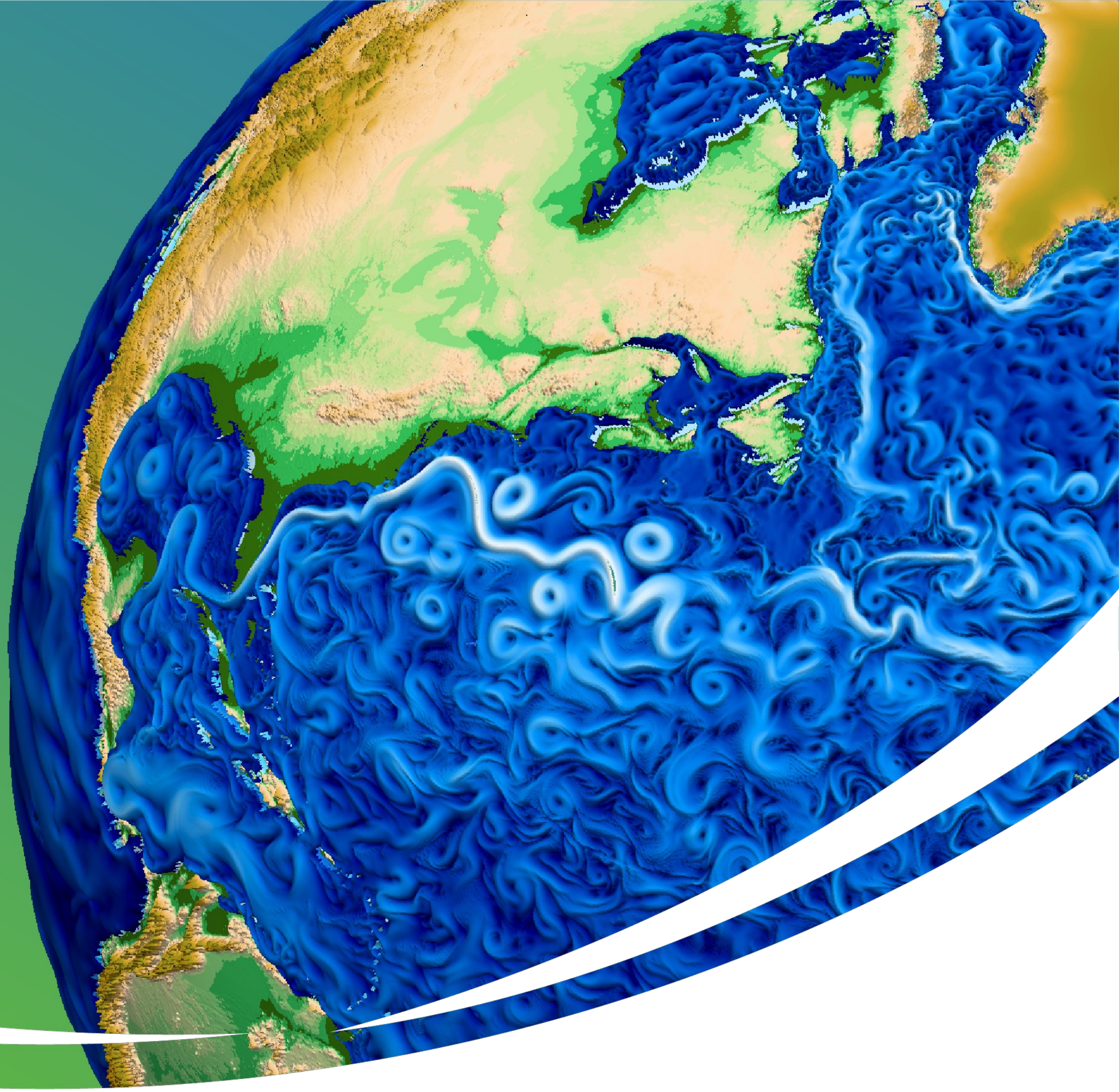
Importance of coupled wind-generated wave processes in global Earth system models



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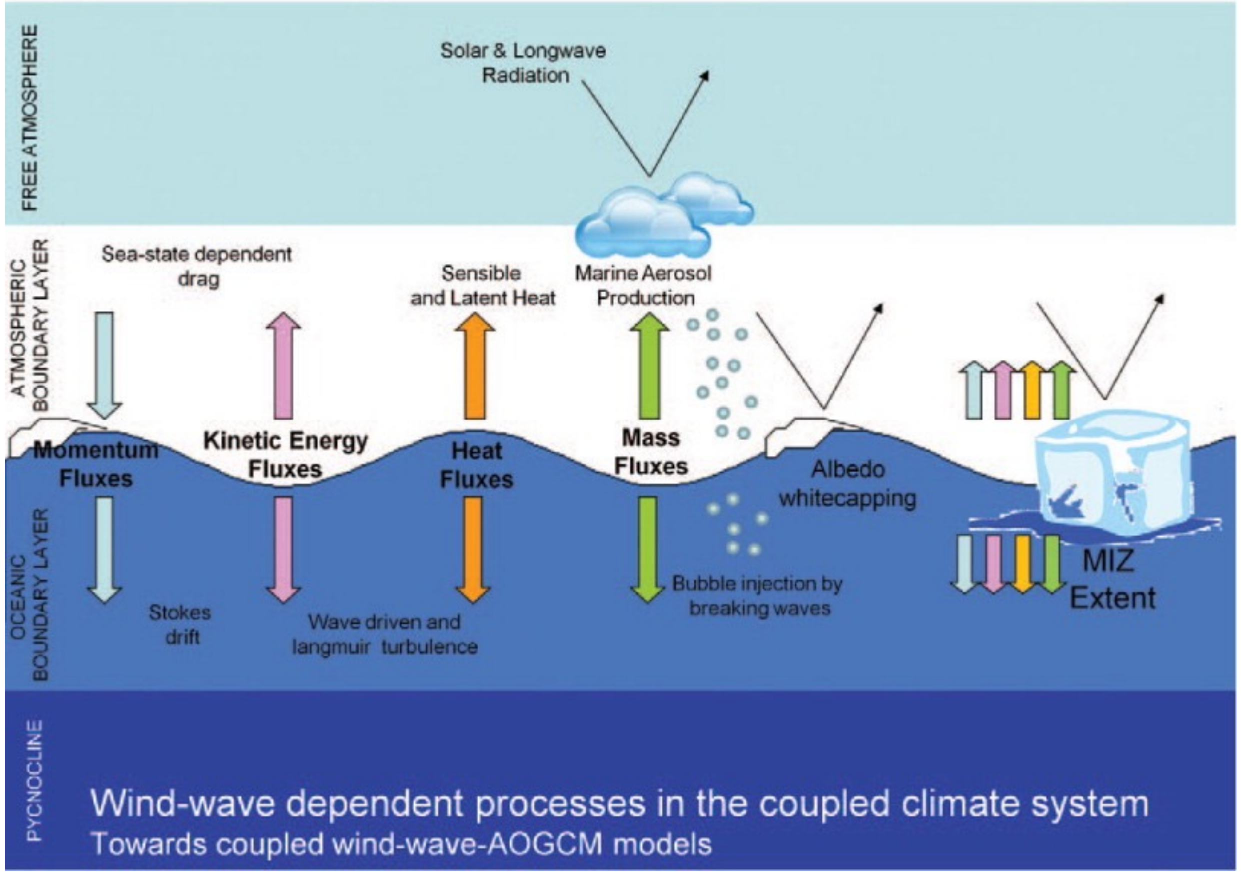
U.S. DEPARTMENT OF ENERGY

