E3SMv3: Wave Configuration Current Status + Future Plans

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LAUR 25-26182

E3SM Energy Exascale Earth System Model

Outline

- **E3SMv3: Overview**
- **E3SMv3: Recent (Relevant) Developments**
  - WAVEWATCHIII Unstructured Mesh
  - Wave – Ocean – Atm Momentum Coupling
  - Wave – Sea Ice Coupling
- ***E3SMv3: Ongoing Efforts + Future Plans***
  - Resolution
  - AI / ML for Waves
  - other big picture ideas for E3SM

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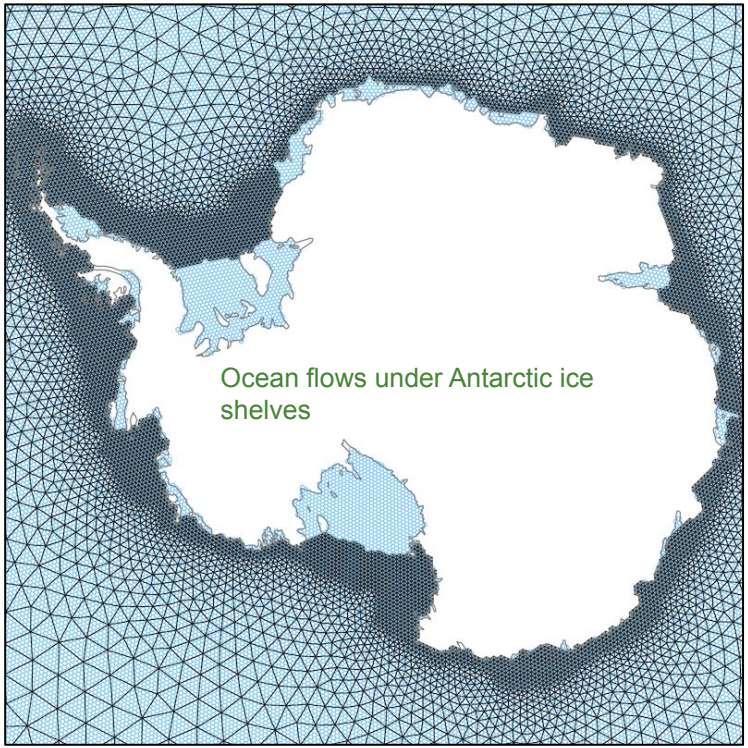
The Energy Exascale Earth System Model

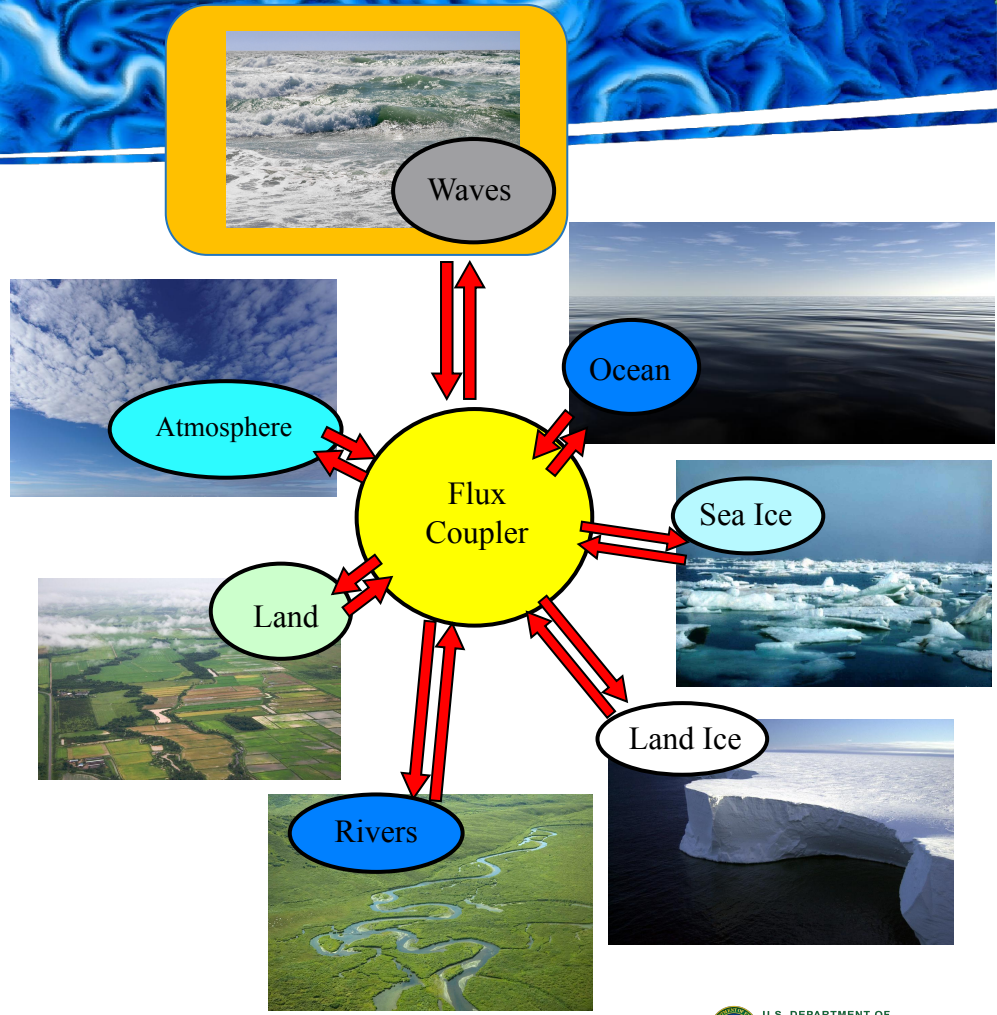


Unstructured ocean-sea ice (blue) and waves (black) meshes

- Flagship Earth system model developed across DOE labs
- **Now includes ice shelves, sea ice floes and wave attenuation**
- Focused on seasonal to multi decadal prediction
- Targeting exascale computing using GPUs & AI
- E3SMv3 (2024) 30km/100km/0.5˚ marine/atmos/land
- E3SMv4 (2027) eddy & cloud resolving target

Current Capabilities in the Energy Exascale Earth System Model (E3SMv3):

- E3SM is a *fully coupled* global Earth system model targeting exascale computing
- **Now Includes:**
  - **Fully coupled Waves (WW3)**
  - **Wave-Ice Interactions (FSD, Icepack)**
  - Antarctic ice shelves
- **Unstructured meshes: capable of regional refinement in the sea ice, ocean, and waves**



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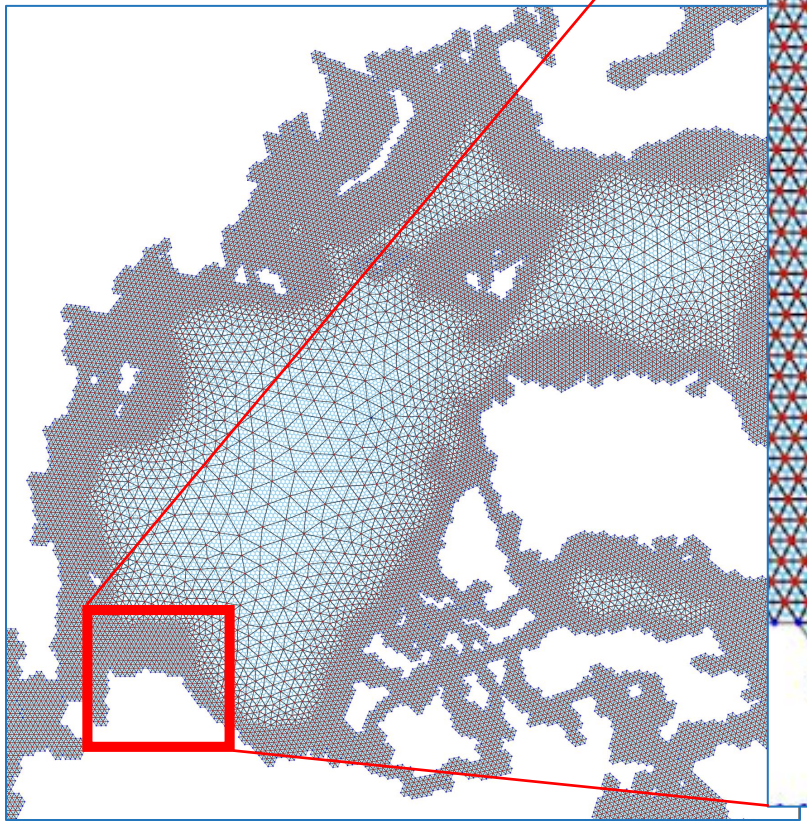
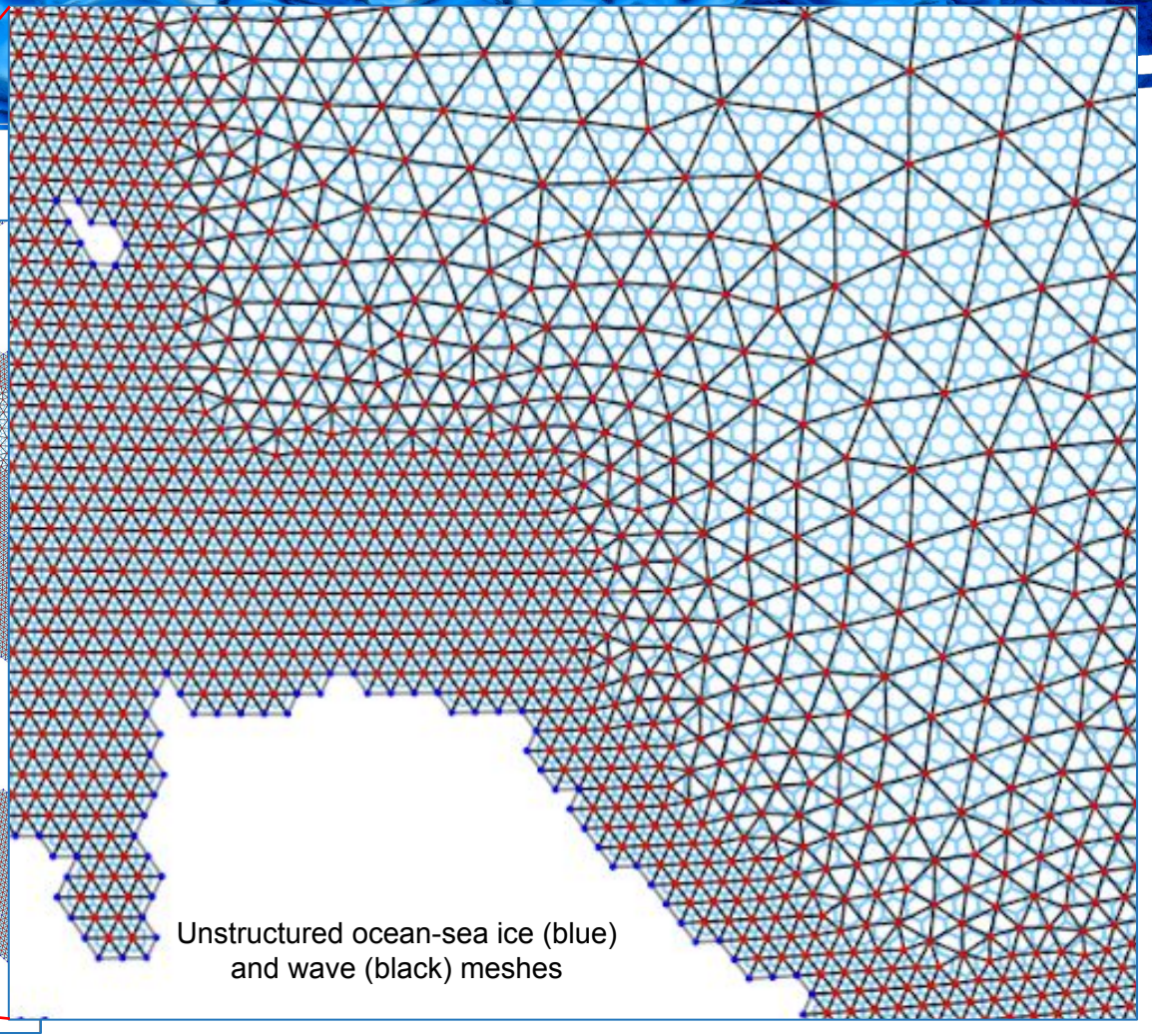
E3SM Energy Exascale Earth System Model

