# Seasonal-to-Decadal (S2D) Variability and Predictability Division

*Division Lead: Tom Delworth*

*Presenters: Andrew Wittenberg, Nat Johnson, Hiroyuki Murakami, Xiaosong Yang*

NOAA GFDL, 2 July 2019

## Key NOAA Goals:

*Weather-Ready Nation*
"A society that is prepared for and responds to weather-related events."

*Climate Adaptation and Mitigation*
"An informed society anticipating and responding to climate and its impacts."

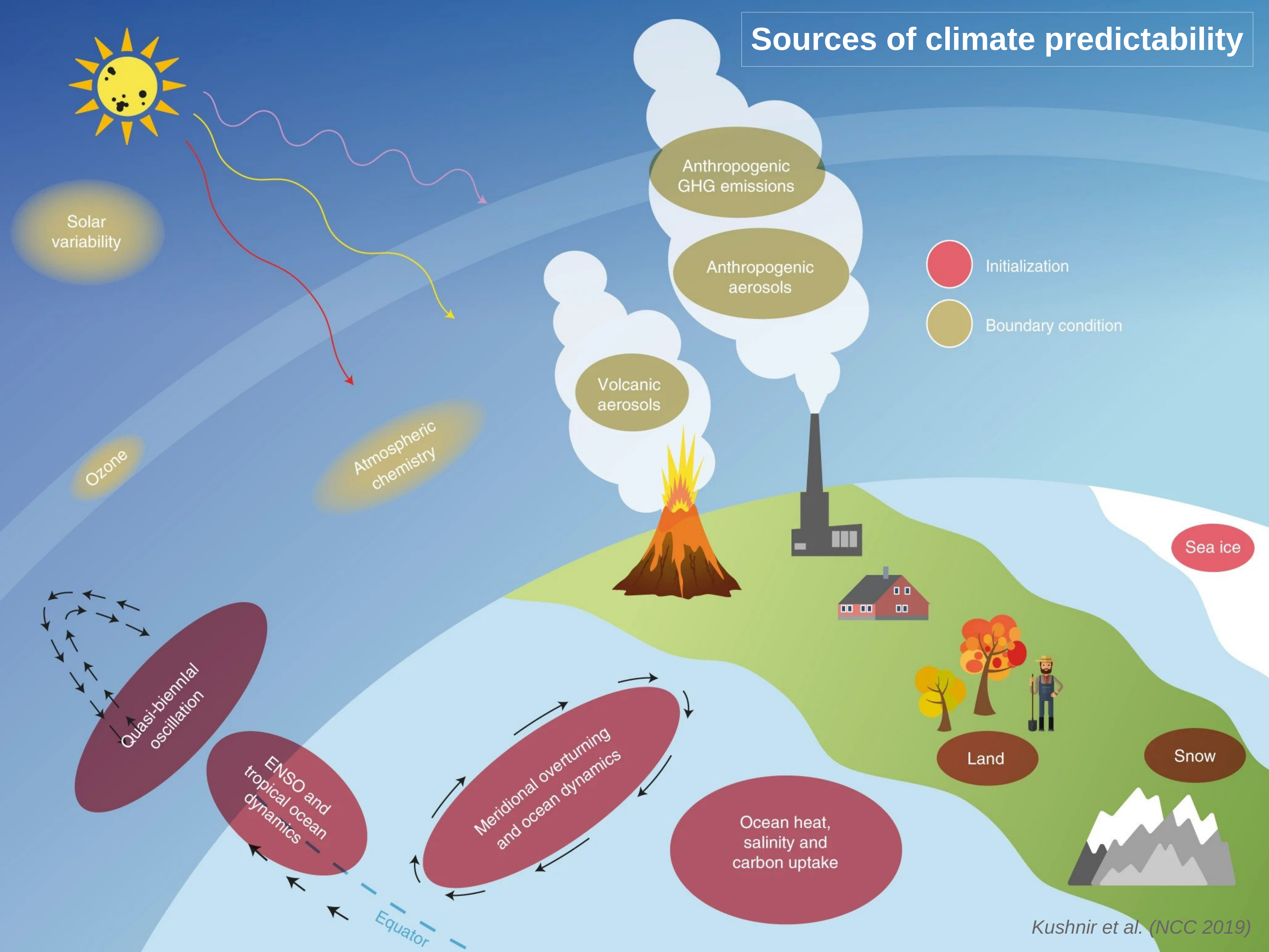
## GFDL's role in NOAA:

- Application-inspired basic research
- **Long-lead** science, targeting fundamental breakthroughs
- Proving ground for **next-gen** technologies and methods
- Work with NOAA partners to adapt advanced models to operations

## GFDL's Mission:

Develop comprehensive, integrated, unified models of the Earth system and apply them to **seamless** understanding, predictions, and projections from **hours to decades** and from **global to regional** scales.

# Sources of climate predictability




Kushnir et al. (NCC 2019)

# Research Foci of the S2D Division

1. Improve **scientific understanding** of seasonal-to-multidecadal variability, arising from variations *internal* to the coupled climate system, and from interactions with *changing radiative forcings*.

2. Develop experimental **prediction systems** and explore **predictability** at lead times of seasons to decades, for high-impact events including hurricanes, severe storms, floods, droughts, heat waves, and El Niño.

3. Provide probabilistic **predictions and projections** of how climate and extremes will evolve over the next several decades, at global to regional scales.

GFDL's **newest prediction systems** harvest the fruits of decades-long research efforts toward *model development* and *initialization systems*.

# Seamless seasonal-to-centennial prediction and projection

*Representative phenomena that give rise to variability & predictability in the climate system*

| Physical Phenomena | Variability & predictability timescale |
|---|---|
| Mid-latitude storms, general circulation | Daily to two-week weather forecast |
| Madden-Julian Oscillation, etc | Subseasonal |
| El Niño/Southern Oscillation (ENSO) | Seasonal to interannual |
| Volcanic aerosol forcing | Seasonal to interannual |
| Decadal-scale ocean-atmosphere variability (AMO, PDO, etc) | Interannual to decadal |
| Anthropogenic greenhouse gases, aerosols, ozone changes | Decadal to centennial |

*Weather Act defines "Seasonal forecast" as three months to two years*

**Desired capability**:

Modeling system that can produce large **ensembles** of **initialized** predictions and projections for time scales ranging from one season to multiple decades in advance.

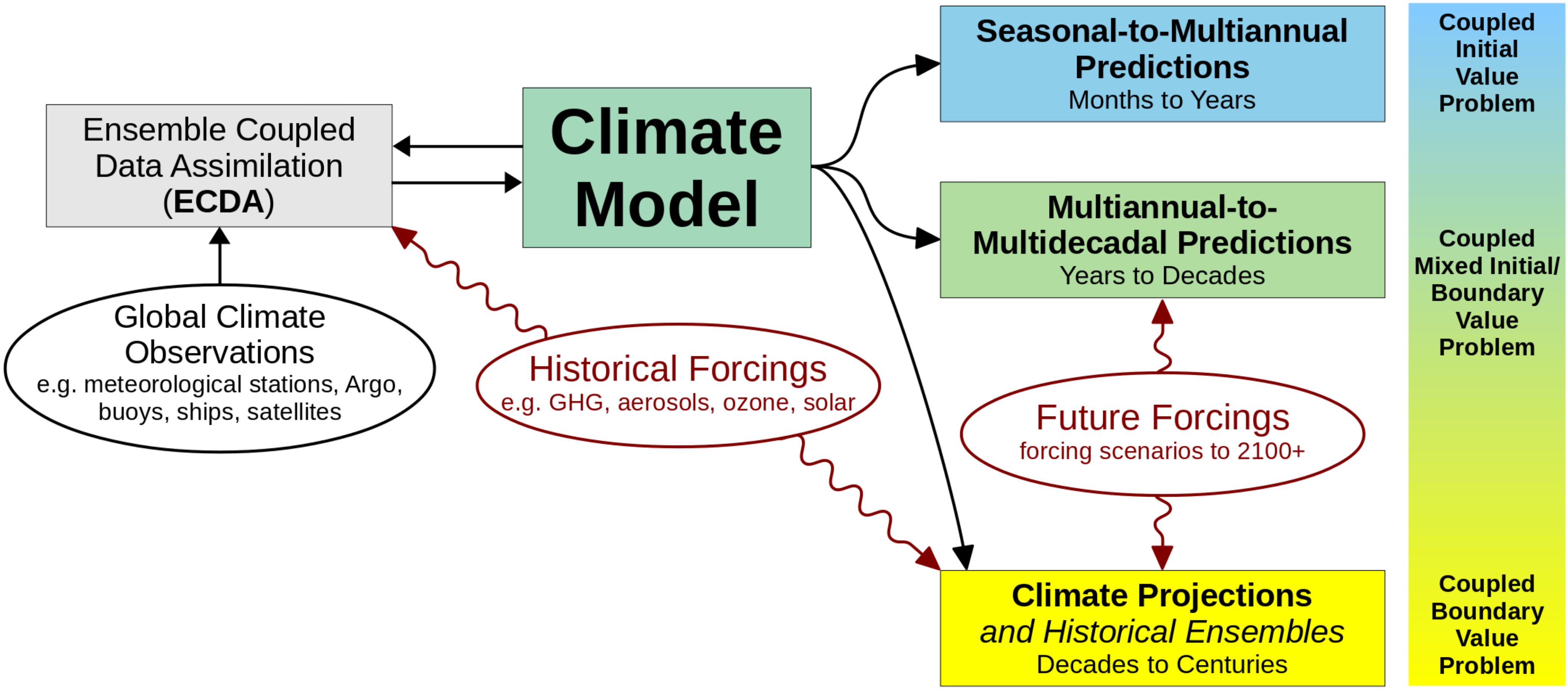
**Desired product:**

**Probabilistic** predictions and projections of climate variations and change that have utility for planning across a range of time and space scales – including seasons to decades.

**Examples**:

- How will predictable changes in ocean temperature influence **tropical storm activity**?
- How likely is it that:
  - ENSO or the AMO will change phase and alter **Atlantic hurricanes** and other climate features?
  - the PDO will change phase and impact **North American hydroclimate**?
- How will anthropogenic climate change alter the probability of **extreme events** over the US for the next decade, including rainfall/flooding and heat waves?

# Seamless Prediction and Projection System




Requires good initialization & transient response & long-term climate.

Global + High resolution + Coupled + Ensembles + Retrospectives

→ **Requires large computing resources.** HPC is a key bottleneck.

# Seasonal-to-Decadal Predictions

Since 2015, GFDL has delivered real-time **seasonal forecasts** on time each month to NMME, CPC, NHC, SIPN. It has provided seasonal forecasts to the IRI and APCC for over a decade.

GFDL contributes **decadal predictions** to the WMO Annual-to-Decadal Climate Prediction (ADCP) project, coordinated by UKMO.