E3SM Energy Exascale Earth System Model

Role of Waves in the Coupled Climate System



Cavaleri et al. (2012)

- Wind-generated waves are an important interfacial process in the climate system
- Some cross-component interactions include:
  - Ocean vertical mixing
  - Sea-state dependent drag
  - White-capping albedo
  - Sea-ice floe size

- Waves are modeled in a phase-averaged sense

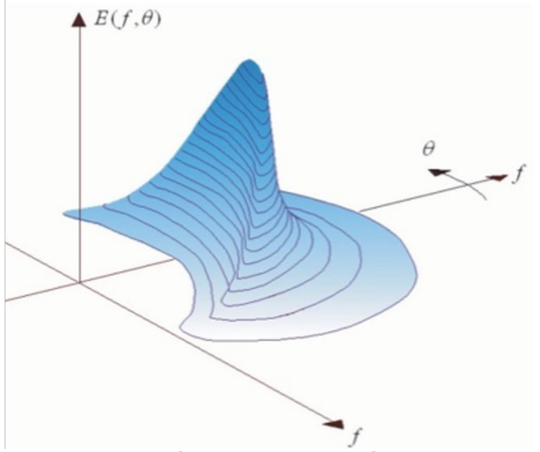
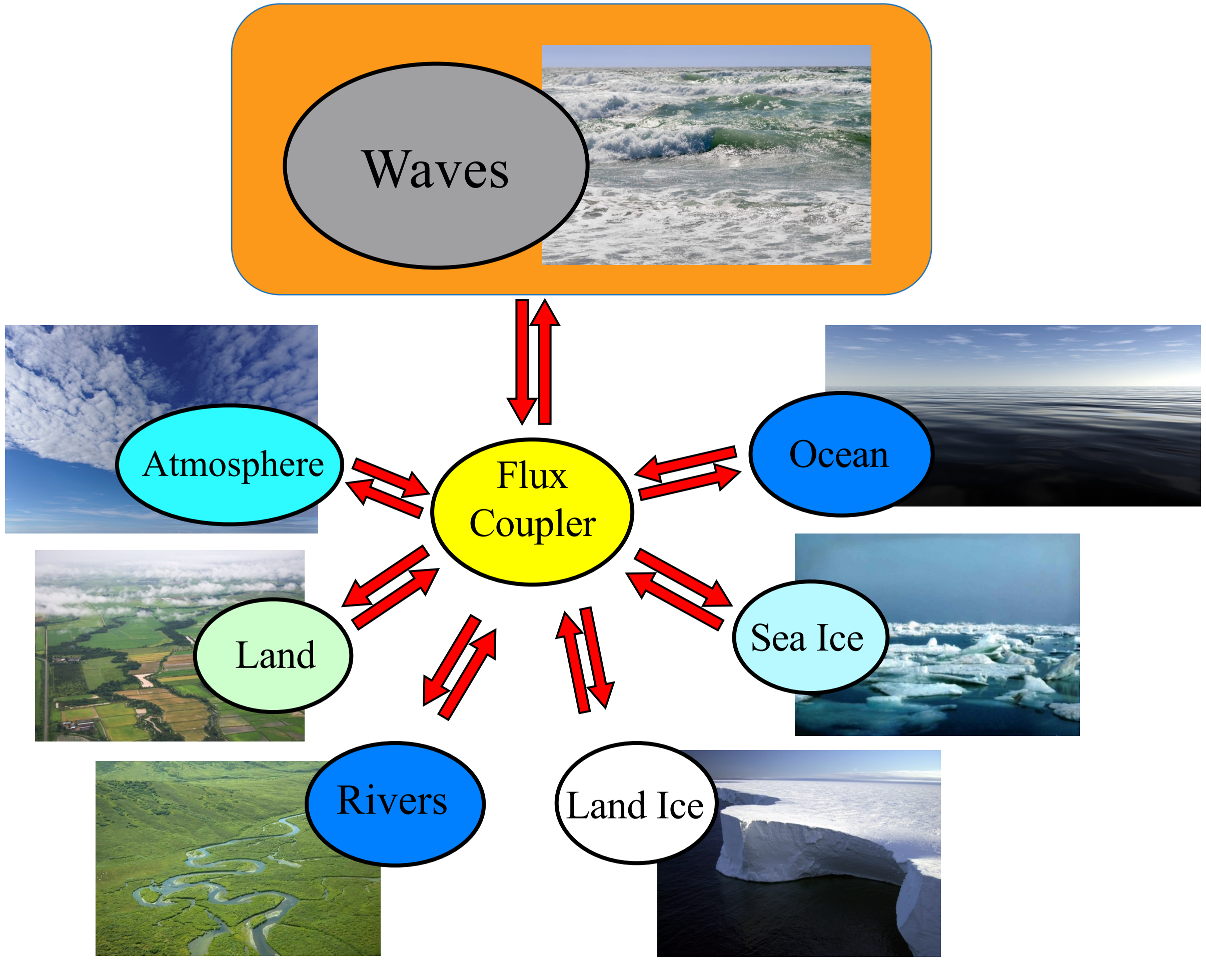


