Particle-in-CelL for Efficient Swell *PiCLES*

Enabling wave-coupling with Earth System Models

.. to be submitted to JAMES

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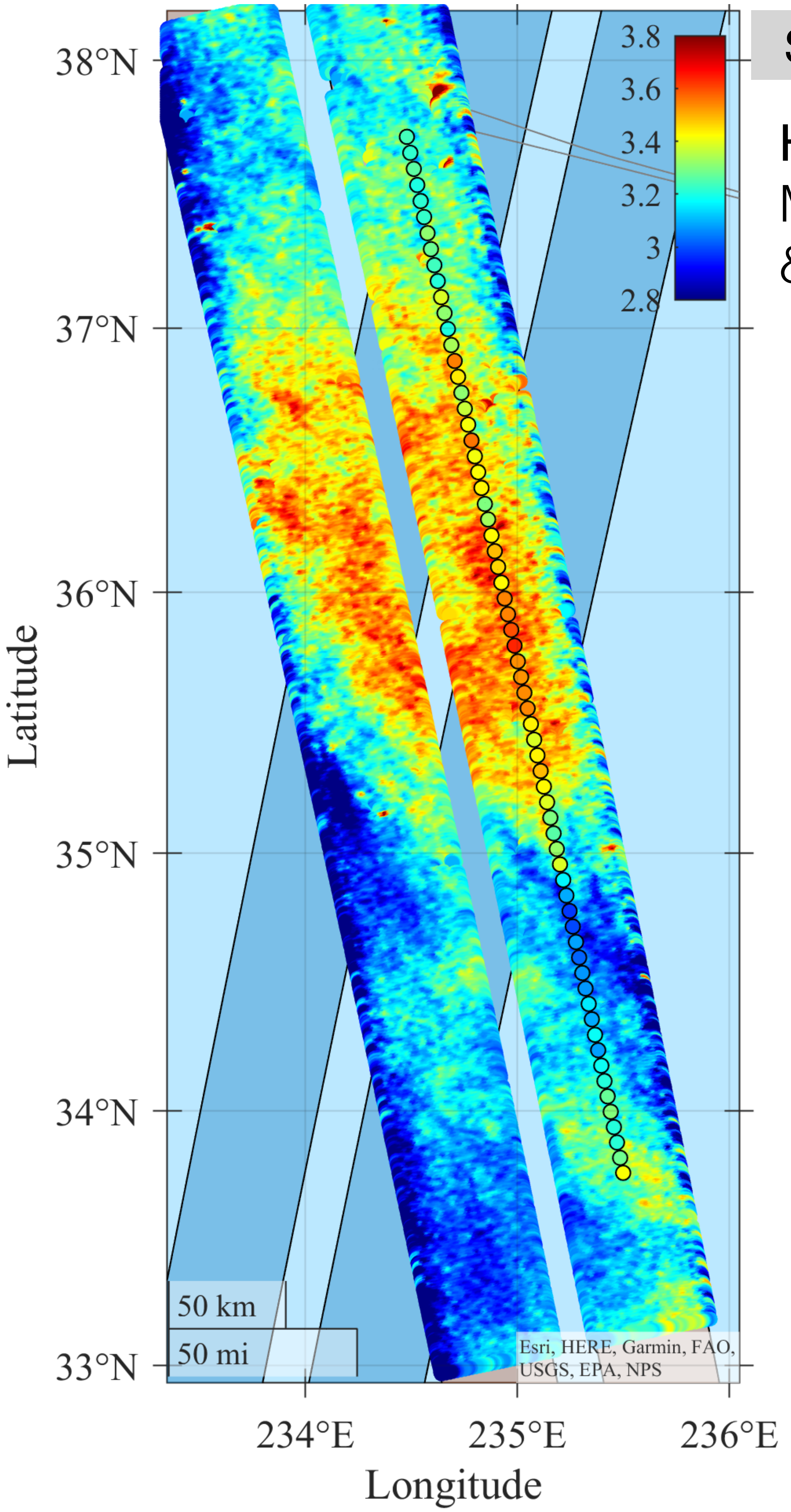
5th workshop on waves and wave-coupled processes

