Seasonal to Decadal Variability and Predictability

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Q2: Concerning NOAA's key mission element of understanding, predicting, and projecting changes in the Earth System, how can GFDL drive further advances in these areas, including extremes and environmental hazards, through scientific innovation based on observations, theory, and modeling? Where are the strengths, gaps, and new frontiers?

NOAA GEOPHYSICAL FLUID DYNAMICS LABORATORY

5-YEAR REVIEW
JANUARY 28-30, 2025

GFDL is advancing the science and application of seasonal-to-decadal predictions and projections.

Quality:

- Promoting global, seamless climate prediction and projection from seasonal to centennial timescales with SPEAR
- Advancing the science of prediction and projection of regional climate extremes

Relevance:

- Directly addressing the four NOAA Research societal challenges
- Developing or enhancing experimental methodologies and products that reach a broadening range of stakeholders

Text in blue boxes represents actions that address a 2019 GFDL Review comment.

Performance:

- Real-time seasonal and decadal forecasts delivered routinely
- Synergistic collaborations consistently delivering high-impact science

Selected publications from 2020 to 2024 -> [Link]

Providing real-time seasonal predictions with SPEAR

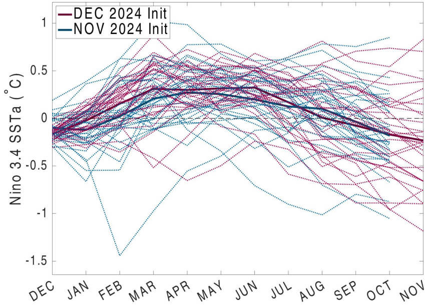
- GFDL provides real-time seasonal predictions to NCEP each month through our participation in the North American Multi-Model Ensemble (NMME).

R3: Be ready to reach out to outside entities
R5: Define appropriate scope toward model development

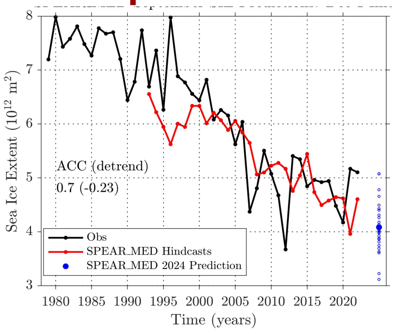
- **Relevance**: Provides actionable guidance for NOAA's climate monitoring and seasonal outlooks
- **Quality**: Provides the community with a unique set of tools for seamless prediction and projection through the combination of retrospective and real-time seasonal forecasts with free-running SPEAR large ensembles
- **Performance**: Reliably delivered each month with demonstrated high skill for societally relevant phenomena

SPEAR Predictions (1 Dec 24 Init)

ENSO



Sep Arctic SIE



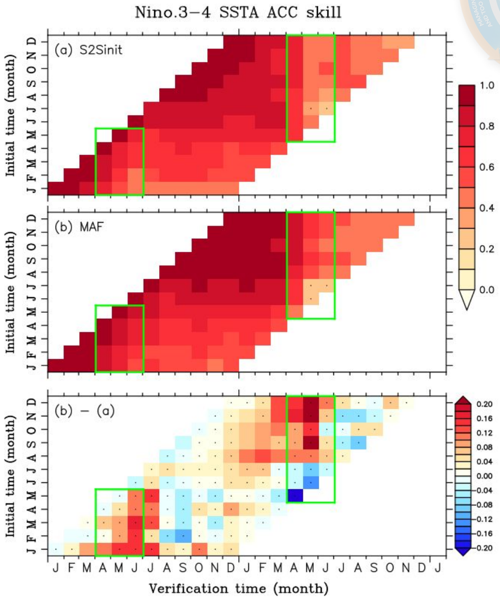
Examples of SPEAR seasonal forecast outputs from the 1 Dec 2024 initialization. (**Top**) 12-month ENSO (Niño-3.4 SSTA index) forecast, including the previous month's forecast. (Solid lines for ensemble means and dotted lines for individual ensemble members.) (**Bottom**) September Arctic sea ice extent forecast (blue) with observations (black) and hindcasts (red).

Innovative approaches for improving simulations and reducing forecast biases

- An innovative **ocean tendency adjustment (OTA)** minimizes ocean biases and climatological drift in seasonal forecasts.

> *R6: Incorporate existing observational data toward GFDL model improvement*

- **Flux-adjustment** (surface heat, salt, and momentum) used as another approach for reducing tropical ocean and global wind biases while also providing a tool for diagnosing sources of biases.
- **Model-analog seasonal forecasts** being developed as a complementary prediction approach that (1) has low computational cost, (2) provides superior forecast skill under some conditions, and (3) makes forecast skill a feasible model-development metric.



Forecast skill (ACC) of the (a) standard and (b) model-analog SPEAR hindcasts of ENSO (Niño-3.4 SSTA index) over the 1991-2022 period. The ACC differences (c) indicate several seasons with superior model-analog forecast performance (warm colors). From Zeng et al. (in prep.).

Expanding the frontiers of seasonal extreme temperature prediction

- SPEAR seasonal predictions demonstrate the potential to predict extreme temperature frequency up to 9 months in advance (Jia et al. 2022, 2023, 2024).