Image Credit: ECMWF

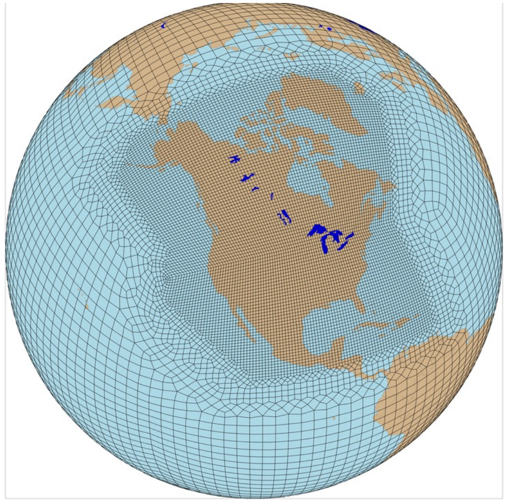
WAVEWATCH III in E3SM

- Coupled wave modeling

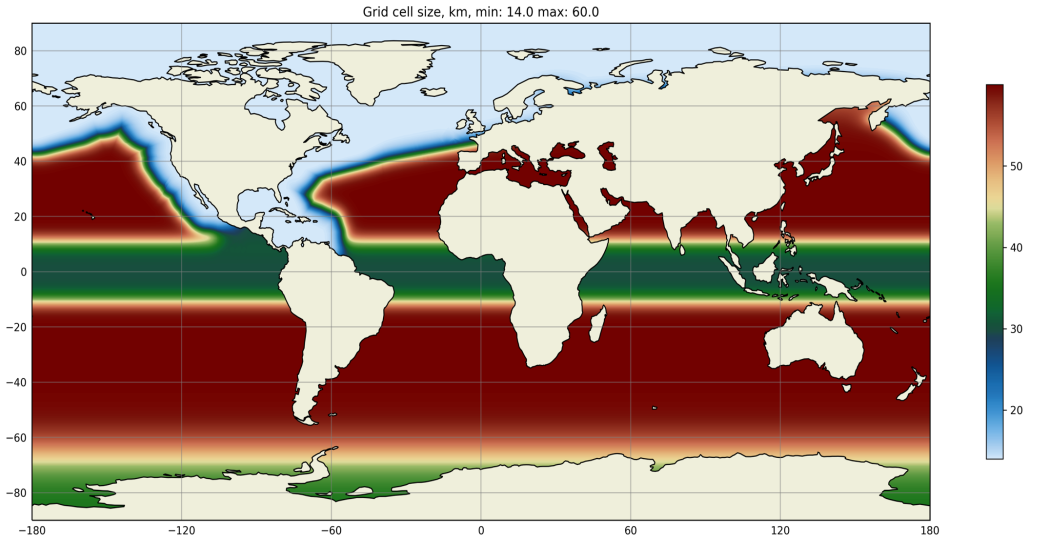


- Regionally Refined Mesh Configurations

Atmosphere/Land



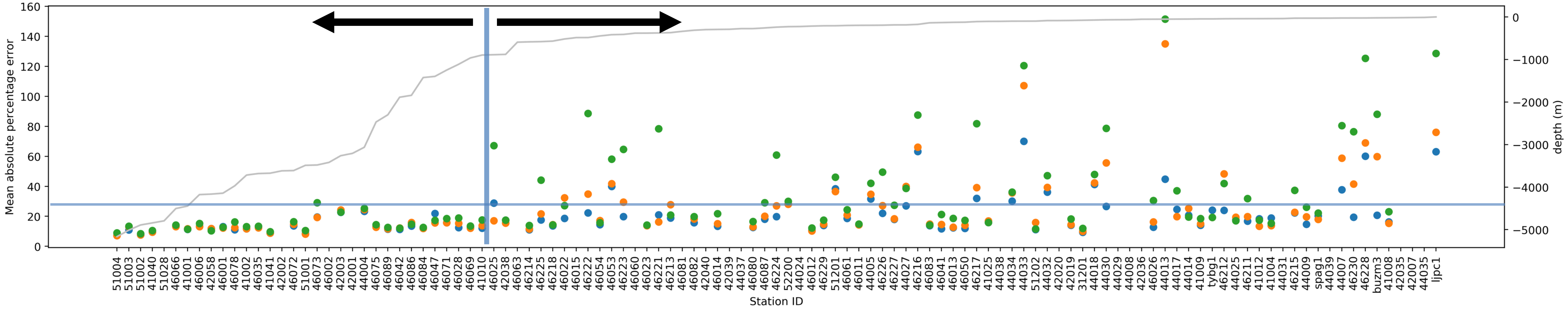
Ocean/Sea ice



Importance of Regional Refinement

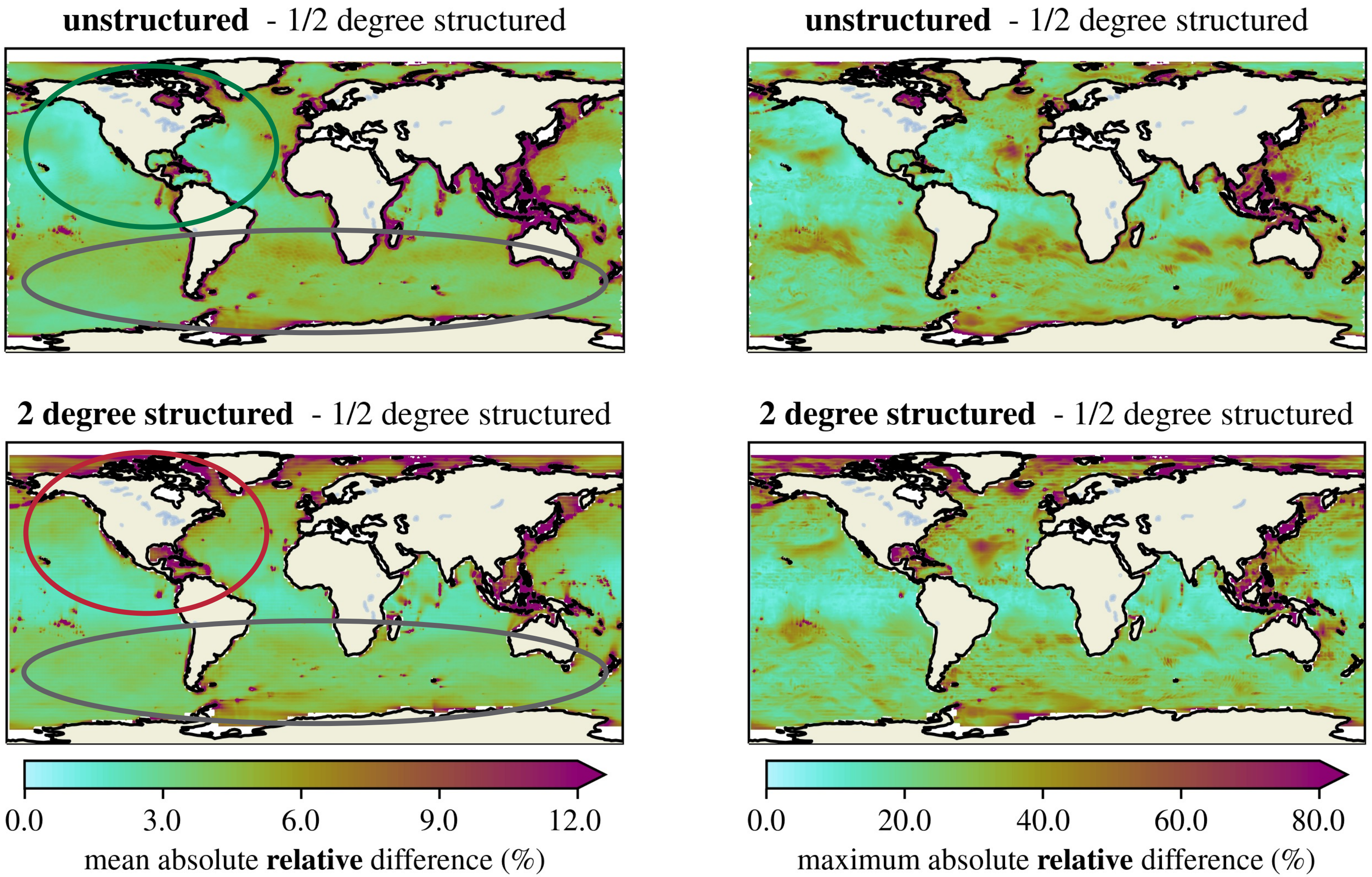
Deeper (open ocean):
Accurate with
lower resolution

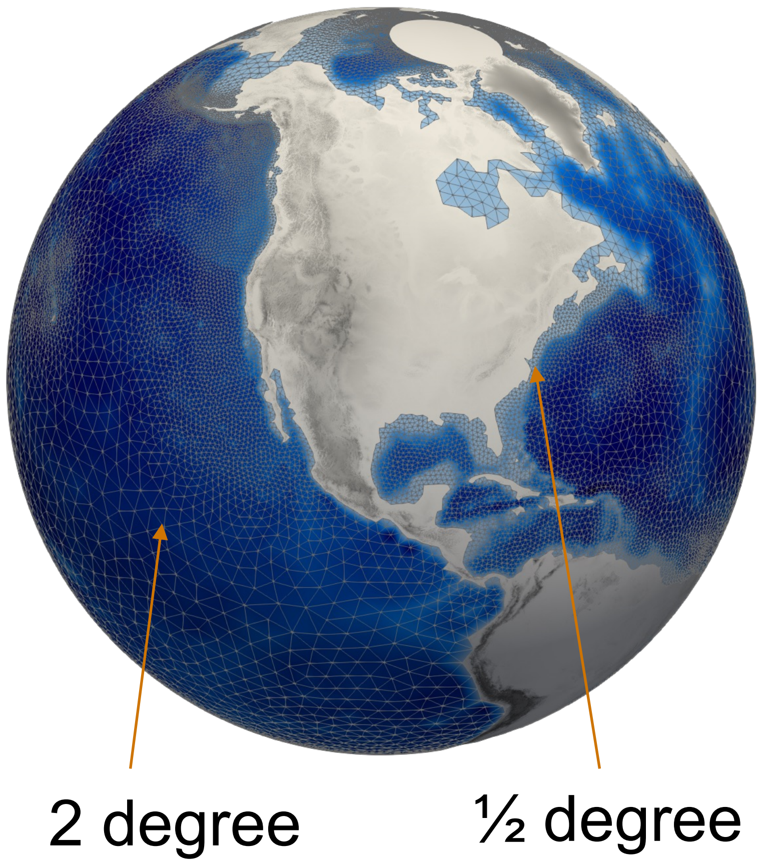
Shallower (coastal):
Requires higher resolution