ECMWF | Reading, UK | 04/12/2024

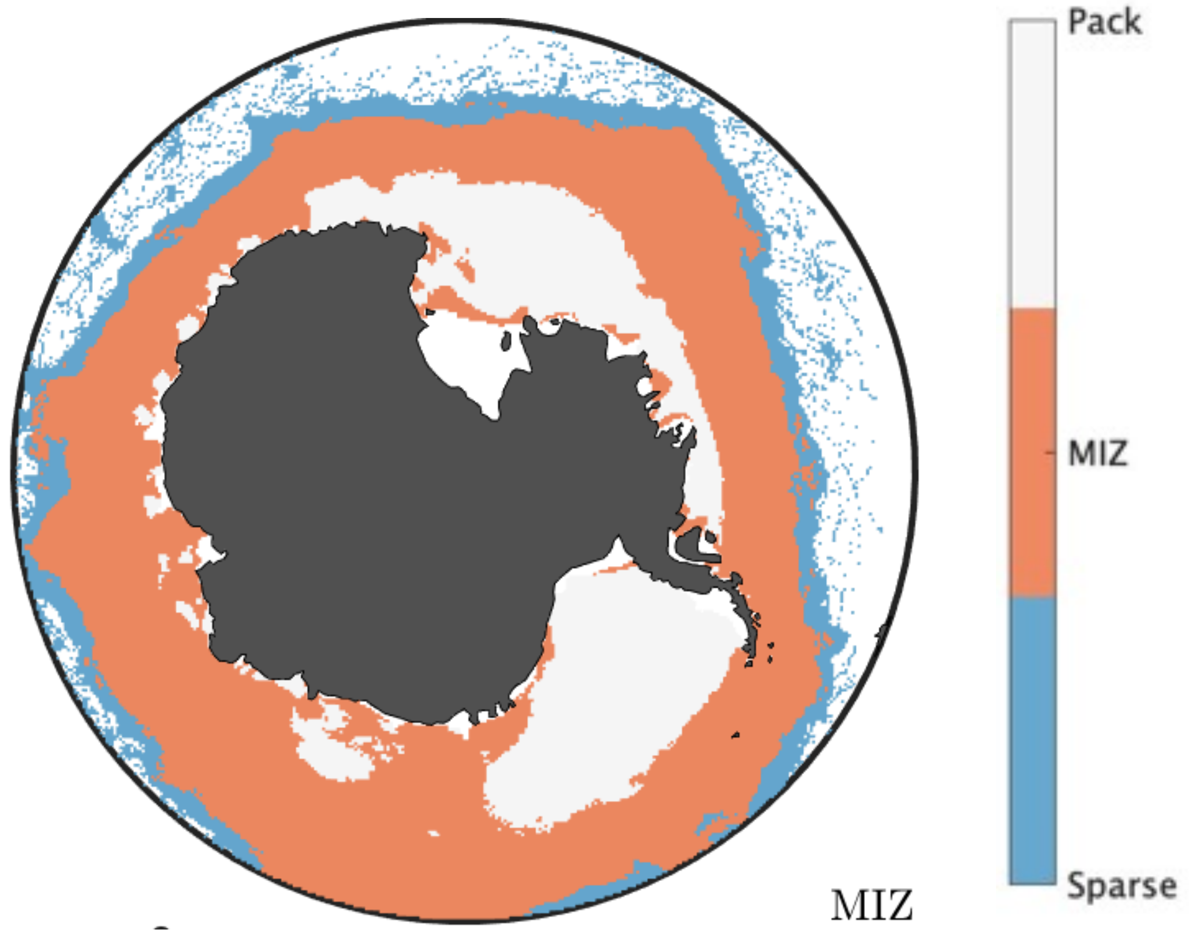
How do we model air-sea interaction in global eddy-resolving models?