***Plans:***

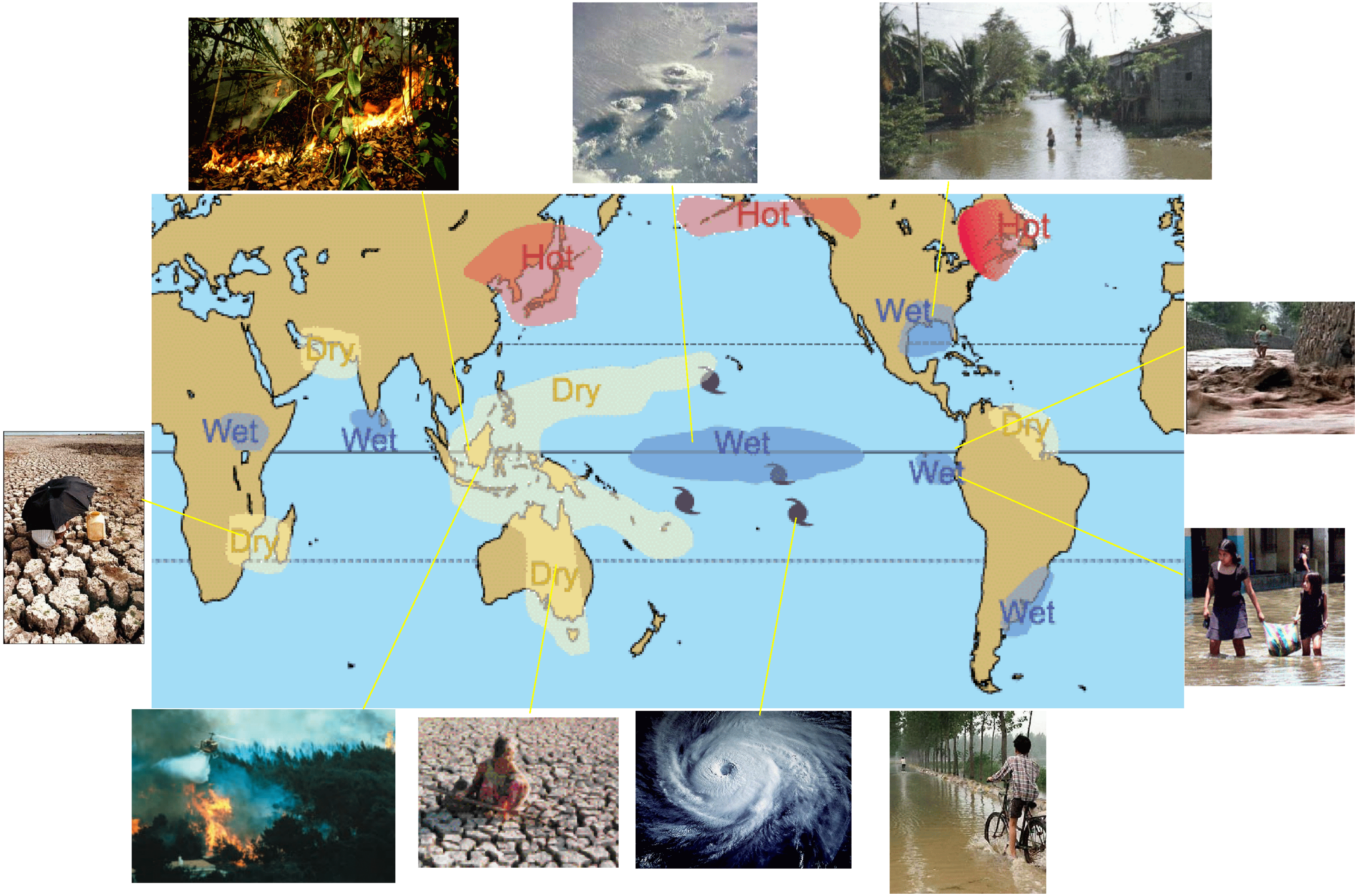
- **Atmosphere**: 50km → 25km → 10km refined mesh over N. America
  better-resolved **stratosphere** → stratosphere/troposphere interactions

- **Ocean**: 100km → 25km (coastal applications)

- **ESM** capabilities (biogeochemistry, carbon, ecosystems, fisheries)

# Seasonal-to-Interannual Variations & Predictability

Driven mainly from the tropics, e.g. ENSO.




Key foci: Temperature, hydroclimate, storms, snowpack, ocean currents, sea ice
→ impact agriculture, water resources, natural disasters, forests, wildfires, fisheries, shipping

# Seasonal-to-Interannual Products and Research

*Products:*

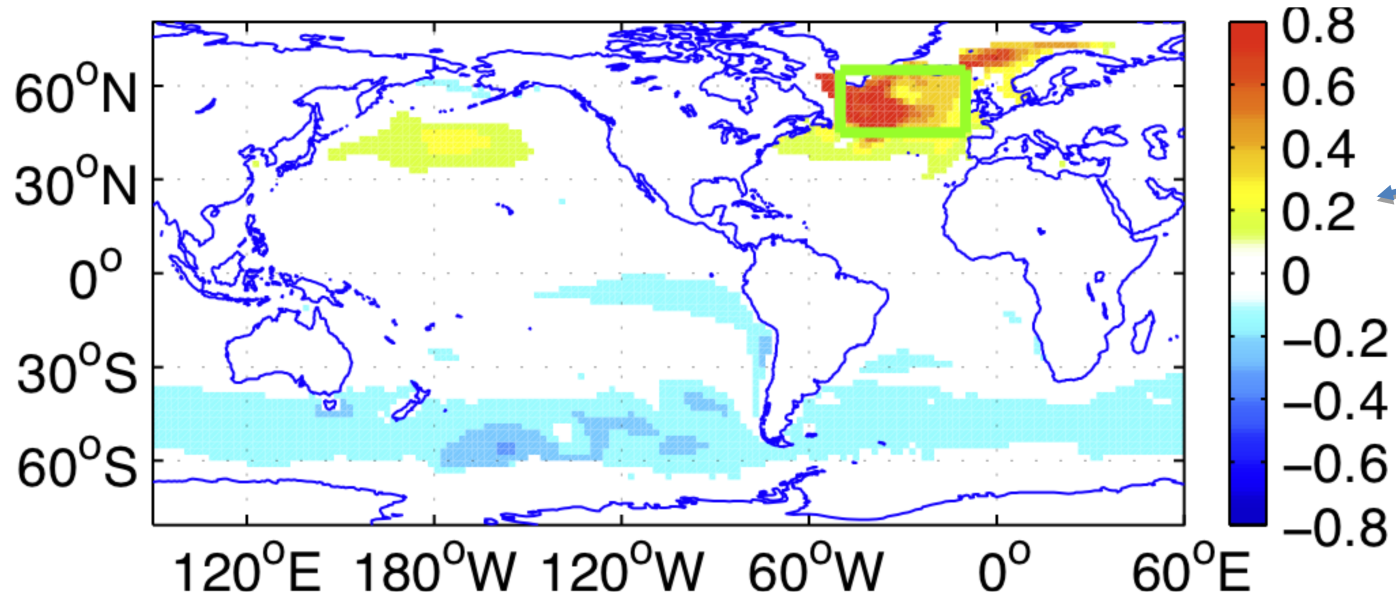
- **Models** (CM2.1, CM2.5, CM2.6, CM3, CM4, FLOR, HiFLOR, SPEAR)
- Simulation **data** & **publications**
- CM2.1/FLOR/HiFLOR **forecast systems** and ensemble **predictions**
- Modern-era coupled **reanalysis**: ECDA using SST, TAO, Argo, XBT, etc.

*Research Highlights:*

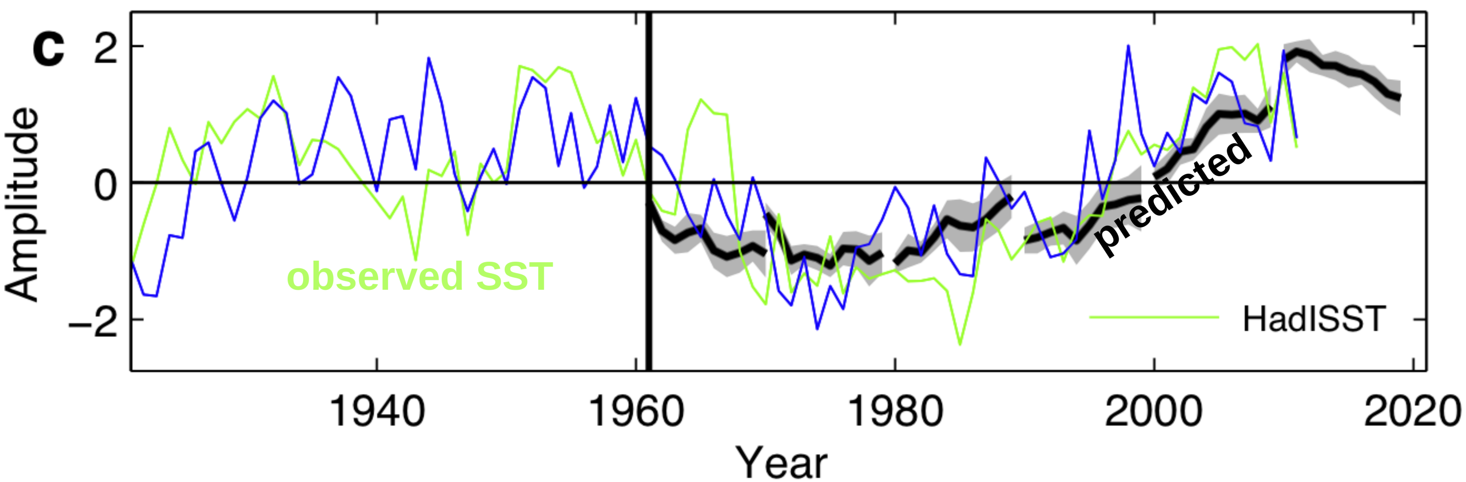
- Processes responsible for **ENSO diversity & sensitivities to forcings**
- Roles of ocean/atmosphere **data assimilation** in seasonal predictions
- Role of **stratosphere** in seasonal predictions
- Impacts of explosive **volcanic eruptions** on ENSO
- ENSO impacts on **tornado outbreaks** over the U.S.

# Decadal-to-Multidecadal Variations & Predictability

*Driven by AMOC, S. Ocean, Arctic/Antarctic sea ice, PDO, ENSO modulation.*




*Most predictable pattern of SST anomalies*




*Substantial predictive skill in the North Atlantic from decadal swings of the Atlantic Meridional Overturning Circulation (AMOC).*

Yang et al. (JC 2013)

**Key Foci:** surface temperature, hydroclimate, storms, cryosphere & snowpack, ocean circulation, changes in modes of variability (ENSO, NAO).

# Decadal-to-Multidecadal Products and Research

*Products:*

- **Models** (CM2.1, CM2.5, FLOR, SPEAR)
- Simulation **data** & **publications**
- CM2.1/FLOR **forecast systems** and ensemble **predictions/projections**
- Historical **reconstruction**: ECDA using SST & surface pressure

*Research Highlights:*

- Role of ocean heat transport variations in **AMV**
  → impacts on **Arctic sea ice, heat waves, monsoon rainfall**
- Predictable multidecadal variability of **S. Ocean sea ice & temperature**
- **PDO** mechanisms and sensitivities to anthropogenic forcings
- Role of tropical SST in **decadal drought over N. America**

# Seasonal Prediction System

# Real-time seasonal prediction at GFDL

| | Atmosphere resolution | Ocean resolution | Ensemble members |
|---|---|---|---|
| CM2.1 | 200 km | $1^o$ | 10 |
| FLOR | 50 km | $1^o$ | 24* |

- **CM2.1** and **FLOR**: run each month as part of the **North American Multi-Model Ensemble (NMME)** since 2015