- Structured lon-lat meshes
- June-August 2005 CFSR winds
- Comparison with NDBC buoys

Unstructured Wave Validation

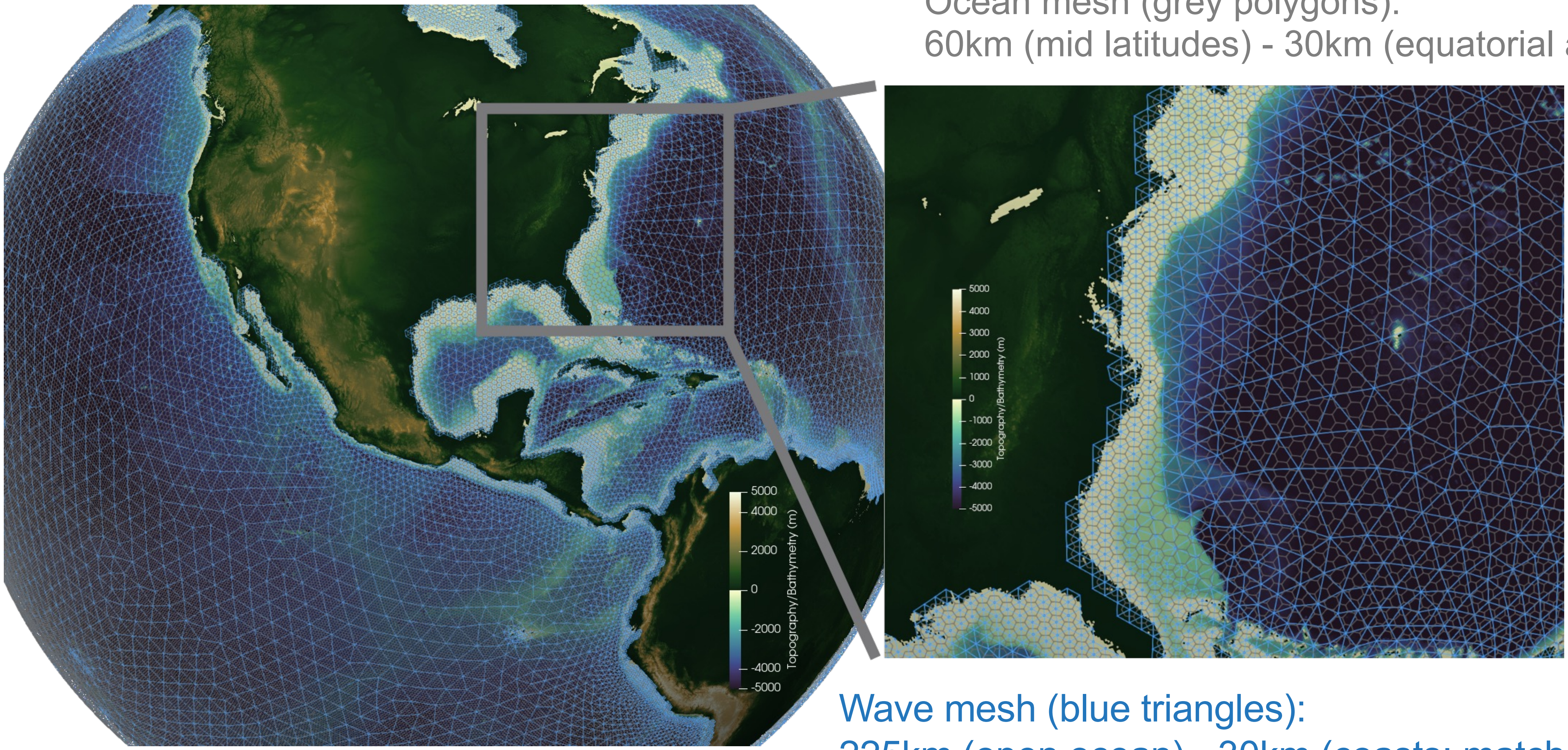




Brus, S.R. et al., 2021.

Unstructured Wave/Ocean Meshes

Ocean mesh (grey polygons):
60km (mid latitudes) - 30km (equatorial and polar)



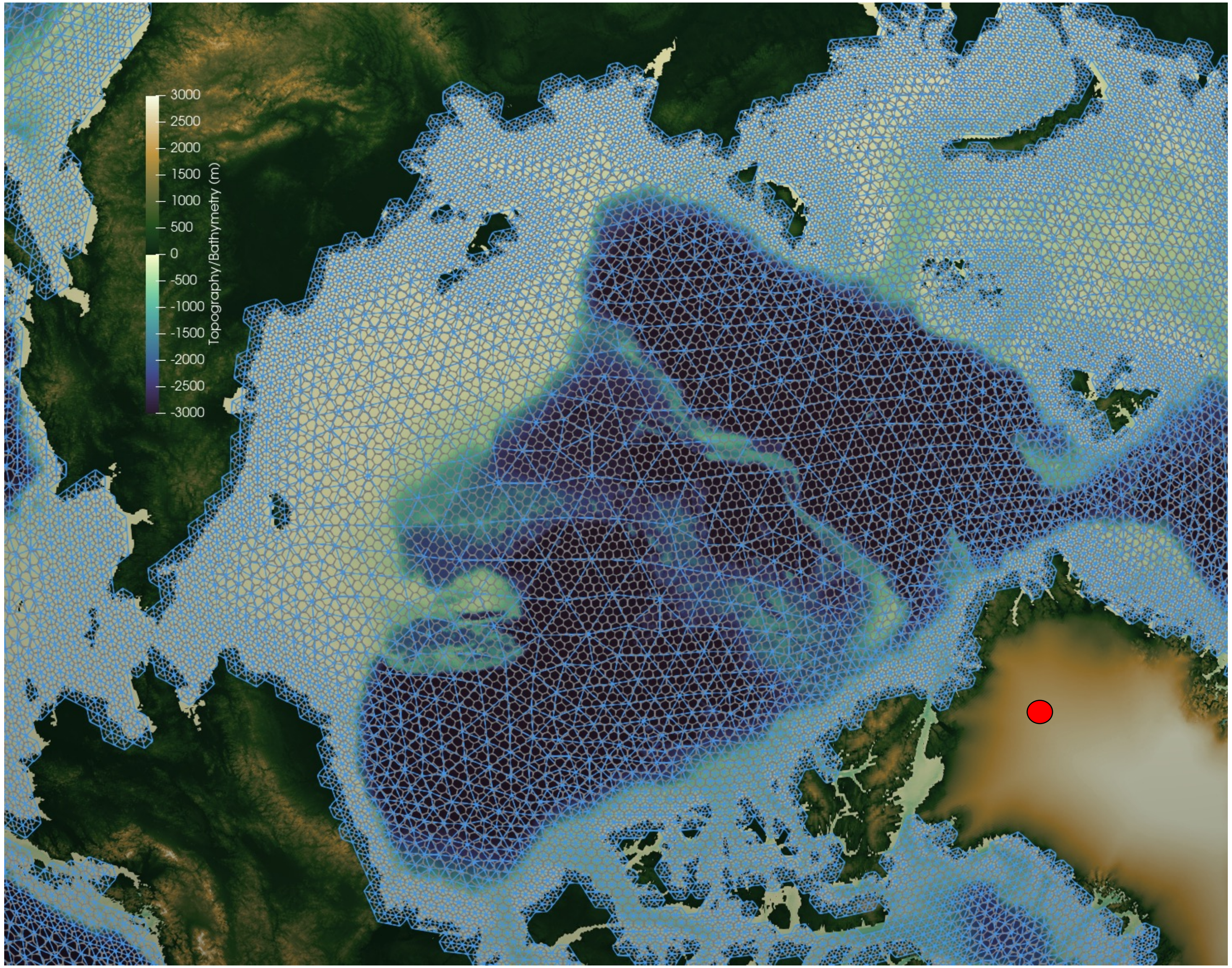
Wave mesh (blue triangles):
225km (open ocean) - 30km (coasts: matches ocean resolution)

