Global Modeling of the Coupled Earth System: Understanding and Predictions

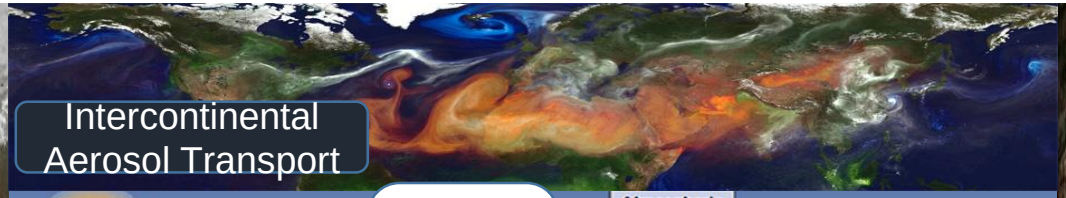
XIX Meeting of Graduate Students in Meteorology (EPGMET)
National Institute of Spatial Research (INPE)

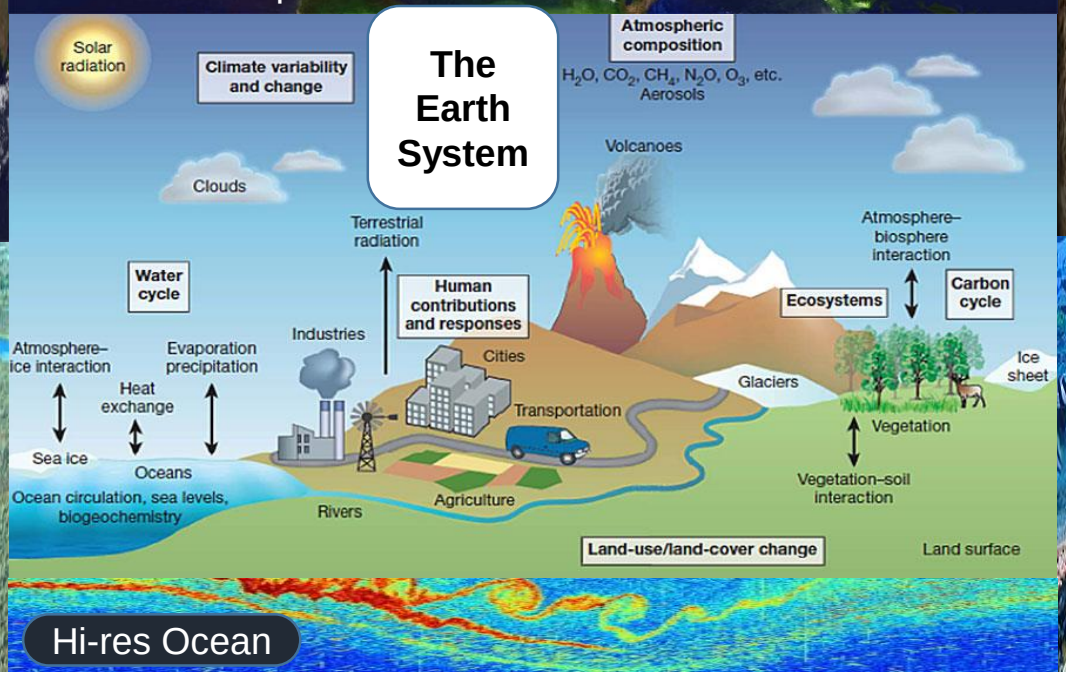
V. Ramaswamy

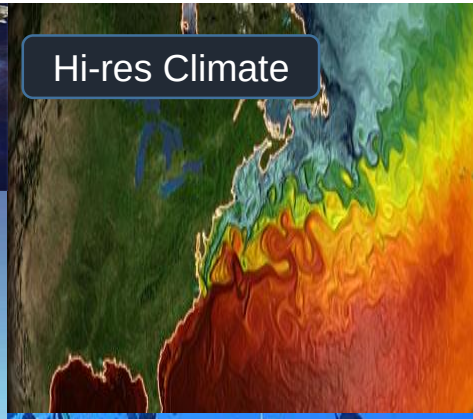
Geophysical Fluid Dynamics Laboratory

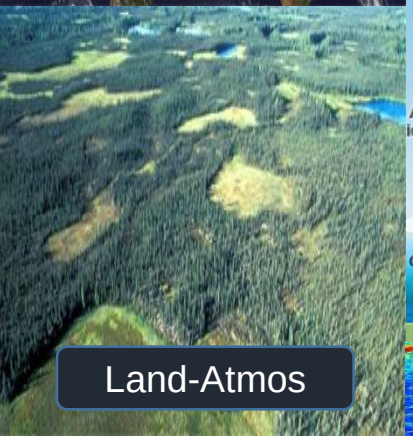
Modeling, Understanding and Predicting the Earth System

NOAA/OAR/GFDL: *An Integrative Modeling Strategy*









Atmosphere, Oceans, Land, Ice, & Ecosystems

Modeling Essentials

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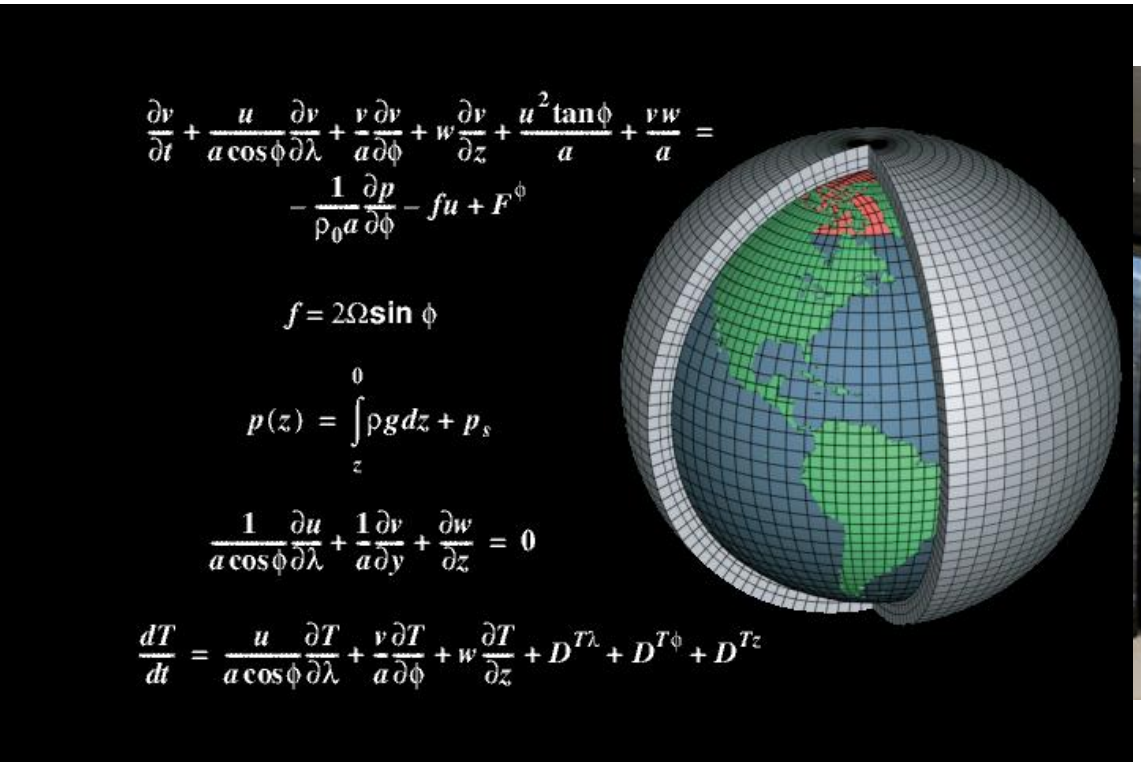
High-Performance Computing

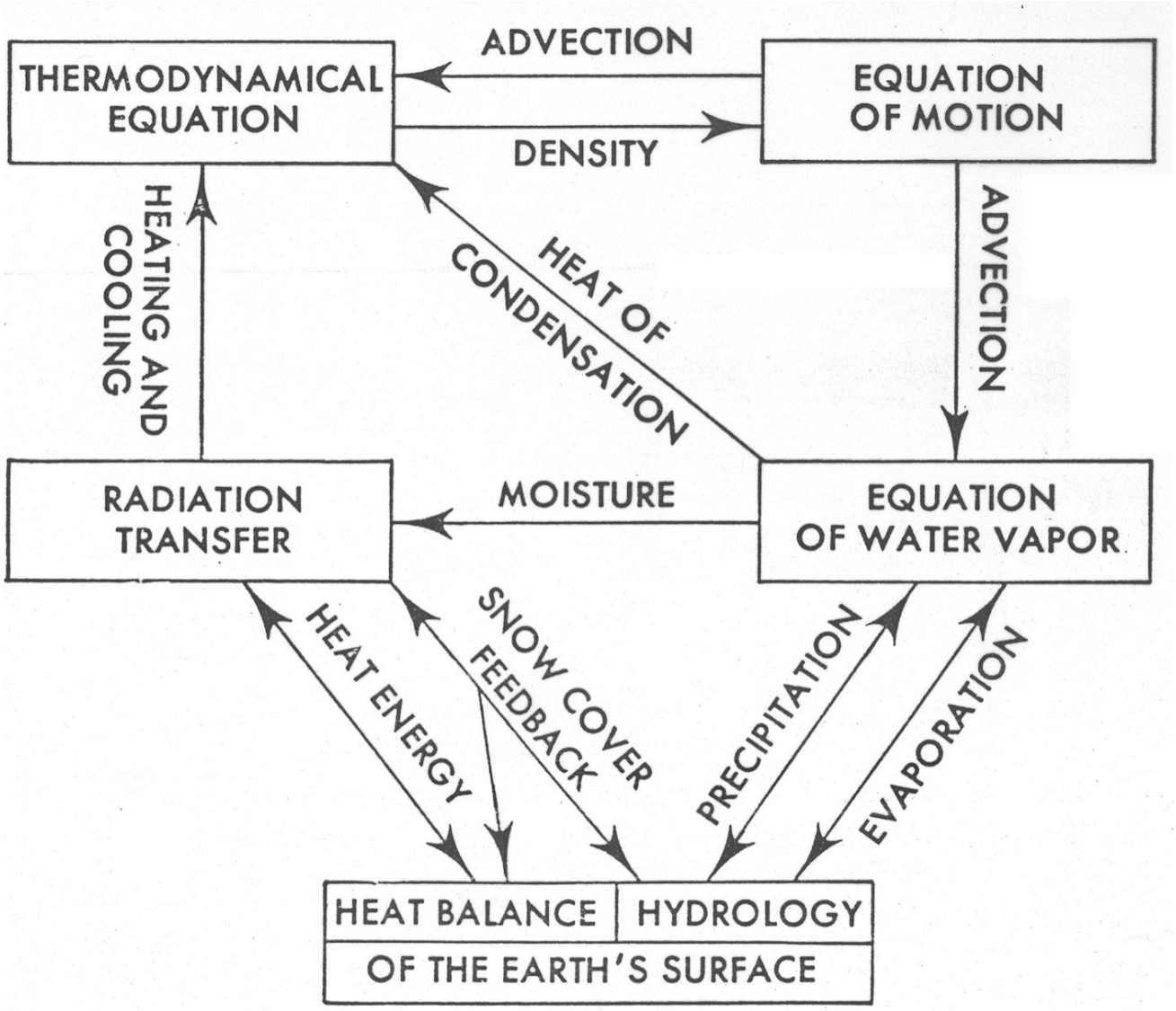
Major advancements in Weather & Climate science have come about through mathematical modeling of the Earth System on High-Performance Computers



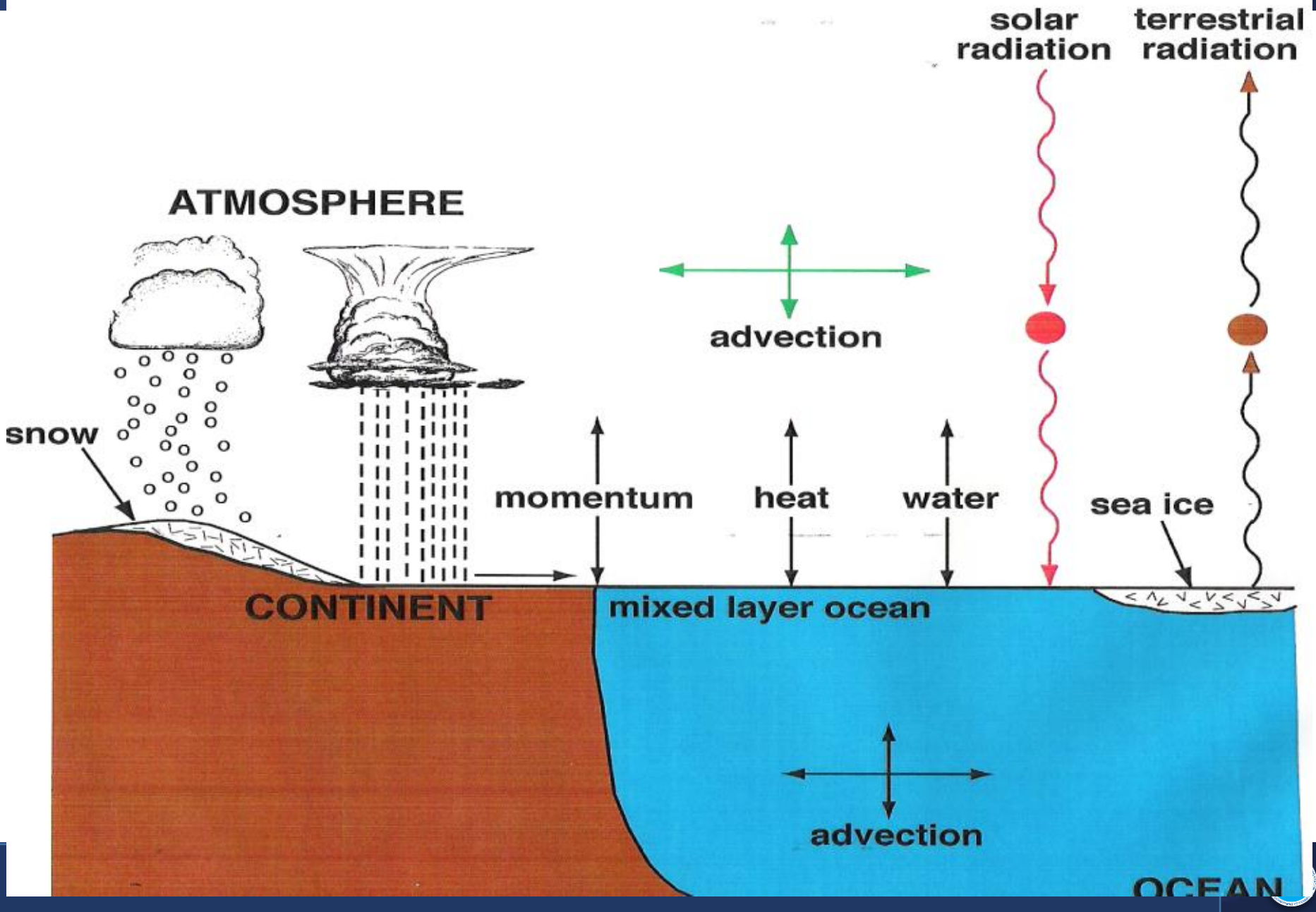
original image source: NOAA -GFDL

source: ncrc.gov (a NOAA/DoE partnership)

Governing Processes



Physical climate: Coupled atmosphere-ocean-land-ice system



Atmosphere & Weather

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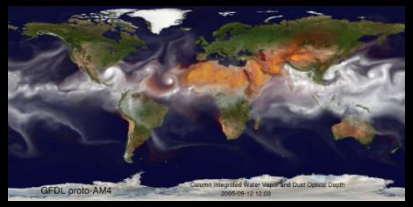
Unified Weather-Climate Prediction System

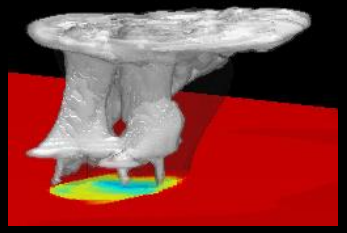


50-km GFDL-AM4

global

GFDL FV3

Regional



1-km GFDL "Super HiRAM"