Unstructured Mesh

Resolution = 30 km along coastlines
to 200+ km in open ocean

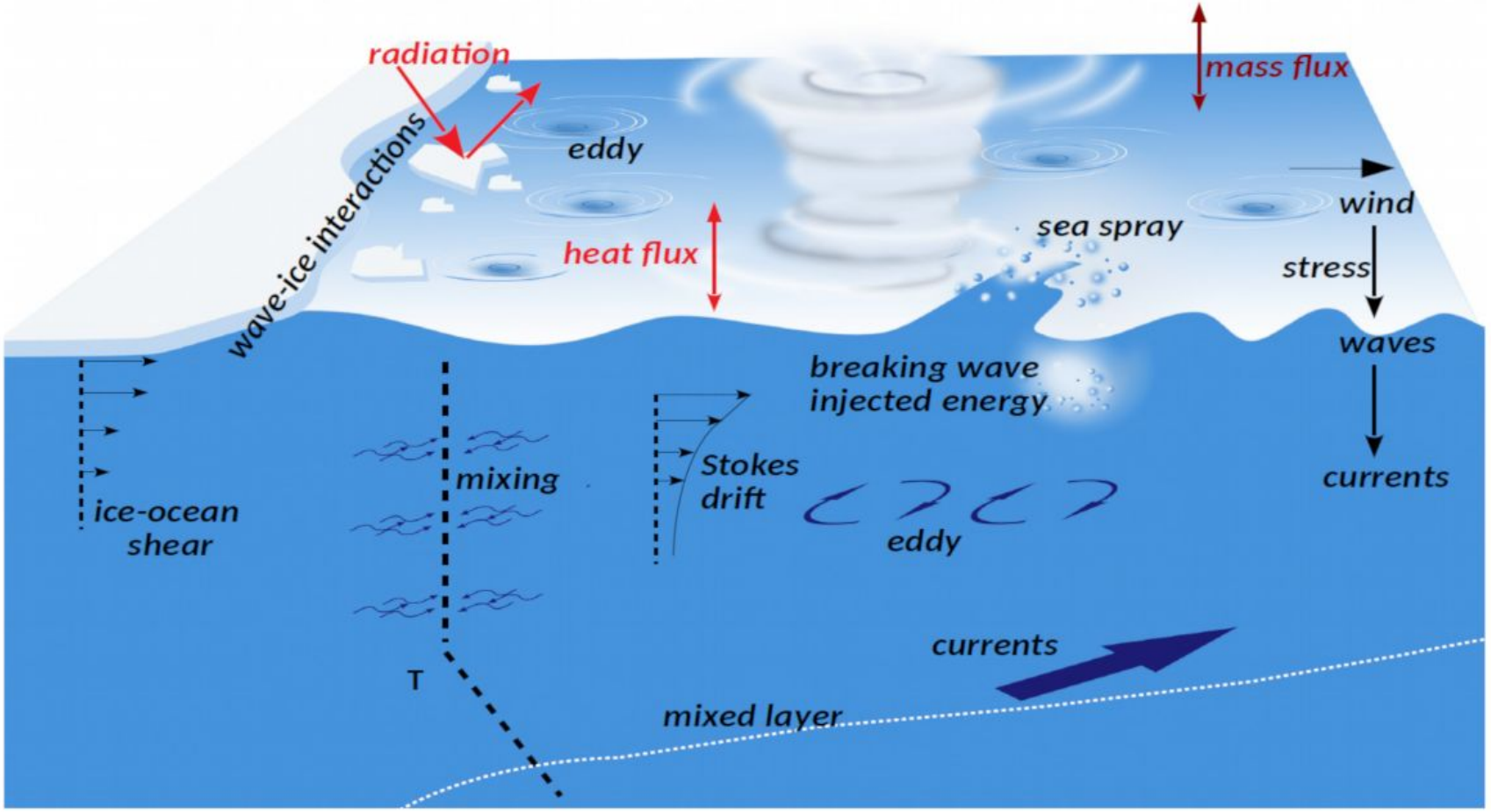




Unstructured ocean-sea ice (blue)
and wave (black) meshes

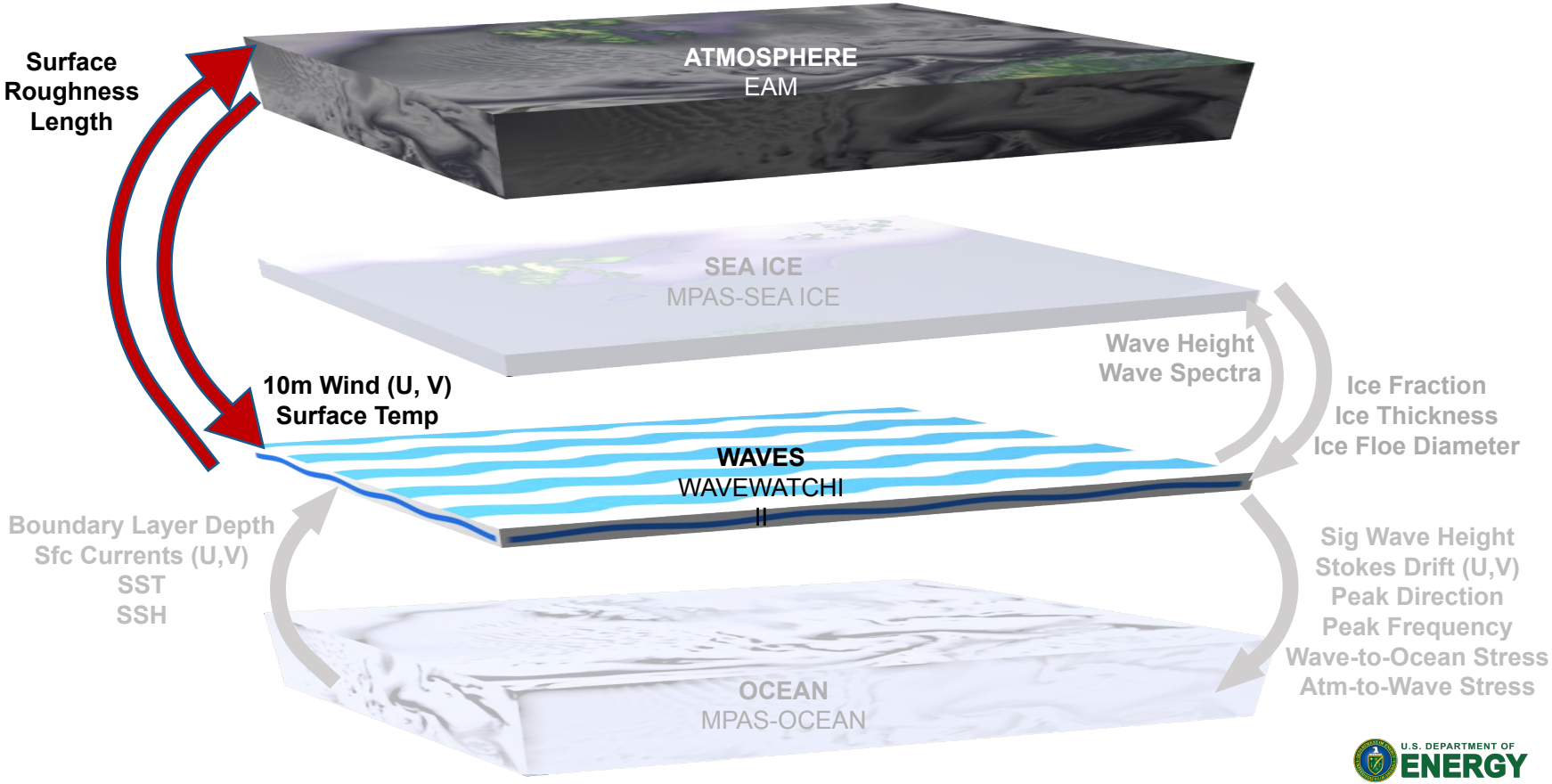
E3SM Energy Exascale Earth System Model

Introduction



E3SM Energy Exascale Earth System Model

Wave - Atmosphere Coupling



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Wave - Atmosphere Coupling

	Neutral drag coefficient (C_{DN})
NCAR	$(2.7U_{10N}^{-1} + 0.142 + 0.0.0764U_{10N}) \times 10^{-3}$
COR3.0a	$C_{\mathrm{DN}}[z_{o,m}[\alpha(U_{10N})]]$
COR3.0a-WAV	$C_{\mathrm{DN}}[z_{o,m}(\alpha_w)]$

