon back into the atmosphere, potentially diminishing the overall benefit. It also provides valuable insights into the complex relationship between CO_2 levels, vegetation growth, and wildfire activity. By highlighting the significant role of the CO_2 fertilization effect, the study paves the way for more informed and effective climate policies that can better address the challenges posed by increasing wildfire risks in a changing world.

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



The increase in fire emissions resulting (in years 100–140) from increased atmospheric CO_2 (left), from the fertilization effects of CO_2 (center), and from the radiative (climate) effect of CO_2 alone (right).

[1]Department of Earth and Planetary Sciences, University of California Riverside, Riverside, CA; [2]NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ

GFDL BULLETIN

Spring-Summer 2024 • Page 6

Linking global terrestrial and ocean biogeochemistry with process-based, coupled freshwater algae-nutrient-solid dynamics in LM3-FANSY v1.0

Geoscientific Model Development

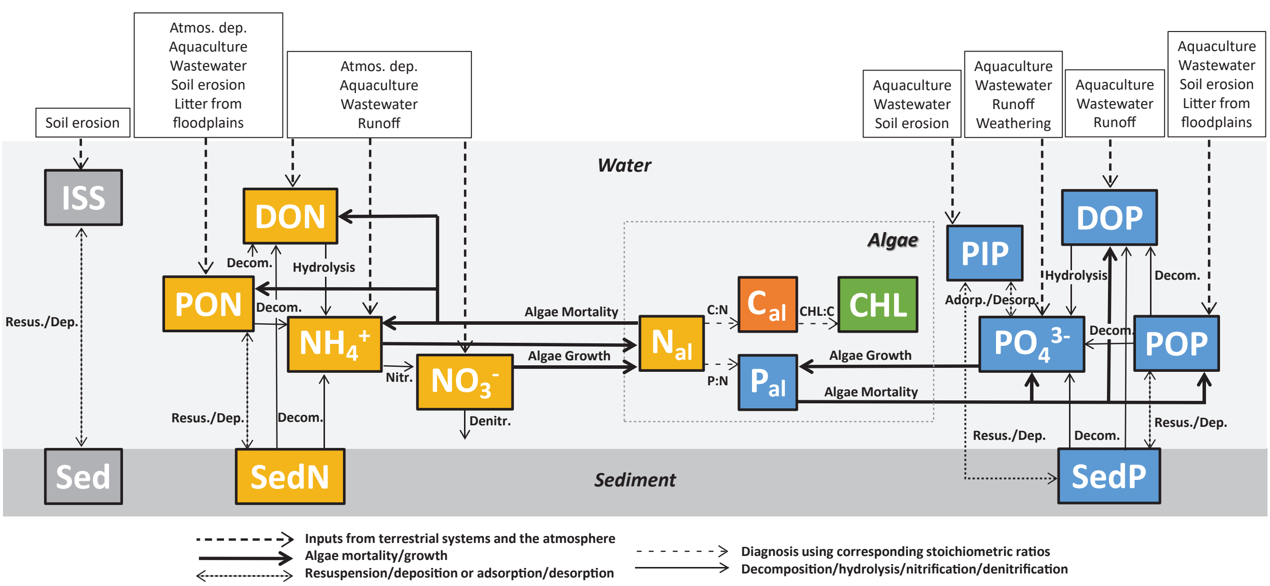
[1]Minjin Lee, [2]Charles A. Stock, [2]John P. Dunne, and [2]Elena Shevliakova

DOI:10.5194/gmd-2022-236

Estimating global river solids, nitrogen (N), and phosphorus (P) is crucial for understanding and addressing coastal hypoxic events, harmful algal blooms (HABs), and other water quality issues that significantly impact society and the economy. Traditional global watershed models often fail to mechanistically resolve these complex interactions. To address this gap, GFDL has developed a global, spatially explicit, process-based Freshwater Algae, Nutrient, and Solid cycling and Yields (FANSY) model, and integrated it within the Land Model LM3, resulting in LM3-FANSY v1.0, which captures interactions between algae, N, P, and solids in rivers and lakes with high spatial and temporal resolution. The model's simulations of suspended solids, N, and P in various forms (particulate/dissolved, organic/inorganic) align well with measurement-based estimates across major global rivers, demonstrating comparable accuracy to other leading models. Additionally, LM3-FANSY effectively simulates global river loads of these materials to the coastal ocean, with distributions and magnitudes consistent with published ranges. While LM3-FANSY successfully captures significant cross-watershed contrasts at a global scale, improvements in nutrient source estimates, refined freshwater dynamics, and enhanced observational data can improve individual river predictions. The time series analysis reveals that simulated suspended solids and nitrogen loads correlate closely with measurement-based data, although the model's ability to represent interannual variability of phosphorus loads is currently limited by the exclusion of terrestrial phosphorus dynamics in LM3. Future enhancements of the LM3-FANSY model will focus on integrating terrestrial phosphorus dynamics, freshwater carbon and alkalinity dynamics, and anthropogenic hydraulic controls. The development of LM3-FANSY marks an important advancement towards a more integrated understanding of terrestrial and ocean biogeochemistry. This model provides a robust tool for understanding the complex dynamics of algae, nutrients, and solids in freshwater systems, facilitating more accurate predictions of coastal and marine ecosystem responses. These advancements will contribute significantly to the improved management and mitigation of water quality issues impacting both the environment and human societies.

OAR Goal: Make Forecasts Better

Structure of Freshwater Algae, Nutrient, and Solid Cycling and Yields (FANSY)



Freshwater Algae, Nutrient, and Solid cycling and Yields (FANSY) model encompasses 13 prognostic state variables: inorganic suspended solids (ISS), benthic sediment inorganic solids (Sed), algae nitrogen (N_{al}), ammonium nitrogen (NH_4^+), nitrate nitrogen (NO_3^-), phosphate phosphorus (PO_4^{3-}), particulate organic nitrogen (PON), benthic sediment nitrogen (SedN), dissolved organic nitrogen (DON), particulate organic phosphorus (POP), benthic sediment phosphorus (SedP), dissolved organic phosphorus (DOP), and particulate inorganic phosphorus (PIP). Additionally, it includes 5 diagnostic state variables: particulate organic matter (POM), suspended solids (SS), algae phosphorus (P_{al}), algae carbon (C_{al}), and chlorophyll a (CHL). The arrows in the figure illustrate the fluxes of algae, nutrients, and solids within rivers and lakes.

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