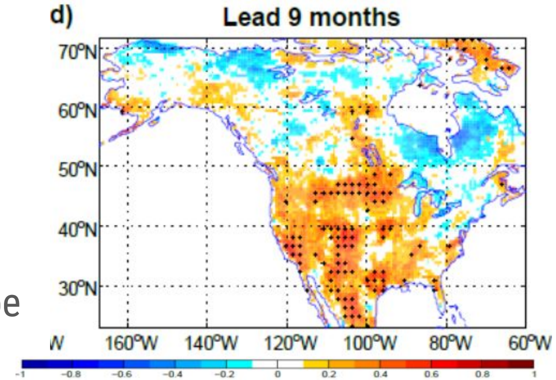
Jia et al. (2022) highlighted in *Nature*

- SPEAR seasonal predictions are being applied to a prototype system for real-time U.S. extreme heat attribution (Barsugli et al. 2022; Schreck et al 2024).

R4: Increase engagement with other NOAA efforts

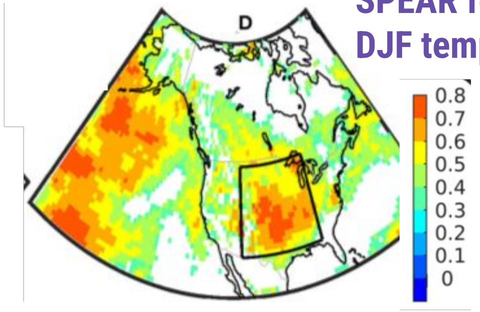
- Broadening the view of extremes: Novel demonstration that wintertime subseasonal “temperature swings” more predictable than seasonal mean temperature over much of CONUS (Yang et al. 2022).

SPEAR forecast skill of JJA heat extremes



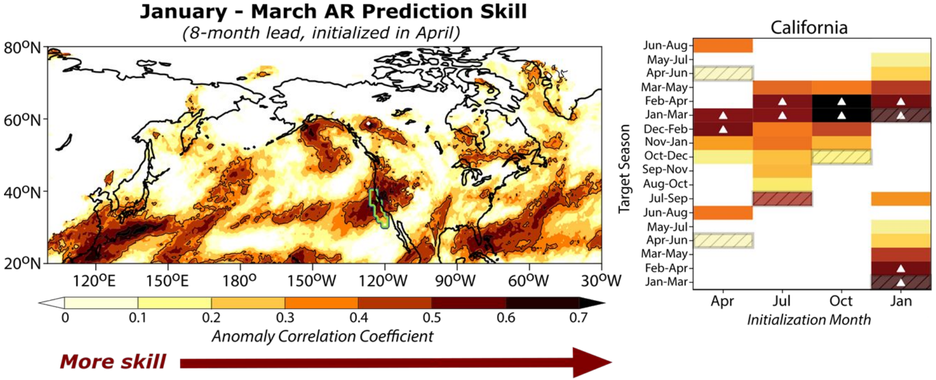
Forecast skill (ACC) of summertime extreme heat occurrences in SPEAR at a lead of 9 months. Stippling indicates statistically significant skill. From Jia et al. (2022).

SPEAR forecast skill of DJF temperature swings



Forecast skill (ACC) of wintertime temperature swings in SPEAR for a 1 Dec initialization. From Yang et al. (2022).

Advancing our ability to anticipate too little or too much water through atmospheric river predictability research



(**Left**) SPEAR forecast skill (ACC) of Jan - Mar atmospheric river (AR) frequency at a lead of 8 months. (**Right**) AR frequency forecast skill over coastal California as a function of initialization month (x-axis) and target season (y-axis). Triangles indicate statistically significant skill. From Tseng et al. (2021).

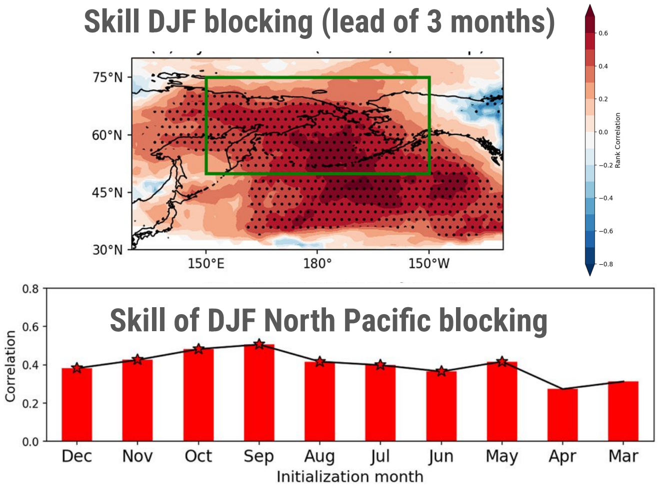
R4: Increase engagement with other NOAA efforts

- Seasonal atmospheric river activity can be predicted with skill to 9 months over western North America in SPEAR (Tseng et al. 2021; Clark et al., in revision).
- This capability is being transitioned to the National Weather Service as a tool for operational forecast guidance through a project funded through the Weather Program Office.

Accelerating progress in the seasonal prediction of high-impact extreme weather

Additional studies demonstrating skillful seasonal predictions with SPEAR that have the potential to advance early warning systems for extreme weather:

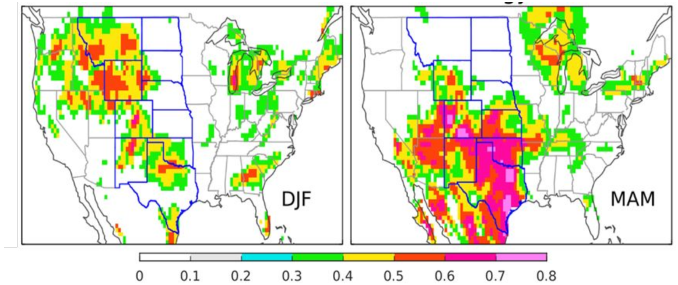
- Seasonal **tropical cyclone** predictions on regional scales (Murakami et al., under revision)
- North Pacific **atmospheric blocking** (Park et al. 2024)
- Springtime CONUS **tornado activity** (Tseng et al., in prep.)
- Summertime East/Japan Sea surface temperature, including **marine heatwaves** (Joh et al. 2024)



(**Top**) Dec - Feb atmospheric blocking skill (rank correlation) at a lead of 3 months from a hybrid dynamical-statistical model with SPEAR. (**Bottom**) North Pacific blocking skill (Pearson correlation) as a function of initialization month. From Park et al. (2024).