Grid-stretching and nesting capabilities

Goals:

- To develop a unified modeling system for weather and climate simulations
- To unify regional (convective-scale) and global modeling systems

- July 2016:
  NOAA selected FV3 (Finite-volume core on the Cubed-Sphere) for NGGPS (Next Generation Global Prediction System)

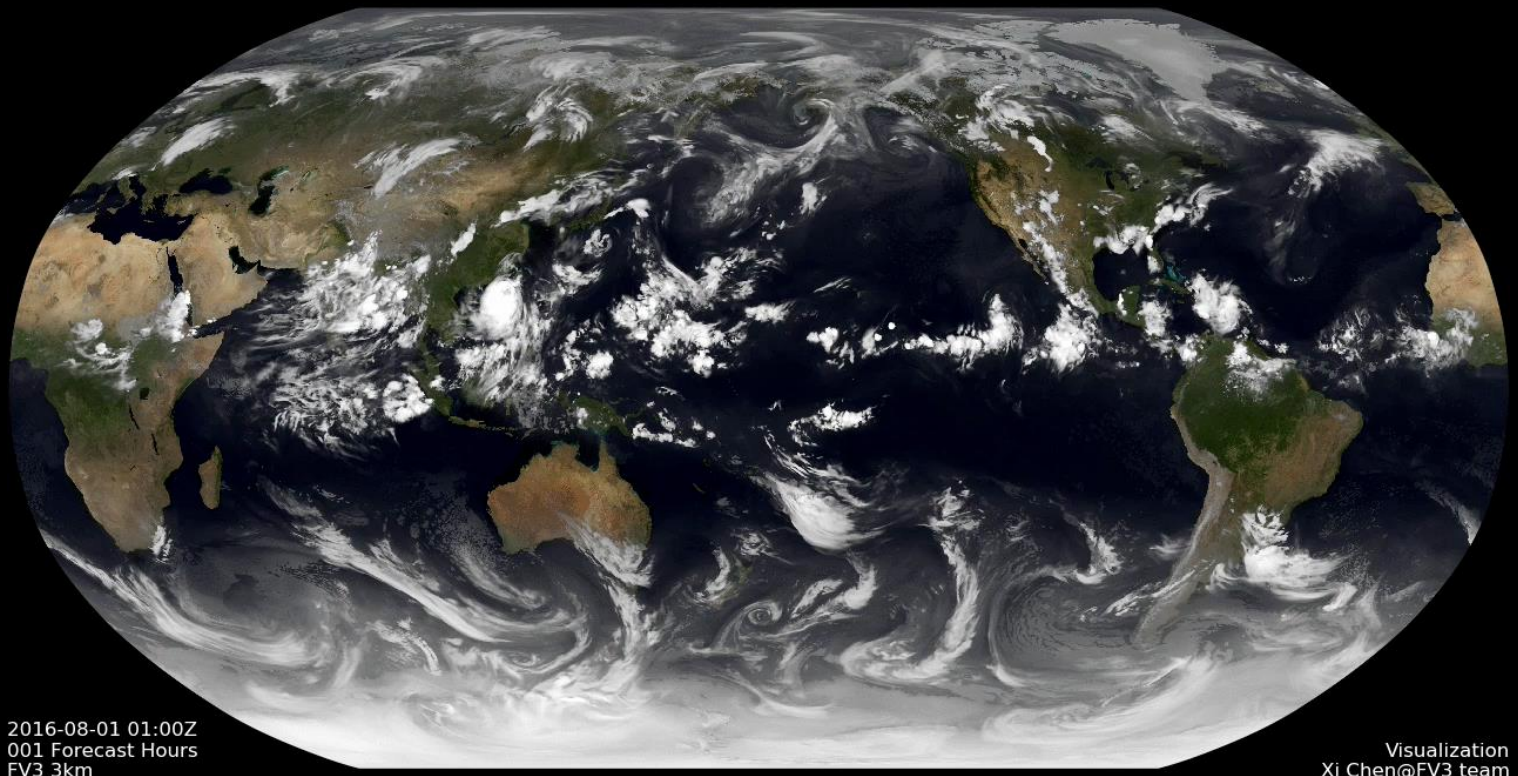
- June 2019:
  NWS operational forecasts with the "GFSv15" (with FV3 dy-core)

Credit:
S. J. Lin

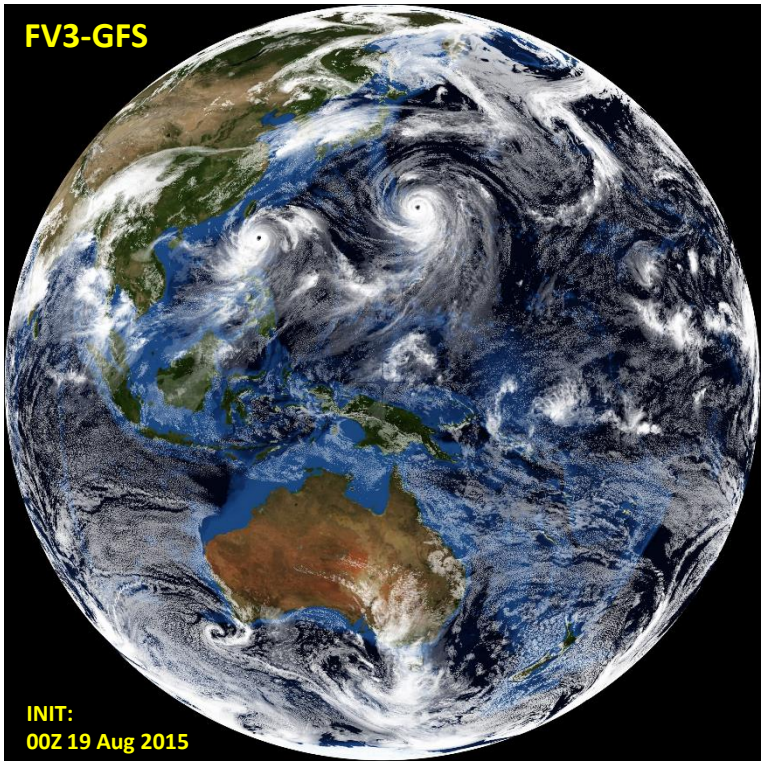
Frontiers in Weather-to-Climate Modeling

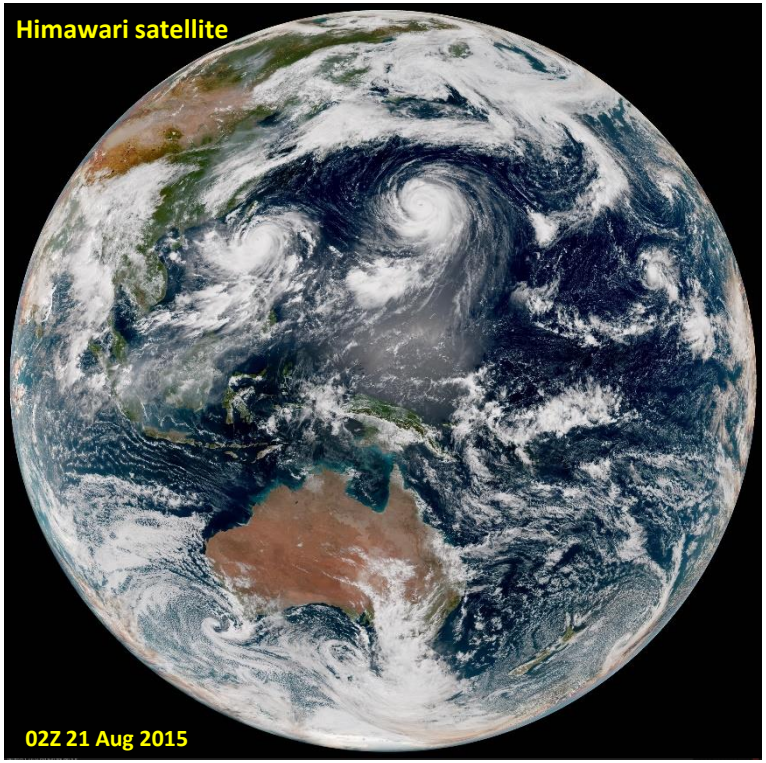
Feasibility, Fidelity, and Forecast accuracy of FV3-based global cloud-resolving model for weather, medium-range, subseasonal, seasonal, annual, decadal

OLR: 40-day prediction experiment (2020 FV3 prototype, 3-km, $\Delta t = 225\ sec$)



FV3-powered GFS for regional-global predictions



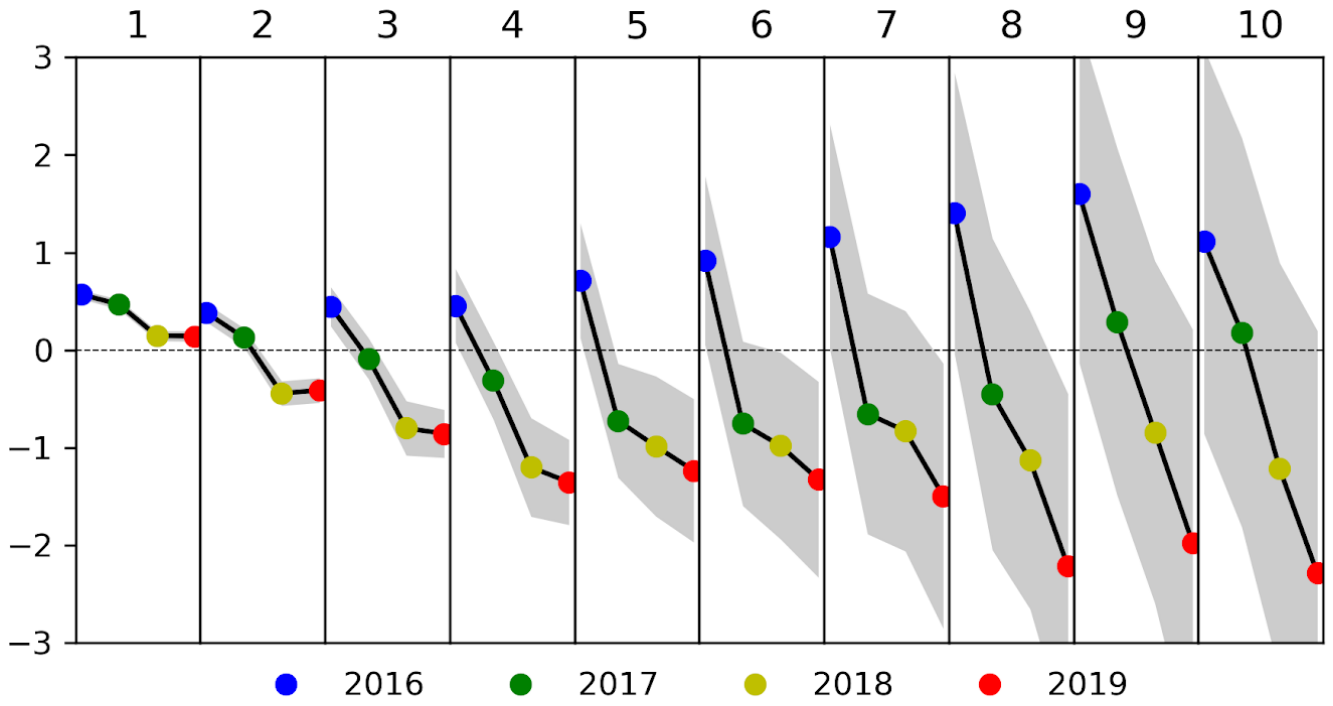


NOAA Forecasts: Evolution of improvements

Incremental improvements in FV3 and Physics

2016	2017	2018	2019	2020
Tuned NGGPS GFS Physics	GFDL Cloud Physics EMC SA-SAS	Inline GFDL MP Pos-Def Advection YSU Turbulence Mixed-layer Ocean	Updated FV3 Revised GFDL MP URI-GFDL Sea State	Overhauled GFDL MP New cloud-radiation UW-EMC Turbulence

Northern Hemisphere 500-mb height RMSE vs. Legacy GFS
m, lower is better

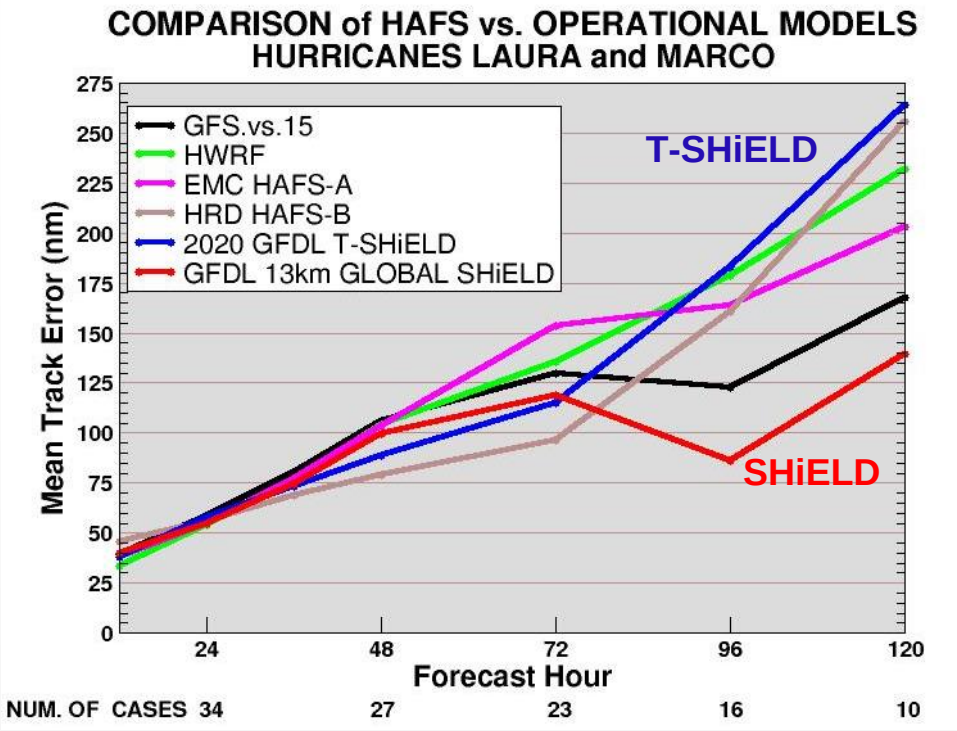


Year-over-year reduction in 500-mb forecast error

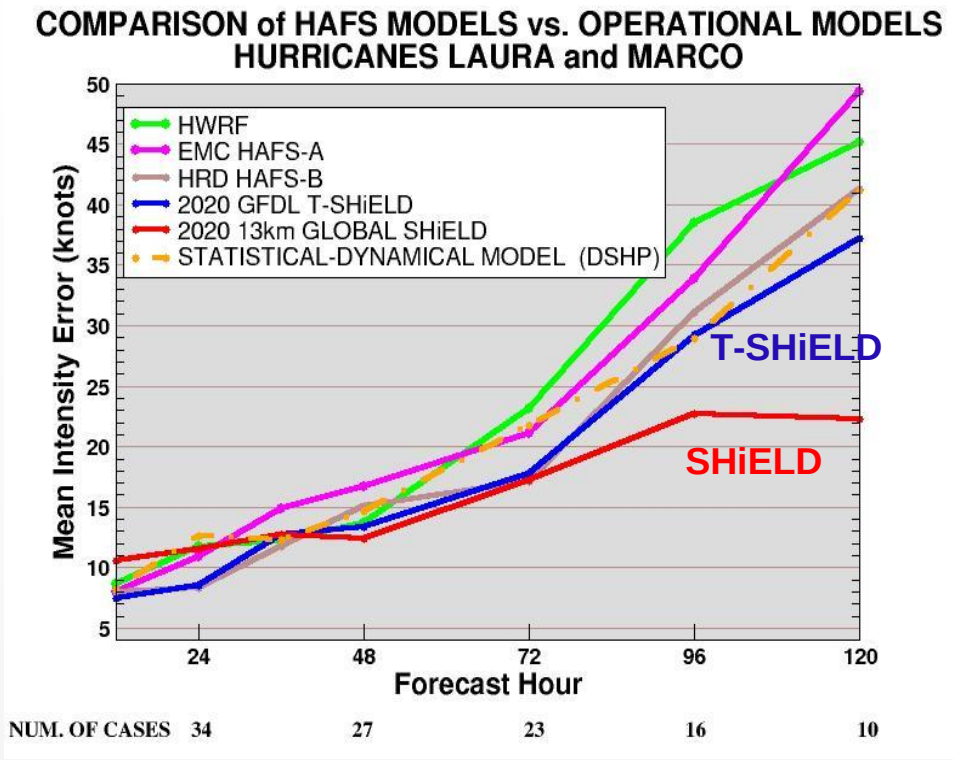
Courtesy Linjiong Zhou; Harris et al, 2020, JAMES

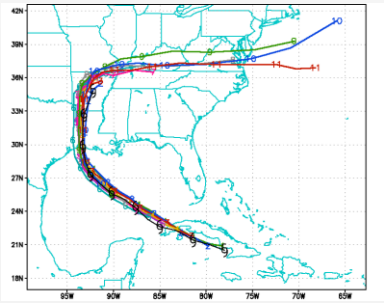
Hurricanes Laura and Marco

Model Track Error



Model Intensity Error





3-km T-SHiELD struggled early but was excellent after Laura passed Cuba.