Small-scale gradients in Hs (< 50km)

Hs from SWOT CalVal 2023
MASS (Air-Sea lab SIO, Lenain)
& SWOT's KaRIn

Non-local swell impact on the MIZ



Southern Ocean MIZ
20-60% of ice extent

Large discrepancy in the MIZ between CMIP6 models, likely due to wave forcing

(Chris Horvat)

We need to provide *not-equilibrated* waves for:

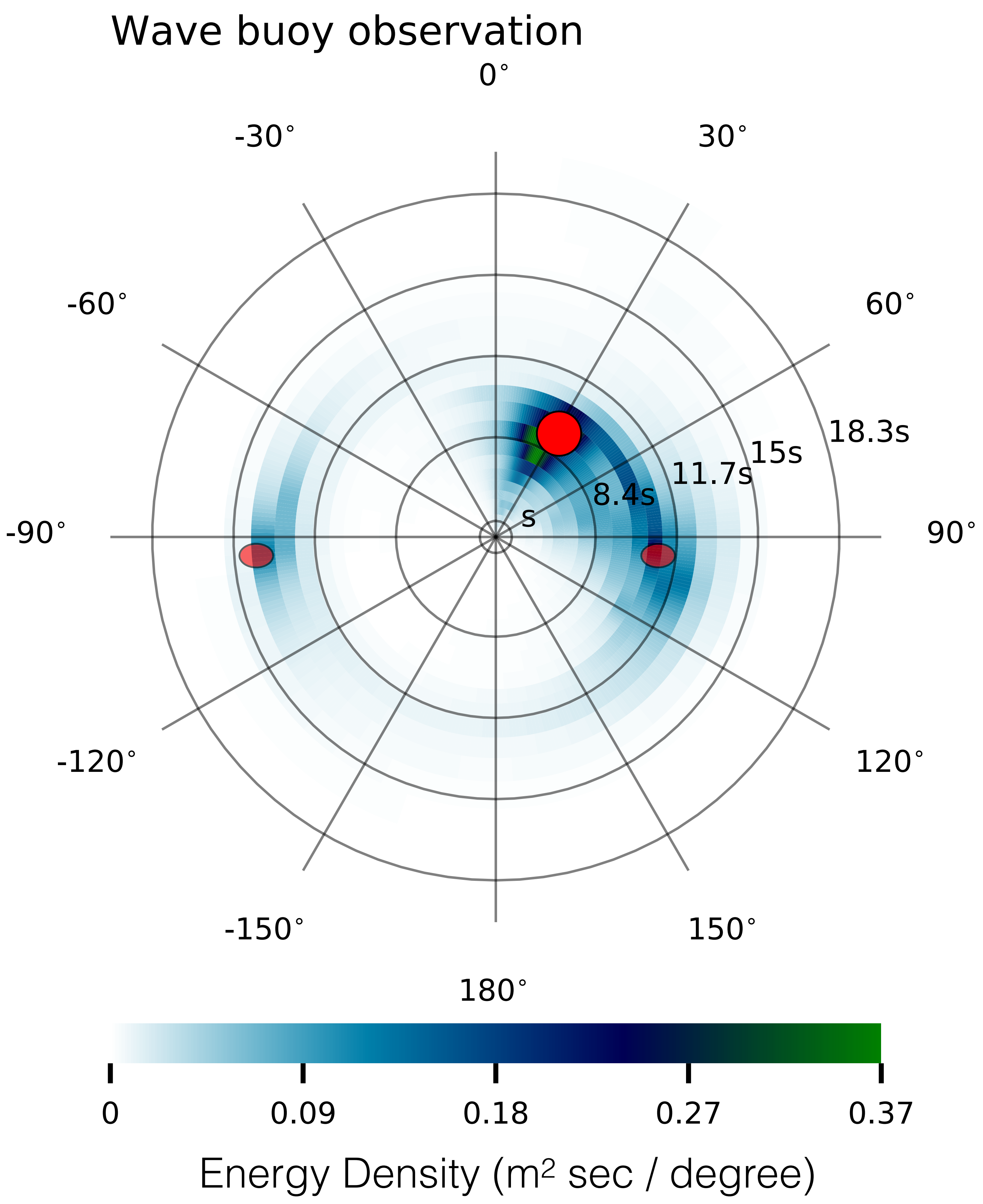
- Waves in the Marginal Ice Zone
- Stokes, Langmuir, and MLD
- White capping, sea spray, and gas fluxes
- Wave-current interaction
- Surface drag under wind-wave miss-alignment
- …