Translating SPEAR seasonal forecasts into industry-relevant products

Prediction Skill for Wind Energy

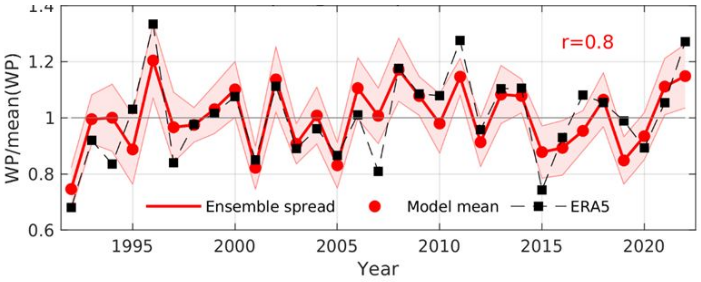


SPEAR forecast skill (ACC) of (**left**) Dec - Feb and (**right**) Mar - May wind energy for a 1 Nov and 1 Feb initialization, respectively. From Yang et al. (2023).

- High skill for major wind energy producing regions of the central U.S.

- Skillful seasonal predictions of wind speed translated to wind energy forecasts that are potentially useful for the energy sector (Yang et al. 2023).
- Storm track variations associated with ENSO the primary source of skill.

Texas



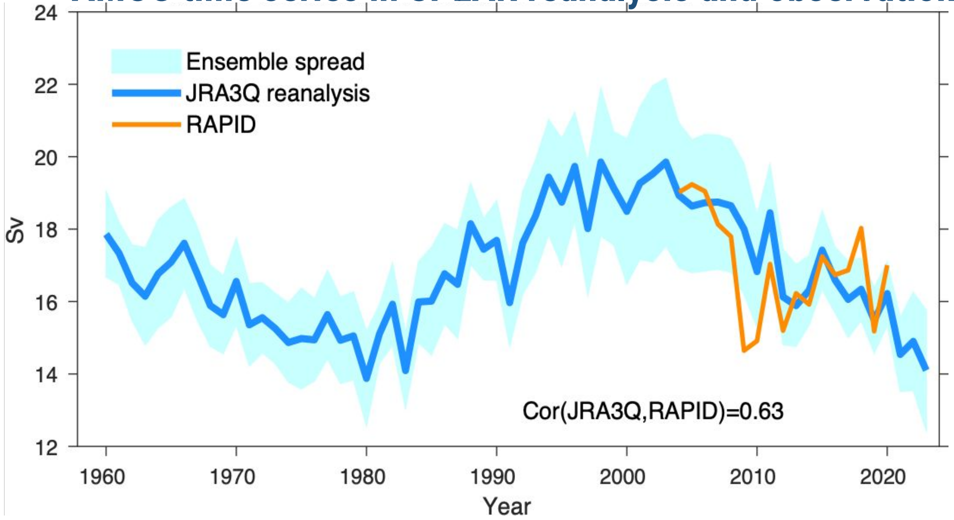
Time series of observed (black) and SPEAR (red) Mar - May wind power averaged over Texas for a 1 Mar initialization. From Yang et al. (2023).

Decadal Prediction system with SPEAR

- Decadal system is initialized from SPEAR global reanalysis (Atmosphere components and SST were constrained by observations, Ocean component is a free ocean) (*Yang et al. 2021, JAMES*).
- The AMOC in SPEAR reanalysis is well constrained by observation.

GFDL sends decadal predictions to WMO (*Leon et al., 2022, BAMS*)
GFDL participates in VolRes-RE (*Sospedra-Alfonso et al., 2024, BAMS*)
Decadal predictions drive high resolution regional ocean models (*Vimal et al. 2024, GRL*)

AMOC time series in SPEAR reanalysis and observation

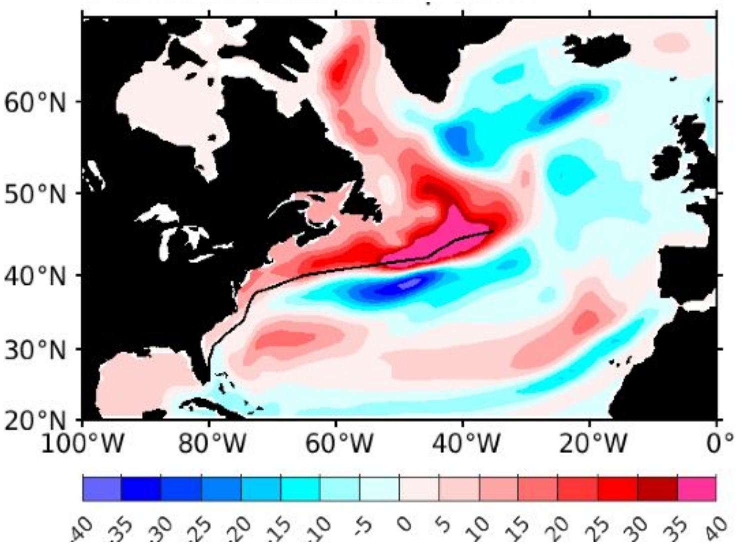


- **Relevance:** Supports NOAA's mission to address decadal prediction of societally-relevant quantities.
- **Quality & Performance:** Outputs include policy implications and international collaboration.