Better Initialization

J-H Chen et al. 2019; M Tong et al. 2020

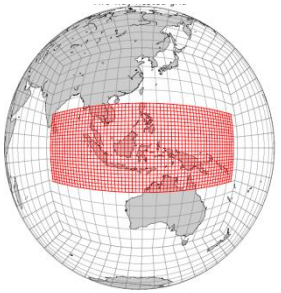
\+ Better Models

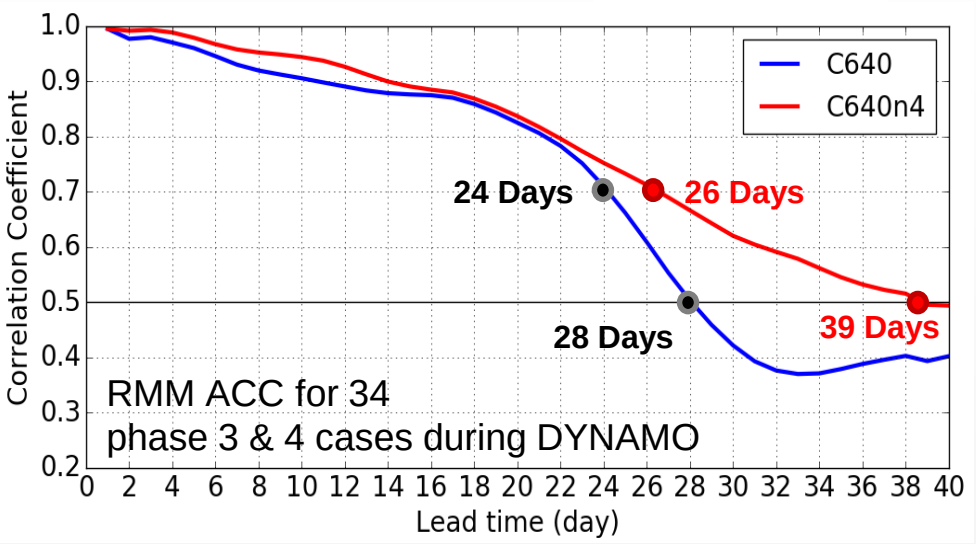
Better Forecasts!

See real-time forecasts at shield.gfdl.noaa.gov

Efficient Convective-Scale S2S

4-km nested TL-SHiELD



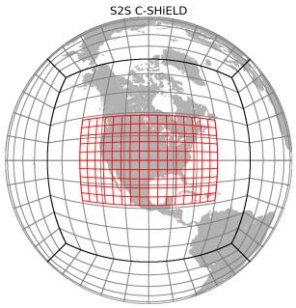


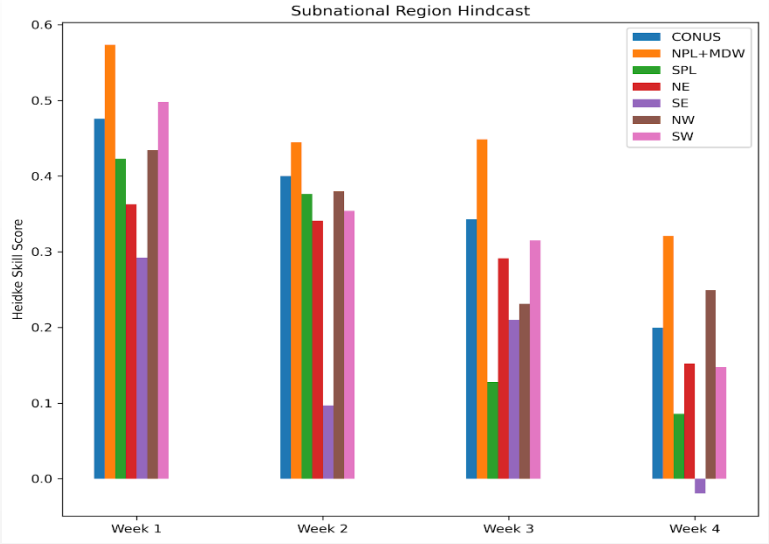
4-km Maritime Continent Two-Way Nest improves predictability and propagation of MJO compared to **16-km uniform**
Simple mixed-layer ocean is a must

➤ 40 days in 8 hours with 4K cores

Courtesy Kun Gao

5-km nested CL-SHiELD





HSS for explicitly-simulated severe weather activity (30 days, March—June) in CL-SHiELD 10-member ensemble

➤ 30 days in 8 hours with 2112 cores

Courtesy Kai-Yuan Cheng

Oceans

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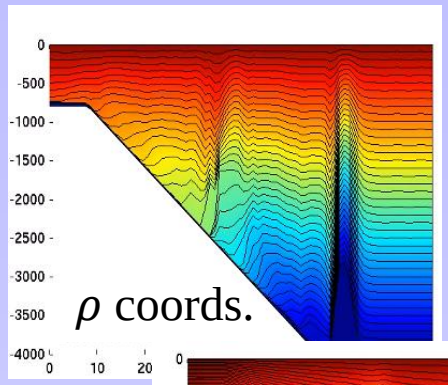
The MOM6 ocean model

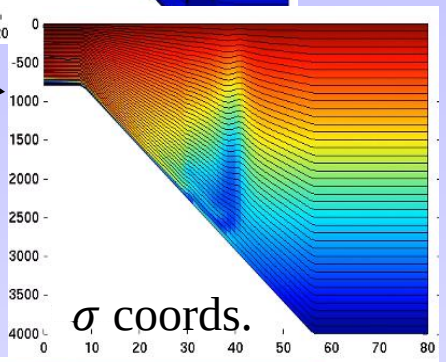
Community ocean model rooted in climate modeling
- Structured C-grid, Finite Volume Core
- Global climate modeling focus; Processes oriented origins
- Hydrostatic Primitive Equations
- Conservative, including wetting & drying (ice shelves)

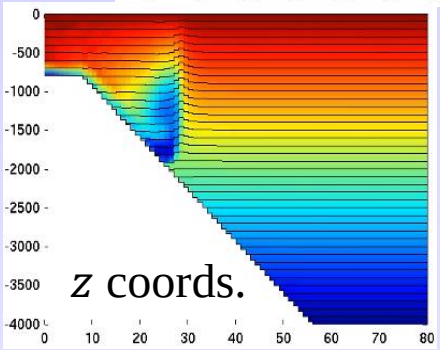
Vertical Lagrangian Remap Method (VLR)
- General vertical coordinates
- No vertical CFL limit on timesteps/resolution
- Reduces numerical diapycnal mixing for some coordinates
- Efficiencies for biogeochemistry & passive tracers

Comprehensive set of physical process parameterizations
- Required for climate model projections into unobserved states
- Moving toward energetics-based formulations of params.

Many capabilities resulted from extensive collaborations
- 5 NSF/NOAA sponsored Climate Process Teams
- CVMix shared NCAR/GFDL/LANL vertical mixing code
- CLIVAR CORE/OMIP ocean-climate model comparisons
- Joint development with NCAR, NOAA/EMC, Universities, …





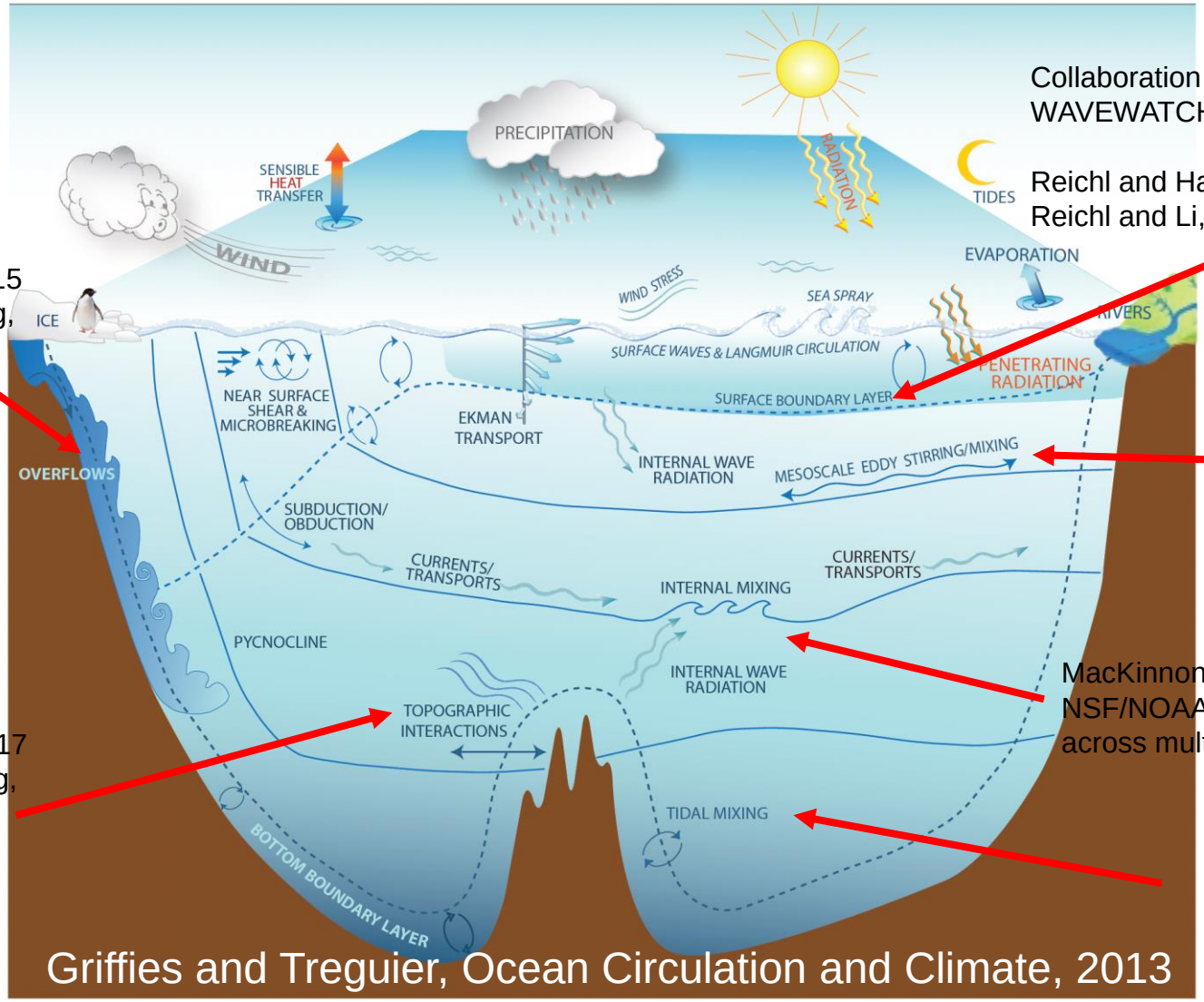


Embedding SIS2 sea-ice & GFDL icebergs in MOM6

Free Community Open Development with deliberate ocean model software design

Design drew upon experience from MOM4/5, MITgcm, HIM, GOLD, Poseidon, …

Submesoscale Ocean Processes are Crucial for Ocean Modeling and Future Predictions and Projections



Griffies and Treguier, Ocean Circulation and Climate, 2013

Collaboration with NCEP/EMC on WAVEWATCH III-MOM6 coupling

Reichl and Hallberg, OM, 2018
Reichl and Li, JPO, 2019

Wang et al. OM, 2015
Yankovsky and Legg, JPO, 2019

Jansen et al. OM, 2015a,b

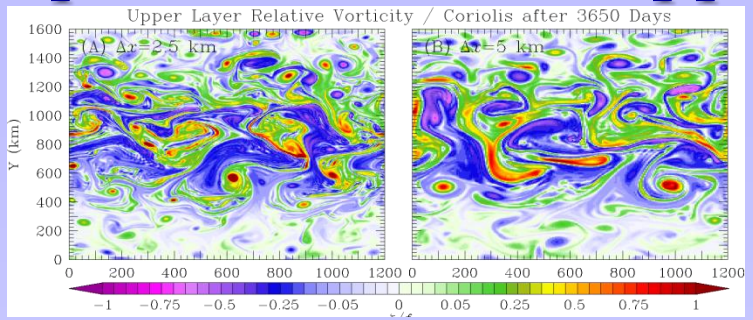
MacKinnon et al. BAMS, 2017
NSF/NOAA funded CPT effort across multiple institutions

Yi et al. Fluids, 2017
Nazarian and Legg, OM, 2017a,b

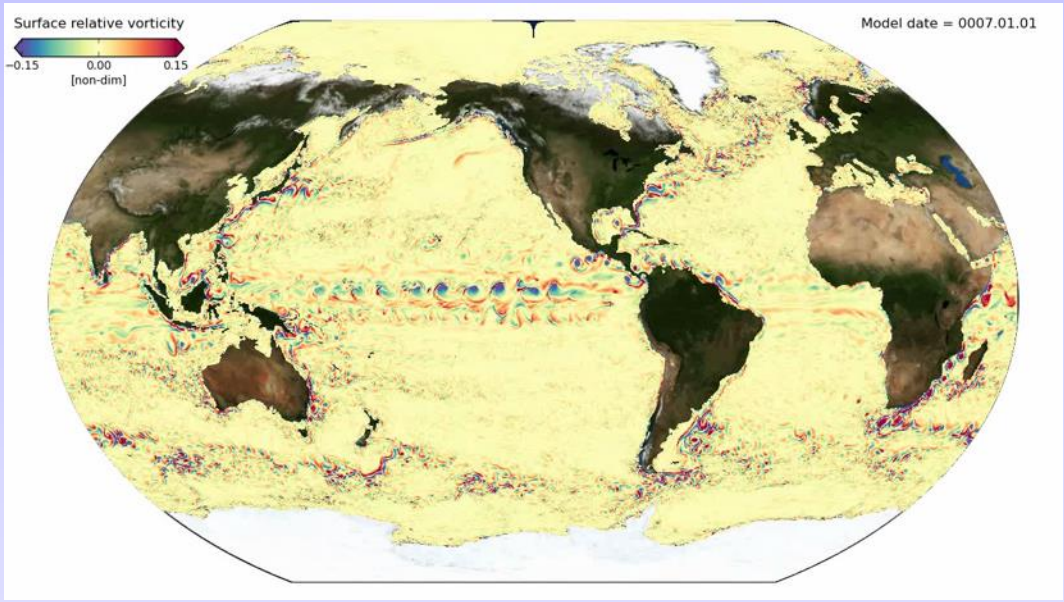
Melet et al. JOC, 2016

Examples of Important MOM6 Applications

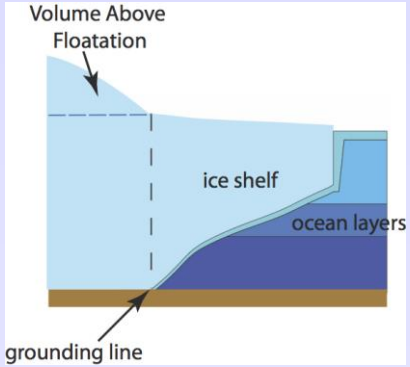
- Idealized process studies
- GFDL's ESM4/CM4, SPEAR coupled models
- Ice-sheet ocean interactions
- NCAR CESM3
- Australian COSIMA Consortium
- Regional configurations for fishery management
- NOAA/NCEP CFS-v3 coupled seasonal forecasts
- U.S. Navy HYCOM successor in near-term forecasts (~2025?)