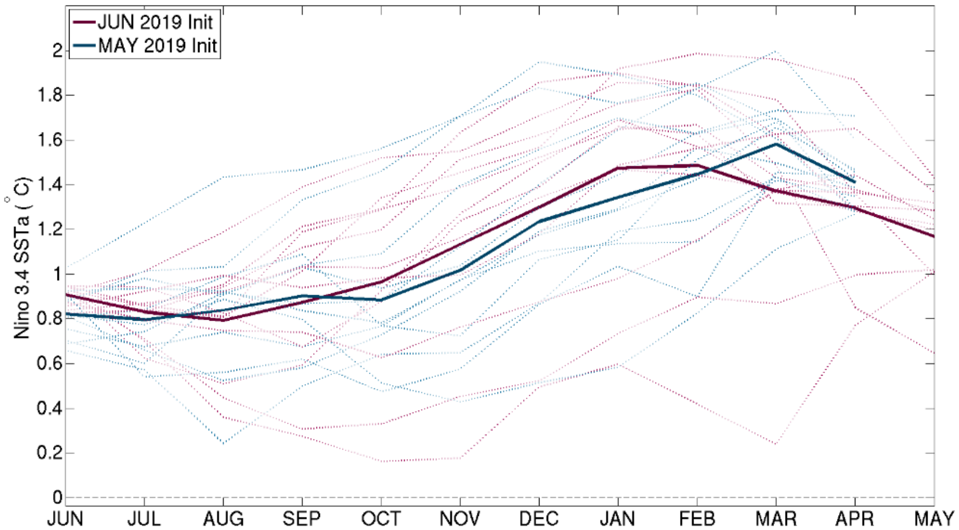
- Output provided to NCEP (National Hurricane Center and Climate Prediction Center) to inform their seasonal outlooks
  - FLOR for hurricanes
  - CM2.1 and FLOR for other climate outlooks, including ENSO, precipitation and temperature

- Ocean reanalysis also provided to NCEP for Multiple Ocean Reanalysis Project

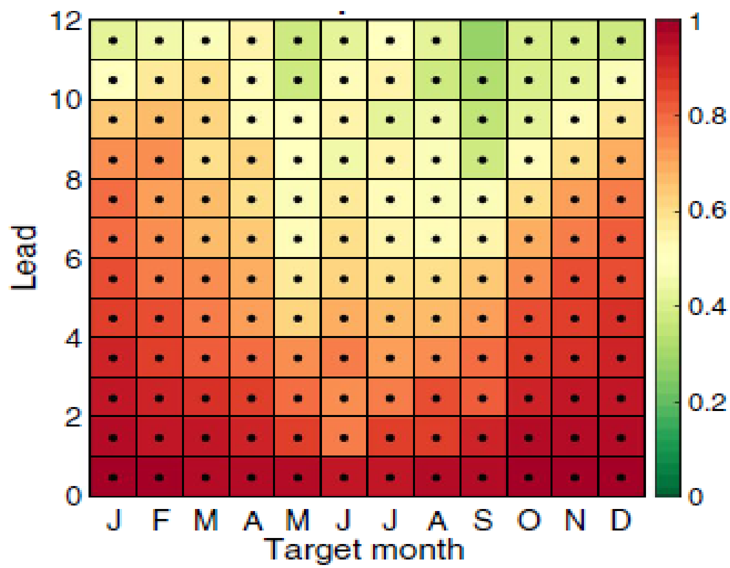
*2 slightly different versions with 12 members each

# GFDL's contribution to the NMME and NOAA's operational seasonal forecasts

## FLOR ENSO forecast plume



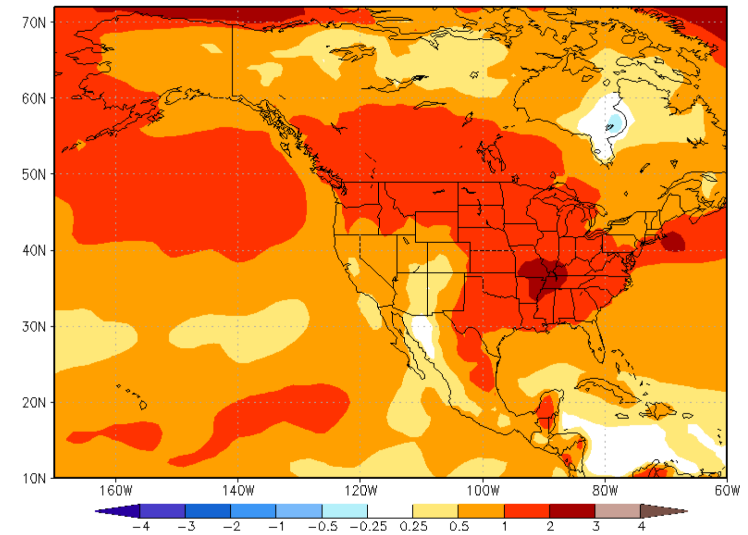

## ENSO Correlation skill



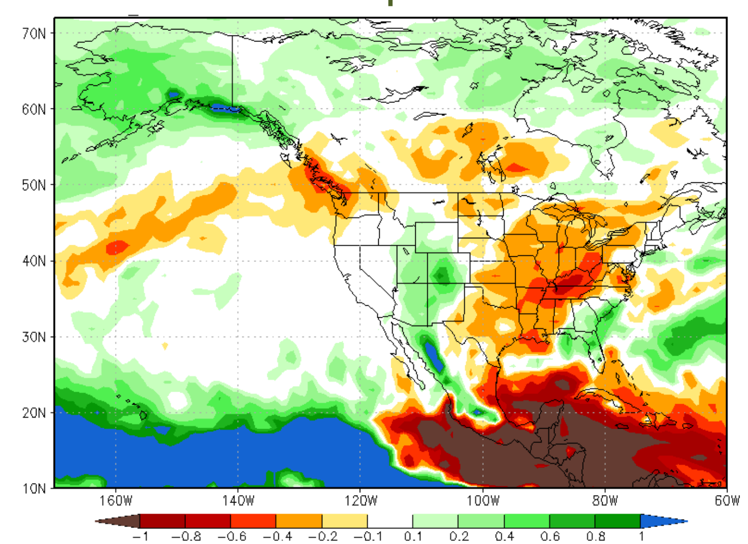

Source: Barnston et al. (2017)

## FLOR July – September temperature and precipitation forecasts

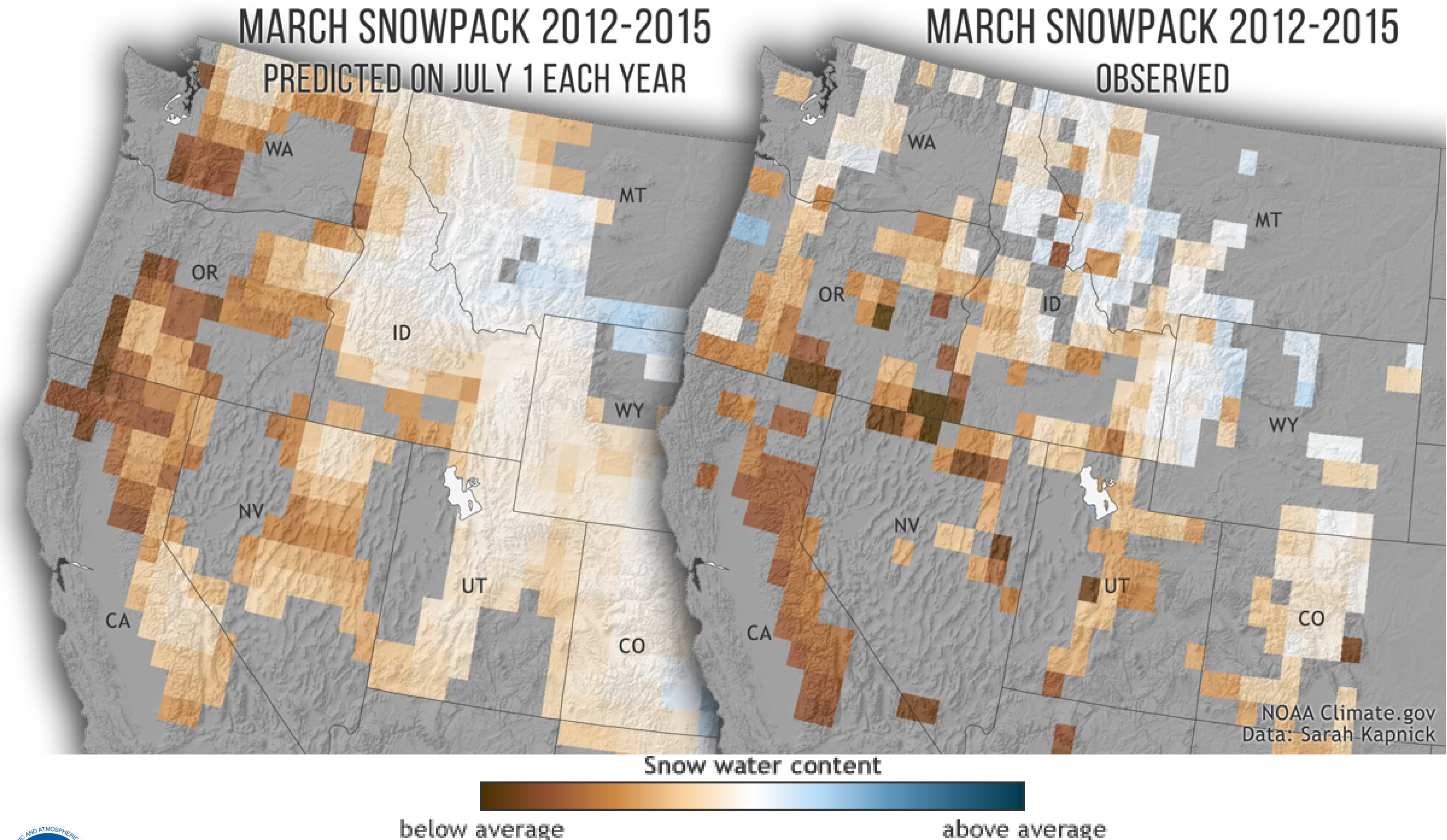
Temperature



Precipitation



# Demonstrated skill in seasonal snowpack prediction




Source: *Climate.gov image adapted from Kapnick et al. (PNAS 2018)*

# Towards a **S**eamless System for **P**rediction and **EA**rth System **R**esearch "SPEAR"

Using latest generation component models to build next generation seamless prediction system. The building blocks are
AM4/FV3 (atmosphere), MOM6 (ocean), SIS2 (sea ice), LM4 (land)

| | Atmosphere res | Ocean res | Status of Development | Reforecasts |
|---|---|---|---|---|
| **SPEAR_LO** | 100 km | $1^{o}$ | **Completed** | In progress |
| **SPEAR_MED** | 50 km | $1^{o}$ | **Completed** | Planned in coming months |
| **SPEAR_HI** | 25 km | $1^{o}$ | **In development** | Very limited set planned due to computational costs |

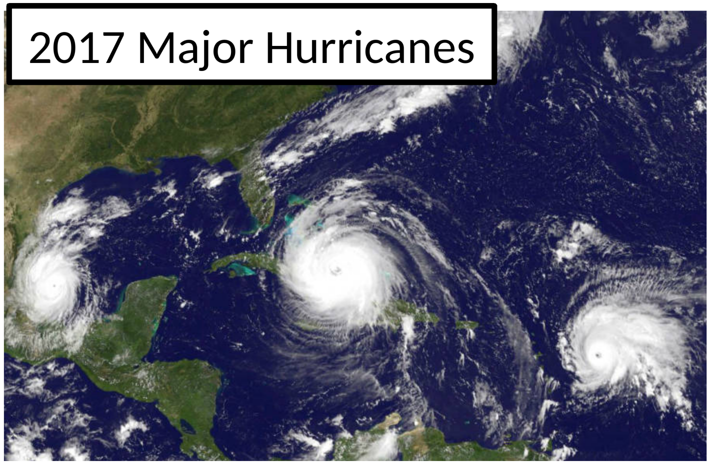
**Current R&D efforts:**

- Development of new initialization systems for seasonal and decadal prediction
- Improving stratospheric resolution

Anticipate that SPEAR-based prediction system will join the NMME in late 2019 or early 2020