R3: Be ready to reach out to outside entities

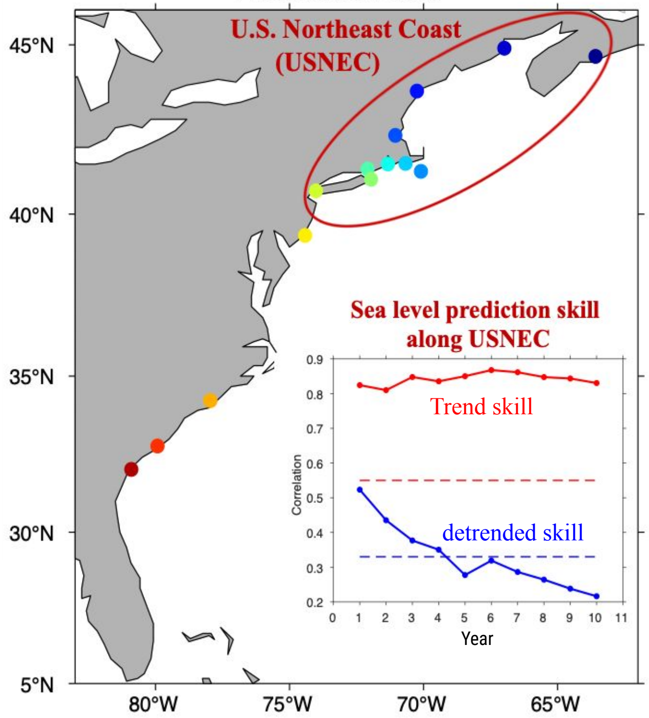
Understanding sea level mechanisms leads to predictive skill

Predictable sea level pattern in SPEAR control run



Sea level has multi-year predictability in control run, arising from multidecadal AMOC fluctuations(*Zhang et al. 2024, Nature Comm. Earth & enviro*;*Gu et al. 2024, npj Clim. & Atm. Science*)

Coastal sea level prediction skill



Coastal skill comes from external radiative forcing and AMOC

- ❑ **Quality:** Addresses NOAA's priority to reduce flood risks through innovative AI methods and predictive modeling.
- ❑ **Relevance:** Supports NOAA's mission to manage too little or too much water.

R4: Increase engagement with other NOAA efforts

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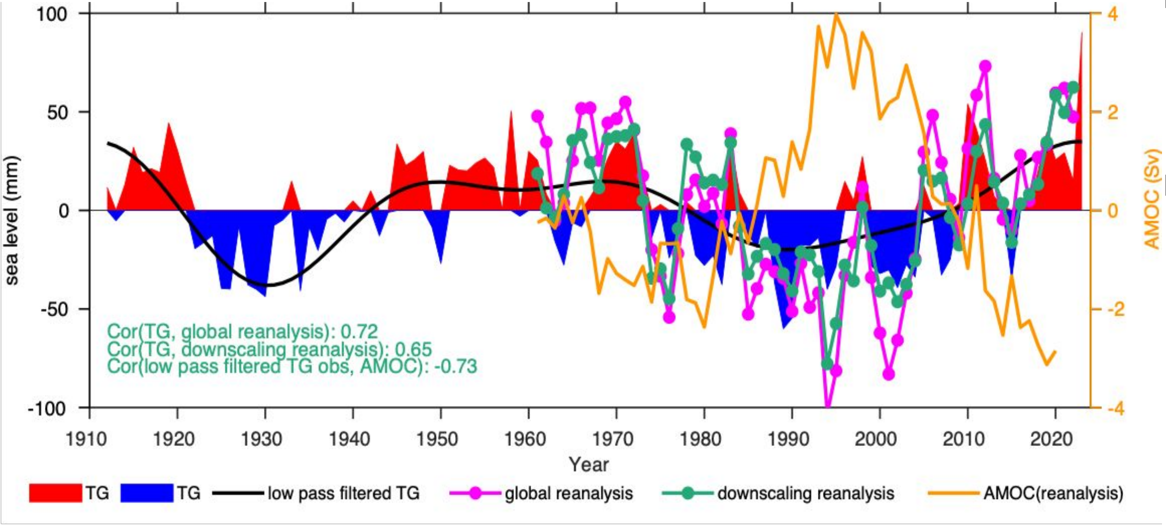
Flood frequency prediction along U.S.Northeast Coast (USNEC)

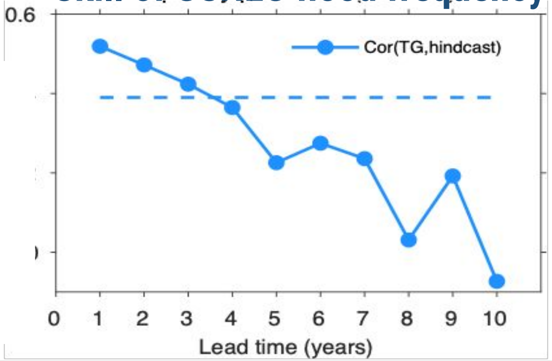
Time series of the AMOC and sea level along the USNEC



- Observed multidecadal fluctuations in sea levels along USNEC are driven by AMOC.
- Background sea level modulates flood frequency and serves as a source of multiyear predictability.