Vorticity in study of resolution dependent eddy params. Hallberg (2013) *Ocean Modelling*



Surface Vorticity in CM4 prototype Adcroft et al. (2019) *JAMES*

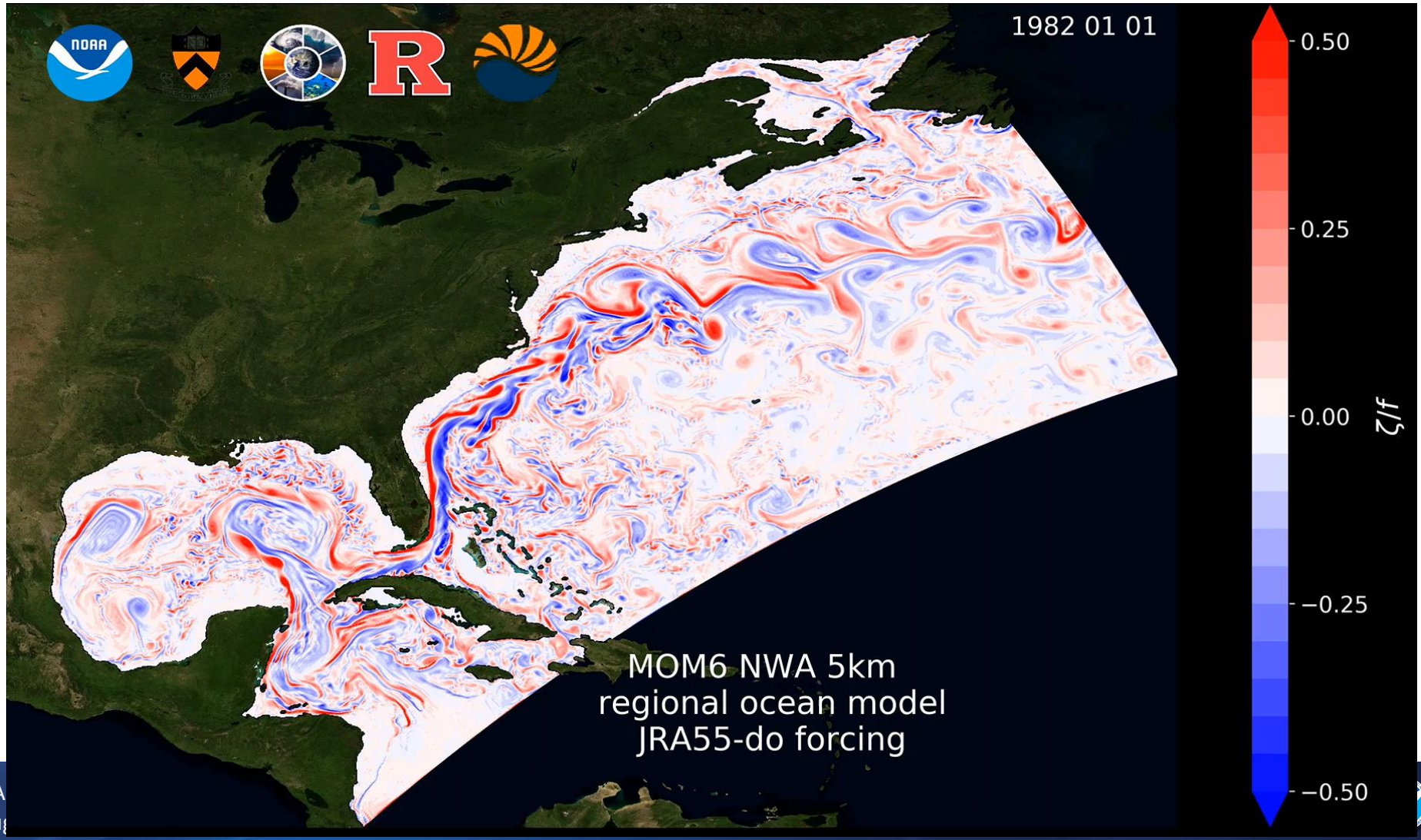


Schematic illustration of dynamically coupled ice-sheet & ocean models. Goldberg et al. (2012) *J. Geophys. Res.*

Future directions: MOM6 regional modeling

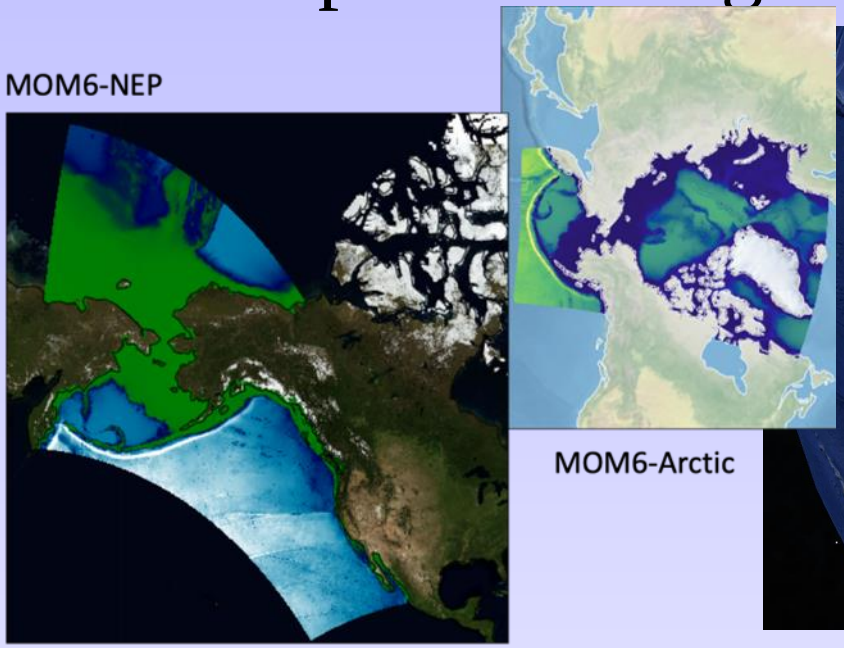
- Regional climate impacts / Process studies / Hi-res development
- Exploratory development in collaboration with Rutgers group

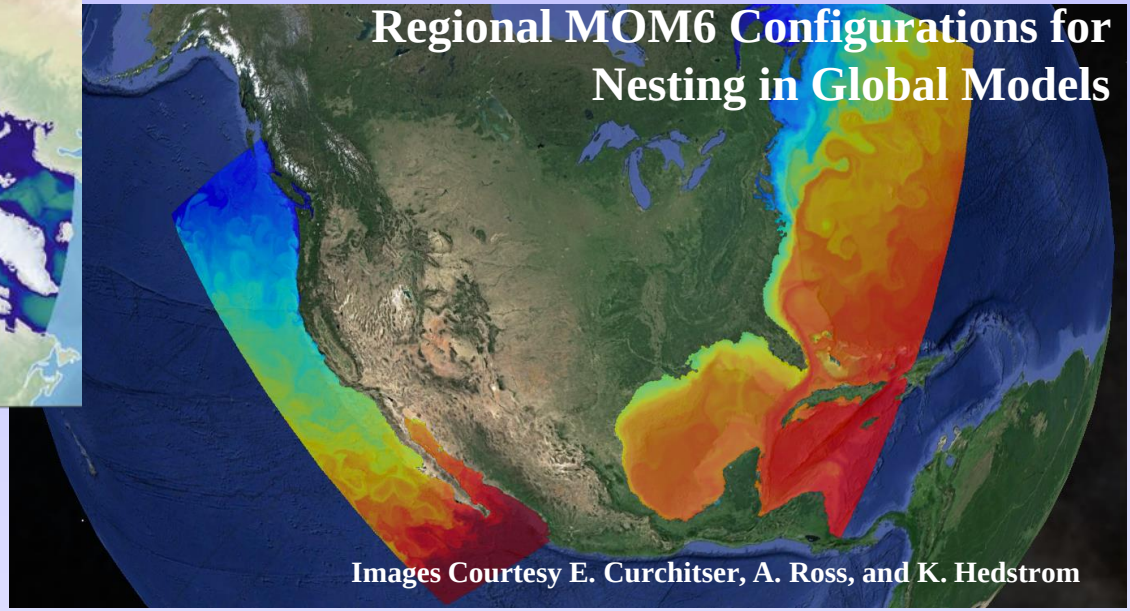
Courtesy Alistair Adcroft



Using MOM6 for Regional Modeling

- Regional models permit much finer resolution than is practical in global configurations.





- The MOM6 algorithm offers advantages & efficiencies for Earth System Models with multiple bio-geo-chemical fields.
  - The same advantages apply to regional ecosystem models.
  - A regional modeling community has developed around MOM6 with NOAA-Fisheries Support and broader interest.

Land and Ecosystems

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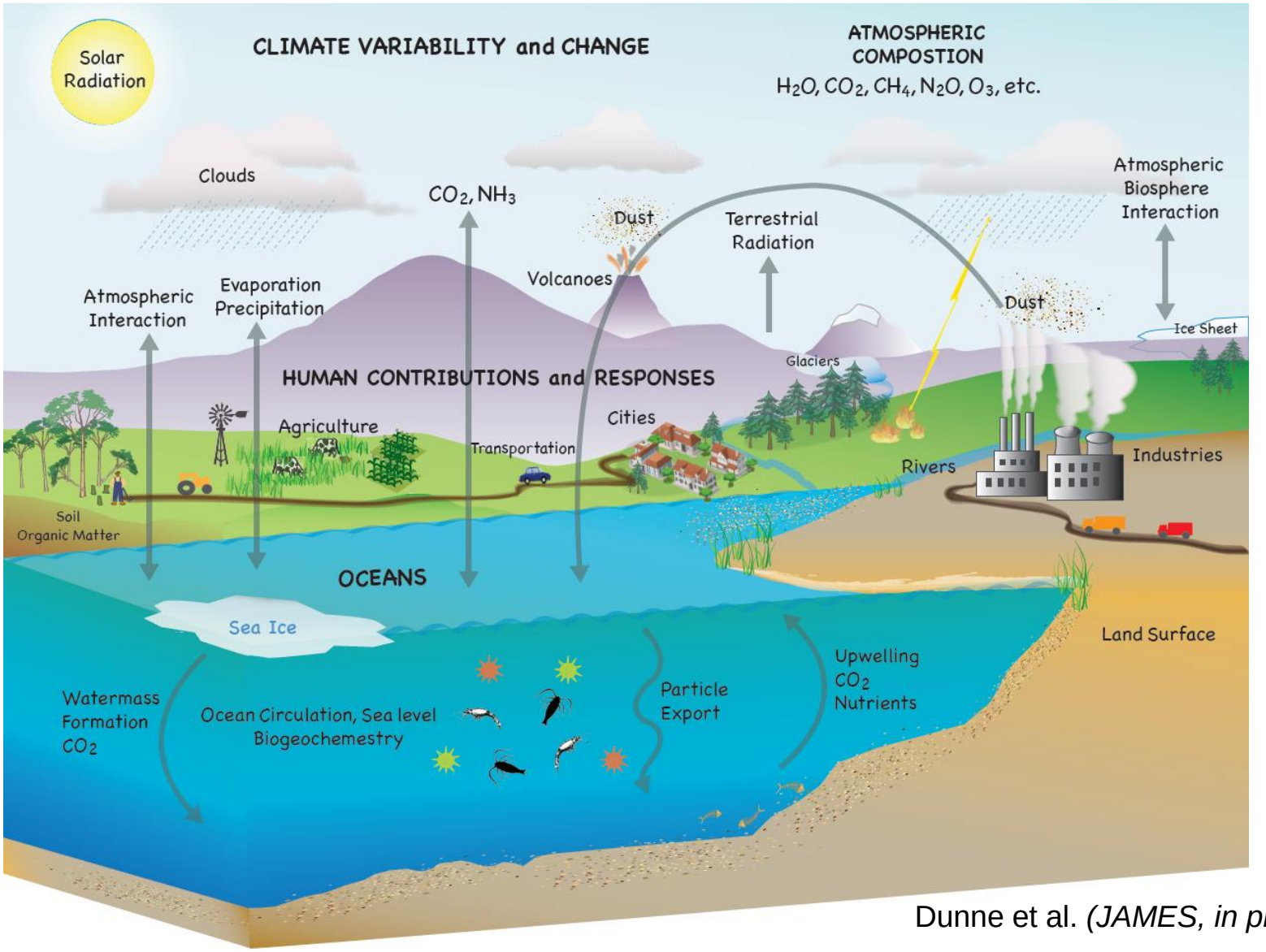
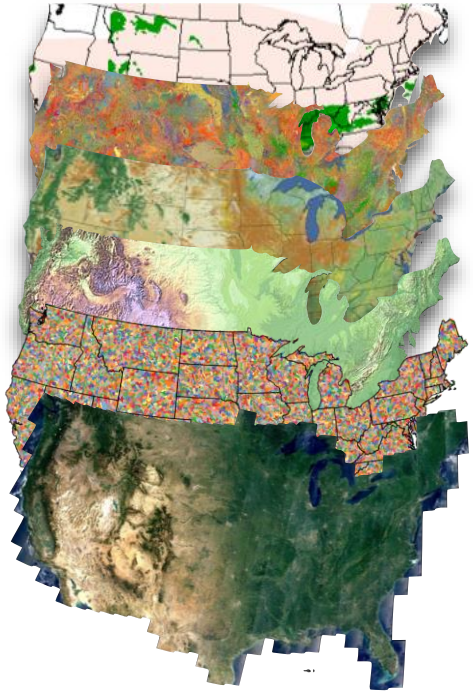
NOAA/OAR/GFDL 4th Generation Coupled model, ESM4.1



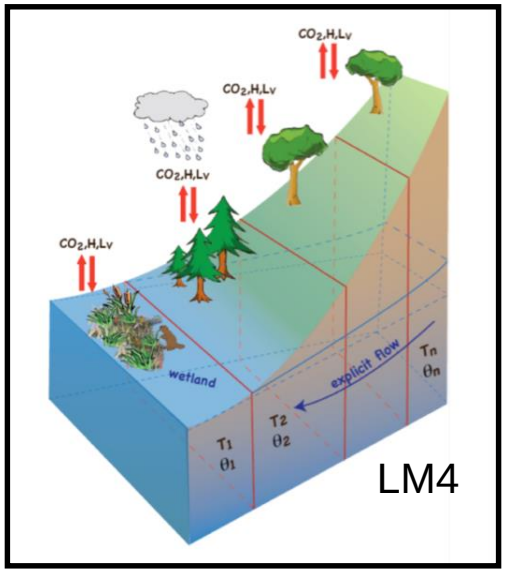
Dunne et al. (*JAMES, in press*)

Land Model capturing 30m-scale water heterogeneity

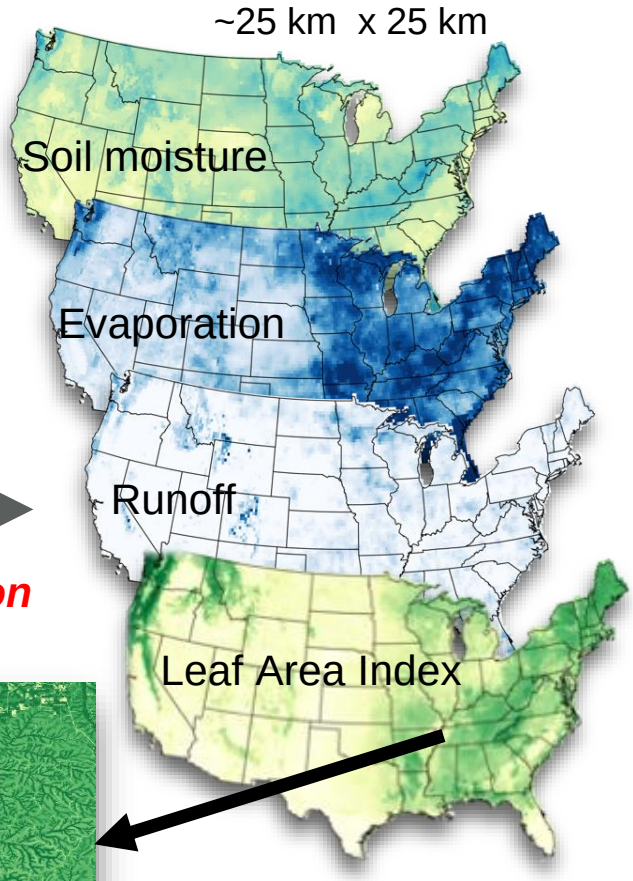
Environmental data



Hydro-blocks



Simulations



Modeling ecosystem information at the forest plot or farm scale!