# Seasonal Hurricane Outlooks

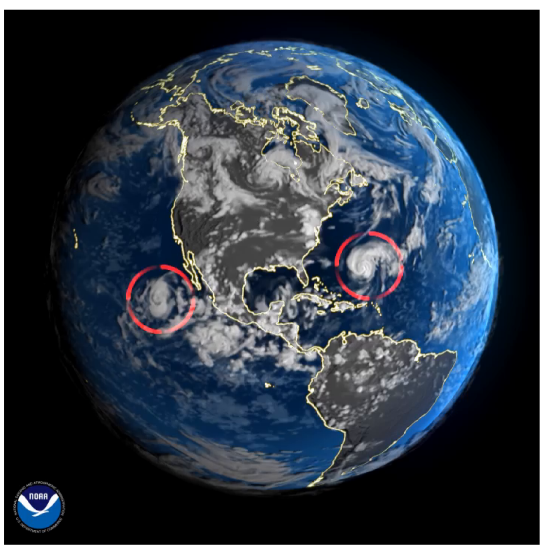
# Motivation for Hurricane Prediction

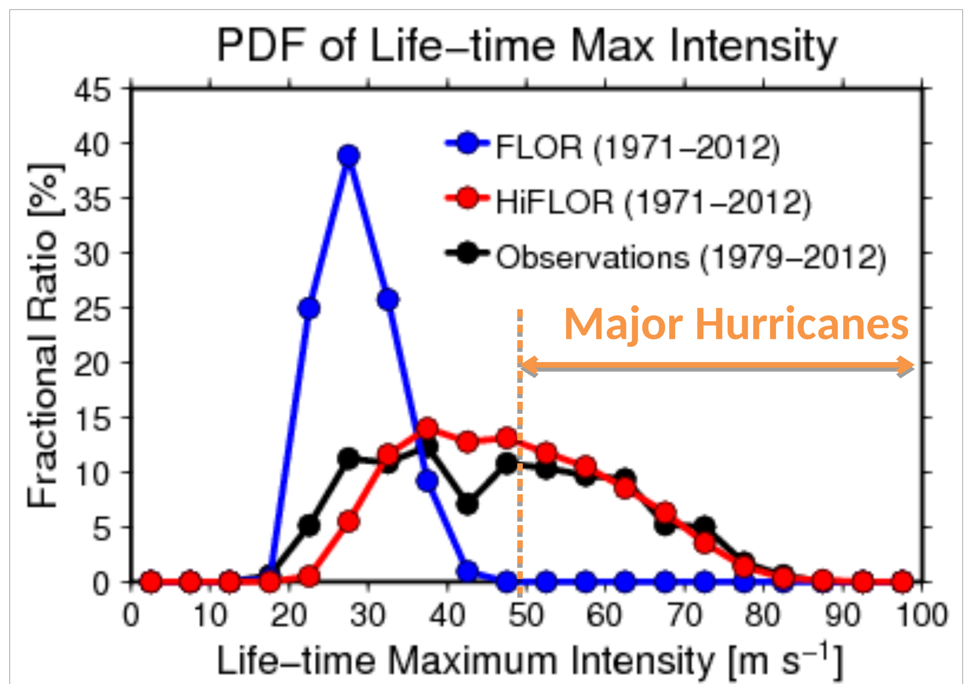




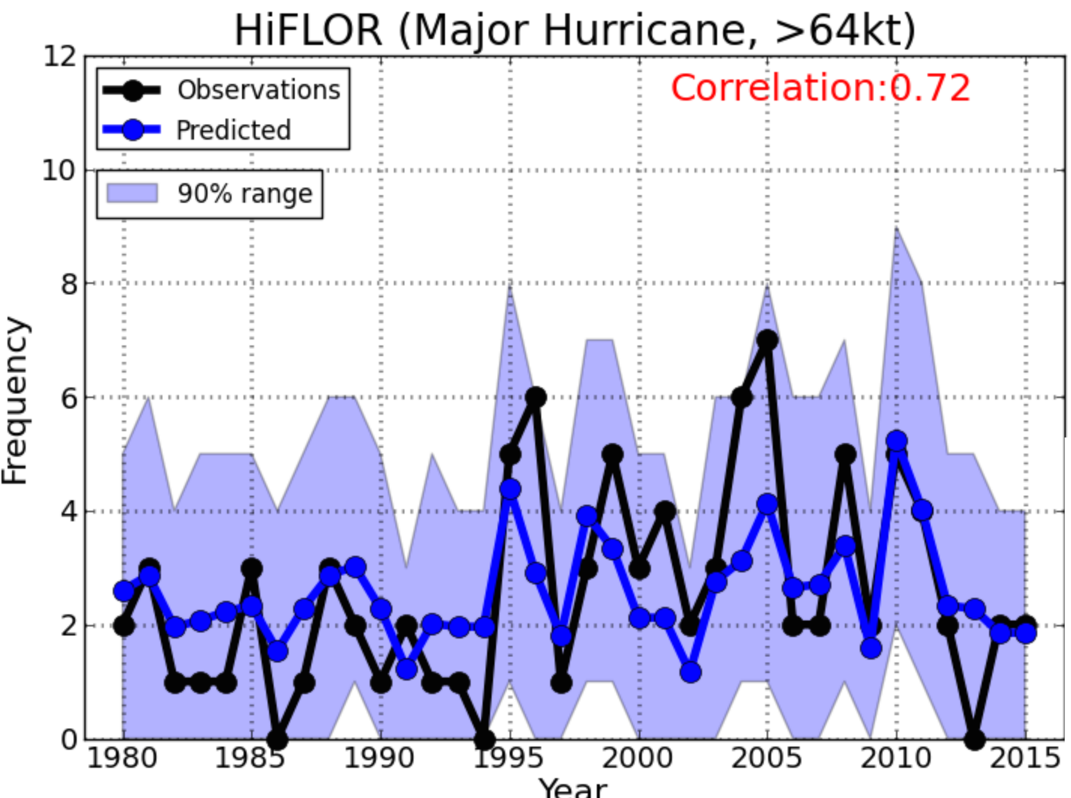
Developing a dynamical model that has skill in predicting **intense hurricanes** is central to NOAA's mission and highly relevant to society.

| | FLOR | HiFLOR |
|---|---|---|
| Resolution | Atmosphere : **50 km**, L32<br>Ocean: 100 km, L50 | Atmosphere : **25 km**, L32<br>Ocean: 100 km, L50 |

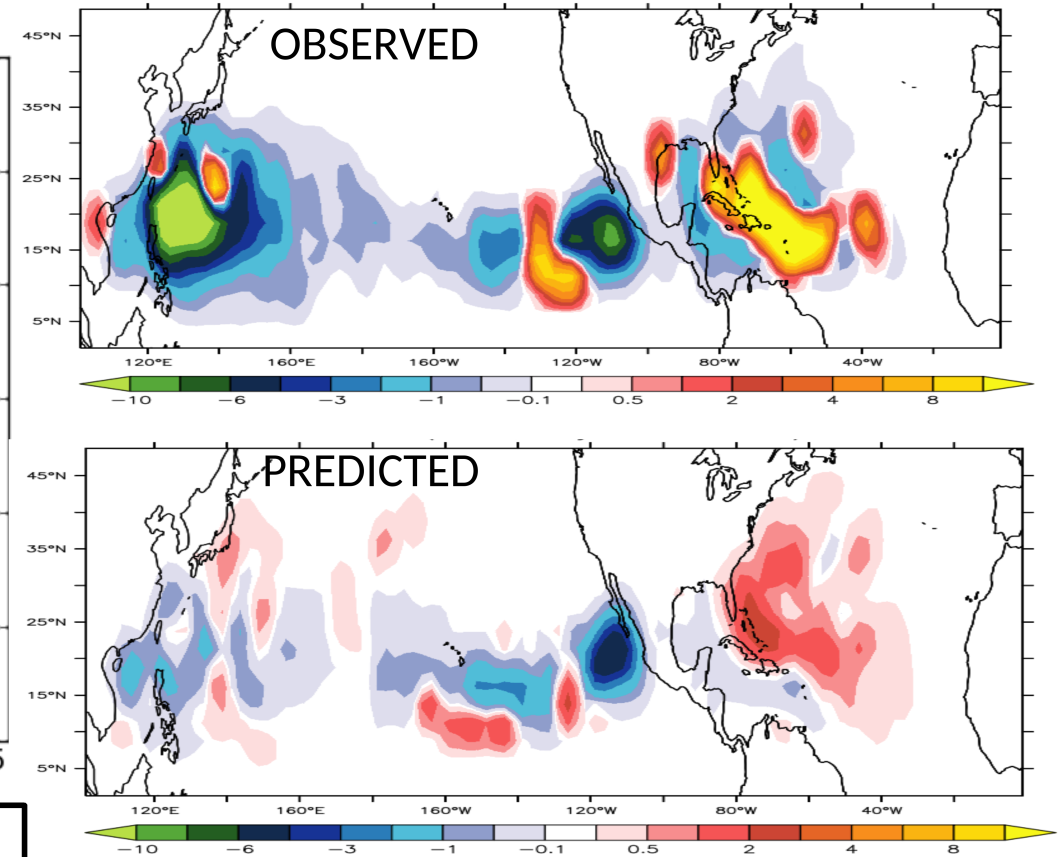




# Seasonal Predictions of Major Hurricane Activity




Predicted major hurricane frequency in the North Atlantic from July 1st initial forecast for each year.

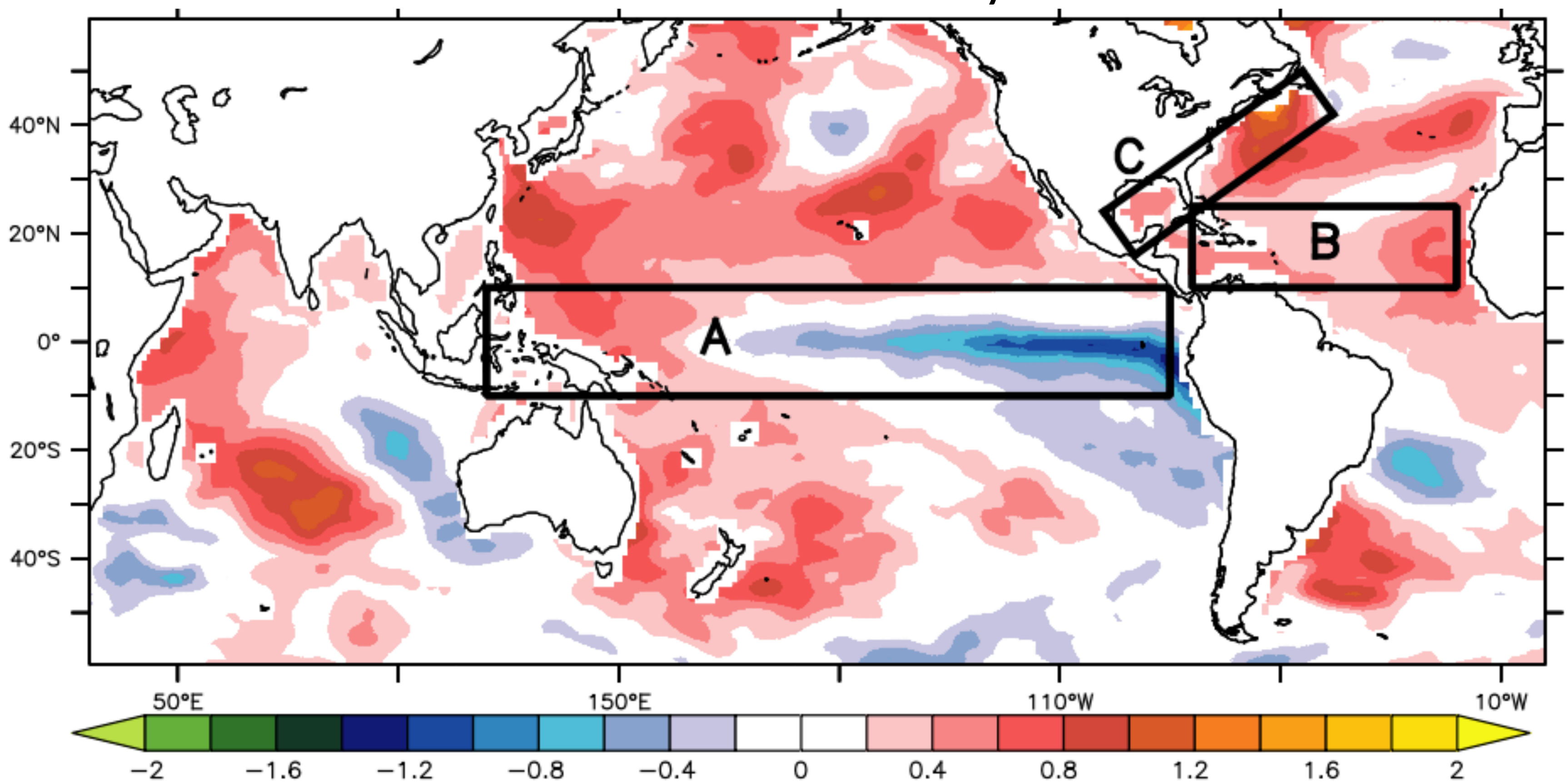



2017 anomalous major hurricane activity

- HiFLOR shows skillful prediction for frequency of major hurricanes a few months in advance.
- The real-time predictions are shared with the experts in National Hurricane Center and Climate Prediction Center to support their seasonal hurricane outlook.