(*Zhang et al Science Advances in review*)

Skill of USNEC flood frequency

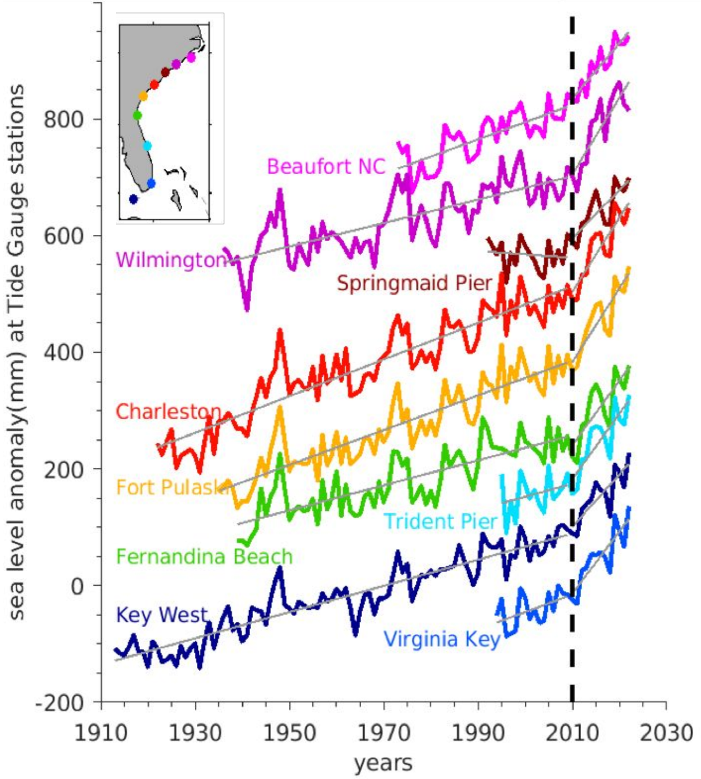


- **Relevance:** Addresses NOAA's priority to predict flood risks through high resolution modeling.
- **Performance:** Leveraging cutting-edge tools (downscaled system *Vimal et al. 2024, GRL*) for accurate and actionable coastal prediction.

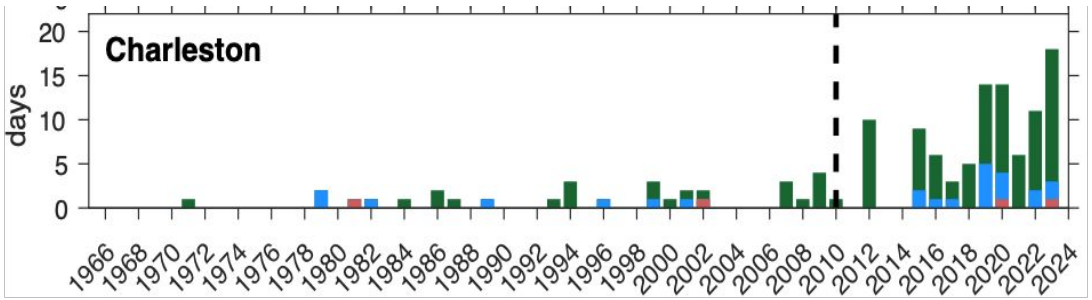
R1: Strengthen internal collaboration within GFDL/Princeton

Rapid acceleration of flooding along U.S.Southeast Coast(USSEC)

Annual mean sea level rise(SLR) along USSEC



Increased flood frequency along USSEC after 2010

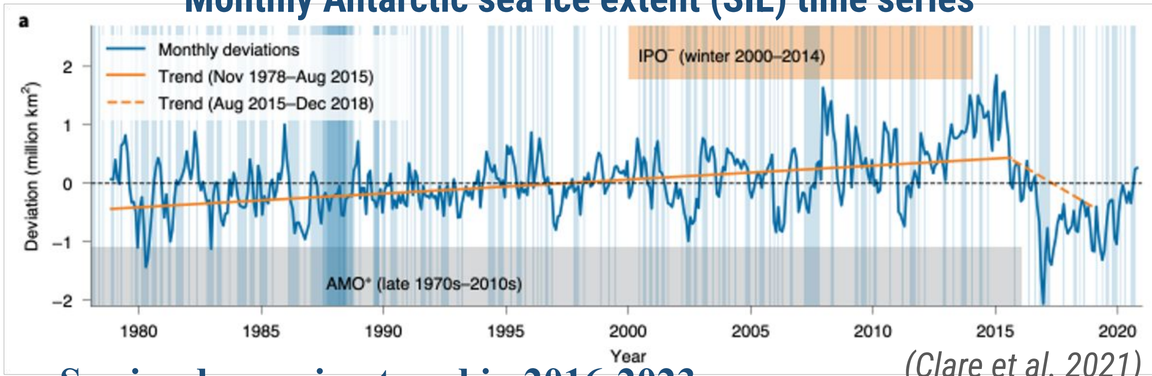


- Accelerated SLR and floods after 2010: compounding effects of radiative forcing, AMOC (5-yr skill) and wind-driven tripole-like response to North Atlantic Oscillation (2-yr skill) (*Zhang et al. 2024, npj Clim. & Atm. Science,* interviewed by *Washington post and CNN*).

- **Relevance:** Addresses NOAA's priority to reduce flood risks through predictive modeling.