Arctic Wave/Ocean Mesh

Ocean mesh (grey polygons):
30km polar

Wave mesh (blue triangles):
150 km (central Arctic)
30km (coasts: matches ocean resolution)

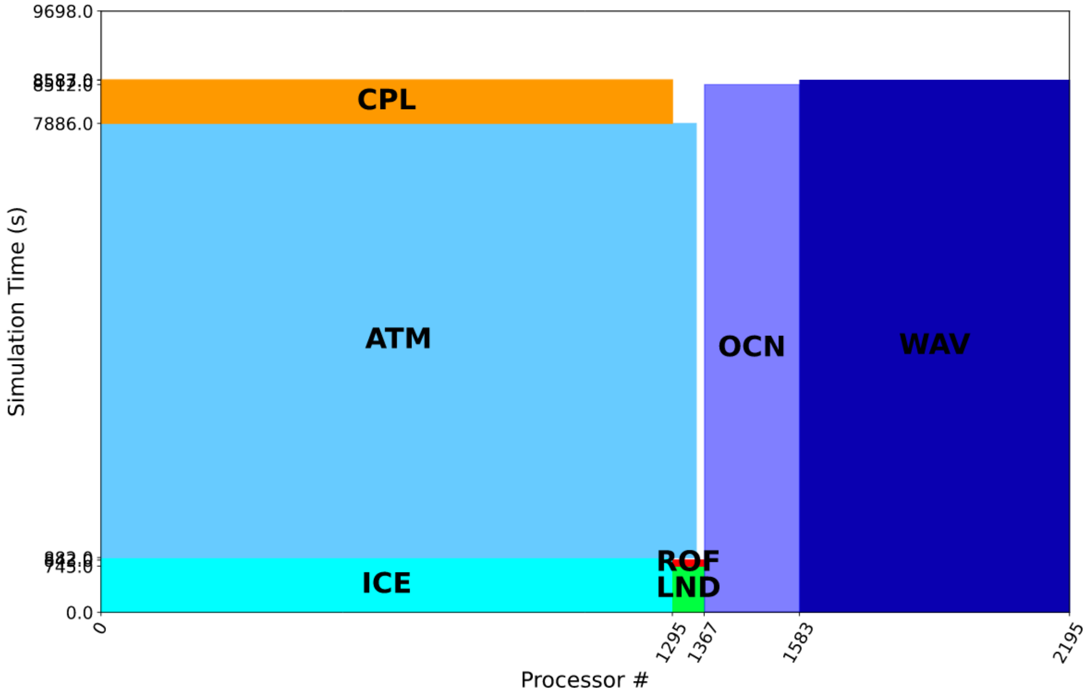
Rotated Pole (to Greenland) for waves mesh allows for complete Arctic coverage



E3SM Energy Exascale Earth System Model

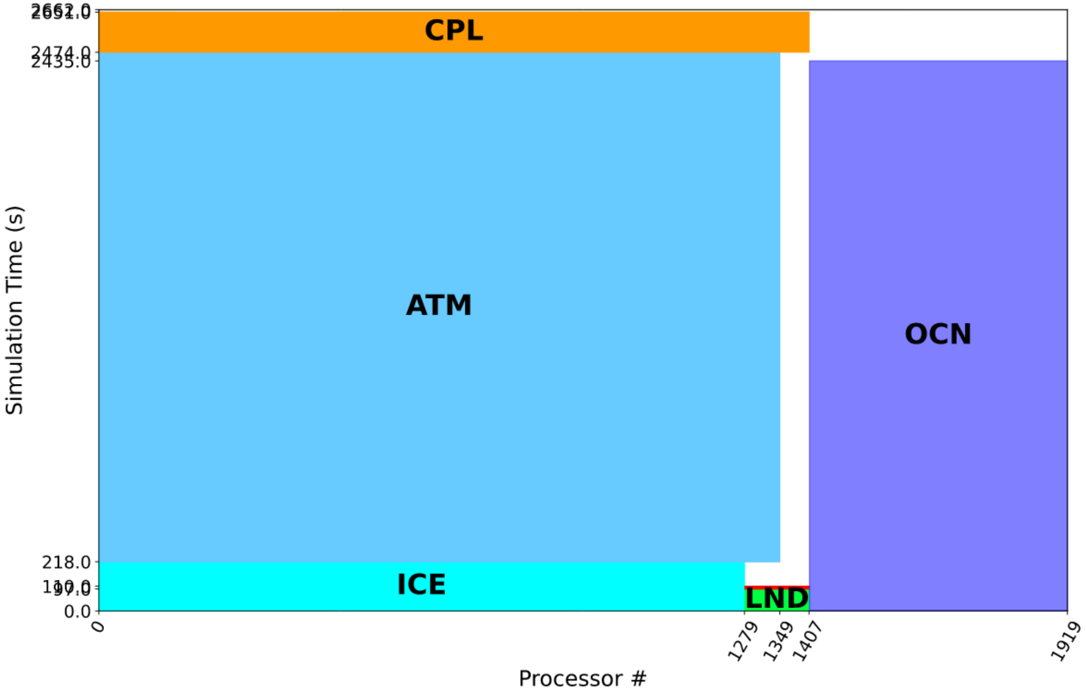
E3SM Performance

With Waves



8.91 SYPD

Standard Fully Coupled



8.00 SYPD

With this waves mesh configuration, similar throughput can be achieved as for a standard fully coupled run using E3SMv1 meshes.