But, when assuming wave-processes have a rectifying effect for prediction and global climate:

Our **current model infrastructure is not capable** of sufficiently representing coupled processes **at global scale,** … and **only partly on regional scale**

Why will we not use a spectral wave model in future Earth System models?

Directional wave spectra at Ocean Station Papa



Typical wave observations

approx. 6-12 variables

Why will we not use a spectral wave model in Earth System models?
Spectral models are *too expensive* for global high-resolution integrations

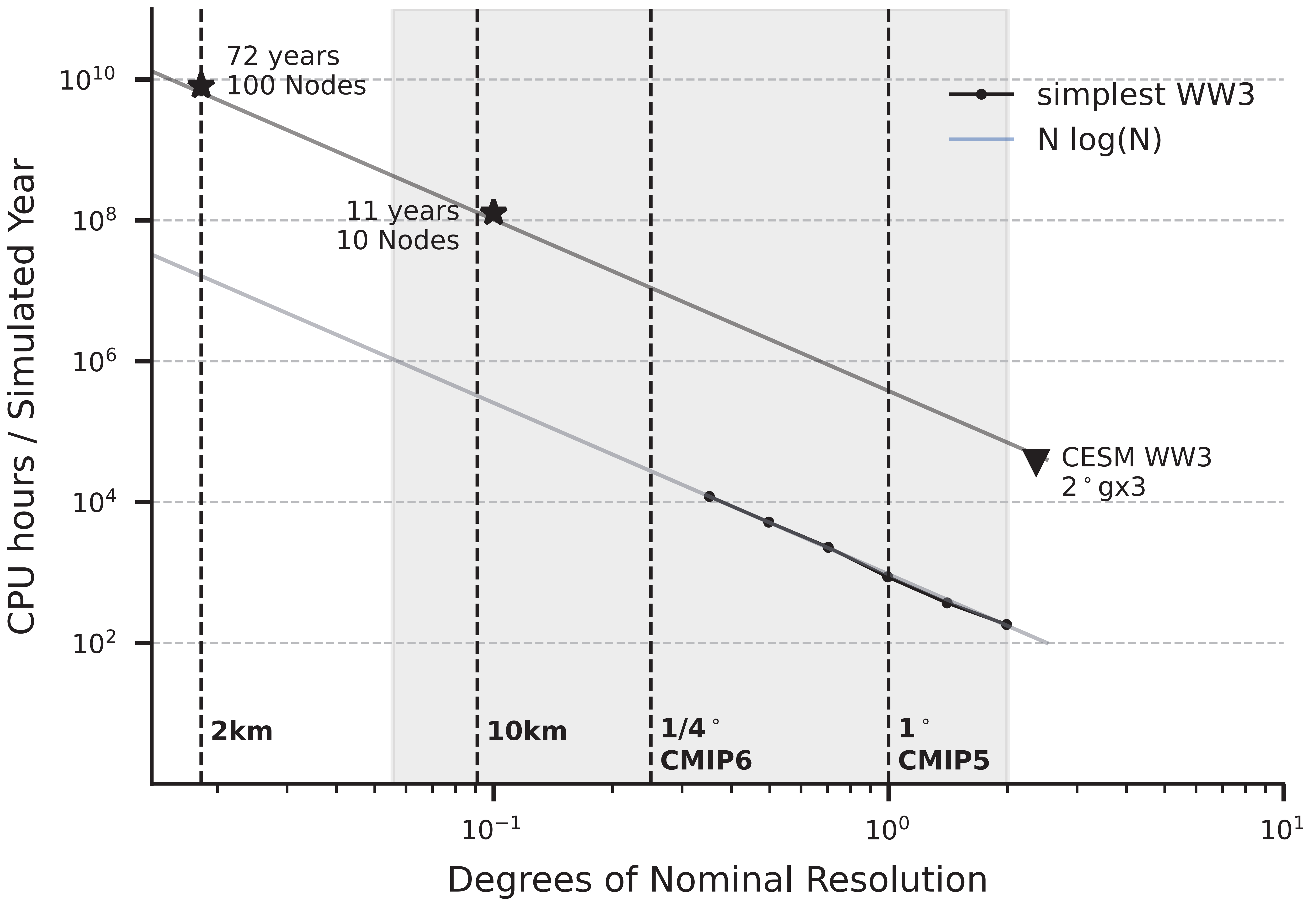
Spectral Models in ESMs

- large state vector (~600)
- coupling needs large overhead
- overhead and S_{nl} are expensive

➡ WaveWatch III is already integrated in CESM2

➡ resolution is currently reduced to 2°

CPU hours per simulated year for a given ocean grid



2nd generation+ wave model

PiCLES

- Solves the wave field along Lagrangien trajectories (particles) that are re-meshed periodically
- Each particle is a representative sample for wave energy & momentum of wave system

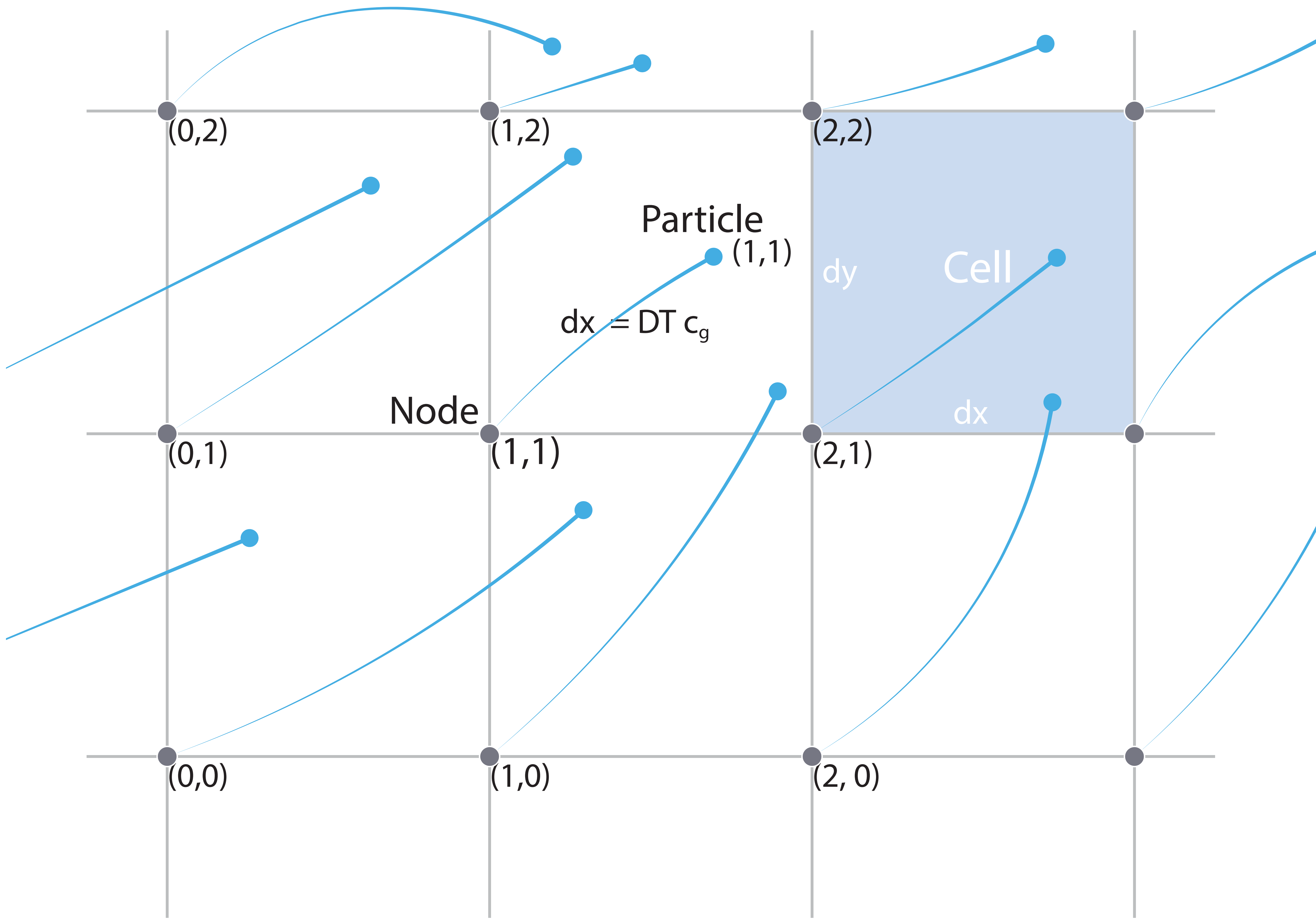
Main Objective:

Trade accuracy for speed and convenience!

- **Find alternative to reduce the high-dimensionality to improve efficiency**
- Describe **sufficiently accurate** surface statistics for air-sea interaction in Earth System Models.

Key Targets:

- Minimize particle interaction
- Good performance on GPUs
- Written in julia
- Focus on open-ocean waves



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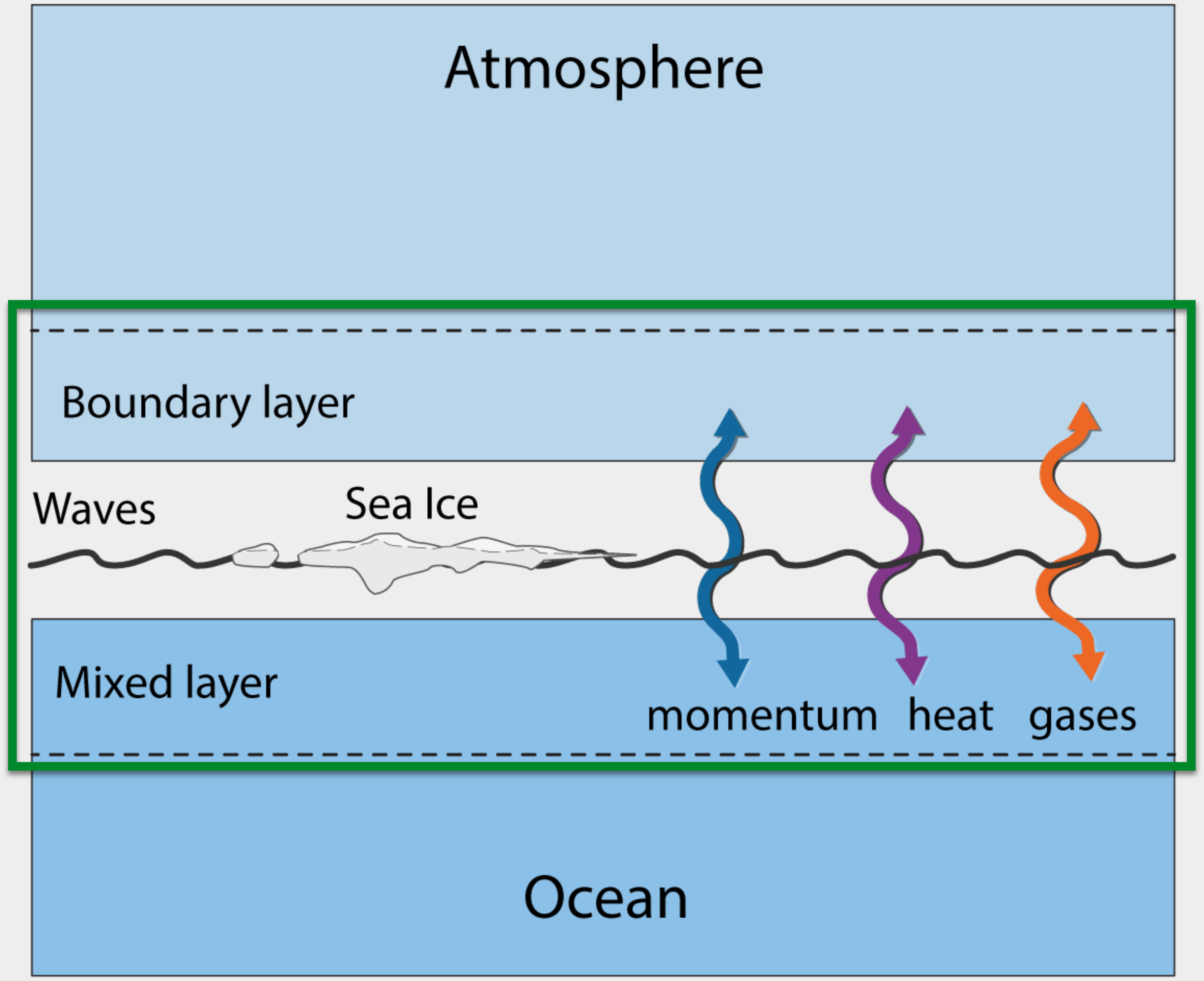
Towards a framework for coupled boundary layers