# What caused the active 2017 major hurricane season?

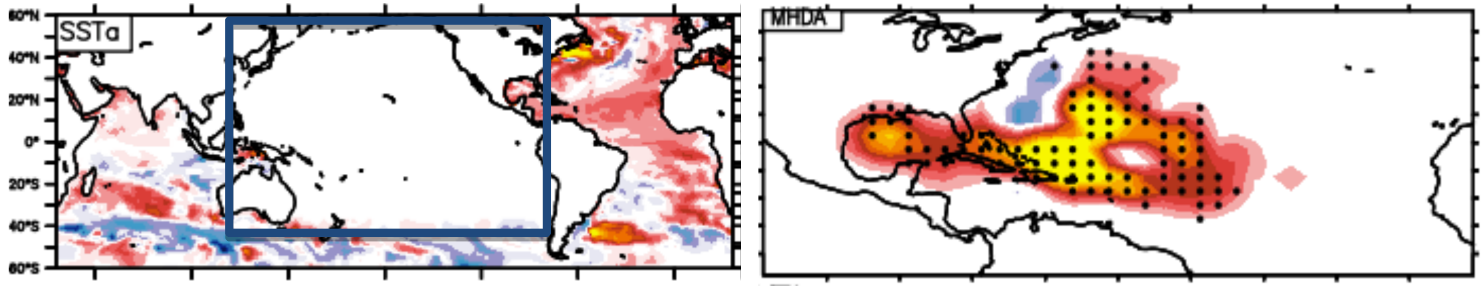
Observed SST Anomaly in 2017




A. Moderate La Niña?
B. Warmer Tropical Atlantic?
C. Warmer off the coast of North America?

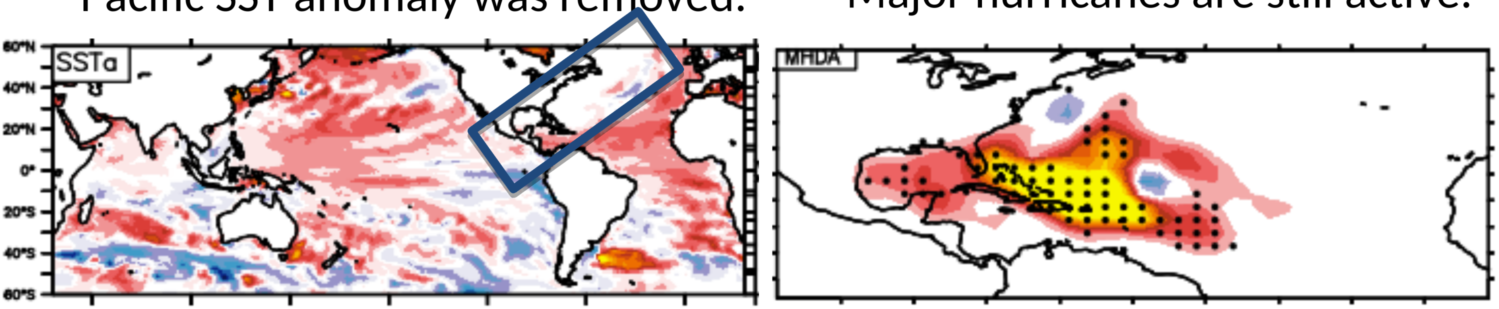
## Seamless prediction facilitates attribution of observed events

Prescribed SST Anomaly | Predicted MH Density Anomaly



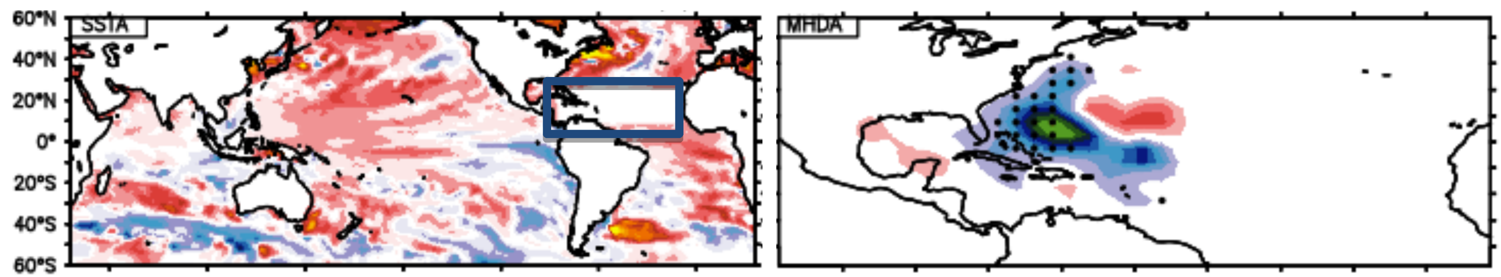

Pacific SST anomaly was removed. | Major hurricanes are still active.

A. Moderate La Niña?




SSTa off the coast of US was removed. | Major hurricanes are still active.

C. Warmer off the coast of North America?




SSTa in the tropical Atlantic was removed. | Major hurricanes reduced.

B. Warmer Tropical Atlantic?

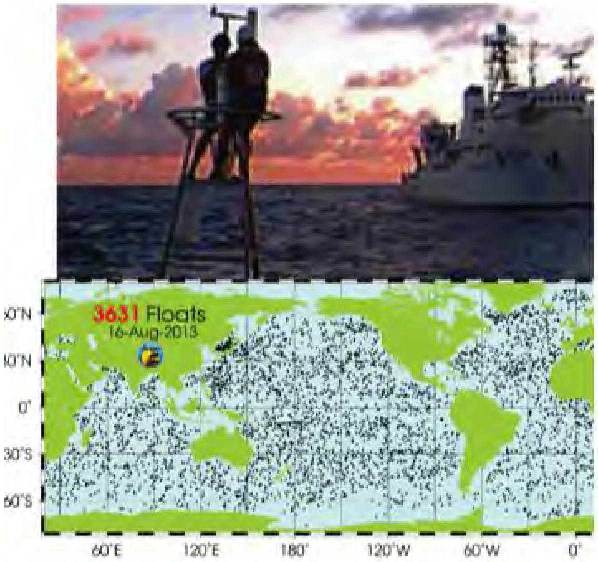
**We find:**

a. Moderate La Nina was not responsible
b. Warming off US East Coast was not responsible
**c. Tropical Atlantic warming played dominant role**

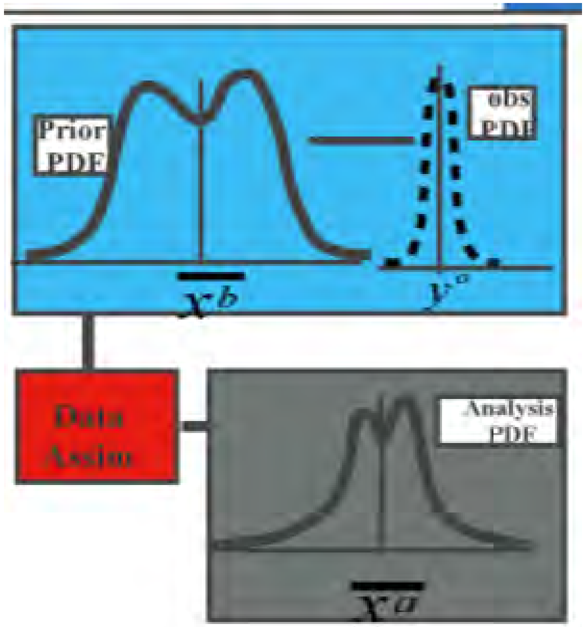
*More details in Murakami et al, 2018, Science*

# Global Data Assimilation

# **GFDL's data assimilation system:** Toward a coupled climate reanalysis (ocean T/S profiles & atmospheric surface pressure)

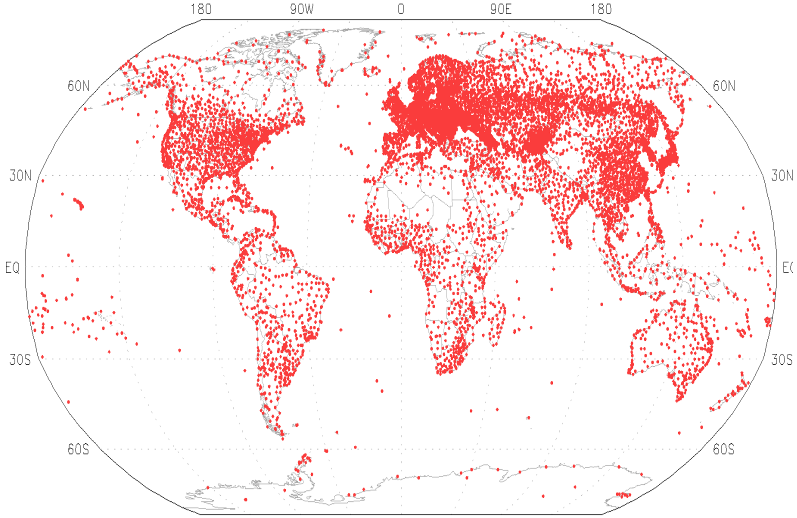



**Data assimilation system:**
Combines observations with coupled climate model to estimate climate state





International Surface Pressure Databank (ISPD)
Compo et al. 2011




Stations:1980

Current data assimilation system:

- An **Ensemble Coupled Data Assimilation (ECDA)** system using GFDL/CM2.1
- SST, Ocean T/S profiles
- Atmosphere T and winds