E3SM default setting = NCAR

No possible wave feedback to the atm since the *drag coefficient is parametrized as a function of only 10m wind speed.*

Wave - Atmosphere Coupling

	Neutral drag coefficient (C_{DN})
NCAR	$(2.7U_{10N}^{-1} + 0.142 + 0.0.0764U_{10N}) \times 10^{-3}$
COR3.0a	$C_{DN}\{z_{o,m}[\alpha(U_{10N})]\}$
COR3.0a-WAV	$C_{DN}[z_{o,m}(\alpha_w)]$

The COARE 3.0 turbulent flux scheme **would** allow for wave coupling through the Charnock parameter

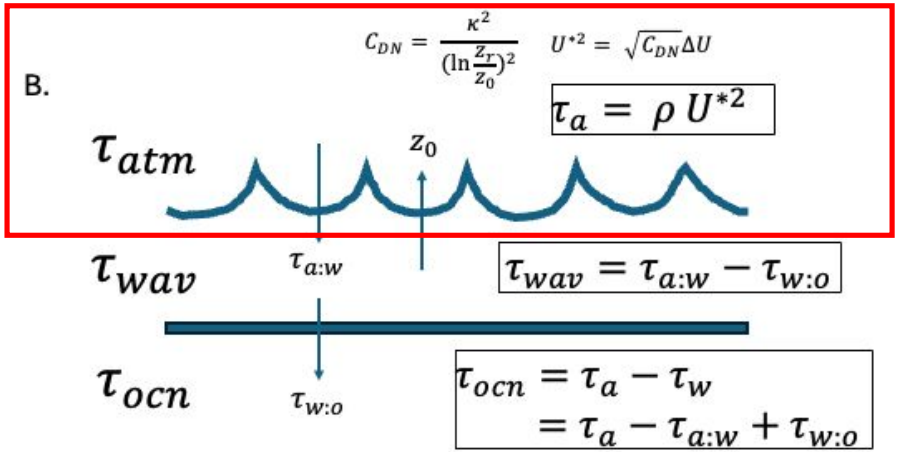
-HOWEVER-

1) this flux scheme is **NOT** used in standard E3SM simulations, so any results are NOT comparable to baseline E3SM simulations.
2) The flux scheme over sea ice is based on the NCAR, so the fluxes over ocean and ice surfaces would be incompatible

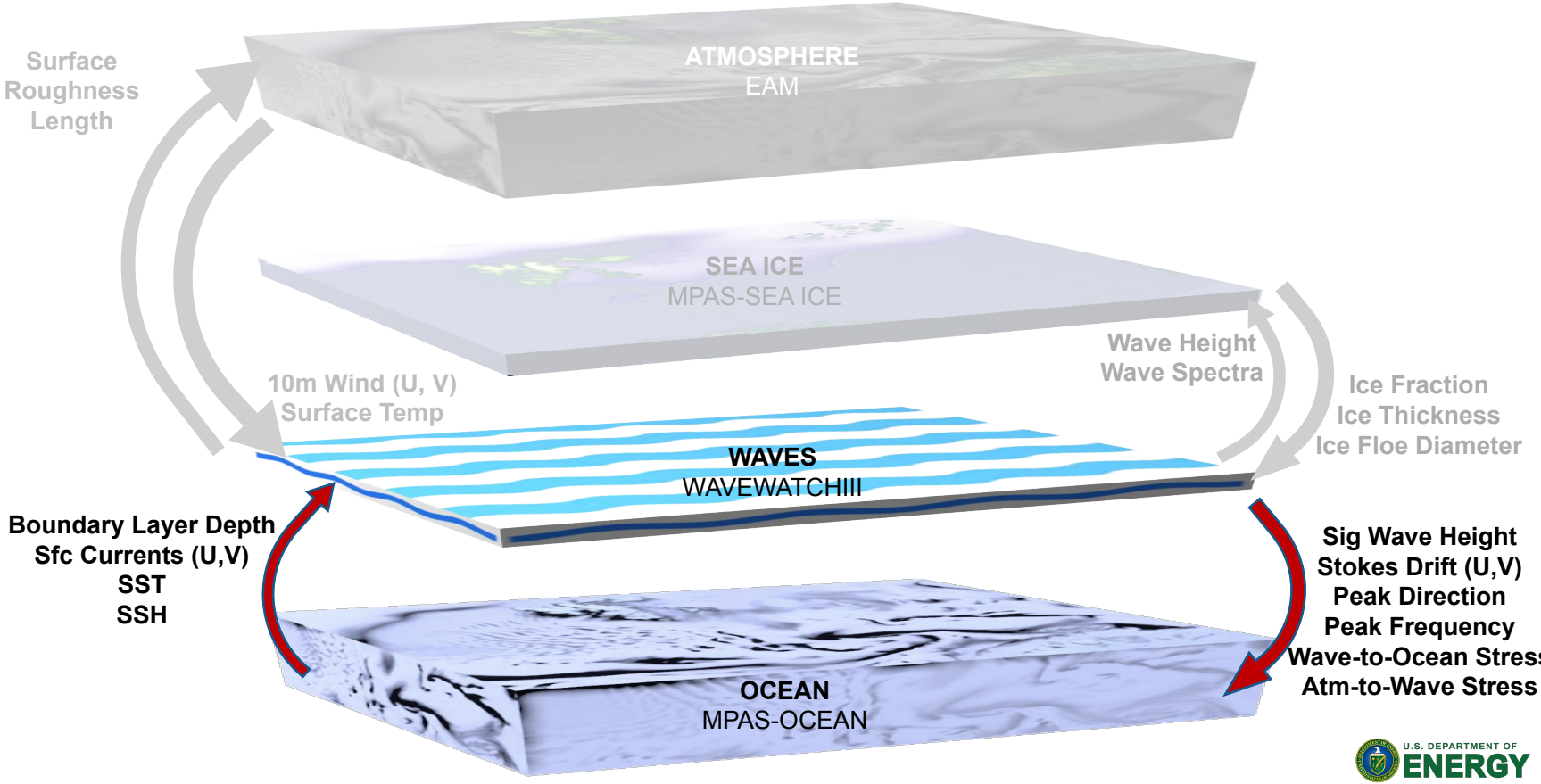
Wave - Atmosphere Coupling

	Neutral drag coefficient (C_{DN})
NCAR	~~$(2.7U_{10N}^{-1} + 0.142 + 0.0764U_{10N}) \times 10^{-3}$~~
COR3.0a	$C_{DN}\{z_{o,m}[\alpha(U_{10N})]\}$
COR3.0a-WAV	$C_{DN}[z_{o,m}(\alpha_w)]$

Therefore, we created *a 'modified NCAR' surface flux scheme that allows for wave coupling by* ***calculating the surface drag coefficient*** *from the surface roughness (****Z0) directly from WW3****:*



Wave - Ocean Coupling



Wave - Ocean Coupling: Mixing

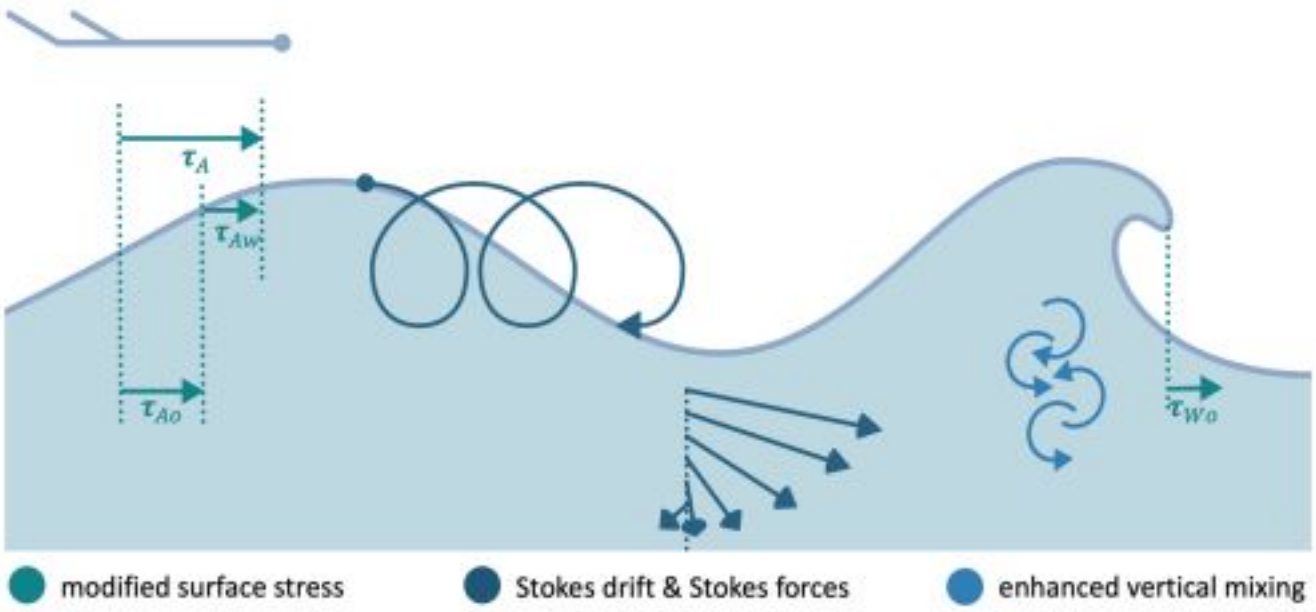


Figure from Rühs, S., et. al., Ocean Sci., 2025

- Partitioned stokes drift values computed in WW3
- Partitioned stokes drift passed from WW3 to MPAS-Ocean
- the full depth profile of the Stokes drift then reconstructed in the ocean model
- In MPAS-O, reconstructed stokes drift used to estimate the Langmuir enhancement factor.

Wave - Ocean Coupling: Momentum

Default Atm-Ocean coupling setup assumes ocean side stress is equal to atm stress….