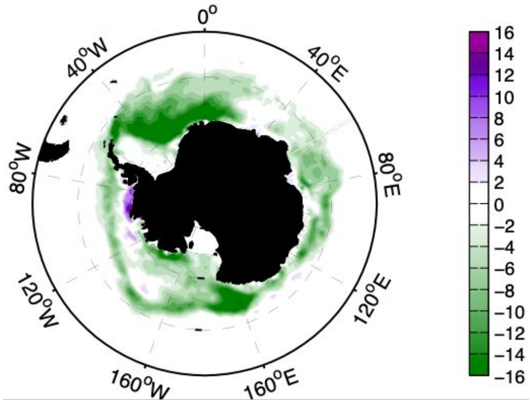
Southern Ocean multidecadal variability and Antarctic sea ice

Monthly Antarctic sea ice extent (SIE) time series



(Clare et al. 2021)

Sea ice decreasing trend in 2016-2023

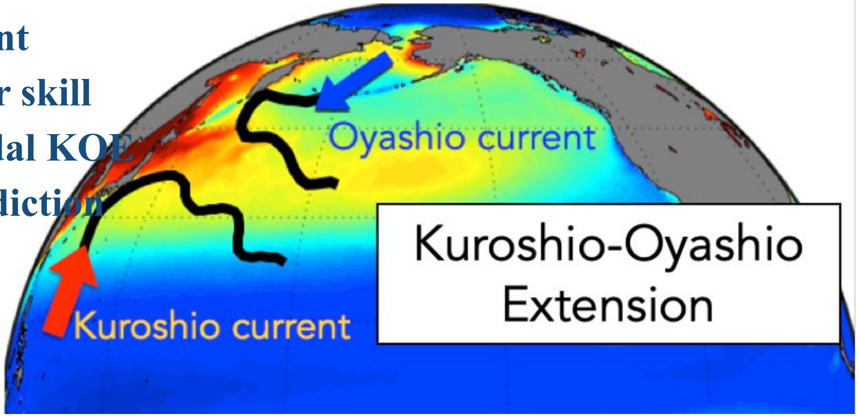


- **Observed positive Antarctic SIE (cold SST) trend in 1979-2015:** Natural variability of Southern ocean convection as a driver of observed trends, potentially predictable. (*Zhang et al. 2019, Nature Clim. Change*; *JC 2021, 2022, 2023*; *Quoted by Carbon Brief*)

- **Persistent negative Antarctic SIE anomalies after 2016:** Subsurface Southern Ocean warming plays a crucial role (~50%) in SIE lows, as a multiyear predictability source. (*Zhang et al. 2023 Comm. Earth & Enviro.*; *Quoted by New York times; Washington Post; E&E news…*)

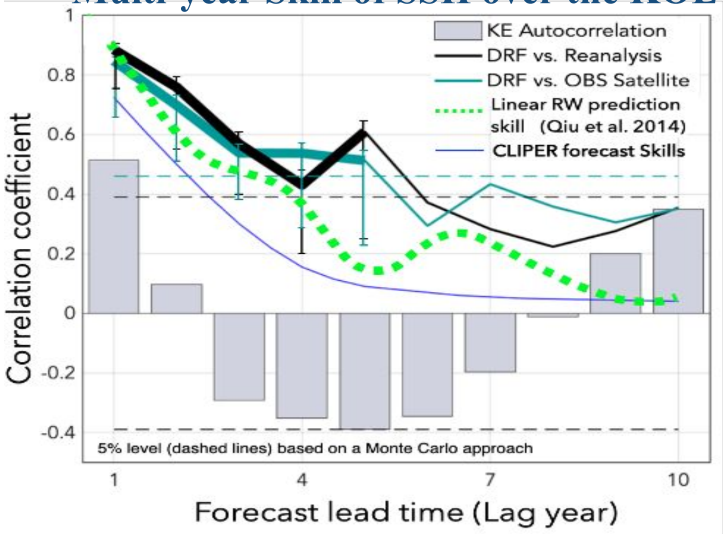
- **Relevance:** Advances understanding of climate-driven extreme weather, aiding NOAA's efforts to enhance climate resilience.

North Pacific decadal variability and predictability



- Sea surface height (SSH) over Kuroshio-Oyashio Extension (KOE) has a 5-yr prediction skill (Joh et al. 2022, JC) due to Rossby wave.

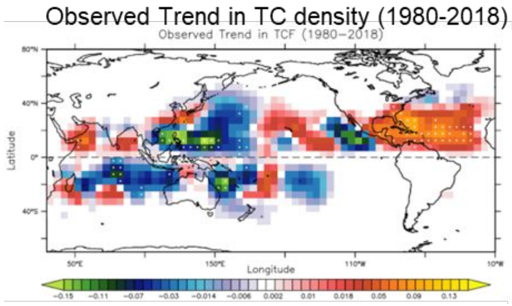
Multi-year Skill of SSH over the KOE

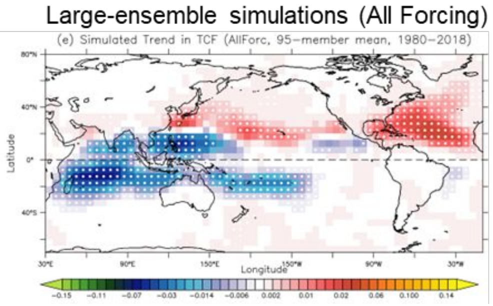


- Substantial increase in the decadal variance of KOE SSH variability in a warmer climate (Joh et al. 2022 npj Clim. & Atm. Science). *Also Pacific Decadal Oscillation time scale change* (*Zhang and Delworth, 2016 JC*).

- **Quality:** Utilizing unique SPEAR large-ensemble simulations to evaluate future changes of North Pacific quantities.

Climate change has impacted the global distribution of tropical cyclones





SPEAR simulations (1980–2018, **right**) show TC trends driven by external forcing (e.g., greenhouse gases, aerosols), aligning with observed patterns (**left**).

Key Finding: Regional changes in tropical cyclone activity since 1980 have been detected and attributed to external forcings, such as greenhouse gases and aerosols.