Grid box of an earth system model



Explicit and efficient surface waves

- better represent processes at the interface
- better use remote-sensing data
- enable learning parametrization

A hierarchy of surface wave models

Time travel to simpler models?

Increasing level of complexity

3rd generation wave models

The wave modeling project (WAM)
International effort that let to the modern wave modeling methods (1984-1994)

WAM, WW3, ecWAM, SWAN
can model non-linear interactions, but often parametrize

space (2D), time, frequency, direction
- Solves wave action equation for each frequency and direction
- provides 2D spectral at each grid point

2nd generation+

A state vector that is more comparable to variables needed for Air-Sea coupling

Particle-in-Cell for Efficient Swell - **PiCLES**
Lagrangian Wave source terms with an integrative remeshing

space (2D) *and* time
- wave growth along particle trajectories, and re-meshes
- provides output on a required grid and tilmestep

Lagrangian Wave modeling
Parameterized non-linear interactions in a moving system
Kudryavtsev, et al. 2015, 2021, Hell et al. 2021, Ardhuin et al. 2000, ..

space (1D) *and* time
Lagrangian wave growth along a particle trajectory

2nd generation

2nd generation wave models — *Fetch relation*
Pierson-Moskowitz, GONO, HYPA, UKMO, JONSWAP, ..
Parameterized non-linear interactions

space (1D) *or* time
simulates wave growth for a given fetch

Equations to solve along a particle trajectory

Conservation of wave action:

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x_j}(\dot{x}_j\, N) + \frac{\partial}{\partial k_j}(\dot{k}_j\, N) = \frac{\mathcal{S}^E}{\sigma},$$

- neglecting currents
- integrating in (2D) wavenumber space
- forming equations for the total energy and momentum *(Kudryavtsev et al. 2021)*

→

parameterized wave-wave interaction

Similar to WW3

Particle Equations

$$\frac{d}{dt} ln\varepsilon = \quad \sigma_p\, r_g\, \tilde{\mathcal{S}}^{cg} \quad + \sigma_p(\tilde{I} - \tilde{D}),$$

$$\frac{d}{dt}\bar{c}_i^g = -\bar{c}_i^g\ \sigma_p\, r_g\, \tilde{\mathcal{S}}^{cg} + [\bar{c}_2^g, -\bar{c}_1^g]^T\ \sigma_p\ \tilde{\mathcal{S}}^{dir}$$