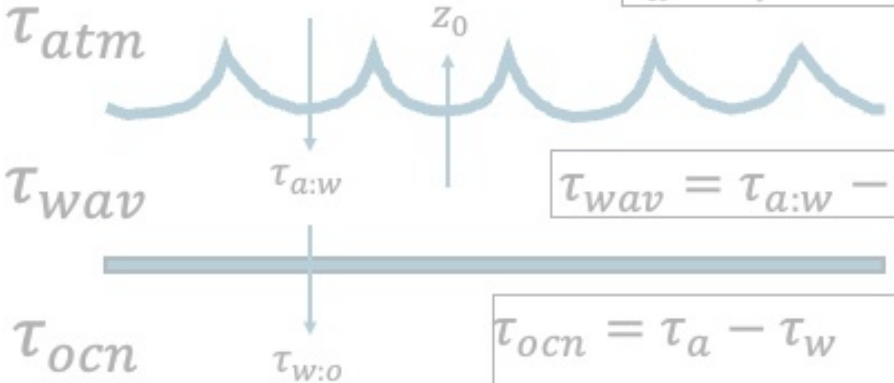
A.

$$\tau_{ocn} = \tau_{atm}$$

B.

$$C_{DN} = \frac{\kappa^2}{(\ln \frac{z_r}{z_0})^2} \qquad U^{*2} = \sqrt{C_{DN}}\Delta U$$

$$\tau_a = \rho\, U^{*2}$$



Wave - Ocean Coupling: Momentum

However: some of Atm momentum is lost to waves ... and waves themselves can impart a stress to the ocean… ***We now account for all of this***

A.

$$\tau_{ocn} = \tau_{atm}$$

B.

$$C_{DN} = \frac{\kappa^2}{(\ln \frac{z_r}{z_0})^2} \qquad U^{*2} = \sqrt{C_{DN}}\Delta U$$

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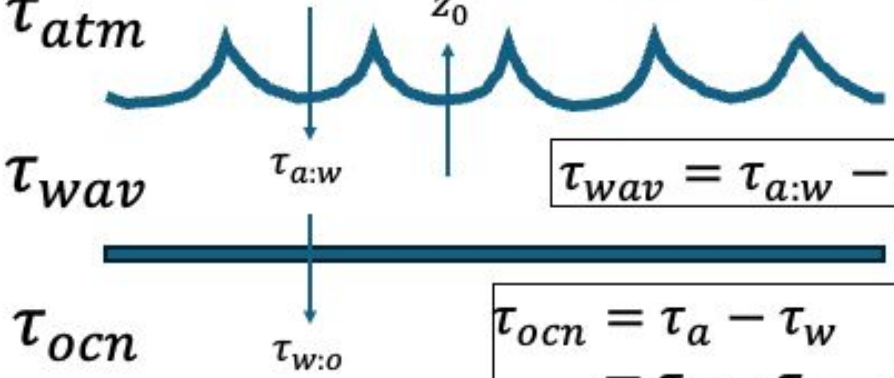
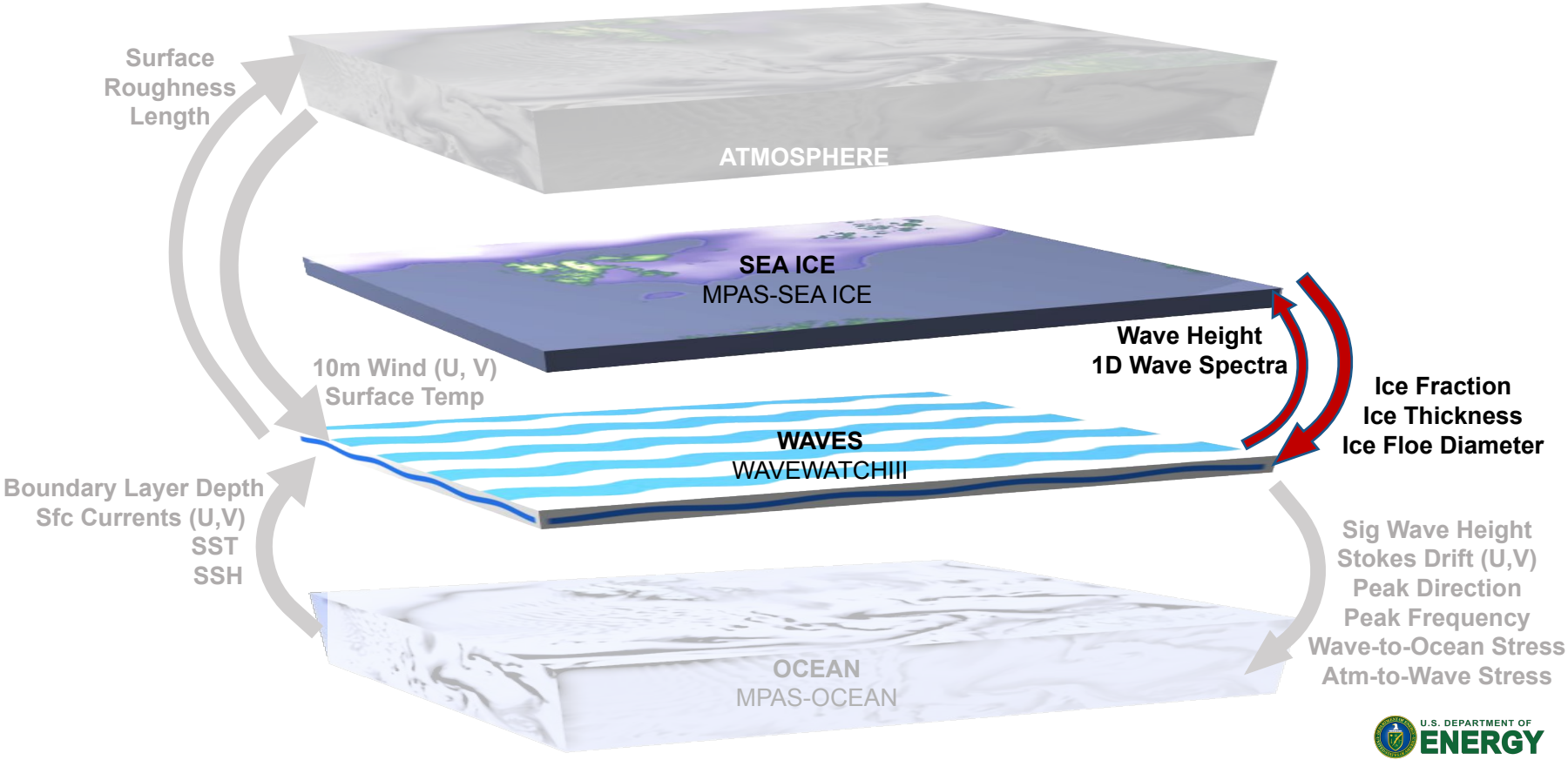


$$\tau_{wav} = \tau_{a:w} - \tau_{w:o}$$

$$\tau_{ocn} = \tau_a - \tau_w = \tau_a - \tau_{a:w} + \tau_{w:o}$$

Wave - Sea Ice Coupling



Wave - Sea Ice Coupling

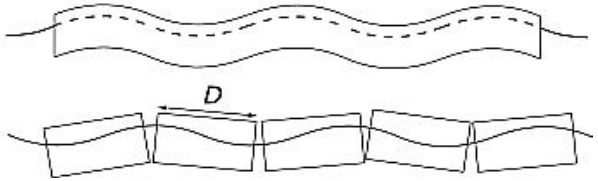
Sea Ice Floe Size Distribution (FSD)

- ICEPACK column physics

$$\frac{\partial f(r,h)}{\partial t} = \overbrace{-\nabla \cdot (f(r,h)\mathbf{v})}^{\text{Advection}} + \underbrace{\mathcal{L}_T}_{\text{Thermodynamics}} + \overbrace{\mathcal{L}_M}^{\text{Mechanical}} + \underbrace{\mathcal{L}_W}_{\text{Waves}}.$$

Floe Breaking Due to Waves

- Default FSD breaking scheme in Icepack
  (Horvat and Tziperman 2015/Roach et al. 2018, 2019)
- Sea ice flexes with the sea surface height field
- Ice Floe breaks if 'strain' exceeds critical threshold



Attenuation from scattering as Function of Wave Period

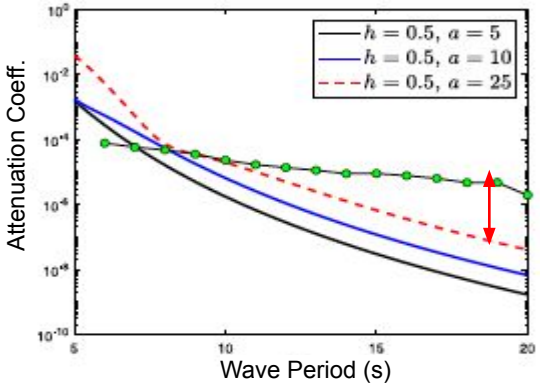


Figure 7
Meylan et al. 2021

Wave Attenuation due to Sea Ice: Meylan et al 2021

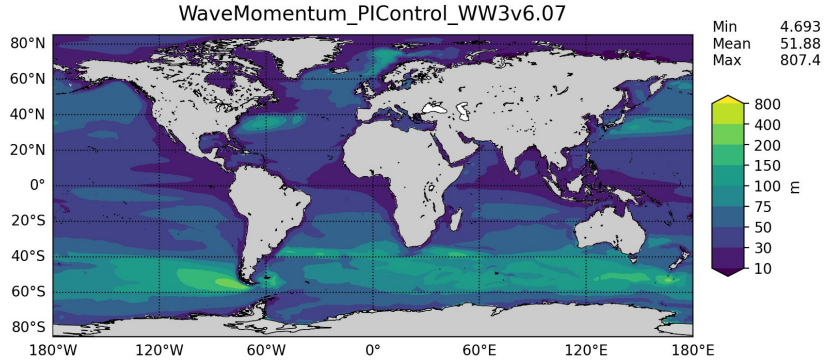
- Dissipation of wave power due to sea ice
  - Low Frequency waves (long wavelengths) dissipate LESS in sea ice (and are critical to wave-ice coupling in models)