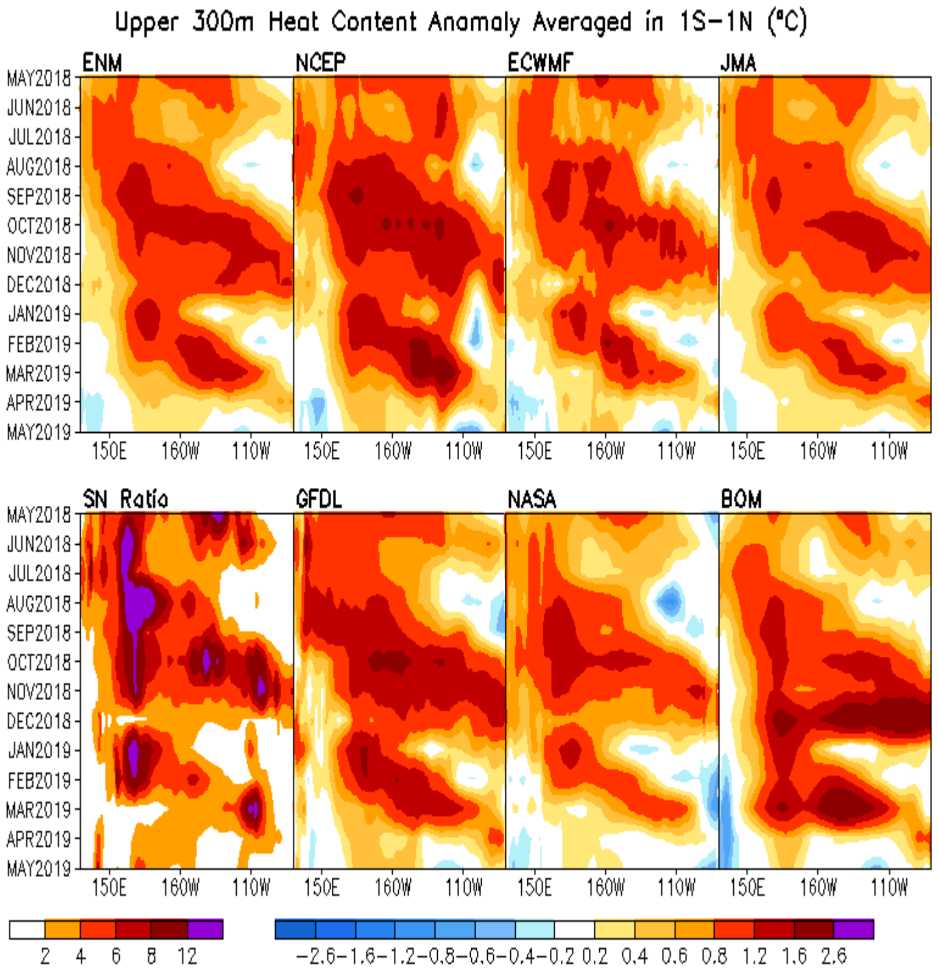
Current development and transition towards the new coupled prediction system:

- Coupled model: SPEAR
- MOM6 Ocean Data Assimilation (Feiyu Lu)
- FV3 Atmosphere Data Assimilation (Xiaosong Yang)

# Assimilation and observing system assessment

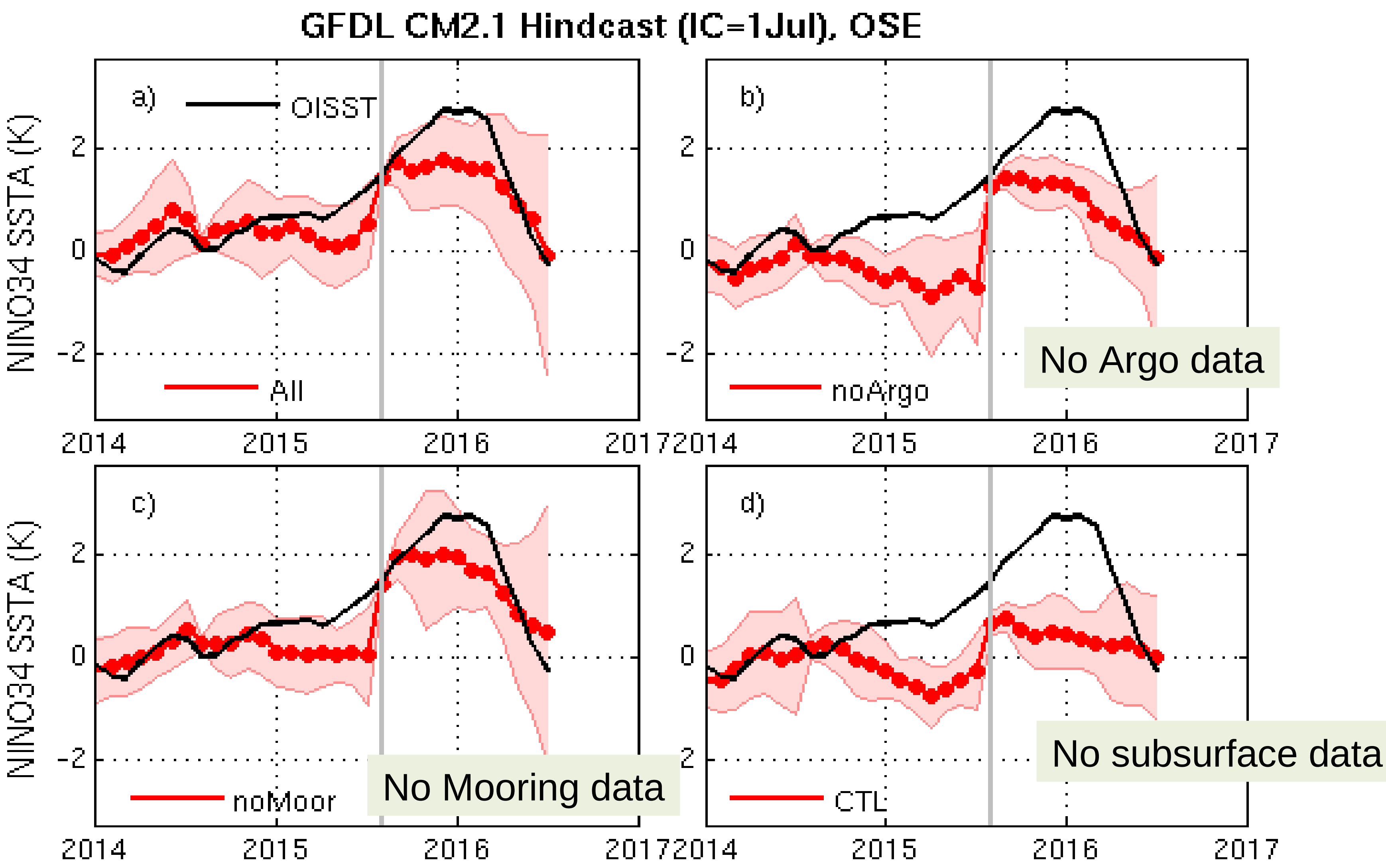
- **Real time prediction and state estimation**
  http://www.gfdl.noaa.gov/ocean-data-assimilation
- Real time multiple ocean reanalysis **intercomparison**
- **Observing system assessment** (*e.g.*, TAO & Argo evaluation OSE; TPOS-2020)
- **SLP Assimilation**: Towards a coupled climate reanalysis and initialization system

## Real-time ocean assessment




https://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html

# **Impact of ocean subsurface observations** on predicting the strong 2015/16 El Niño (Initial condition: 1July, from OSE)



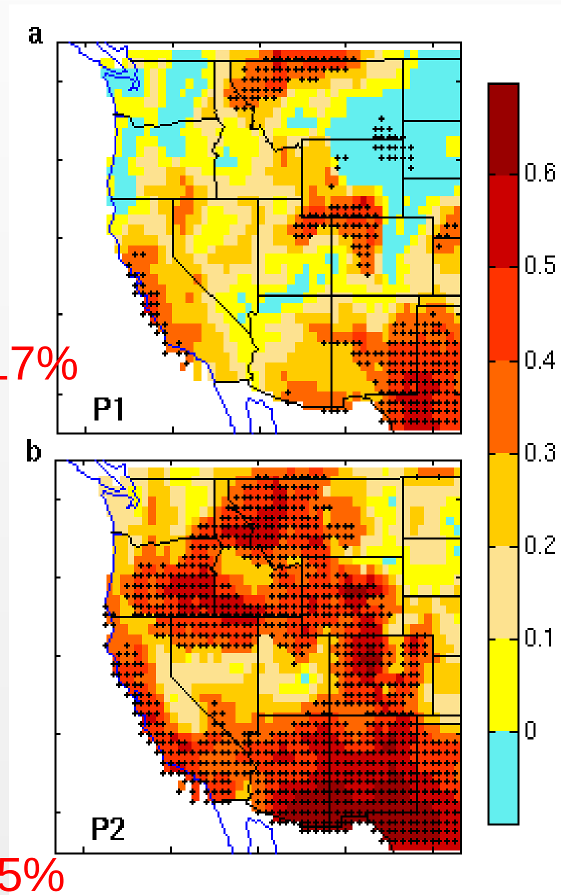
# Understanding sources of predictability for first-season prediction: Roles of atmosphere/land initialization

Winter precip skill

Winter T2m skill

Fcst
Ocean
Obs.
Ini.

Fcst
Ocean/
Atm/
Land
Obs. Ini.

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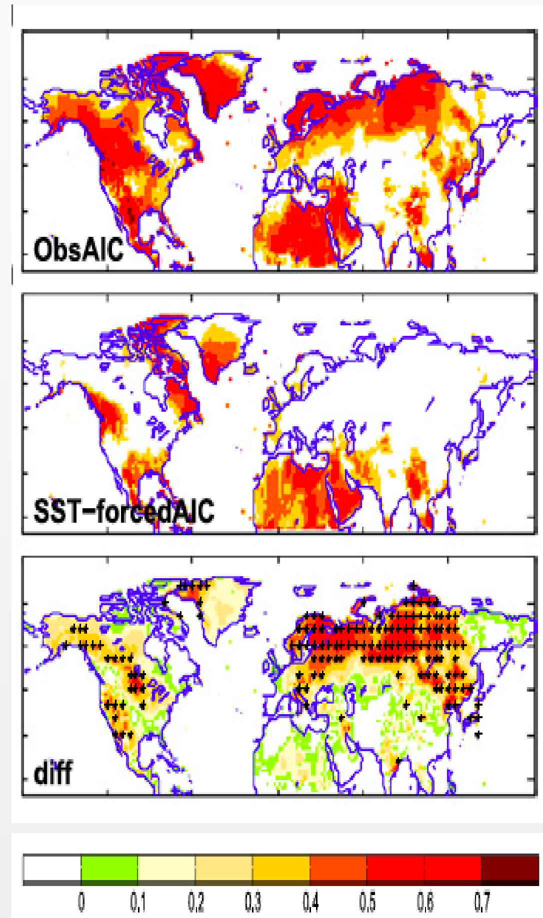
55%




Fcst
Ocean/
Atm/
Land
Obs. Ini.

Fcst
Ocean
Obs. Ini.

Diff.

The atmosphere initial condition plays an important role in predicting the unusual 2015/16 winter precipitation pattern over the western U.S.

Jia et al. (2017, J. Clim.)
Yang et al. (2018, Clim. Dyn.)