(note slightly different processor layout)

Momentum Flux Coupling

Charnock parameter estimation based on wave state (Janssen 1991):

$$\alpha_{wave} = \frac{\hat{\alpha}}{\sqrt{1 - \tau_{wave}^{atm} / \tau_{atm}}}$$

$$\hat{\alpha} = 0.01$$

Momentum flux to from atm to wavefield

$$\tau_{wave}^{atm} = \rho_w g \int_0^{2\pi} \int_0^{\infty} \frac{k}{\omega} S_{in} d\omega d\theta$$

Momentum flux into ocean from wave dissipation

$$\tau_{ocean}^{wave} = \rho_w g \int_0^{2\pi} \int_0^{\infty} \frac{k}{\omega} S_{ds} d\omega d\theta$$

	NCAR	COARE3.0a	COARE3.0a_WAVE
Drag Coefficient (Atm Side)	$C_D = f(U_{10})$	$C_D = f\left(Z_0(\alpha(U_{10}))\right)$	$C_D = f\left(Z_0(\alpha_{wave})\right)$
Wind Stress (Ocean Side)	$\tau_{atm} = \tau_{ocean}$	$\tau_{atm} = \tau_{ocean}$	$\tau_{ocean} = \tau_{atm}(\alpha_{wave}) - \tau_{wave}^{atm} - \tau_{ocean}^{wave}$

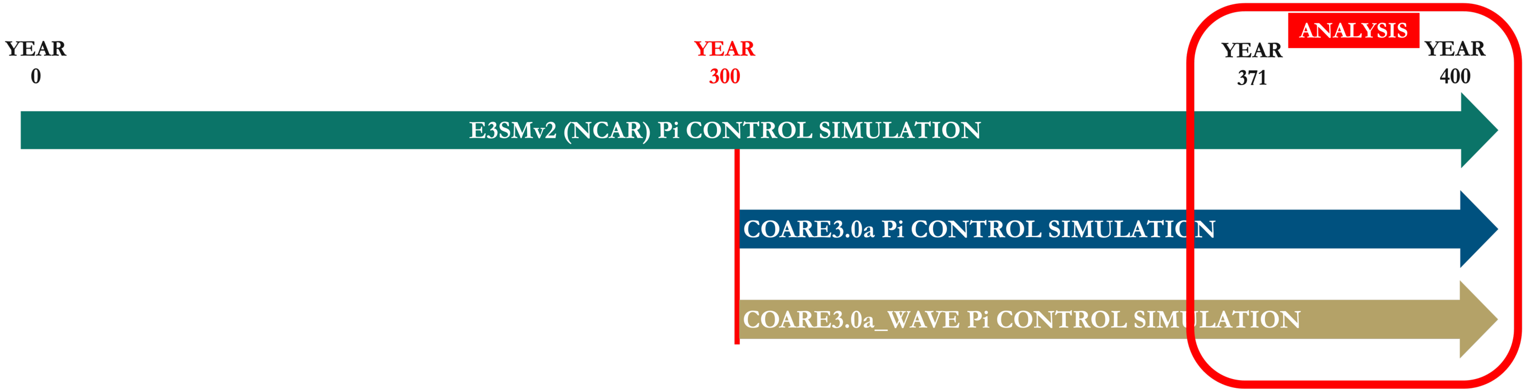
Experimental Setup

E3SMv2 LR

Atmosphere (EAM):
ne30pg2

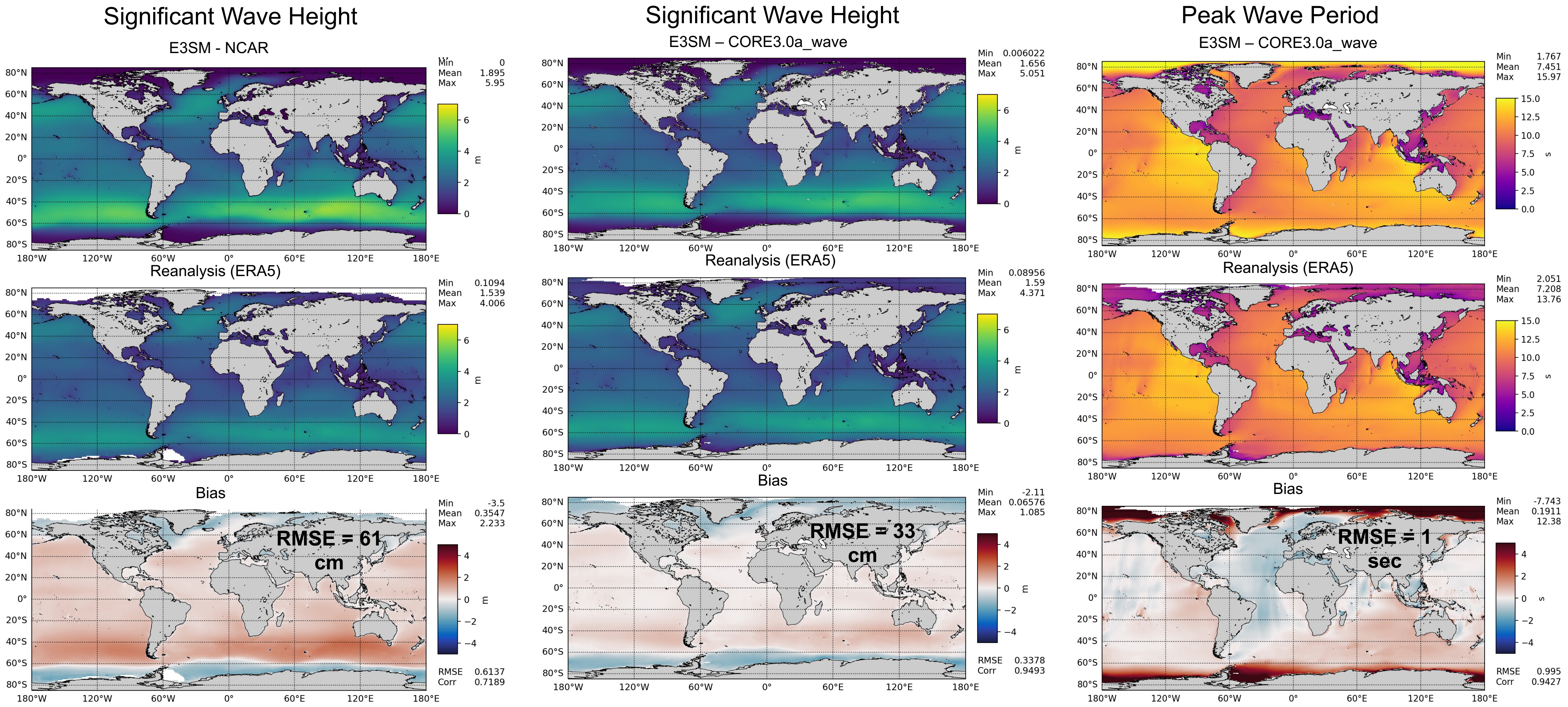
Ocean (MPAS-Ocean)
30km – 60km with 60 vertical levels