Quick Summary of Results

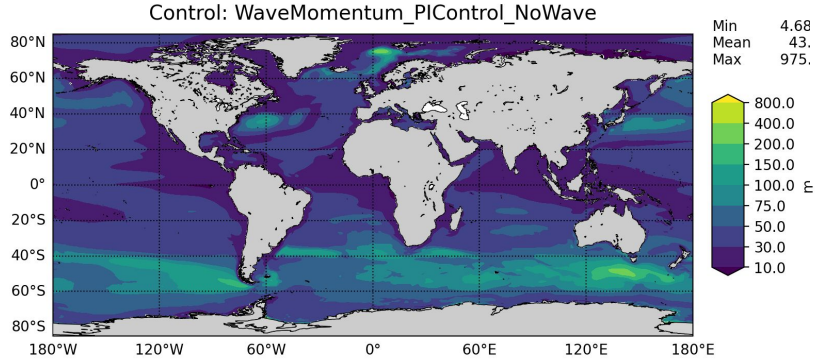
50-Yr Annual Mean MLD

MLD (ANN, years 0001-0050)

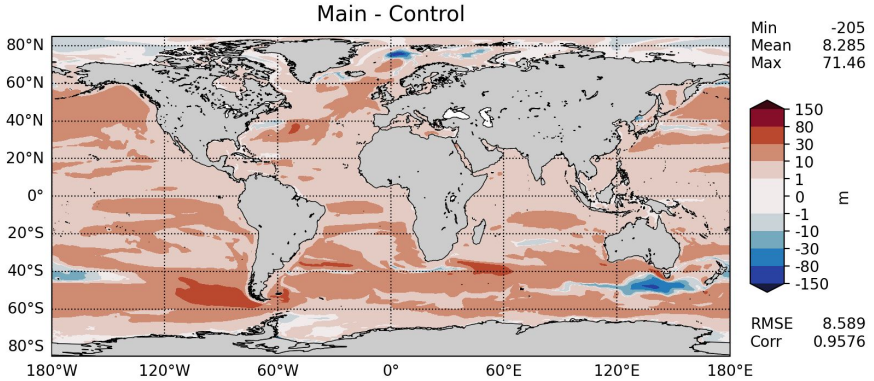
Wave Ocean Atm Coupling



No Wave



Wave-Ocean-Atm coupling: MLD increases (Stokes/ Langmuir)



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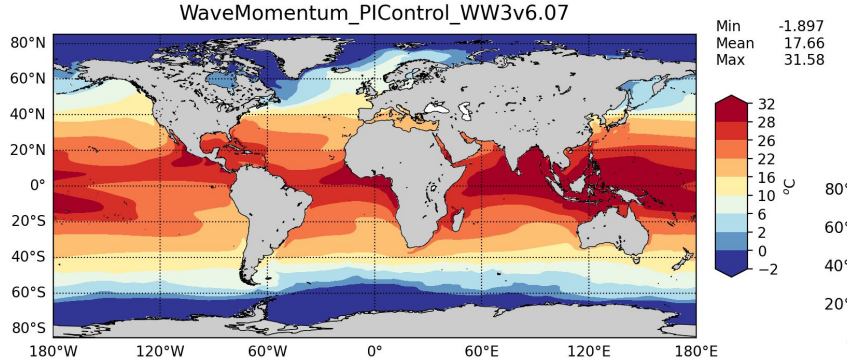
Quick Summary of Results

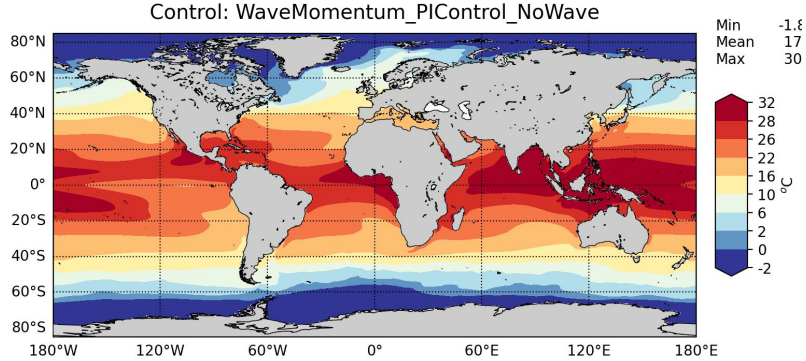
50-Yr Annual Mean SST

SST (ANN, years 0001-0050)

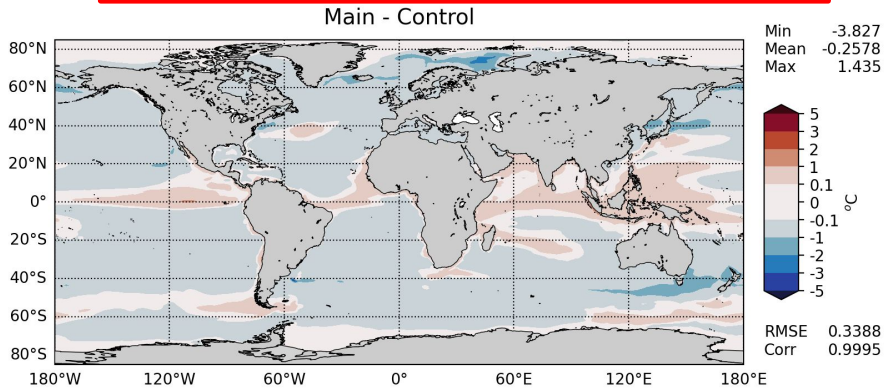
Wave Ocean Atm Coupling



No Wave



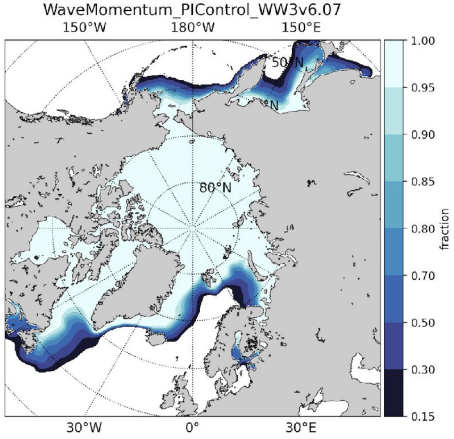
Wave-Ocean-Atm coupling: increased mixing = cooling



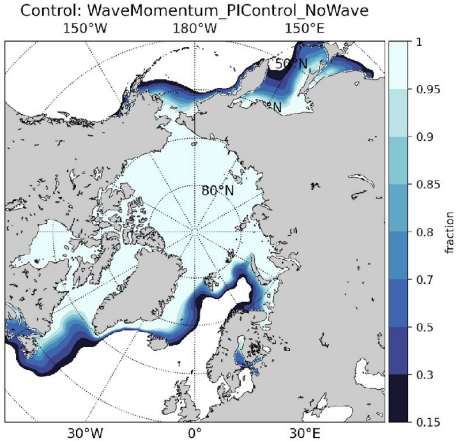
Quick Summary of Results

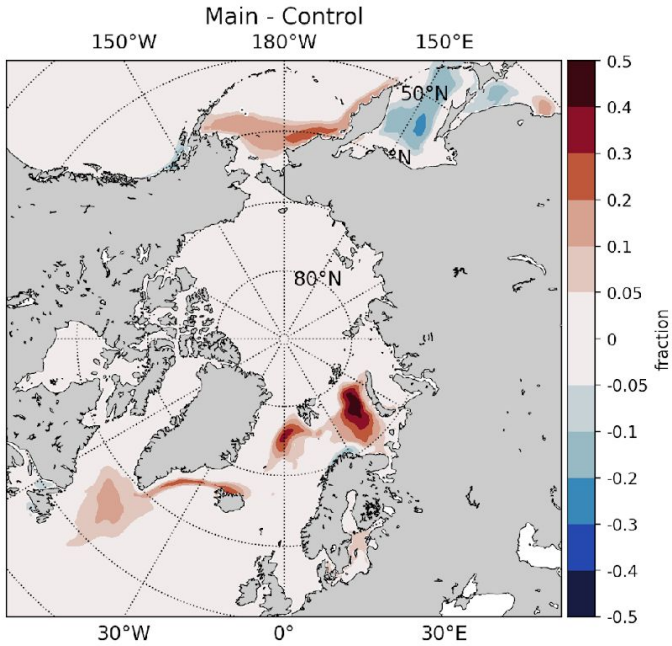
50-Yr JFM Mean Sea Ice Area

Wave
Ocean
Atm
Coupling



No
Wave





Wave-Ocean-Atm coupling:

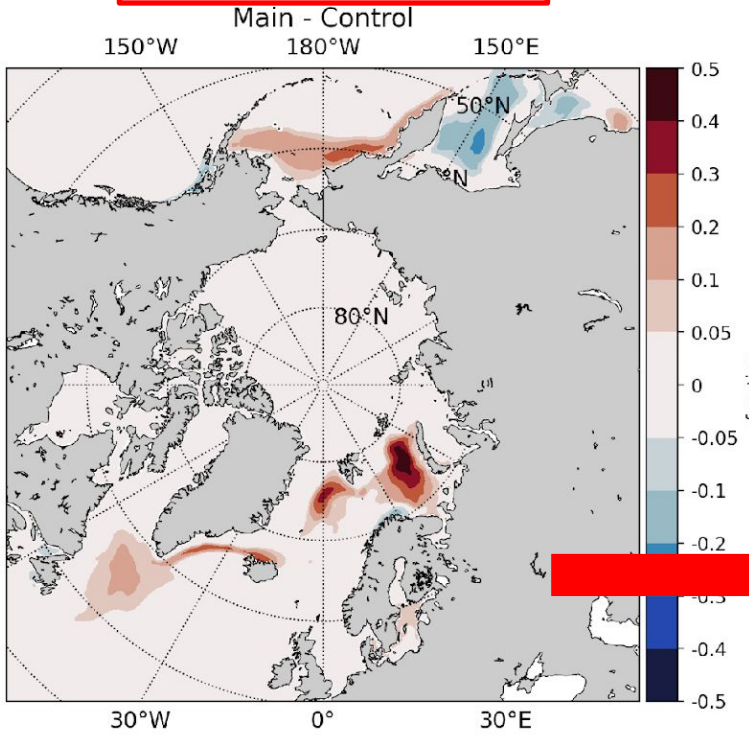
Cooling = Increased sea ice area (and increased thickness)