- Land model run on a 1/4 degree grid over CONUS
- ~100 tiles per 1/4 degree grid cell (~13000 cells)
  - ~1.5 million different tiles over CONUS
  - Each 30 meter grid cell belongs to a tile
- Simulations between 2002 and 2014 (Spin-up 1974-2001)

Chaney et al, 2018

Where we want to go: Incorporation of fine scale local information for decision-relevant Earth System Model Predictions

NOAA/ GFDL
Seamless Modeling System (from Weather to Climate)

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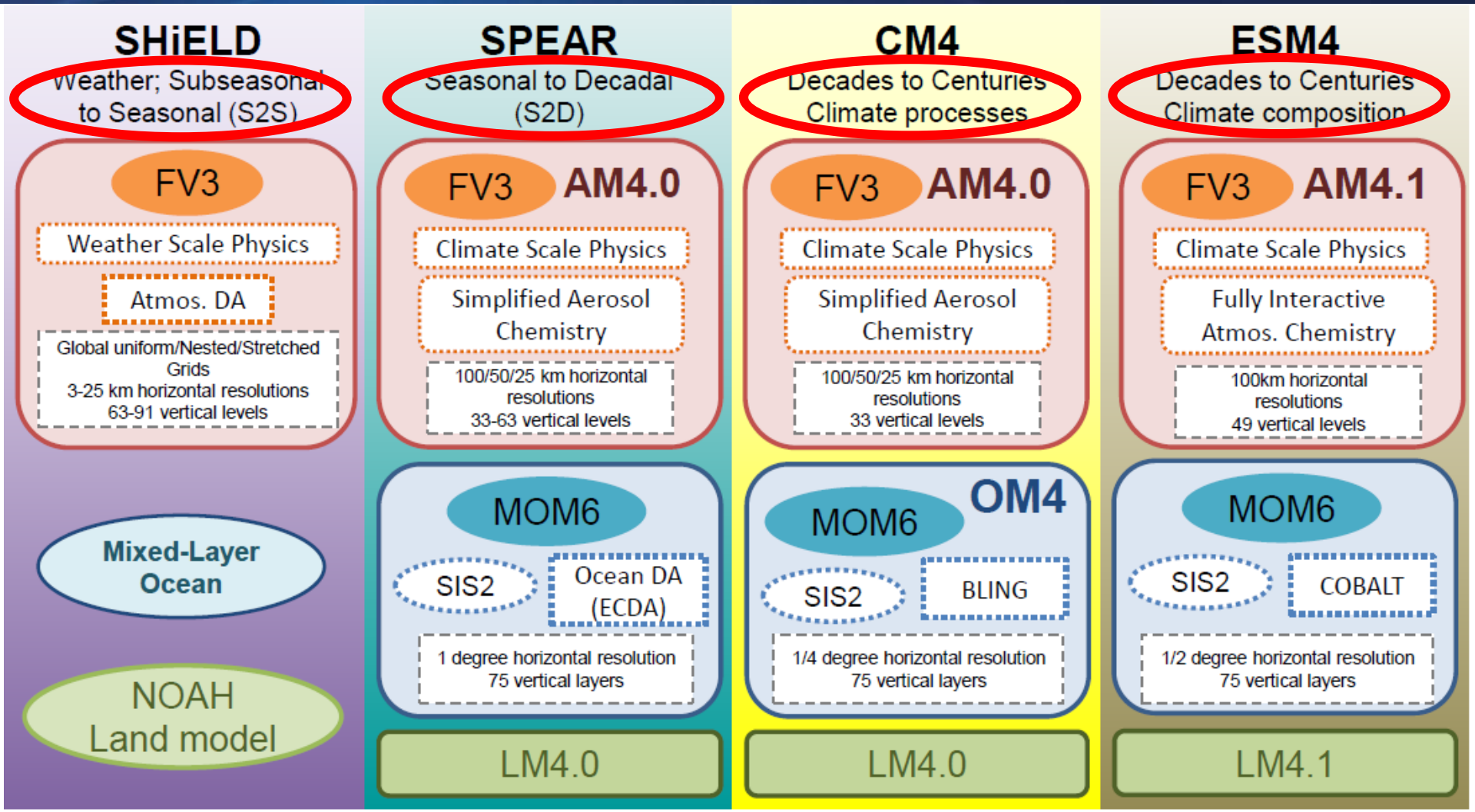
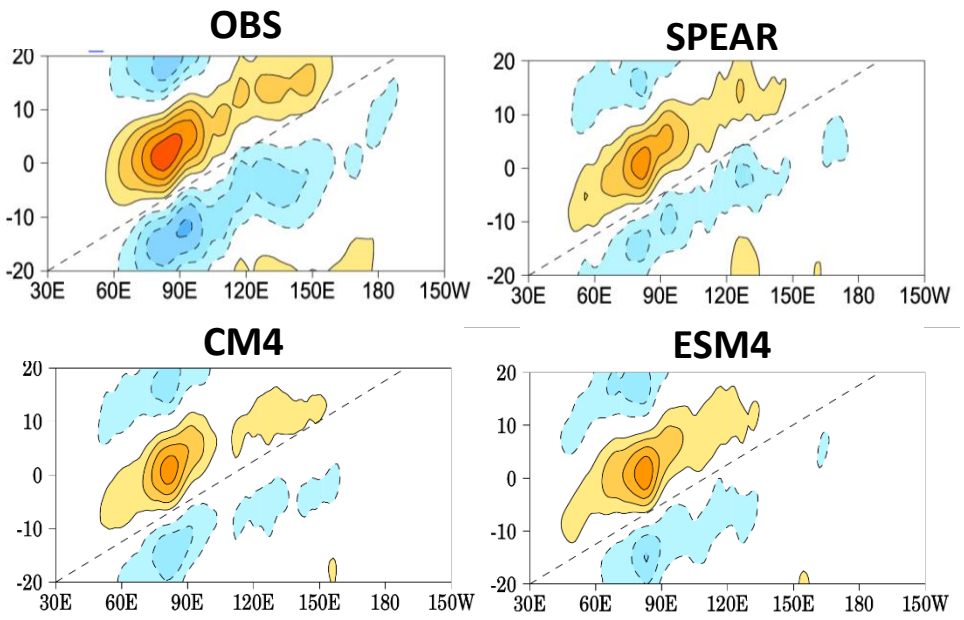
NOAA: Seamless Modeling of the Earth System



➔ ➔Understanding, Applications, Predictions & Projections

Series-4 Models: Reduction of biases

MJO Eastward Propagation



AMIP RMSE Comparison (SST coupled)

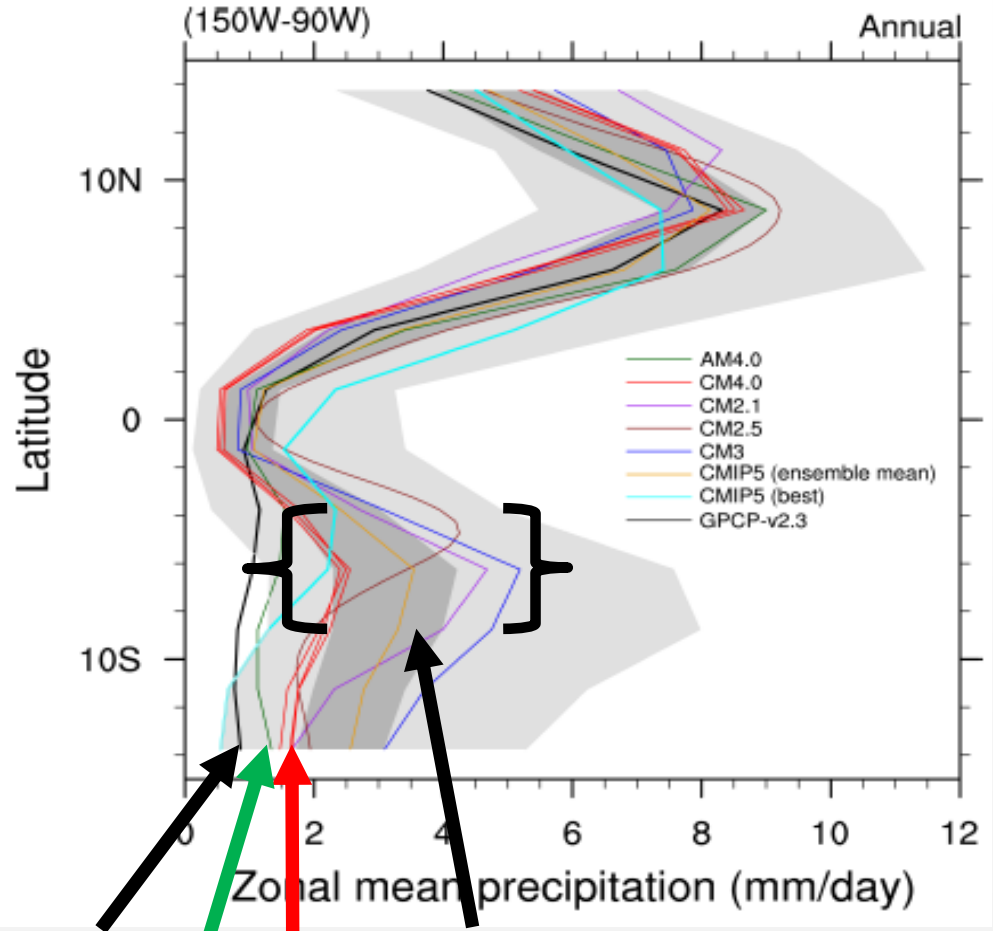
Model	CM2/AM2	CM3/AM3	CM4/AM4
(CM) SST (K)	1.2	1.1	0.84
OLR (W/m2)	7.3	8.3	4.3
TOA SW (W/m2)	12.7	11.4	7.6
Precipitation (mm/day)	1.14	1.03	0.84
NH DJF SLP (hPa)	2.39	1.87	1.84
Zonal mean zonal wind (m/s)	1.52	1.52	0.76

Series-4 Models: AM4, CM4, ESM4:
NOAA models for WCRP CMIP6

Credit: Ming Zhao

Strongly Improved Regional Precipitation

Pacific "Double ITCZ" Precipitation Challenge



AM4: NOAA/GFDL 4th generation Atmosphere model

CM4: NOAA/GFDL 4th generation Climate model

Climate Predictions and Projections (Seasonal-to-Centennial)

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Components of Research Modeling Systems for the Study of Seamless Variability, Predictability and Projections

- **Observing Systems**
- **Assimilation Systems**
- **Models**
- **Changing radiative forcing**

Initial Value Problem
(synoptic to seasonal prediction)

Boundary Value Problem
(multi-decadal to centennial projection)

Hours to subseasonal to
Seasonal to
Decadal to
Multi-decadal
Predictions
and
Projections

Goal: ***Seamless system for improved understanding leading to predictions and projections across Weather and Climate time scales.***

Weather/ Climate events and extremes
➔ widespread disruptions and losses





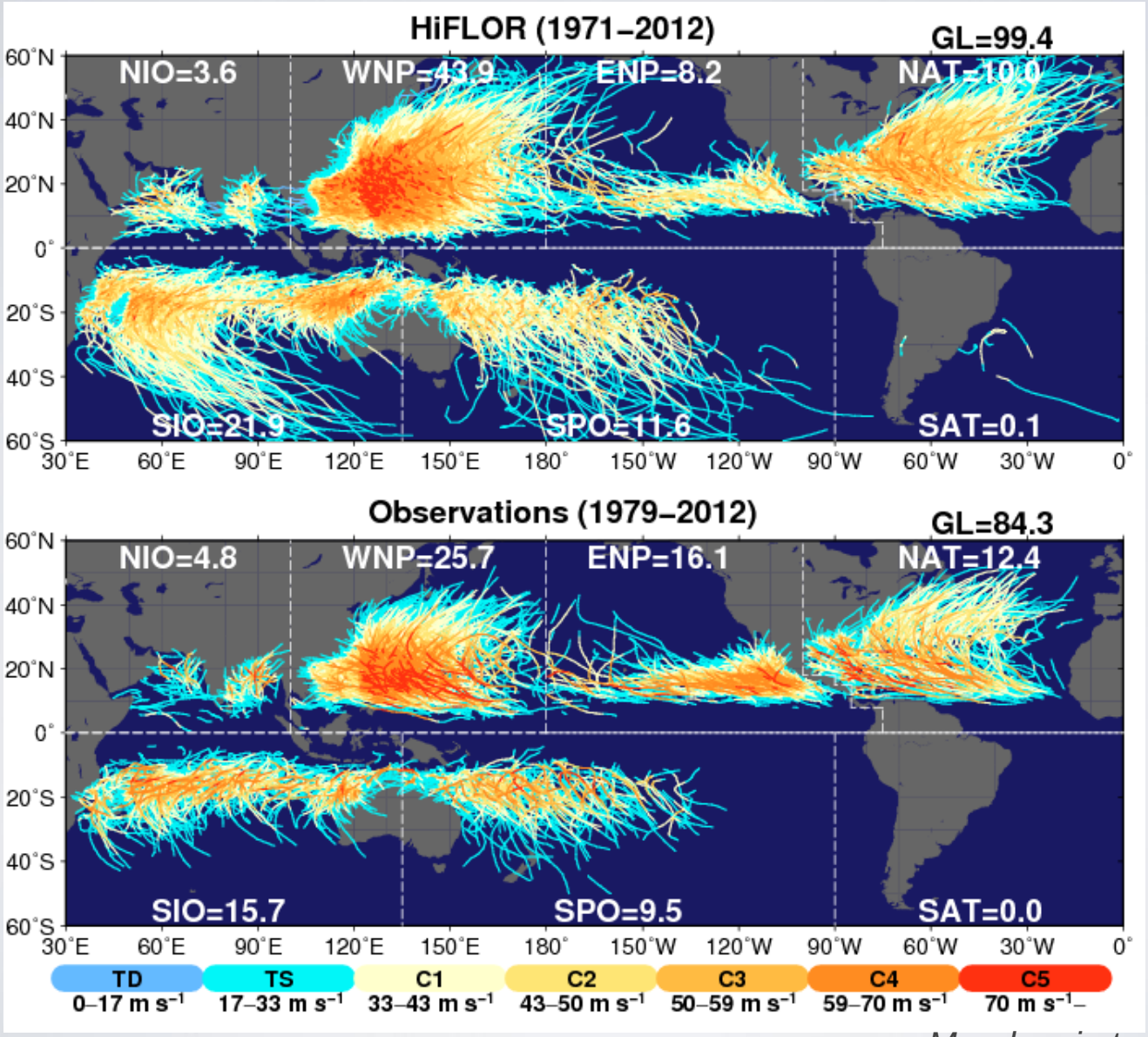






Seasonal Phenomena (Tropical storms)