# Reserve Slides

# Selected accomplishments with CM2.1, FLOR, and HIFLOR

- **Simulation, prediction, attribution of hurricanes, including Cat 4/5** *(Murakami et al, 2015, J. Climate; 2016, 2017)*
- **Attribution of causes of 2017 Major Hurricanes in Atlantic** (Murakami et al, 2018, Science)

- **Seasonal sea ice prediction** *(Bushuk et al, 2017, Geophys. Res. Letters; 2017, J Climate)*

- **Improved seasonal prediction of temperature and precipitation with improved initialization** (Jia et al, 2016, J Climate; 2017, J. Climate )
- **Seasonal prediction of winter storminess** *(Yang et al, 2015, J. Climate)*
- **Western US snow pack** (Kapnick et al, 2018, PNAS)
  - Skill in predicting western US snowpack 8 months in advance
- **Western US precip, 2015/2016 ENSO** (Yang et al, 2018, Climate Dynamics)
  - Impact of initialization system on seasonal prediction of precipitation

- **Interannual to decadal prediction of Atlantic ocean temperature** (Yang et al., 2013, J. Climate)

- **Decadal predictability and prediction of Southern Ocean** (Zhang et al, 2017a, J. Climate; 2017b, J. Climate)
- **Causes of Southern Ocean trends in sea ice** (Zhang et al, 2018, Nature Climate Change)

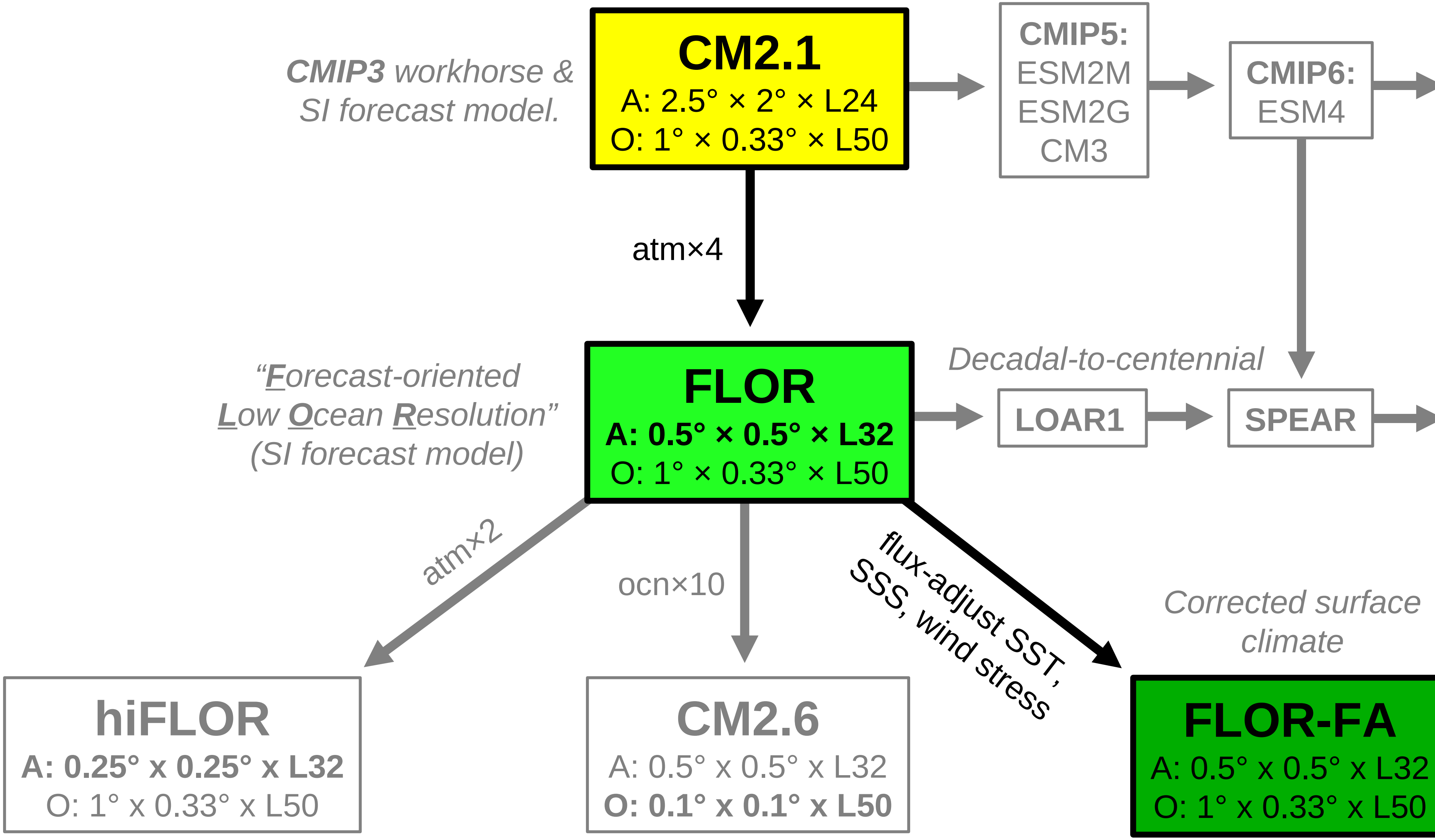
- **Projection & attribution of Arabian Sea tropical storms in response to anthropogenic forcing** (Murakami et al., 2017)
- Attribution of anomalous 2015 Pacific hurricane season (Murakami et al., 2017)

- **Multi-decadal projection of US & Global Hydroclimate** (Zhang and Delworth, 2018a, 2018b)

- **Seasonal to decadal biogeochemical prediction** (Park et al., 2018, Climate Dynamics)

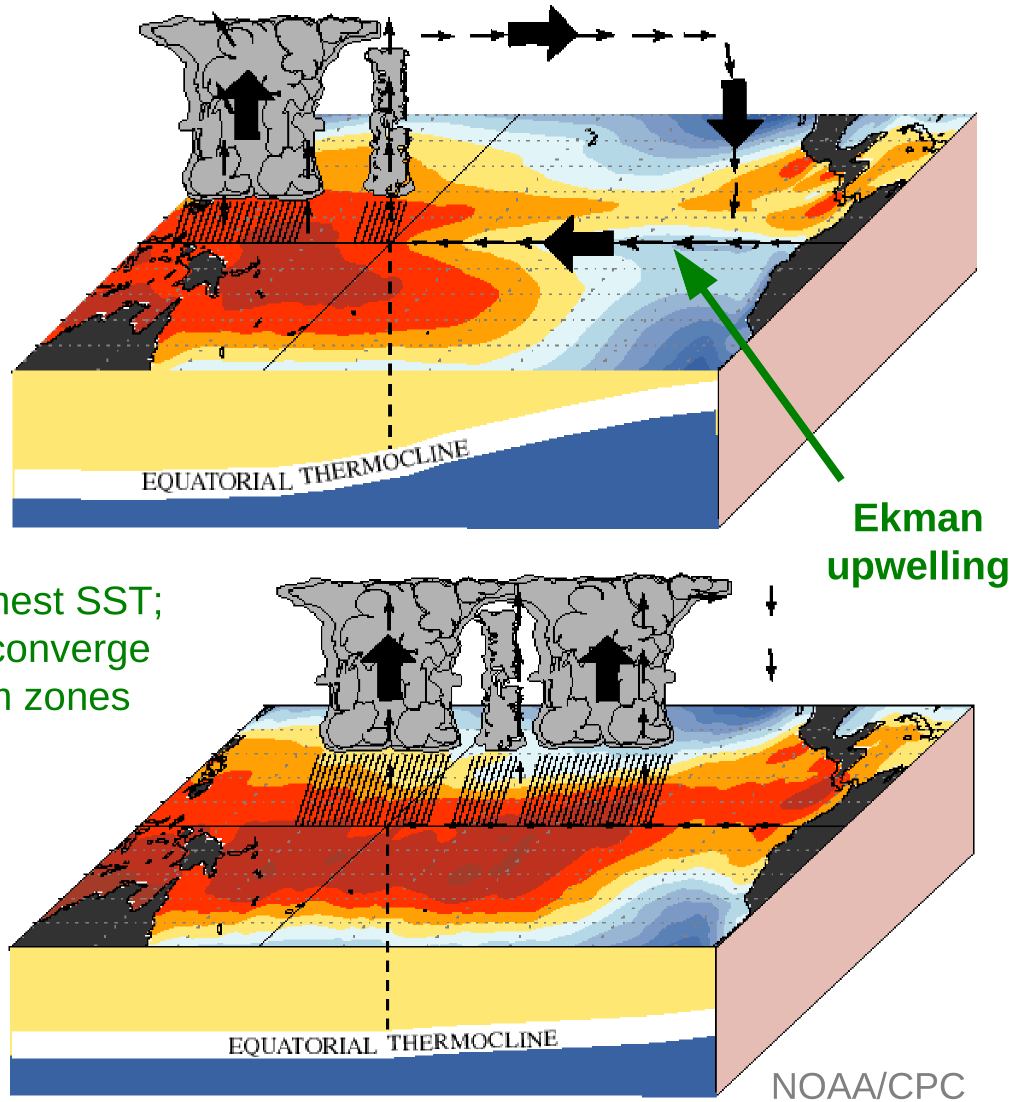
See https://www.gfdl.noaa.gov/bibliography/
for searchable database of GFDL papers

# GFDL coupled GCM development




***FLOR connects many of GFDL's newest climate models,***
*and is used extensively for seasonal-to-interannual research and forecasts.*

# Earth's dominant interannual climate fluctuation:




**Normal**

**Asymmetric:**
cold tongue, warm pool;
ITCZ north of equator;
**easterly** trade winds;
sea level slopes **up** to west,
thermocline **down** to west

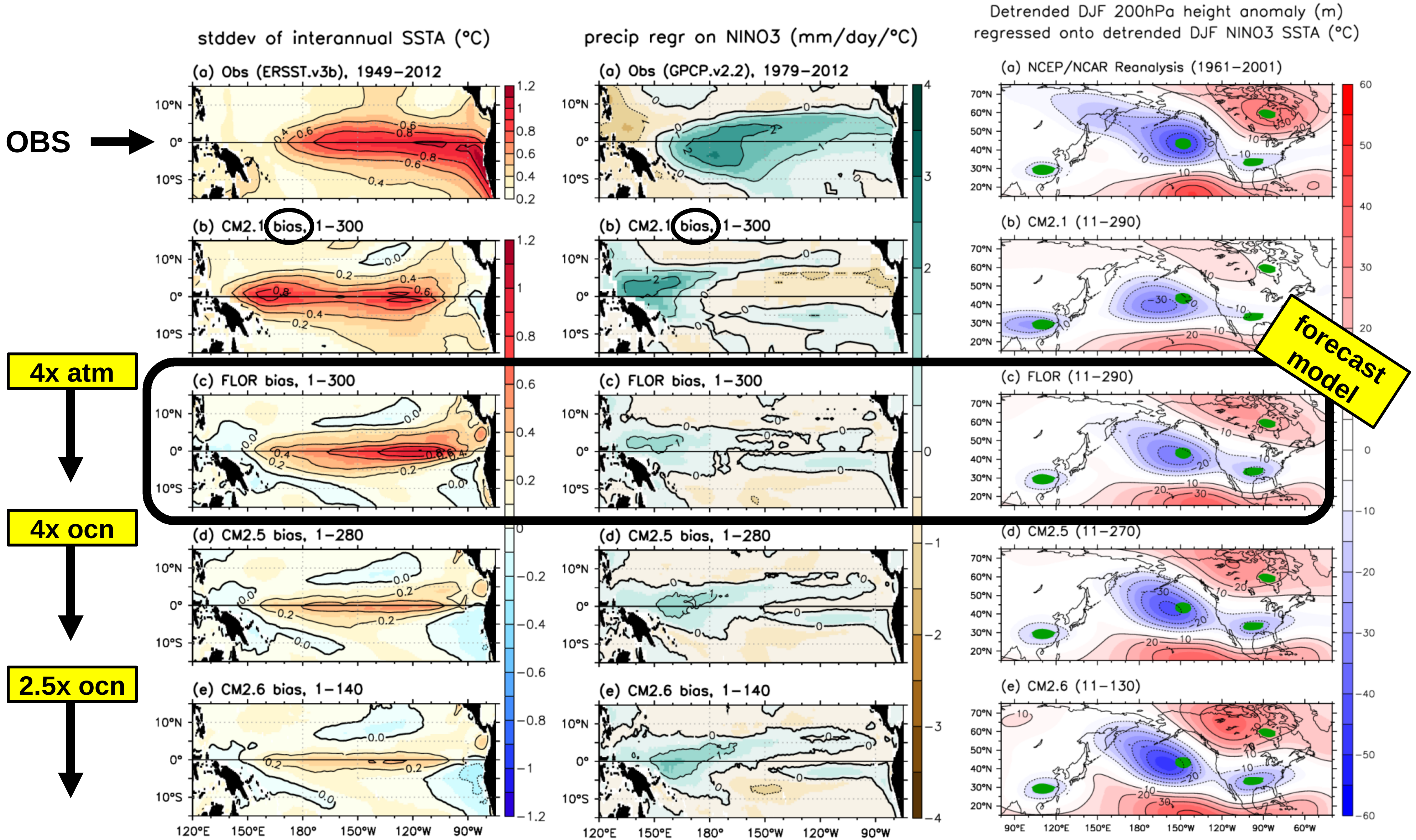
**rain** follows warmest SST;
**surface winds** converge
onto rainy/warm zones

**El Niño**

Events occur at
irregular intervals (2-8yr);
peak around Nov-Dec;
last about a year;
often followed by La Niña

Fundamentally coupled phenomenon,
involving troposphere + top 300m of the tropical Pacific ocean.