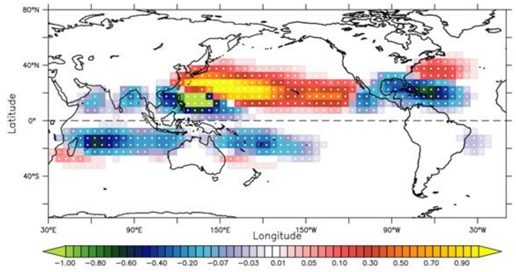
Quality: Highly cited peer review publications: *PNAS*, *Sci. Adv.*, *npj Clim. Atmos. Sci.*, *GRL*

Relevance: Advances understanding of climate-driven extreme weather, aiding NOAA's efforts to enhance climate resilience. Addresses a key public question: How is climate change affecting tropical cyclones? (CNN News, AP, New York Times)

Quantifying future risks of tropical cyclones

- **Reducing gaps in global TC frequency projections** (Vecchi et al. 2019, *Clim. Dyn.*, Murakami et al. 2020 *PNAS*)
- **Rising threat of rapid intensification** (Bhatia et al. 2022, *Nat. Comm.*)
- **Examining evolving extratropical transition** (Bieli et al. 2020, *JAMES*)
- **Projected intensified TC rainfall** (Jong et al. 2024, *Earth's Future*)
- **Assessing risks from slower-moving TCs** (Zhang et al. 2020, *Sci. Adv.*)

- **Compound risks of major hurricanes and wildfire** (Murakami et al. 2024, *Commun. Earth Environ.*)



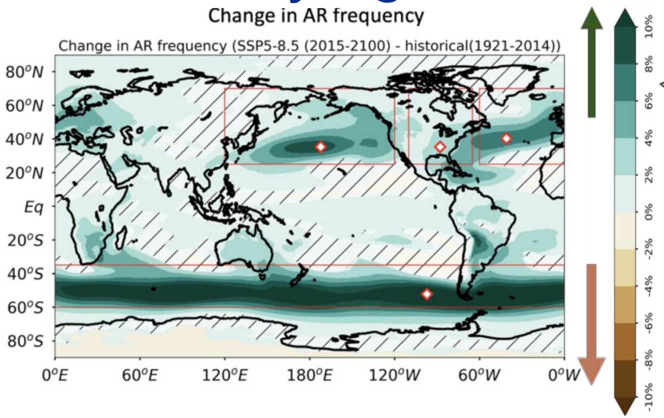
Future change in major hurricane occurrence, showing increasing major hurricanes and associated increases in wildfires in the Central Pacific

- **Increasing events of rare rainfall pattern caused by tropical cyclones** (Murakami et al. 2022, *Earth's Future*)

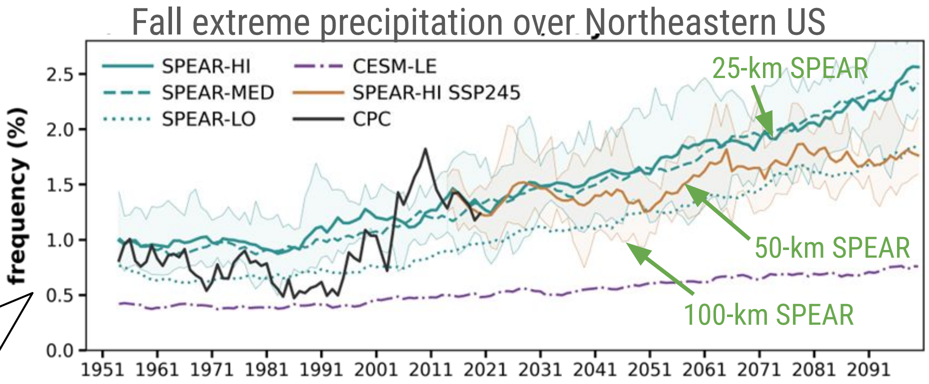
Quality: High-resolution models (e.g., SPEAR_HI) ensure robust projections for extreme events.
Relevance: Supports NOAA's goal to protect lives and property from extreme weather.
Performance: Collaborates with AOML, Princeton University, Lamont-Doherty Earth Observatory, JAMSTEC, and MRI

R1: Strengthen internal collaboration within GFDL/Princeton
R4: Increase engagement with other NOAA efforts

Quantifying risk of extreme rainfall events in the future



Global increase in atmospheric rivers with anthropogenic impacts emerging by 2040 in Northwest and Northeast US
Tseng et al. 2022, *J. Geophys. Res.*

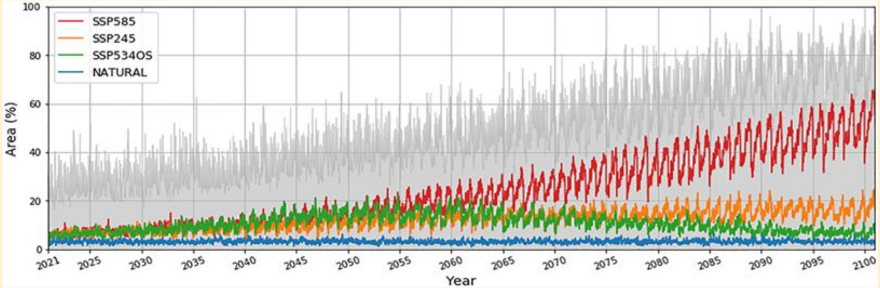


SPEAR_HI projects sixfold increase in Northeastern U.S. extreme precipitation by 2100, emphasizing infrastructure resilience
Jong et al. 2023, *npj Clim. Atmos. Sci.*; 2024, *Earth's Future*