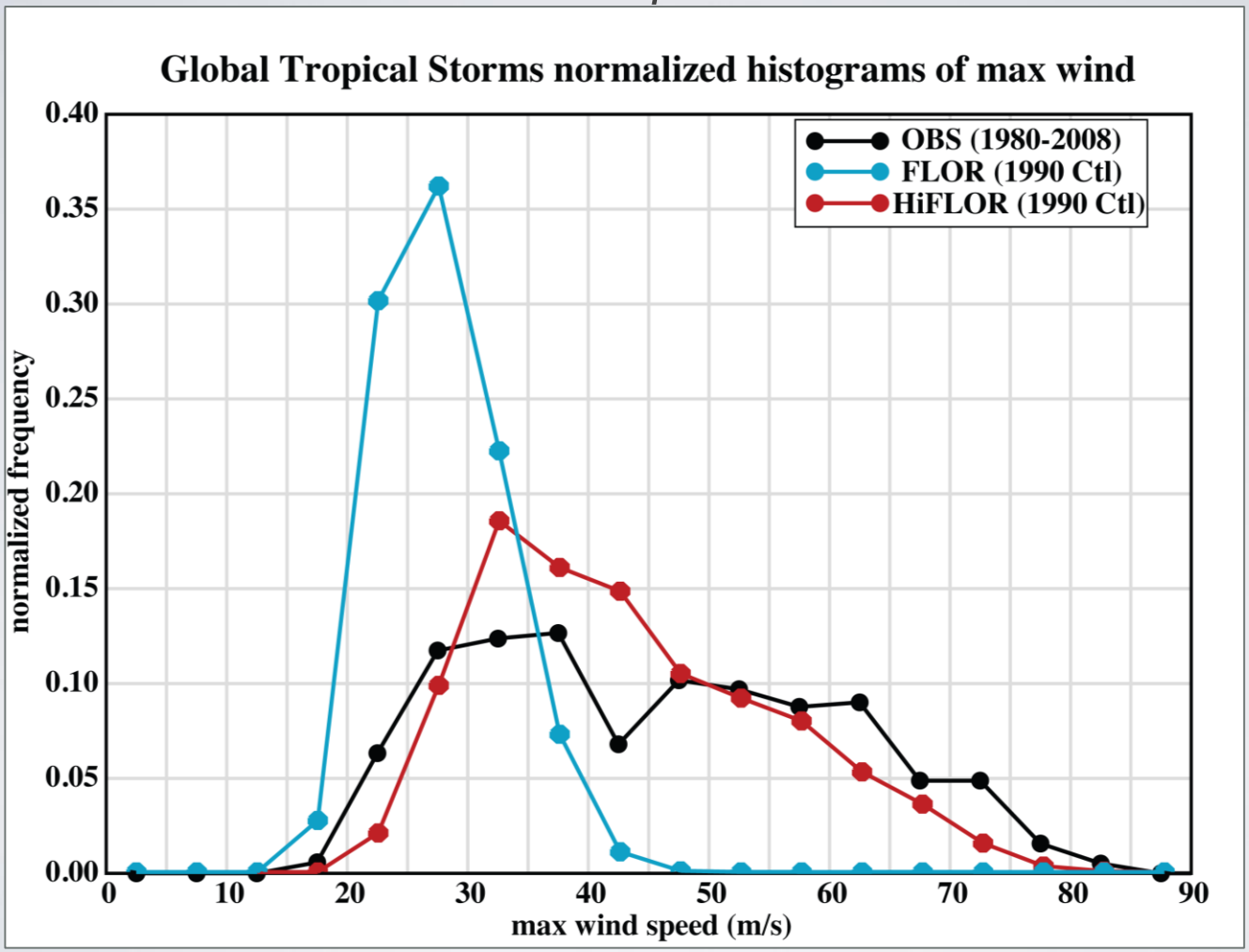
NOAA/ GFDL Modeling: 1st global climate model to simulate category 4 and 5 hurricanes



Murakami et al. (2015, J. Climate)

Simulating Category 4-5 storms.

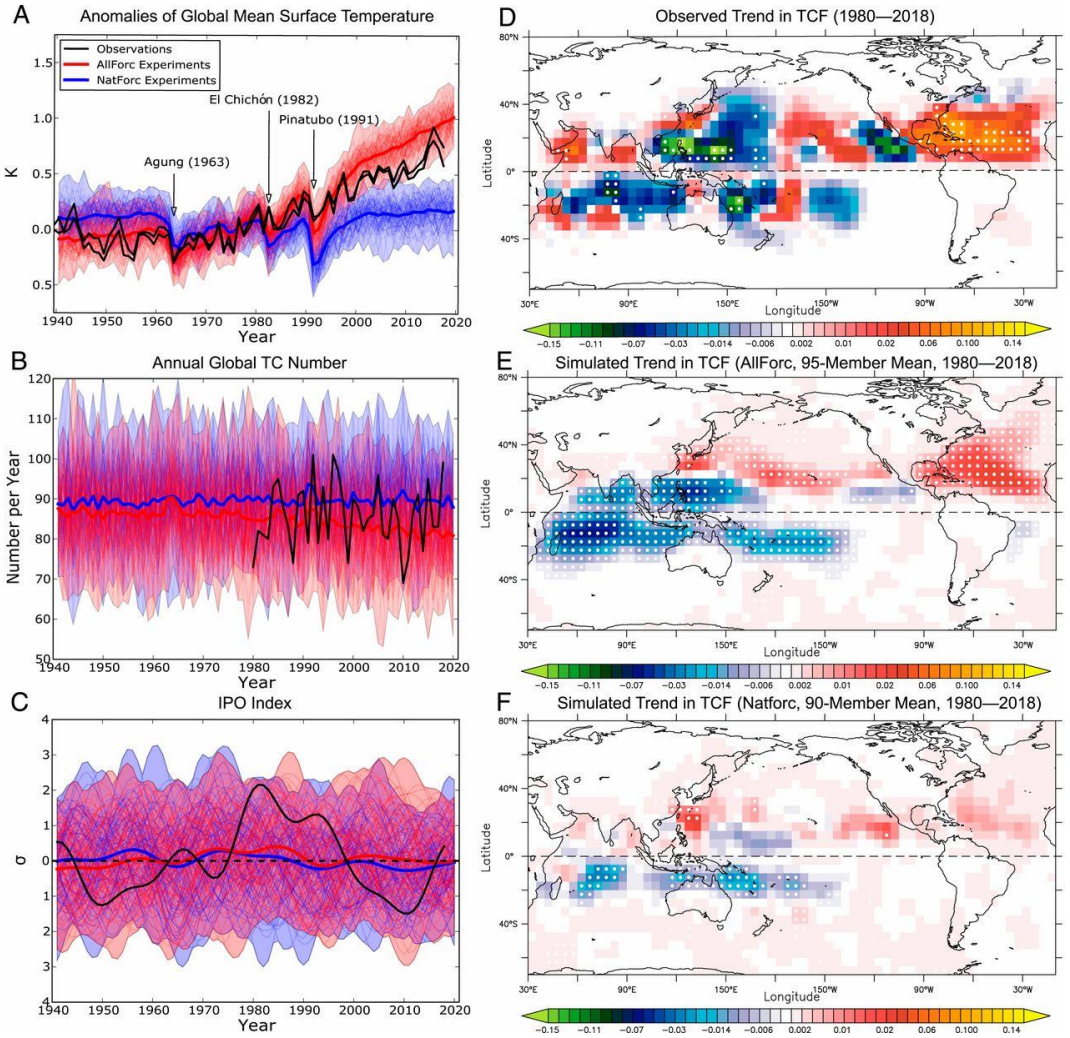
Strong hurricanes tend to cause the most impacts. A prediction model is needed that can capture these storms.



(25km FV3 atmosphere model coupled to 1° MOM5 ocean model)

Murakami et al. (2015, J. Clim)

Time series of surface temperature, global TC number, IPO, and linear trends in TCF. Model simulations versus Observations

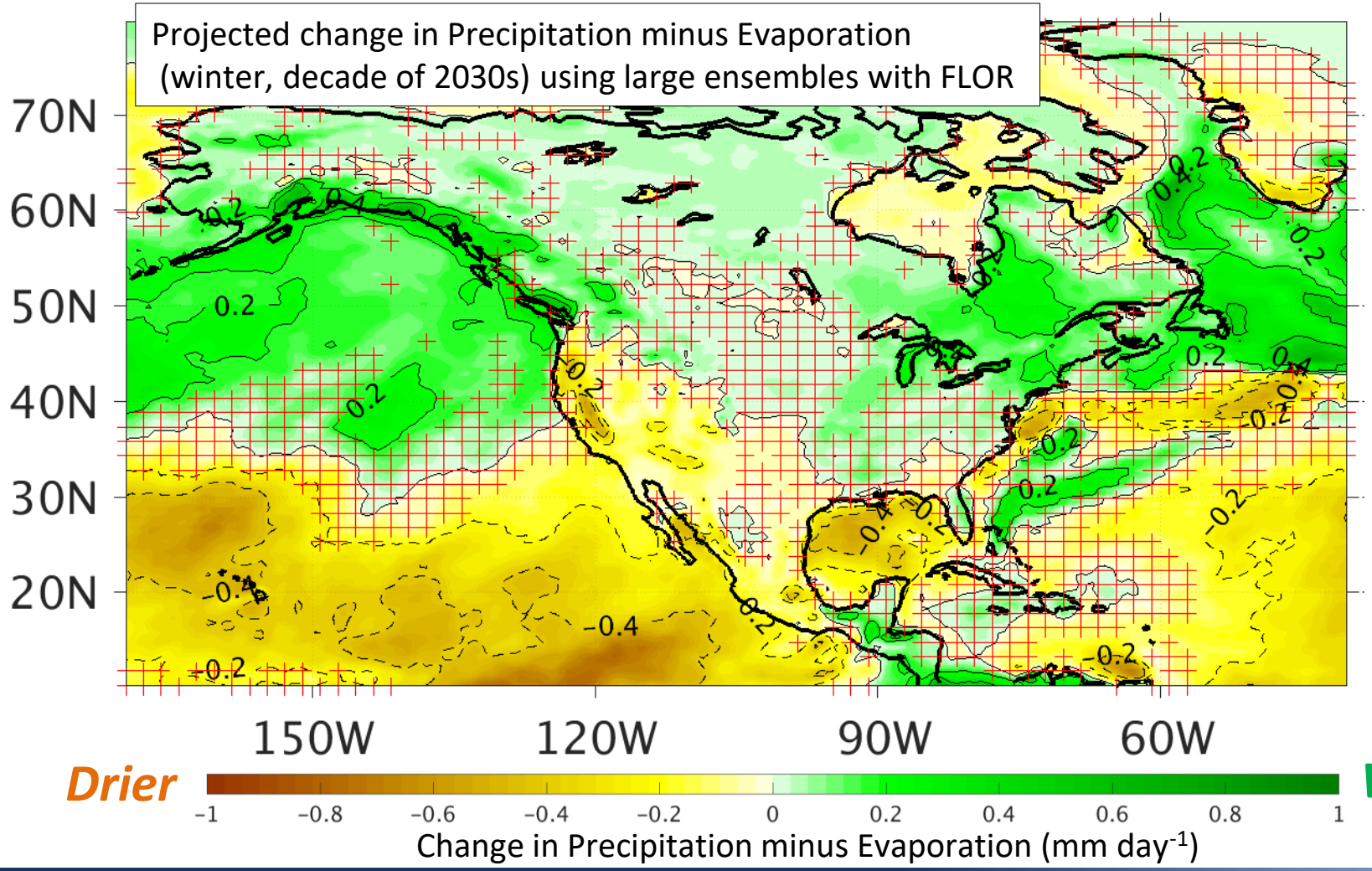


Hiroyuki Murakami et al. PNAS 2020;117:20:10706-10714

Decadal to Multi-decadal Studies & Predictions

Projecting decadal scale changes in North American Hyrdoclimate ➔ anomalies in excess/ deficit of water

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



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

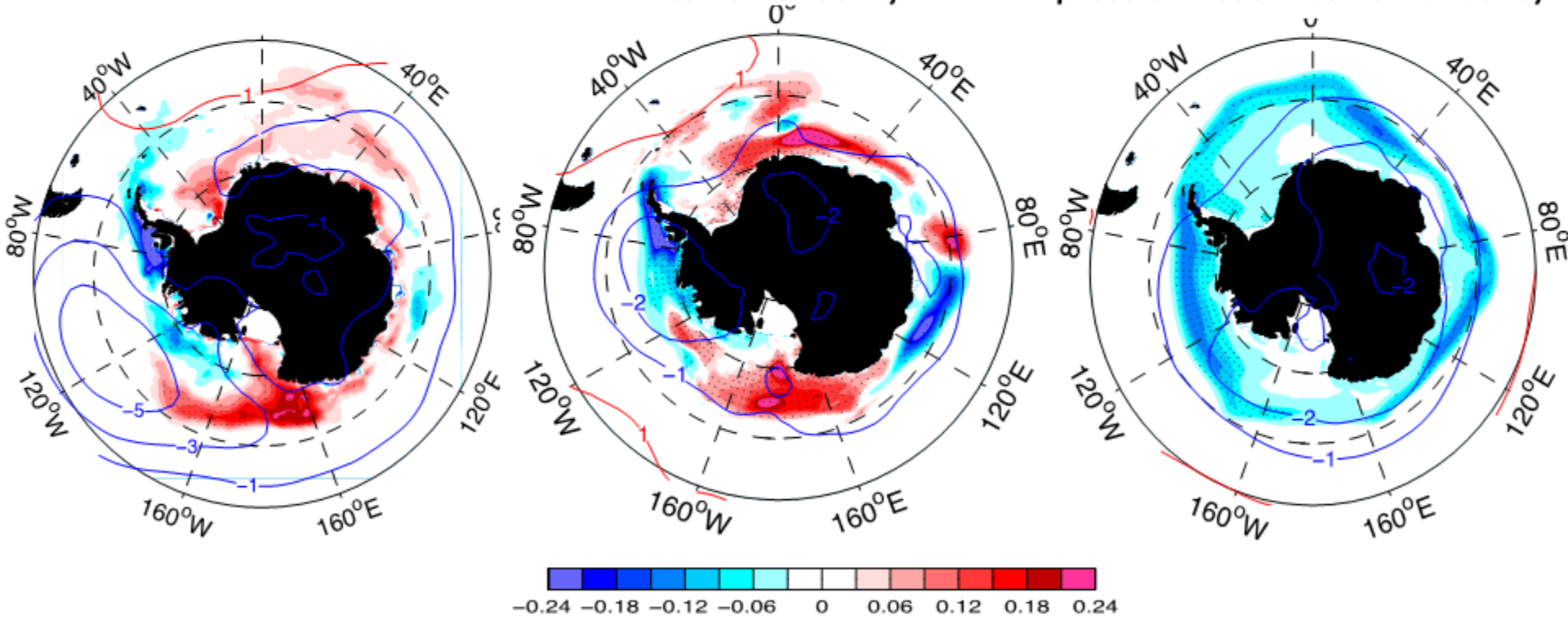
Southern Ocean multidecadal sea trends may be significantly influenced by internal variability

Zhang et al, 2019
Nature Climate Change

Observed sea ice trend
1979-2012

Simulated sea ice trend when model initialized from active phase of model internal variability

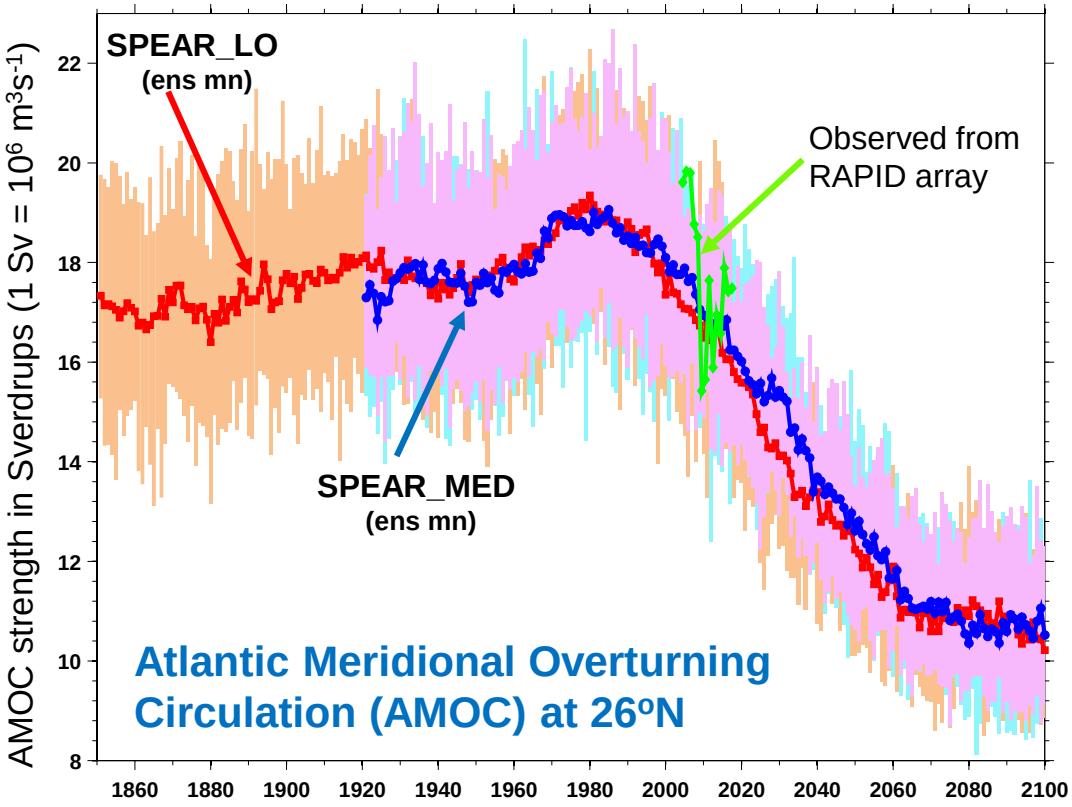
Simulated sea ice trend when model initialized from neutral phase of model internal variability