Waves (WW3 v6.07)
30km - 225km



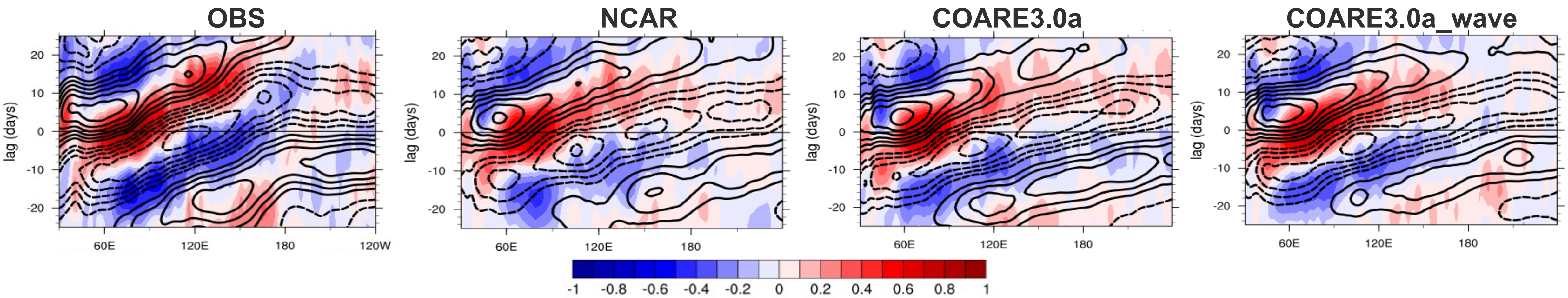
Observations:
OLR: NOAA Interpolated Outgoing Longwave Radiation (OLR) - 1981 -2010
PRECT: NOAA Daily GPCP Satellite-Gauge Combined Precipitation – 1996 - 2015
WIND: NCEP-NCAR Reanalysis 1 - 1981-2010

Waves Results

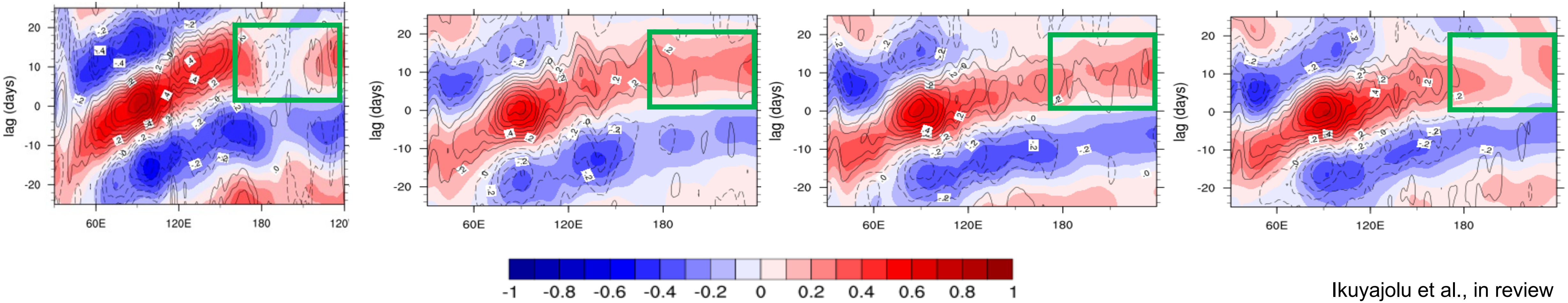


MJO Improvements

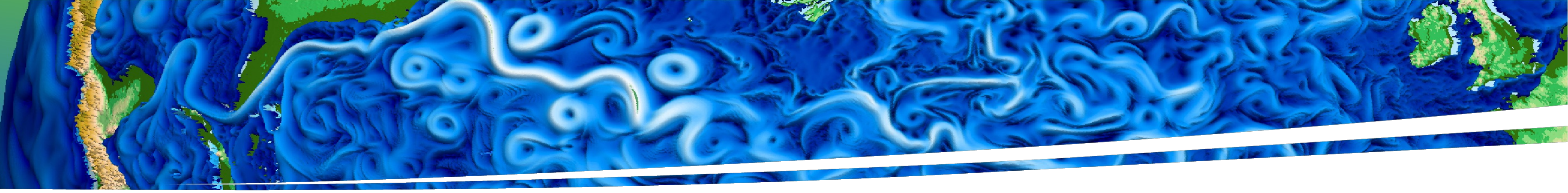
Nov-Apr 10°N–10°S precipitation (colors) and 850-hPa zonal wind anomalies (contours) correlated against precipitation OLR at the Indian Ocean reference box (10°S–5°N, 75°–100°E)



$$\left\langle \frac{\partial m}{\partial t} \right\rangle_{MJO} = -\left\langle \omega \frac{\partial m}{\partial p}\right\rangle_{MJO} - \langle \mathbf{v}\cdot\nabla m\rangle_{MJO} + \underbrace{LH_{MJO}+SH_{MJO}}_{F_{surf}} + \underbrace{LW_{MJO}+SW_{MJO}}_{QR}$$



Ikuyajolu et al., in review



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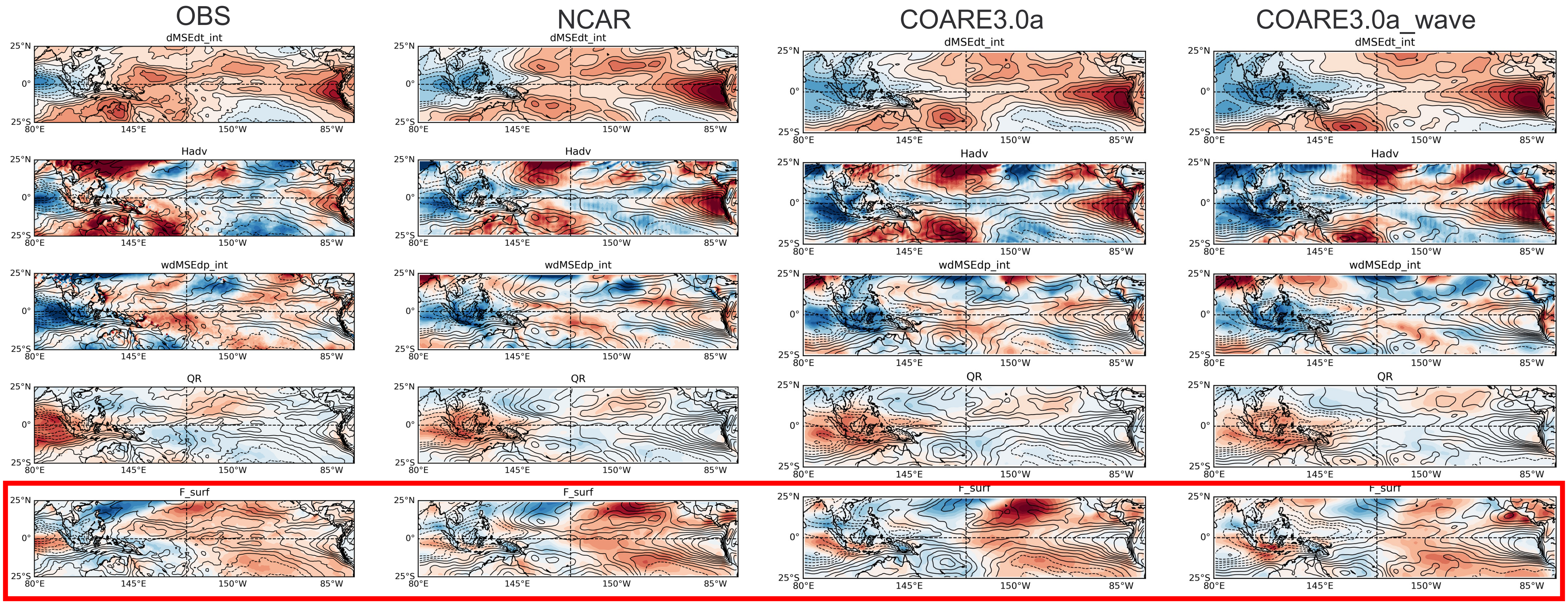
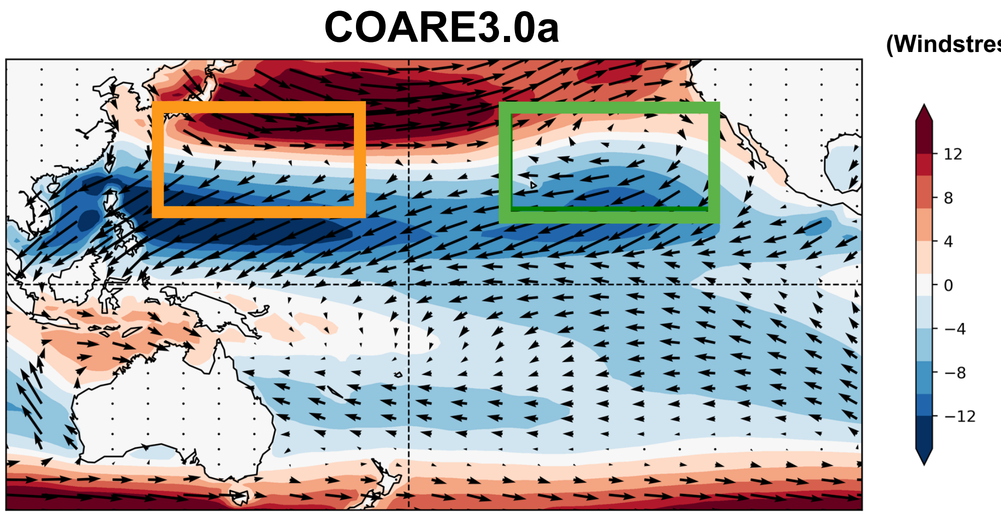
MJO Phase 4+5 Composite