# ENSO improvements with increasing resolution



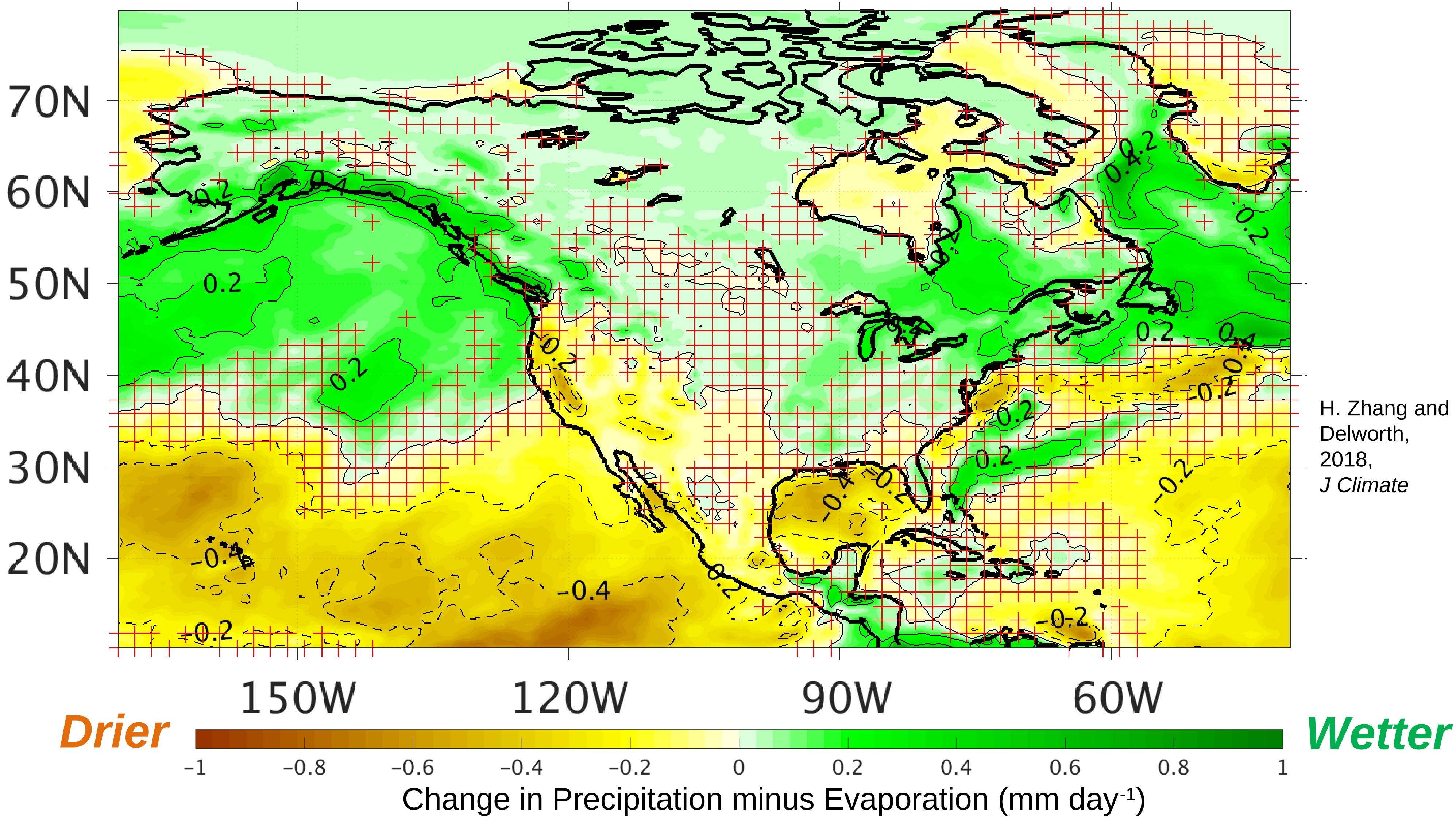

Delworth et al. (2012); Vecchi et al. (JC 2014); Jia et al. (JC 2015); Wittenberg et al. (JAMES 2018)

# Projecting decadal scale changes in North American Hydroclimate

**Key goal:** **Probabilistic assessment** of decadal changes in weather extremes over North America

- *Precipitation extremes and water resources, especially over North America*
- *Characteristics and impacts of changing tropical and extratropical storms*
- *Snowpack and western water resources*

*Projected change in P-E (winter, for decade of 2030s) using large ensembles with FLOR*



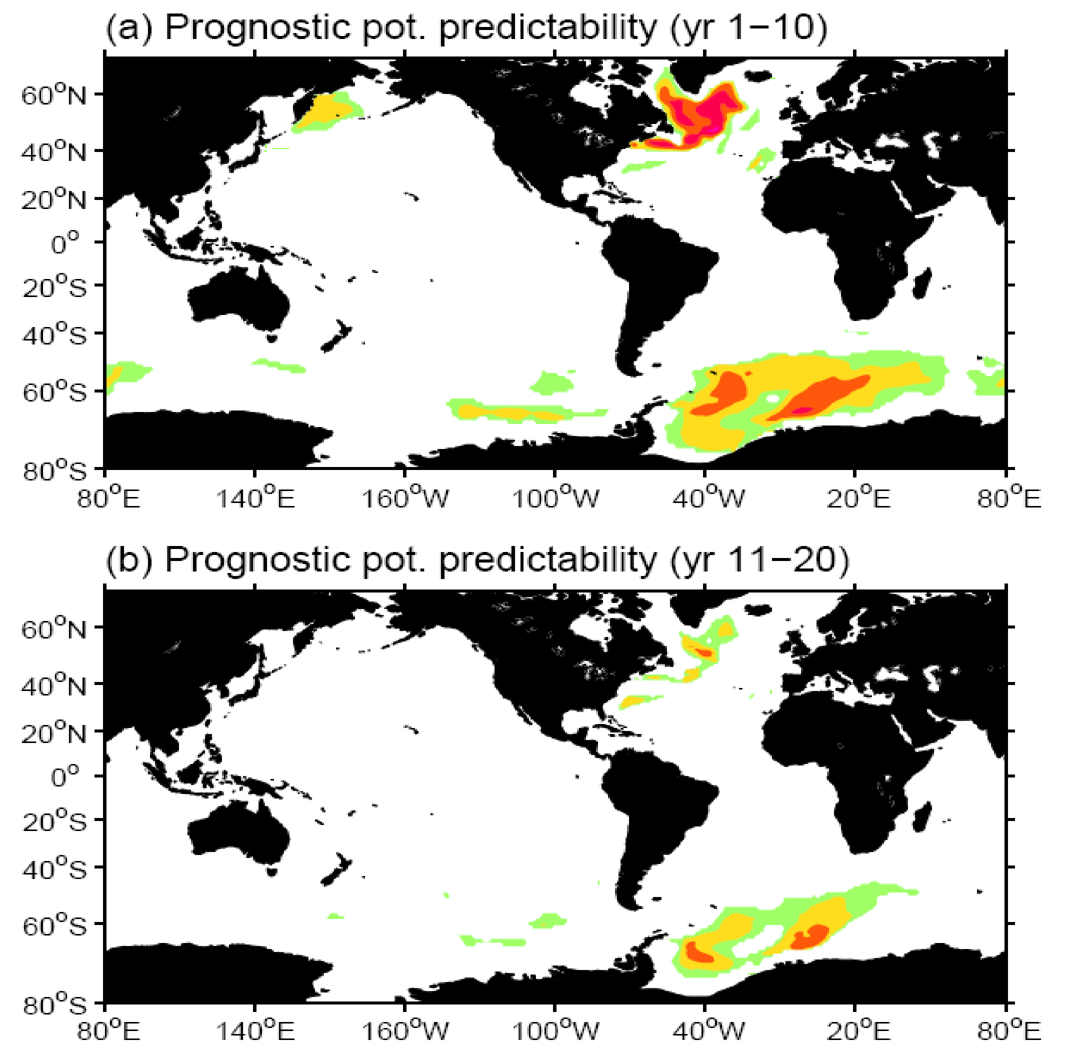

H. Zhang and Delworth, 2018, *J Climate*

There are a number of phenomena with decadal predictive skill from internal variability:

1. Atlantic Ocean surface and subsurface temperature (AMOC, ocean circulation)

2. Pacific Decadal Oscillation (less predictable than North Atlantic)

3. Southern Ocean – potentially predictable on long time scales



# TRADEOFFS: Building the best prediction system given available computing resources

| | *Base Case* | *Alternative Reforecast Characteristics* | *Alternative Computer Resource Options* | |
|---|---|---|---|---|
| | COMPUTER: 10% of GAEA[1]<br>DURATION: 30 reforecast yrs<br>START MONTHS: 12 per yr<br>ENSEMBLE MEMBERS: 30 | COMPUTER: 10% of GAEA[1]<br>DURATION: 20 reforecast yrs<br>START MONTHS: 12 per yr<br>ENSEMBLE MEMBERS: 20 | COMPUTER: 40% of GAEA[1]<br>DURATION: 30 reforecast yrs<br>START MONTHS: 12 per yr<br>ENSEMBLE MEMBERS: 30 | COMPUTER: 40% of GAEA[1]<br>DURATION: 30 reforecast yrs<br>START MONTHS: 4 per yr<br>ENSEMBLE MEMBERS: 30 |
| ***100 km*** | 2.1 | 0.9 | 0.5 | 0.2 |
| ***50 km*** | 7.4 | 3.3 | 1.8 | 0.6 |
| ***25 km*** | 47.6 | 21.2 | 11.9 | 4.0 |

The table above shows how long it would take (in months) to complete a reforecast suite for three resolutions of an atmospheric model (*100* km, *50* km, and *25* km) coupled to a 1° ocean model. The different columns make different assumptions about either the characteristics of the reforecast suite (duration of the reforecast, start months, or ensemble members) or the available computational resources to understand the viability of reforecast selections. Based on experience, a set of reforecasts that would take *5* or more months is not viable (these boxes are shaded in red). Such a long process would not allow for the normal iterative process that is necessary in the development of models and prediction systems. A box shaded in yellow is at the margins of viability.

The "Base Case" assumes 10% of the NOAA GAEA supercomputer system is used for a full suite of reforecasts producing *10,800* model simulation years.

An "alternative reforecast suite" (20 ensemble members and 20 years of reforecasts) makes a 50 km viable in addition to the 100 km model. Altering computer resources (rightmost columns) and limiting the number of start months to quarterly improves the viability of higher resolution models.

NOAA currently allocates 74 million CPU hours per month on the GAEA supercomputer. In this document we refer to 100% of GAEA as 74 million CPU hours per month.

[1]*NOAA currently allocates 74 million CPU hours per month on the GAEA supercomputer. In this document we refer to 100% of GAEA as 74 million CPU hours per month.*