Large Ensembles

Seasonal/Decadal prediction model is used to generate 30-member ensembles of projections for 1851-2100. ["SPEAR": NOAA/GFDL's latest Seasonal-to-Decadal Prediction Model]

- 1851-2010: Use observed atmospheric composition
- 2011-2100: Use projected atmospheric composition from SSP5-85

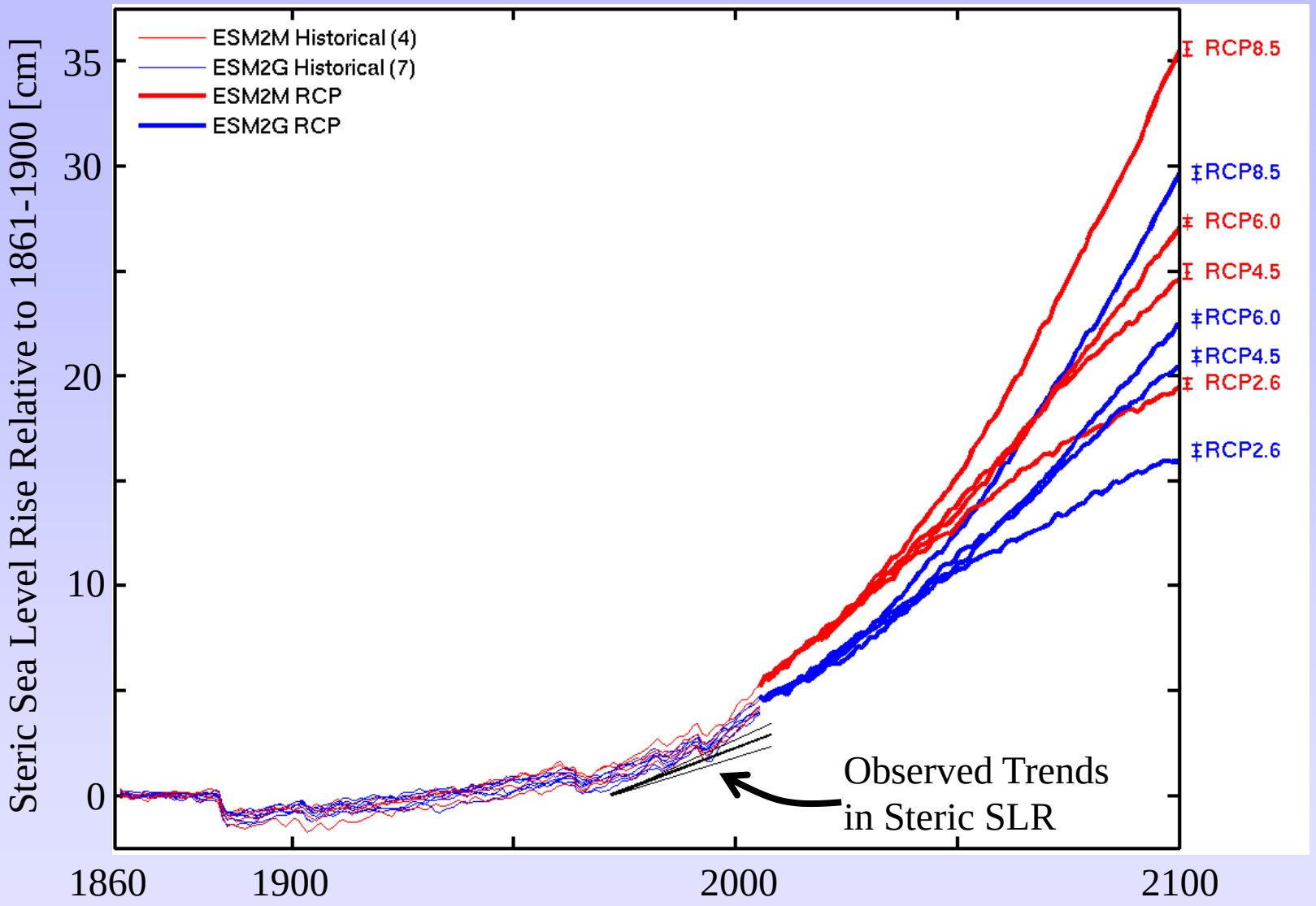


30-member ensembles using both SPEAR_LO (100 km atmosphere) and SPEAR_MED (50 km atmosphere)

Observations from NOAA RAPID array fall within model spread.

Large ensembles help to separate the signal of climate change from the noise of climate variability

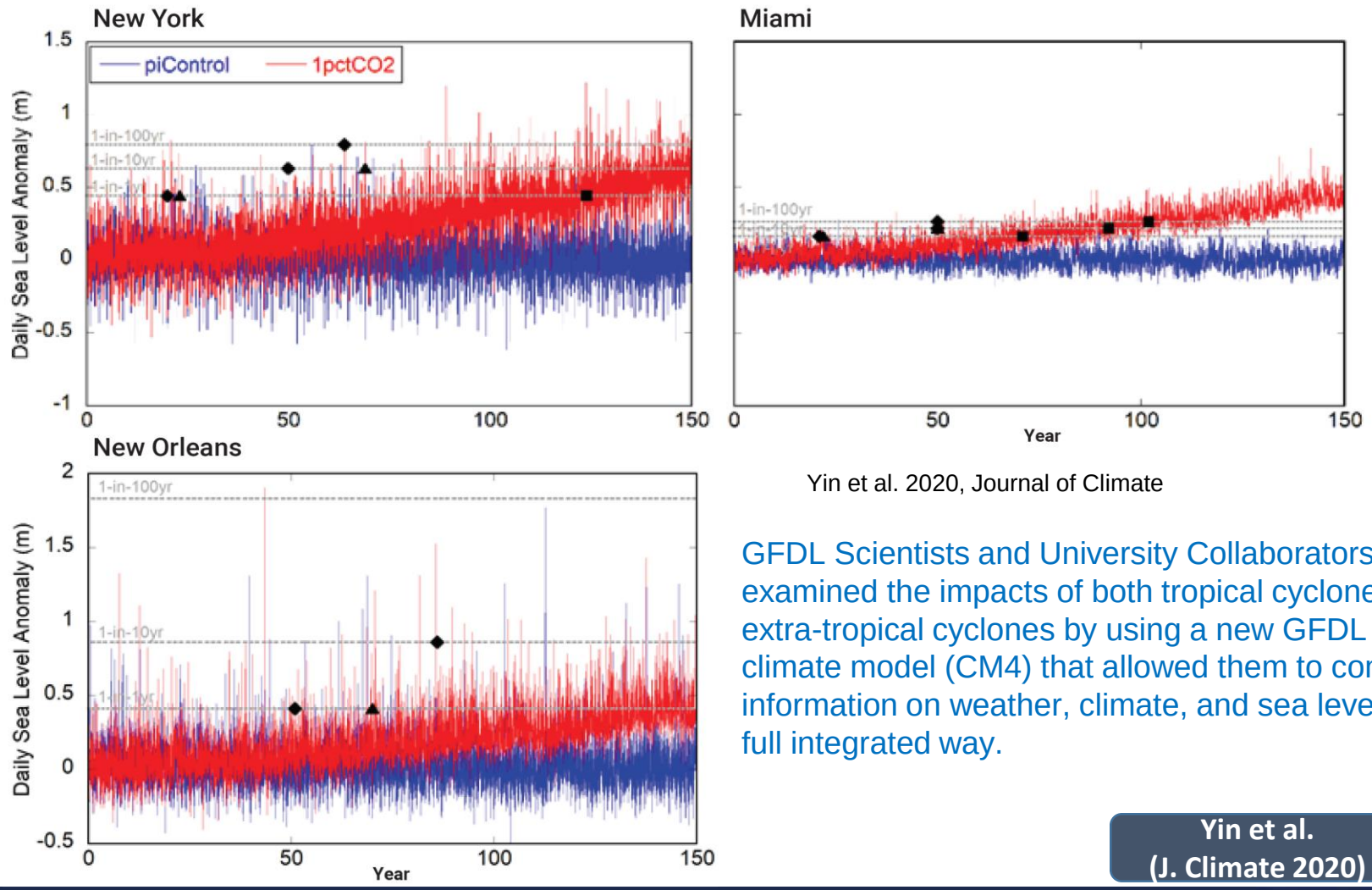
Historical & Scenario-projected Steric Sea Level Rise



- Both models agree with observed steric sea level rise trends.
- GFDL/ESM2M exhibits 18% more 21st century steric sea level rise than ESM2G.

Response of Storm-Related Extreme Sea Level Along the U.S. Atlantic Coast to Combined Weather and Climate Forcing

Time of emergence of the anthropogenic signal in storm related extreme sea level for New York, Miami, and New Orleans

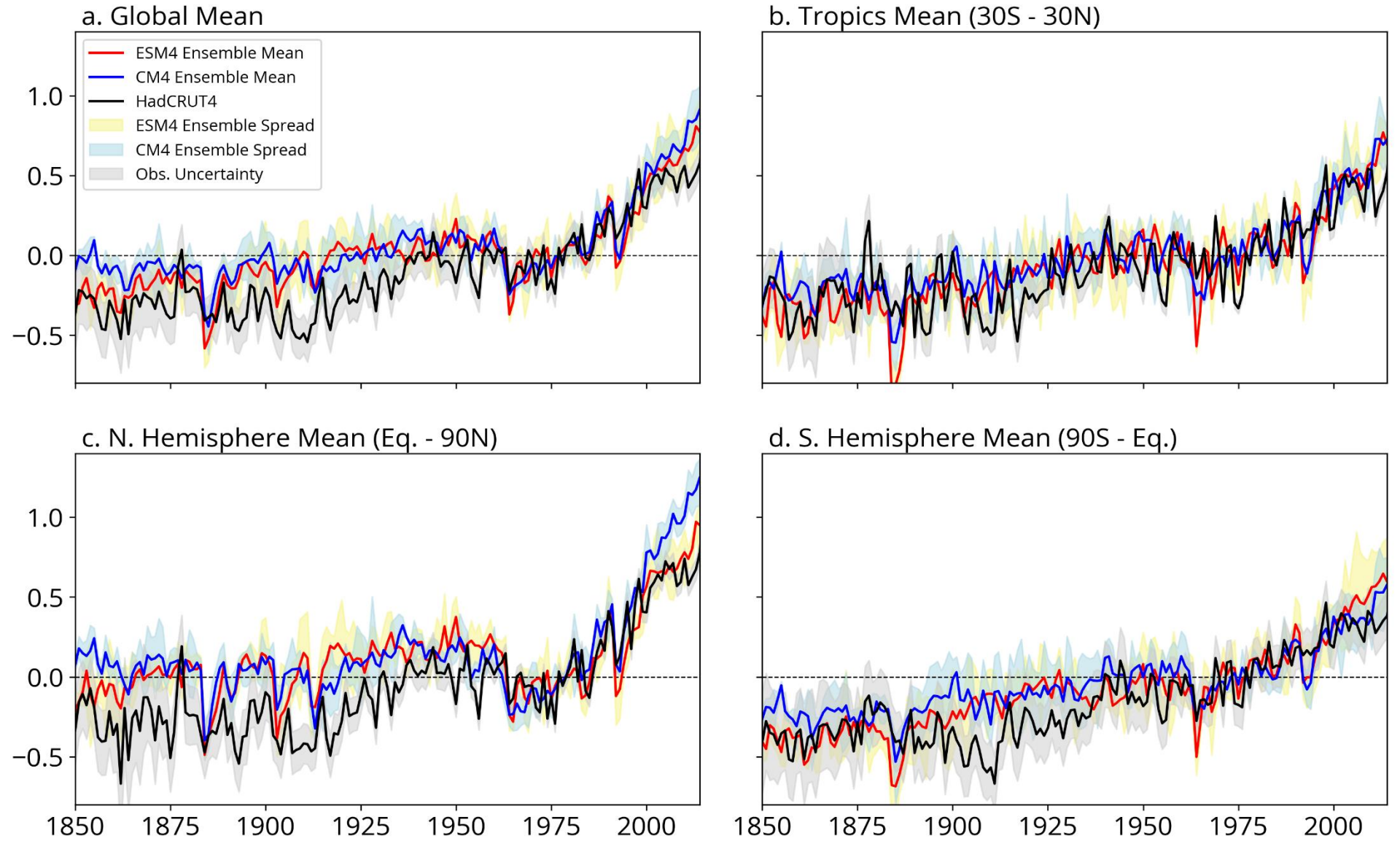


Yin et al. 2020, Journal of Climate

GFDL Scientists and University Collaborators examined the impacts of both tropical cyclones and extra-tropical cyclones by using a new GFDL climate model (CM4) that allowed them to combine information on weather, climate, and sea level in a full integrated way.

Yin et al. (J. Climate 2020)

CM4.0 more recent NH warming than ESM4.1



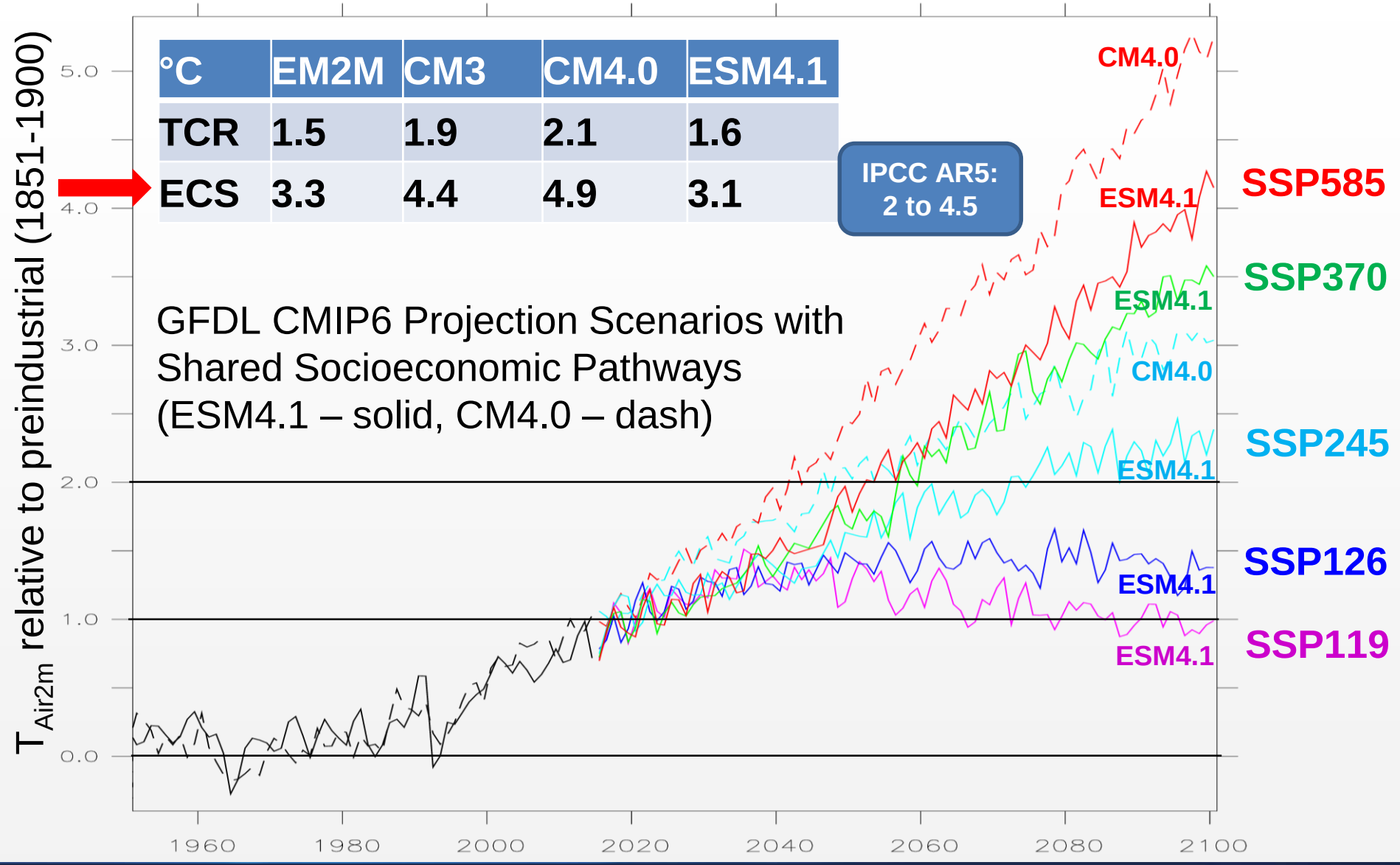
anomalies relative to the 1961-1990 base period