Relevance: Addresses NOAA's priority to reduce flood risks through predictive modeling
Performance: Leveraging cutting-edge tools (SPEAR_HI) for accurate and actionable projections

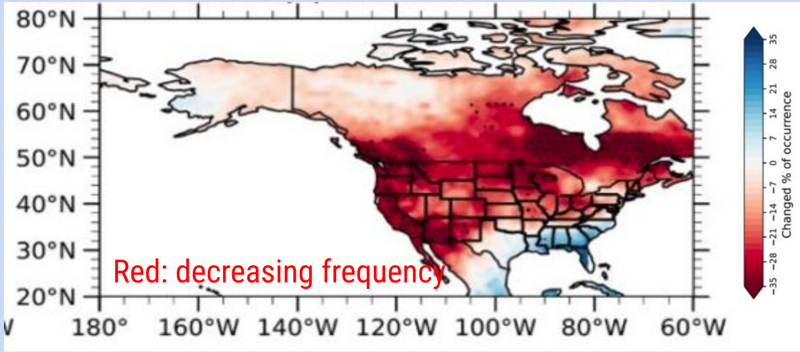
Quantifying future changes in extreme heat and cold over the US

Extreme Heat



- Rising frequency of extreme heat events over CONUS (McHugh et al. 2022, *Earth's Future*)
- Compound heat and humidity events affecting human health and ecosystems (Jia et al. 2024, *npj Clim. Atmos. Sci.*)
- Increasing risk of Alaskan summer heat extremes (Weidman et al. 2021, *Earth's Future*)

Extreme Cold

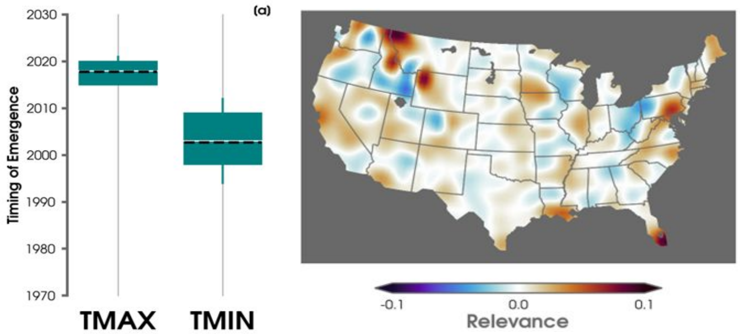


- Stationary waves weaken under high emissions, reducing cold extremes
- Wave shifts alter North American climate patterns. (Park et al. 2024, *Nat. Comm.*)

Quality: Utilizing unique SPEAR high-resolution large-ensemble simulations to evaluate future changes in extreme temperature events

Relevance: Supports NOAA's mission to address societal impacts of heat/cold extremes.

Advancing climate research with AI: Enhancing predictions and detecting anthropogenic signals



Neural networks detect U.S. summertime temperature emergence (**left**) and key prediction areas (**right**)

- Use neural networks to identify the emergence timing of U.S. summertime temperatures (figure)
  - Labe et al. 2024, *Earth's Future*
- Neural networks with the SPEAR large ensemble extract spatial distribution patterns of temperature and precipitation related to climate change
  - Murakami et al. 2022, *Earth's Future*, Labe et al. 2024, *JGR*

Quality: Employing innovative AI methods and SPEAR climate simulations to push the boundaries of climate research, exploring robust and actionable insights.
Relevance: Explainable AI provides critical insights for mitigation strategies and demonstrates potential for near real-time observation tracking, directly supporting NOAA's mission.

Key research advancing understanding of climate variability and impacts on societal resilience

- Variability in the Northwestern Pacific and implications for ENSO teleconnections. (Joh et al. 2023, 2024)
- AMOC reversibility and its impact on Mediterranean precipitation patterns. (Delworth et al. 2022)
- Western U.S. snow droughts and transitions to no-snow conditions by 2100. (Schmitt et al. 2024)
- Increasing risk of another Cape Town "Day Zero" event. (Pascale et al. 2020)
- SST variability drives vapor pressure deficit changes in the southwestern U.S. (Lou et al. under review)
- Advancing ENSO diagnostics to improve understanding of ENSO's mechanisms. (Johnson et al. 2022)
- Central American drought trends under anthropogenic climate change. (Pascale et al. 2021)
- Late 21st-century climate mitigation reduces ocean heat uptake, with the Southern Ocean as the main heat exchanger. (Li et al. 2024)

- **Relevance:** Each study aligns with NOAA's mission to address climate variability and societal resilience.
- **Quality & Performance:** Outputs include actionable insights, policy implications, and international collaboration.

Summary of Achievements, Gaps, and Frontiers

Achievements:

- Publications bridging robust science and practical societal applications through SPEAR predictions and projections (Selected publications from 2020 to 2024 -> Link).
- Contributions to society, including initiatives for NMME and SPEAR Large Ensemble, supporting societal resilience and providing data for decision-making.

Gaps:

- Persistent model biases in Tropical Pacific warm pool rainfall, trade winds, and cold tongue.
- Systematic errors in ENSO, Pacific decadal trends, and the Central U.S. “warming hole.”

Frontiers:

- Advancing AI/ML for climate predictions.
- Exploring high-resolution modeling for extremes and air-sea interactions.
- Strengthening links between predictions and societal impacts (e.g., landfalling TCs, flood risks).
- Enhancing high-resolution predictions capabilities and improving data assimilation/initialization processes.
- Investigating climate reversibility and its implications for reversing human-induced change and long-term sustainability.