Quick Summary of Results

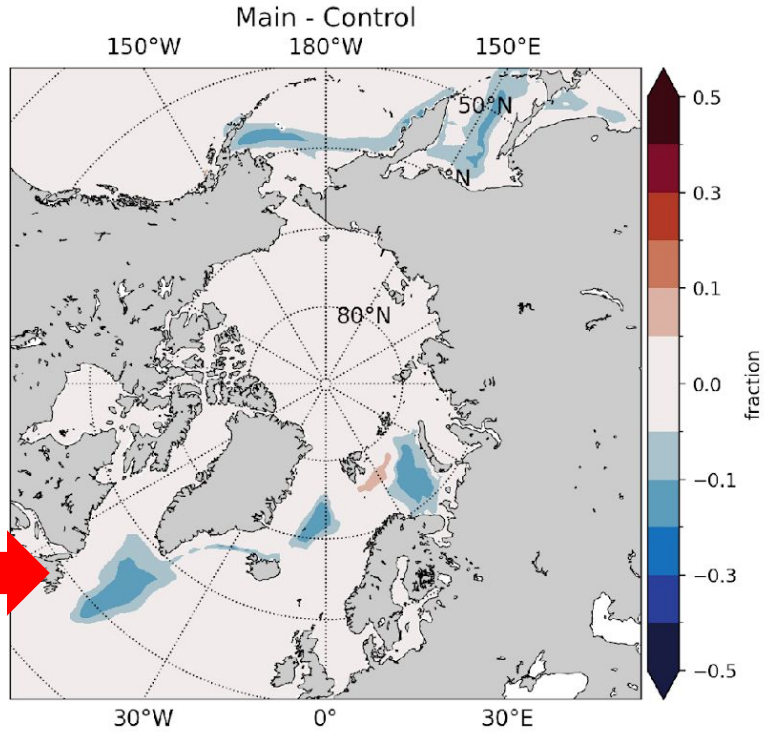
Wave-Ocean-Atm minus NoWave

50-Yr JFM Mean Sea Ice Area

Wave-Ocean-Atm-Ice minus Wave-Ocean-Atm



Wave-Ice coupling generally counteracts the impacts of wave-ocean coupling (lateral melt)

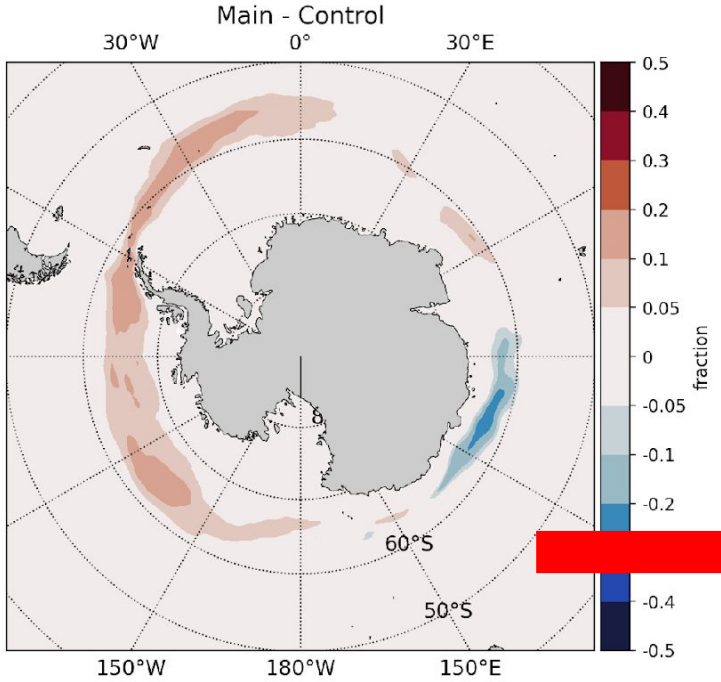


Quick Summary of Results

Wave-Ocean-Atm minus NoWave

50-Yr JJA Mean Sea Ice Area

Wave-Ocean-Atm-Ice minus Wave-Ocean-Atm



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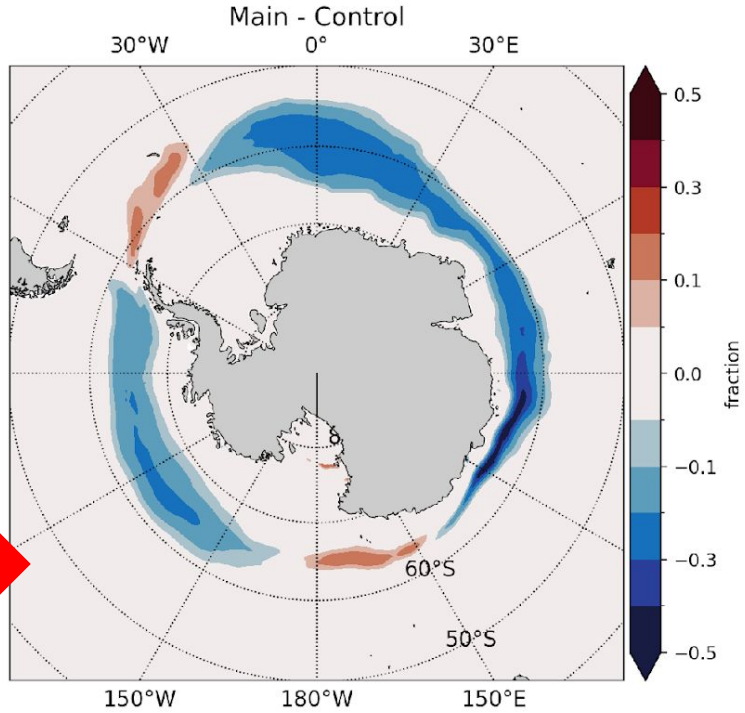

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E3SM: Ongoing Efforts + Future Plans

- Resolution
- AI / ML
- S2S / S2D

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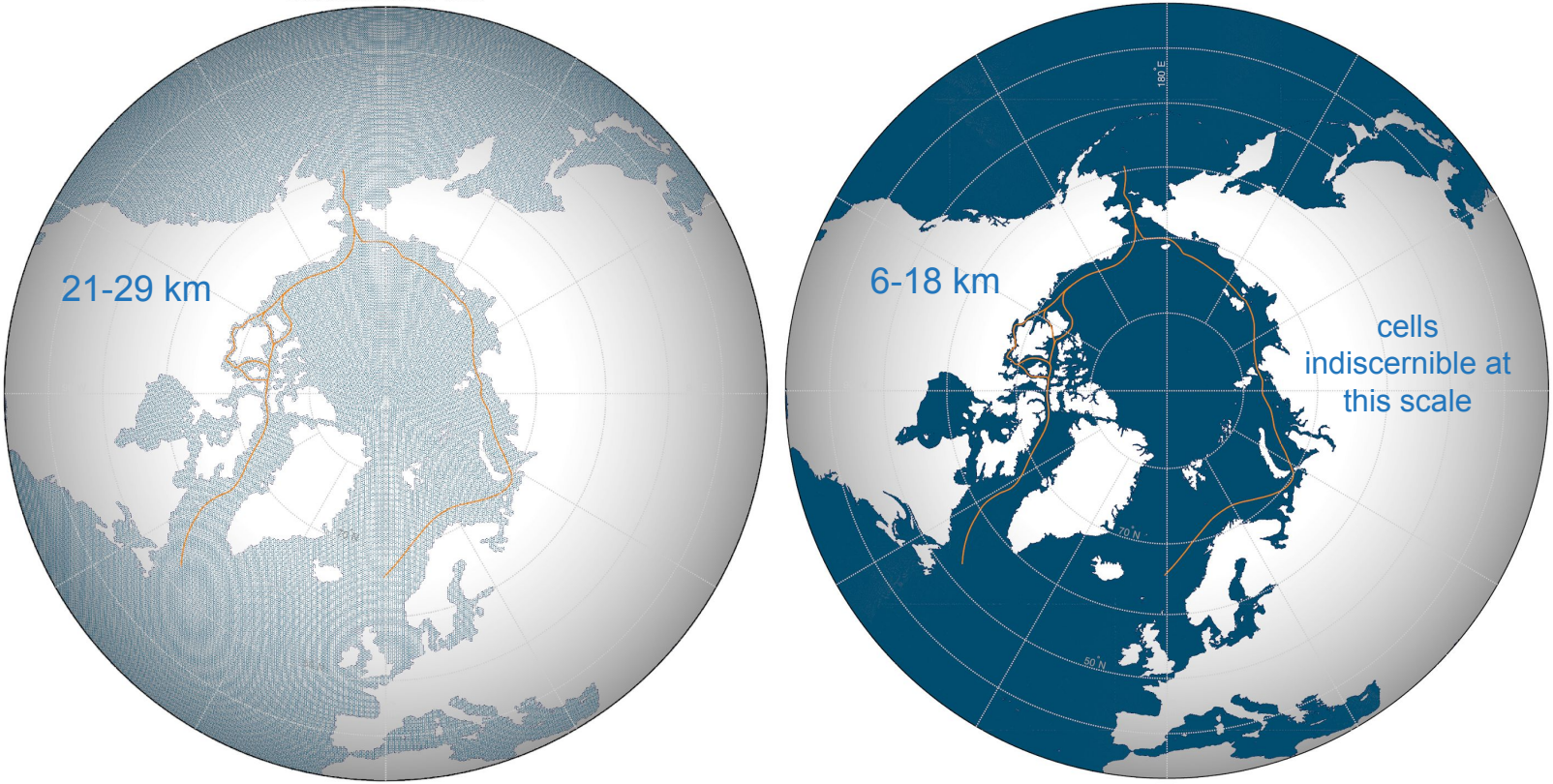
E3SM: Goals for Resolution … Everywhere