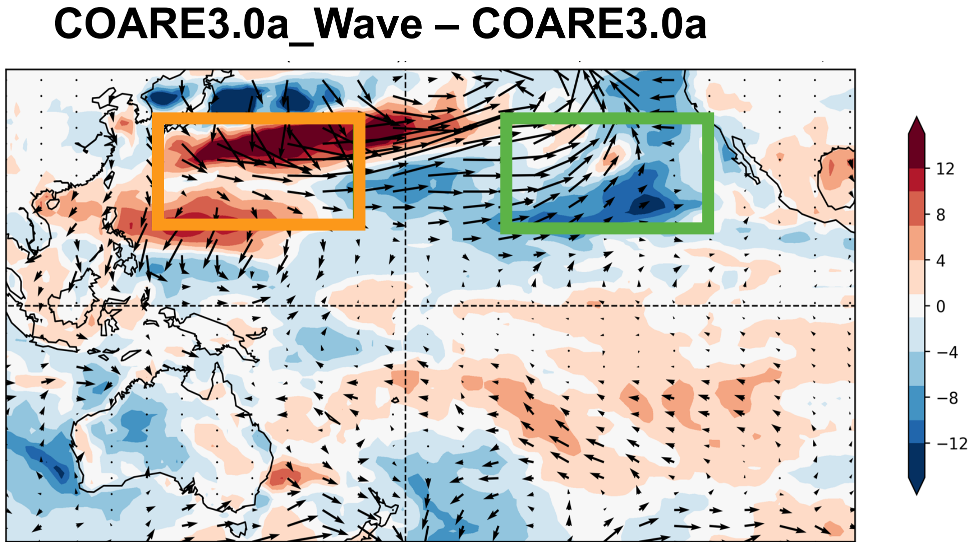
Excess latent heat flux anomalies in COARE3.0a responsible for MJO propagation after the dateline Waves reduce the LHFLX and inhibit MJO Propagation after the dateline

Ikuyajolu et al., in review

Winter DJF



Vector: Windstress
Shading : Zonal Windstress



Vector: Windstress
Shading: LH flux

Ikuyajolu et al., in review

Near the regime shift from easterlies to westerlies, surface waves reduce easterlies over the north equatorial central Pacific.

Reduced easterlies induce less evaporation (latent heat flux), thus, dry the atmosphere above.

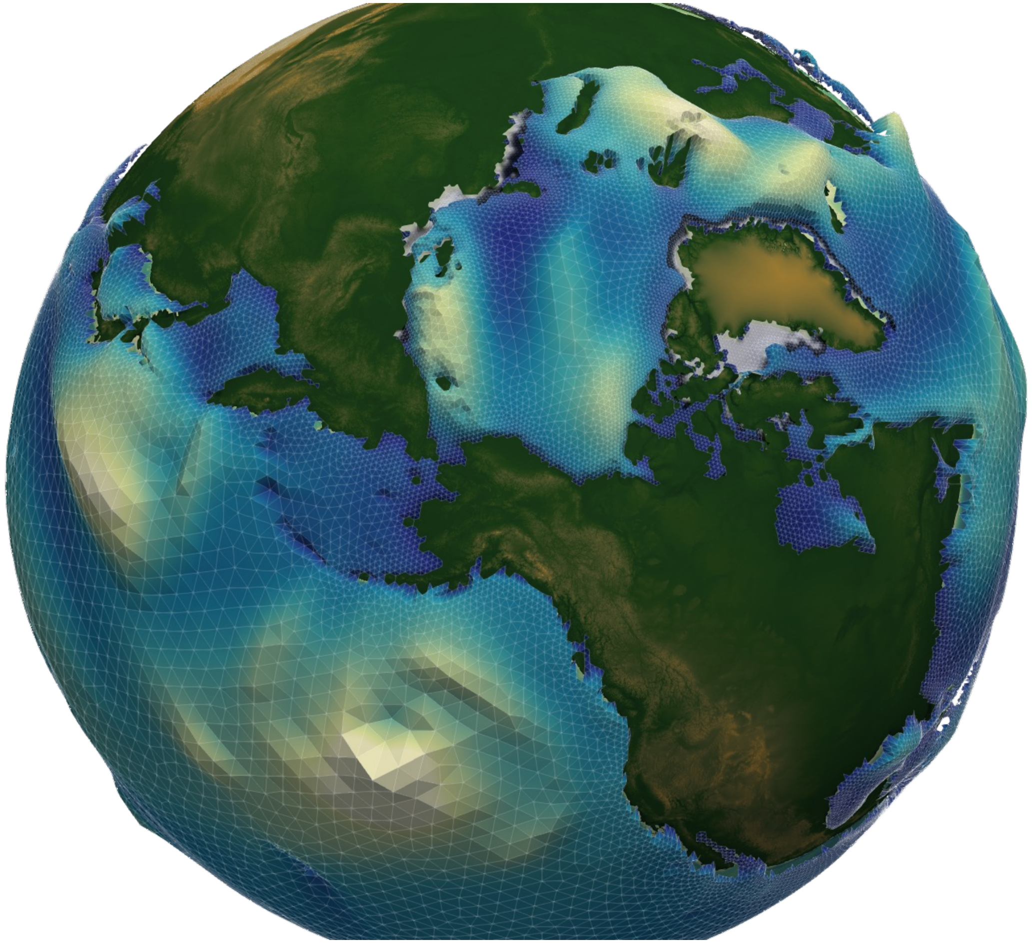
Reduced latent heat flux inhibits MJO propagation and maintenance after the dateline.

In Winter, near the regime shift from easterlies to westerlies (storm track), surface waves increases westerlies over the north equatorial eastern Pacific.

Increased westerlies increase evaporation (latent heat flux), thus, moisten the atmosphere above.

Increased latent heat flux enhance MJO precipitation in the western Pacific.

Thank you!



E3SM is funded by the Office of Science Biological and Environmental Research Program Office