ESM4.1 Lower Climate Sensitivity than CM4.0

°C	EM2M	CM3	CM4.0	ESM4.1
TCR	1.5	1.9	2.1	1.6
ECS	3.3	4.4	4.9	3.1

IPCC AR5: 2 to 4.5

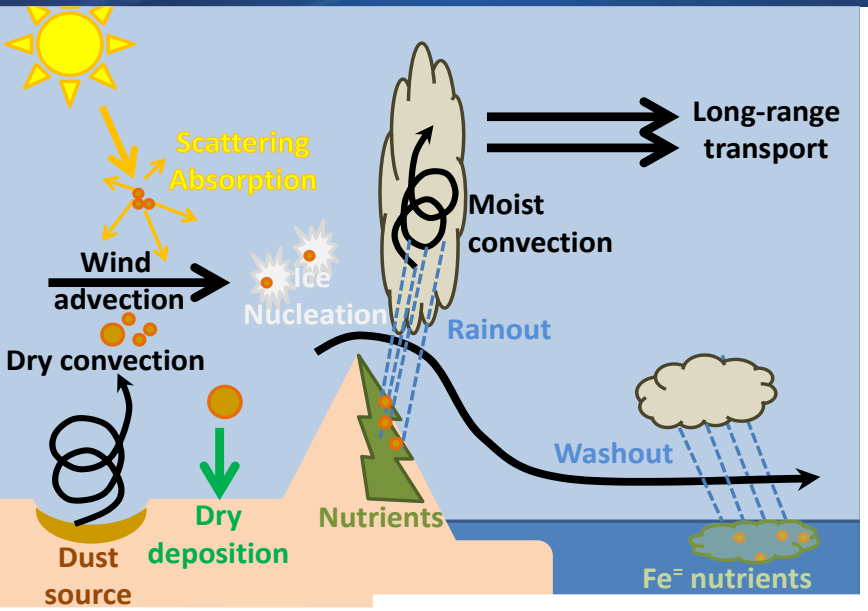
GFDL CMIP6 Projection Scenarios with Shared Socioeconomic Pathways (ESM4.1 – solid, CM4.0 – dash)



Earth System (Physical system and Ecosystem interactions)

Geophysical Fluid Dynamics Laboratory

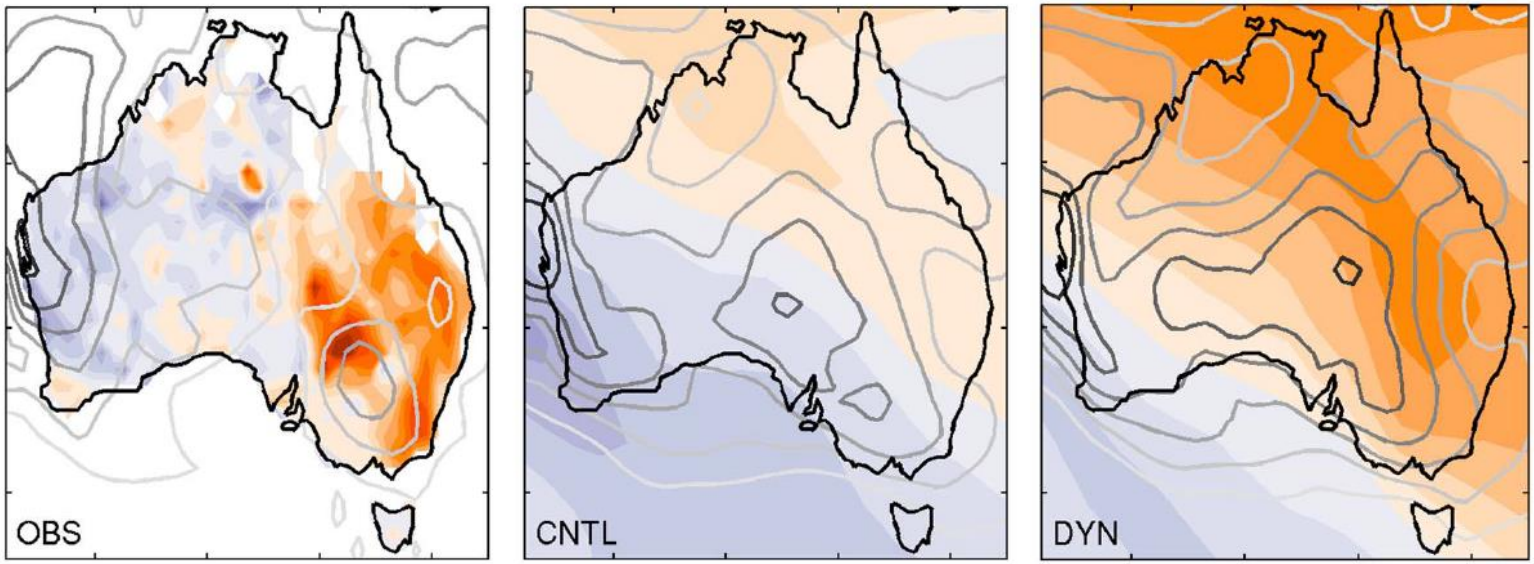
Dynamic dust-ecosystems-climate interactions



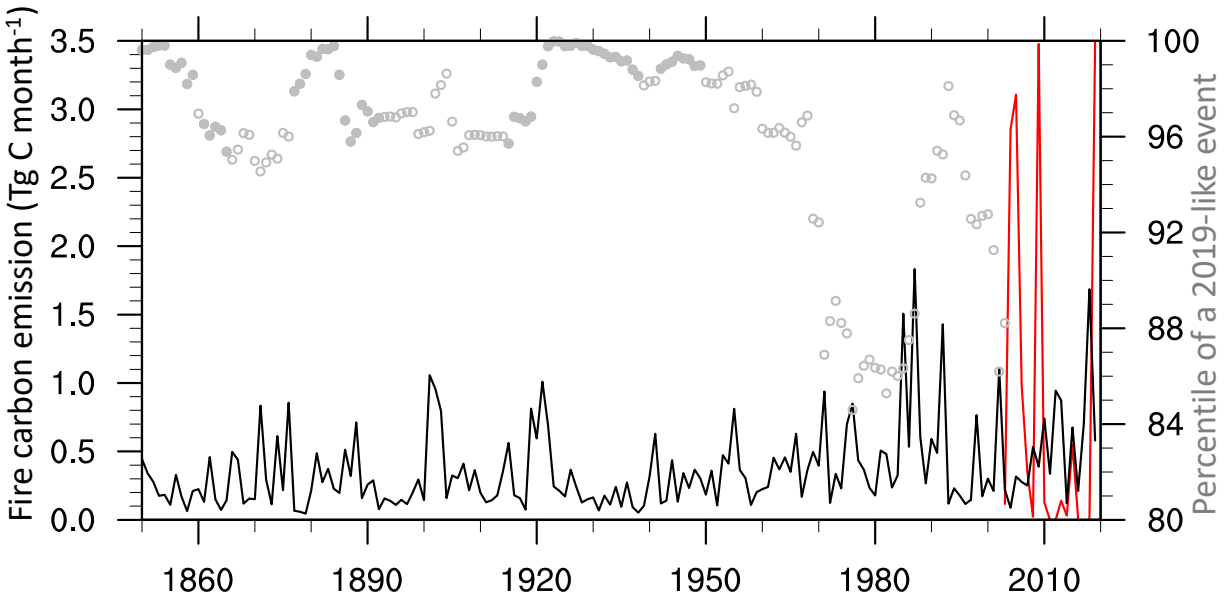
- Dynamic hydrology and vegetation connect Australian dust emissions with ENSO
- ENSO creates precip anomalies =>dust anomalies.
- Dust optical depth anomalies are 30% up from seasonal mean
- Precip anomalies are 50% of seasonal mean

Evans, Ginoux et al., 2016, GRL

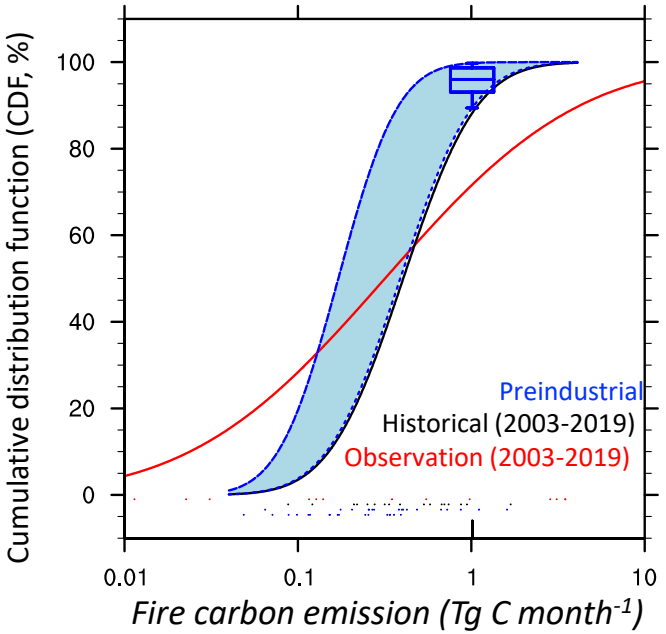
Regression of Dust Optical Depth (color) and Precip (gray) with ENSO



Attribution of Alaska's extreme fire season to anthropogenic activity – fire carbon emission

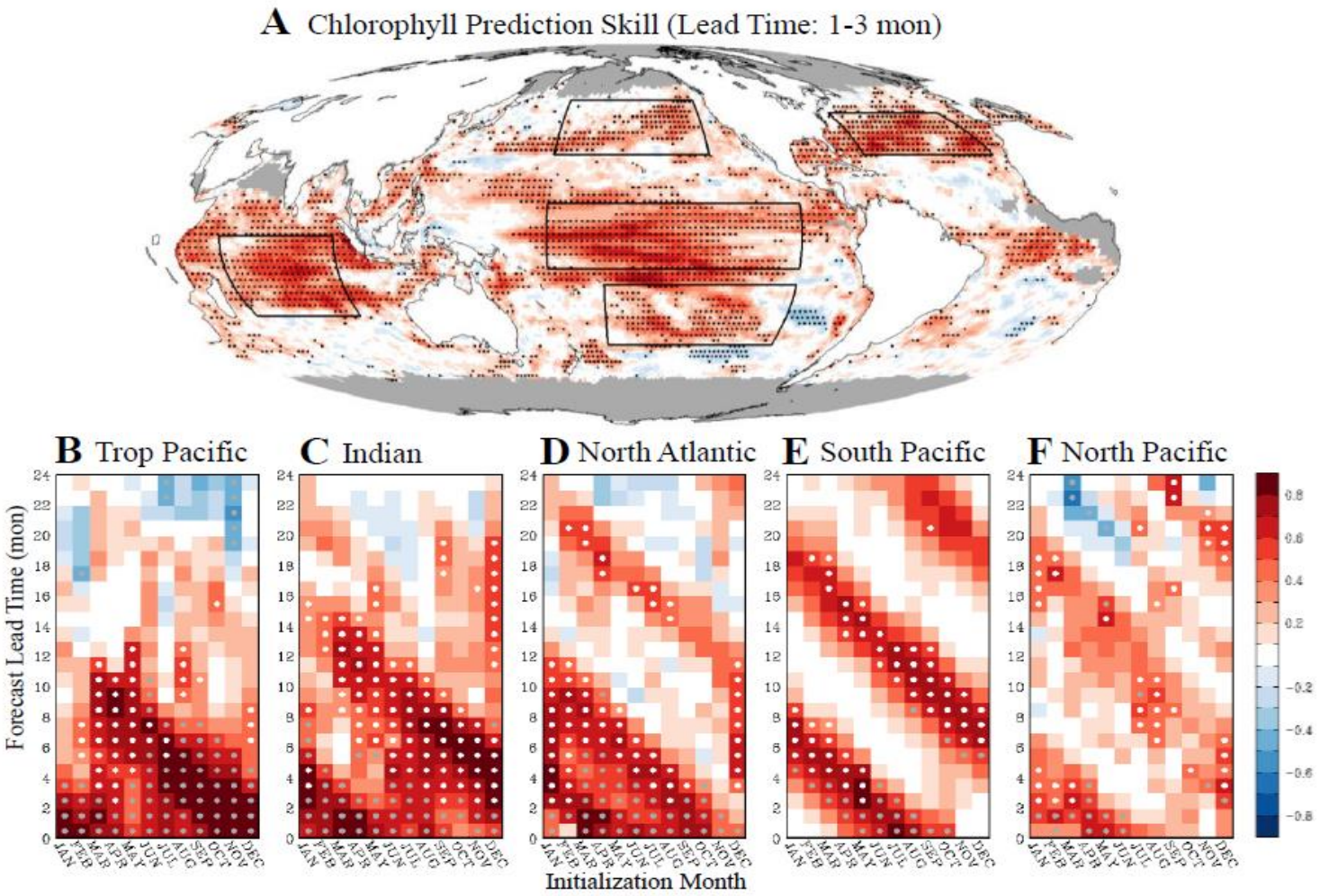


Analysis of fire carbon emission confirms the variability and attribution of Alaska's extreme fire season to anthropogenic activity.



Fire carbon emission from the ECMWF Copernicus Atmosphere Monitoring Service (CAMS) Global Fire Assimilation System (GFAS)

Skillful chlorophyll prediction in oceans beyond 1 year



Park et al., 2019. Seasonal to multiannual marine ecosystem prediction with a global Earth system model. Science. 365 (6450) 284-288.

Multiple weather-climate phenomena
Variability, extremes, and change

National Research Council (2012) Recommendation:
"Unified" modeling approaches

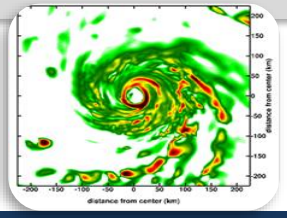
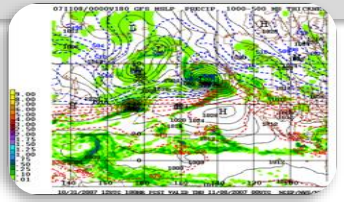
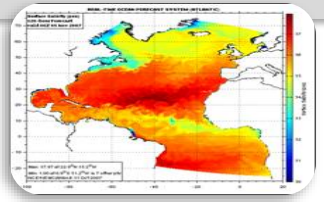
Internal Variability and External Forcings

Tornadoes	Heat Waves	El Niño-Southern Oscillation	Decadal to Multi-decadal Variability	Ocean: Circulation, SLR, Heat Content
Snowstorms	Storm Track Variations	Precipitation extreme	Cryospheric	Greenhouse Gases and Aerosols
Hurricanes	Madden-Julian Oscillation	Intra- & Inter-season Variation	Solar Variability	
Typhoons		Changes in the Arctic		

1 DAY | 30 DAYS | 1 SEASON | 3 YEARS | 10 YEARS | 30 YEARS | 100 YEARS

WEATHER | SHORT-TERM | INTERANNUAL | DECADE-TO-CENTURY

Sub-seasonal-to-Seasonal	Seasonal-to-Interannual	Interannual-to-Decadal	Decadal-to-Multidecadal

Weather to Climate is "Seamless"