Ocean
+
Sea Ice

E3SMv3 Standard Resolution

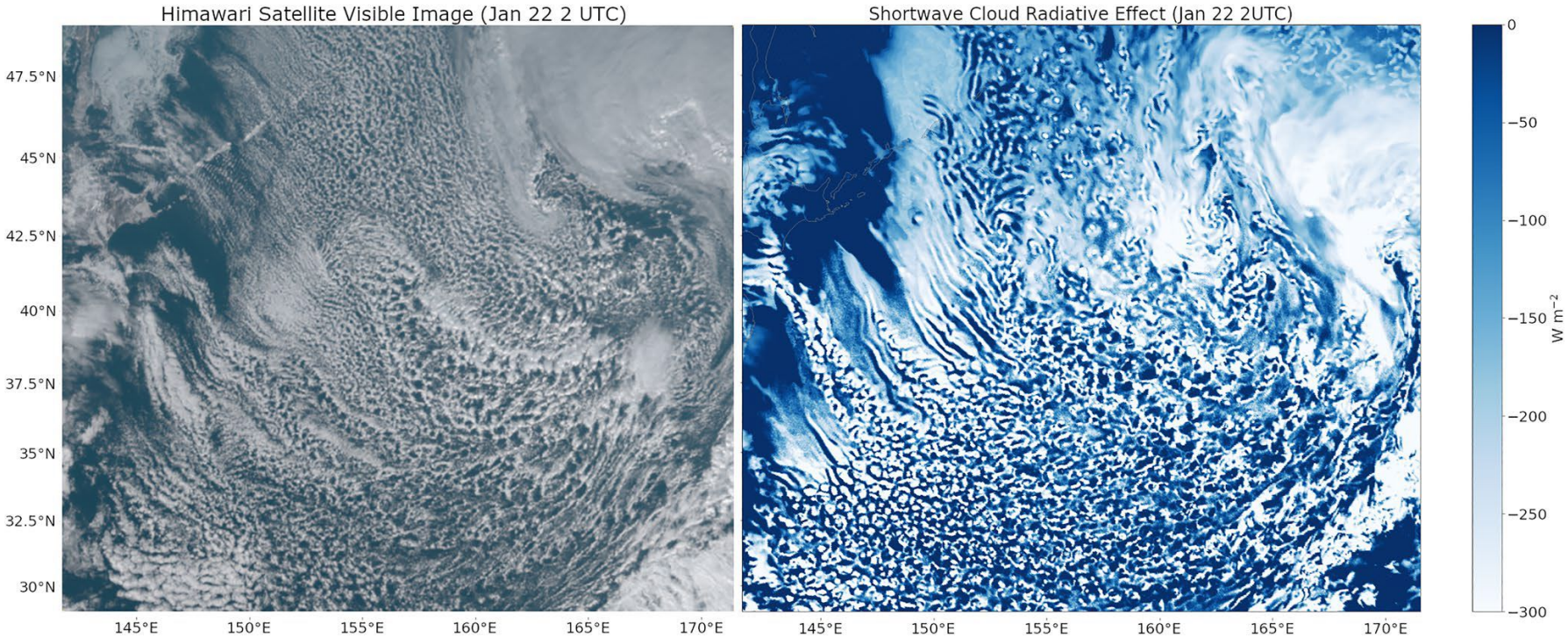
E3SMv3 High Resolution



Standard (left) versus high-resolution (right) E3SM meshes (17-fold data volume difference for surface fields)

E3SM: Goals for Resolution … Everywhere

Atmosphere: 3km cloud resolving atmosphere



Cold-air outbreak off Siberia on January 22, 2020 at 2:00:00 UTC (~local noon) from a Himawari visible satellite image (left) and shortwave cloud radiative effect from SCREAM (right) from convection permitting model by Caldwell et al. (2021)

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- AI / ML (example for Waves)

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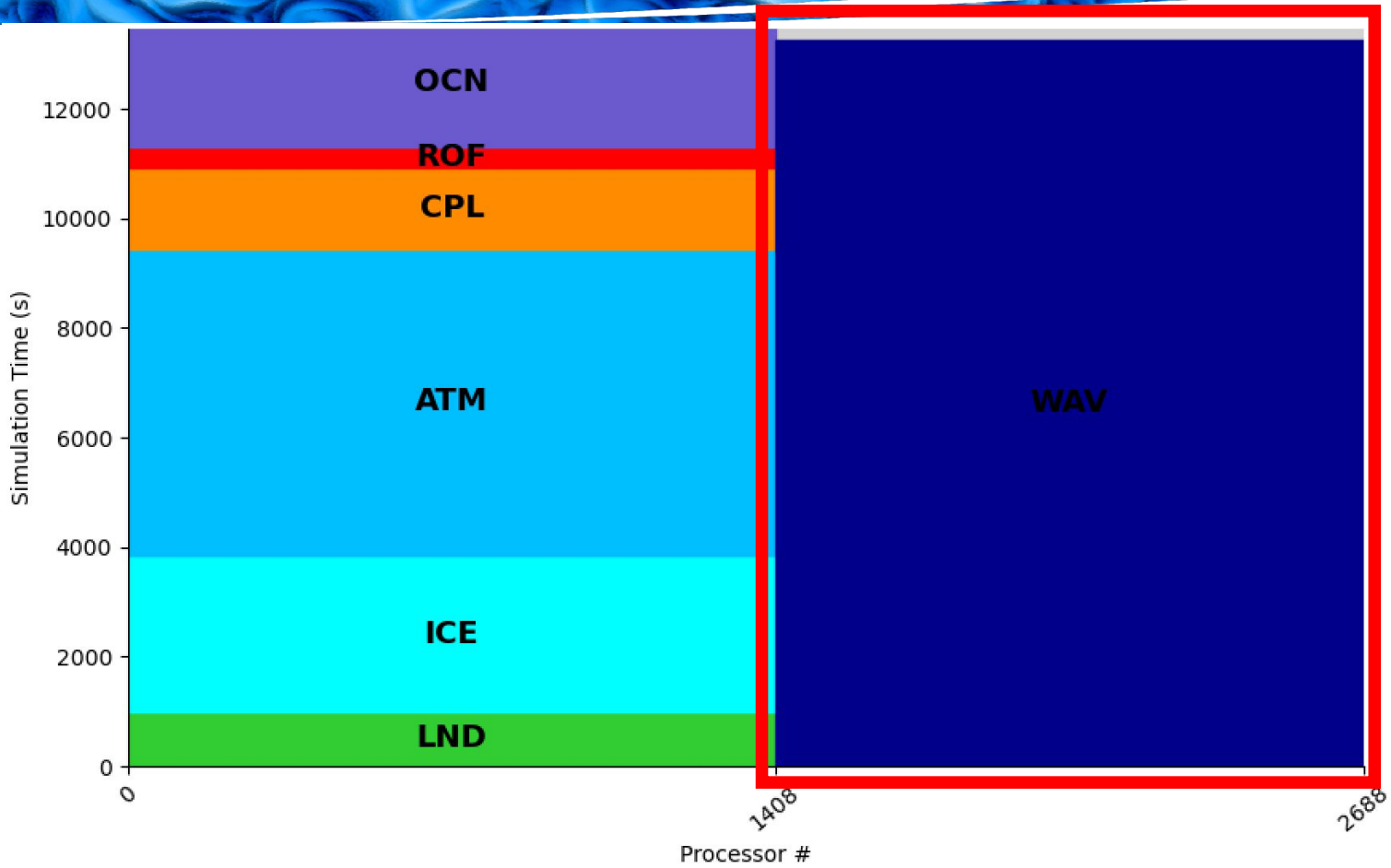
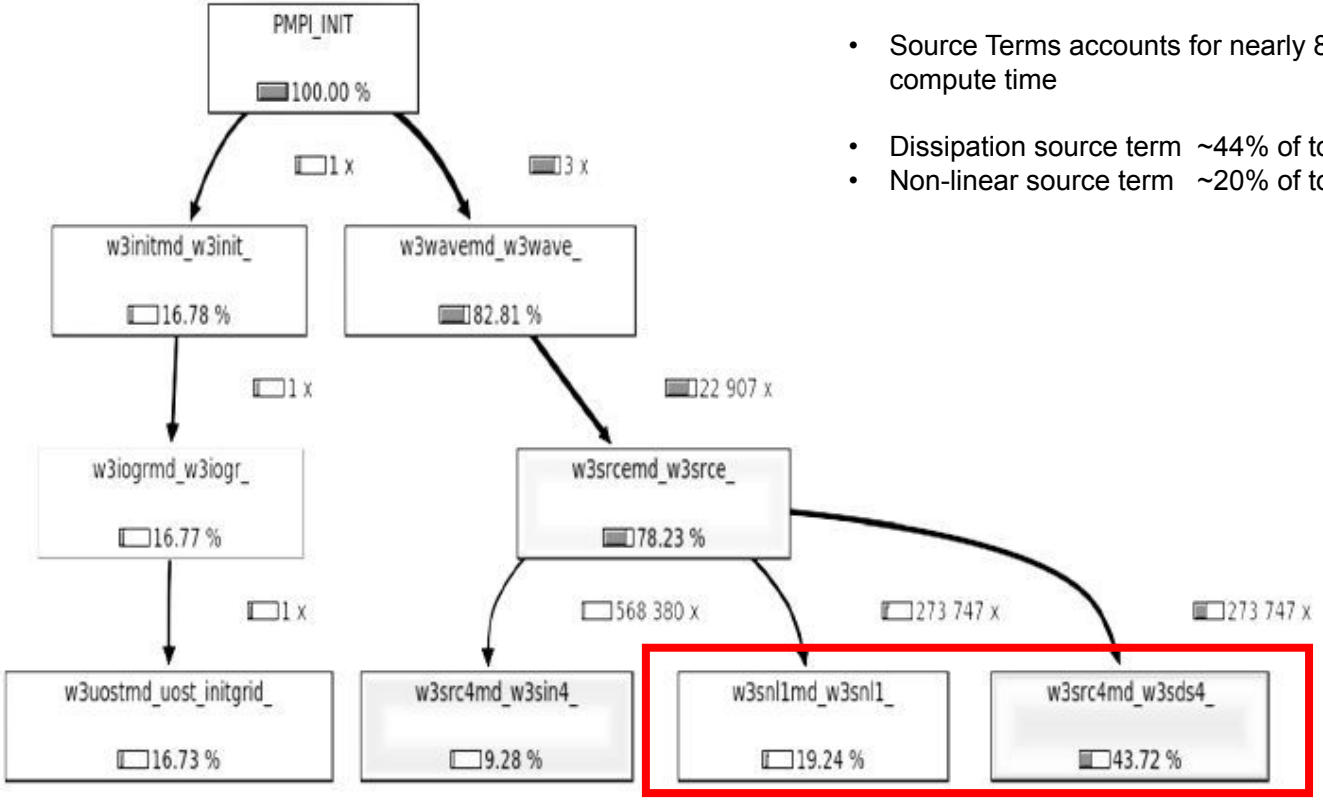
ML Applications: Waves

WW3 is a **significant** computational cost in LR E3SMv3



ML Applications: Waves



- Source Terms accounts for nearly 80% of total compute time
- Dissipation source term ~44% of total
- Non-linear source term ~20% of total

Figure 4. The Callgraph obtained by profiling WAVEWATCHIII with 8 CPUs. Each box includes the name of the subroutine and its relative execution time as a percentage

Ikuyajolu et al. Geosci Model Dev. 2023

ML Applications: Waves

Machine Learning Emulation of Non-linear Wave Interactions

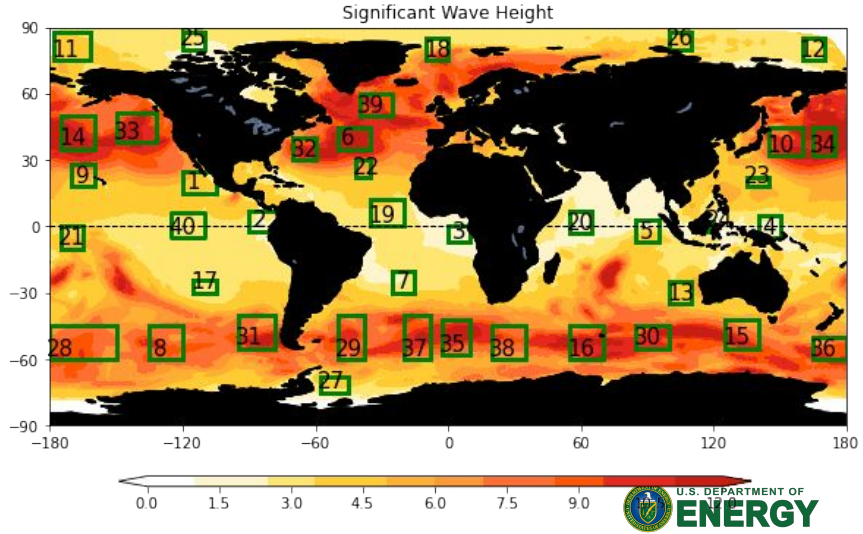
Exact (WRT) nonlinear wave interactions (S_{nl}) is 10^2 - 10^3 more costly than Discrete Interaction Approximation (DIA) method due to the 6D Boltzmann integral.

- DIA sacrifices accuracy for speed

Can we develop a neural network emulator that has the accuracy of the **WRT** and the speed of **DIA ?**

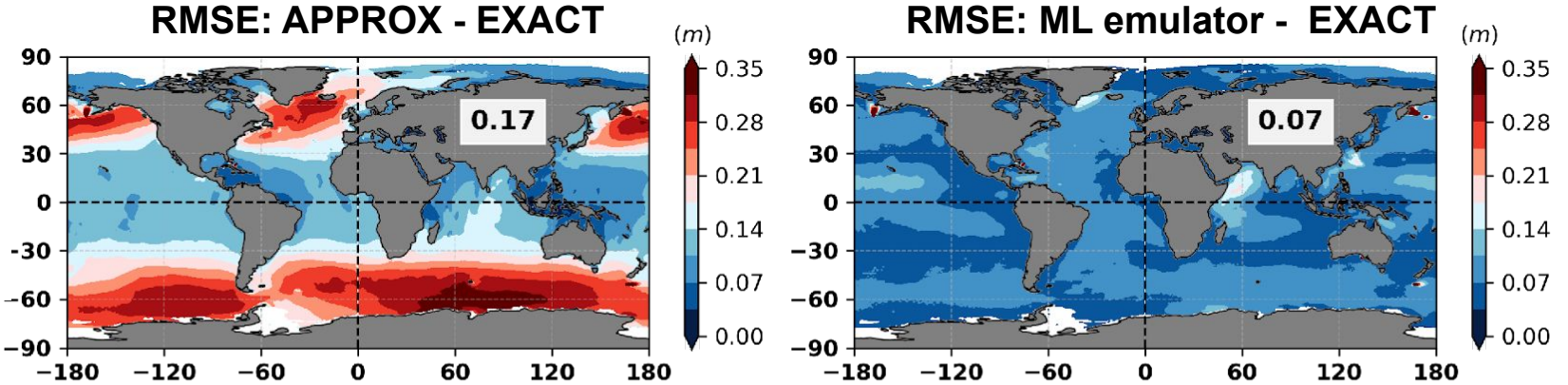
- **ML model**
  - 4 hidden layers with 3072 neurons
  - Trained on wave-spectra (50 freq x 36 dir)
  - **stand-alone WW3 simulation for 2010**

Randomly selected training data locations shown as boxed regions over areas of high and low wave activity.

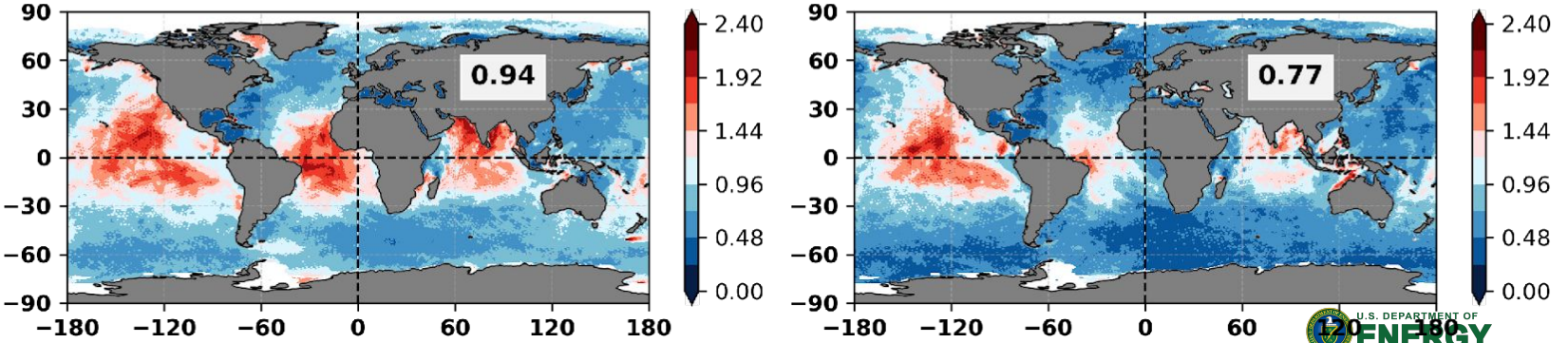


ML Applications: Waves

Significant Wave Height



Peak Wave Period

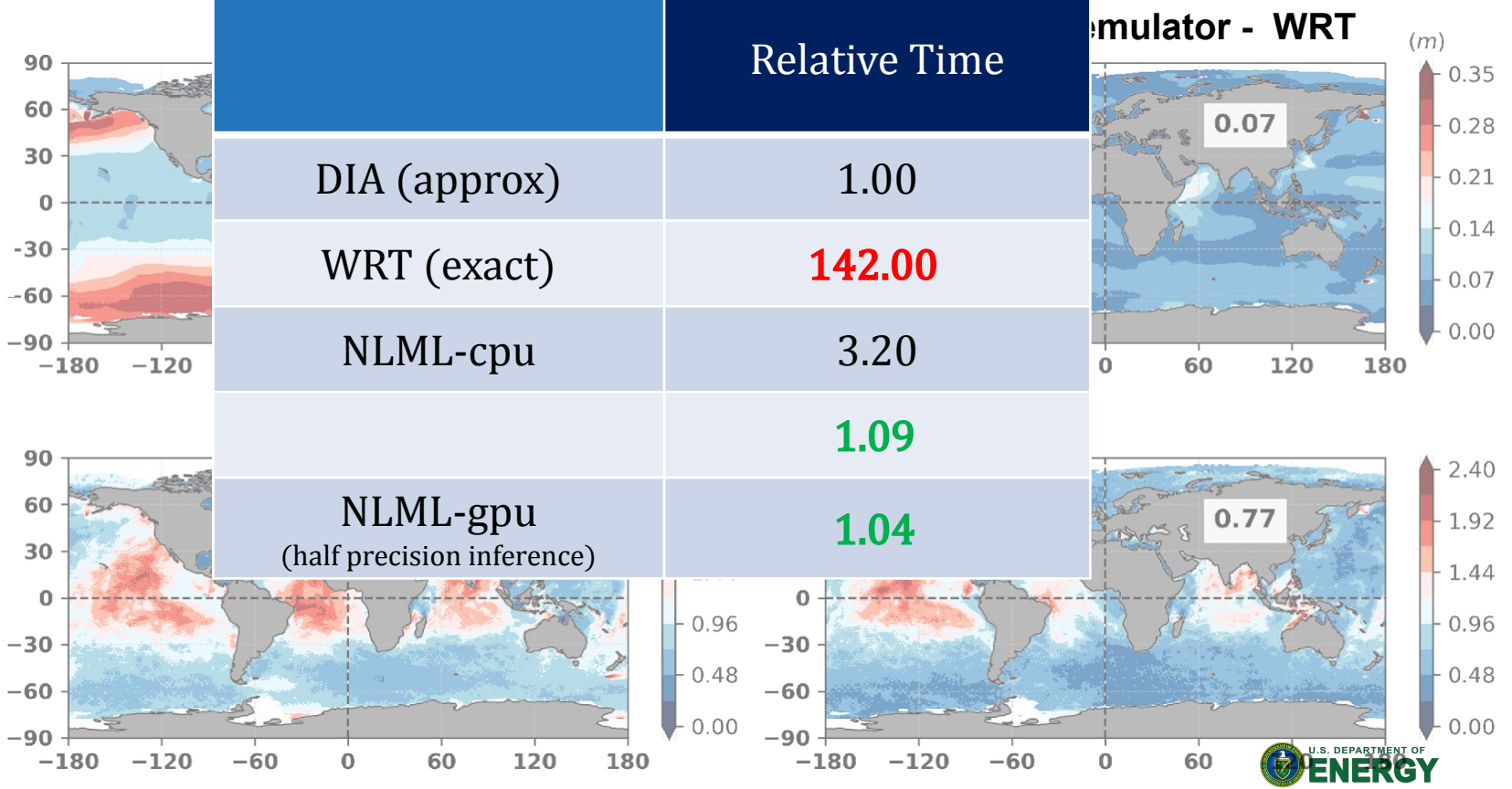


ML Applications: Waves

	Relative Time
DIA (approx)	1.00
WRT (exact)	142.00
NLML-cpu	3.20
	1.09
NLML-gpu (half precision inference)	1.04

Significant Wave Height

Peak Wave Period



ethomas@lanl.gov

E3SM
Energy Exascale Earth System Model

- *E3SMv3 Wave – Enabled Configuration*
- *Ongoing Efforts + Future Plans*
  - *Resolution*
  - *AI/ML*
  - *Shorter time scales (S2S, S2D)*

Thank You!

https://e3sm.org

https://github.com/CICE-Consortium

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