$$\frac{d}{dt}x_i = \bar{c}_i^g.$$

Parametrized change in direction

- Wave-wave interaction along the trajectory is parametrized

Particle state vector

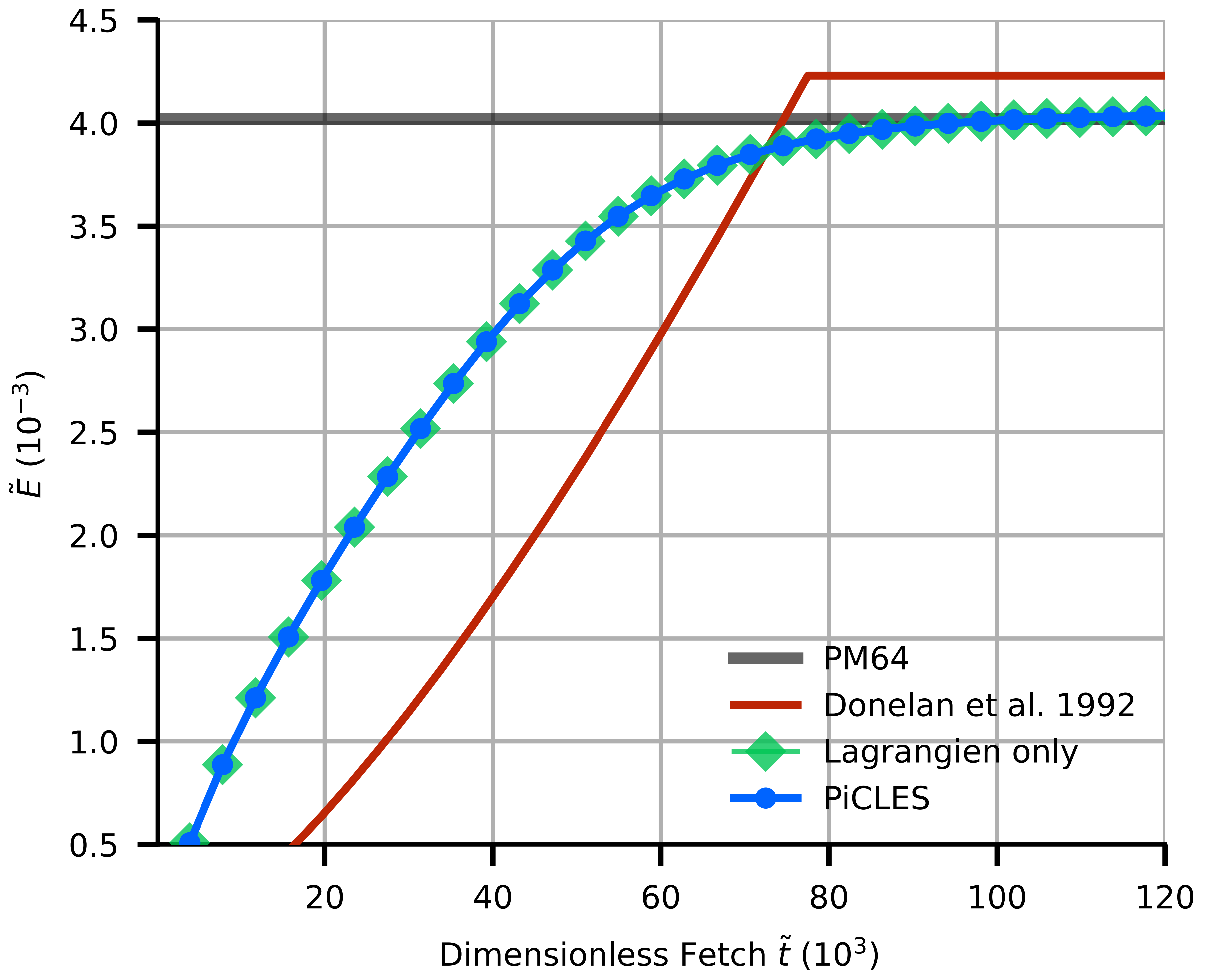
$$\mathbf{p} = [\ \ln(\varepsilon),\ \bar{c}_1^g,\ \bar{c}_2^g,\ x,\ y\ ]^T$$

Accuracy | Comparing to WW3

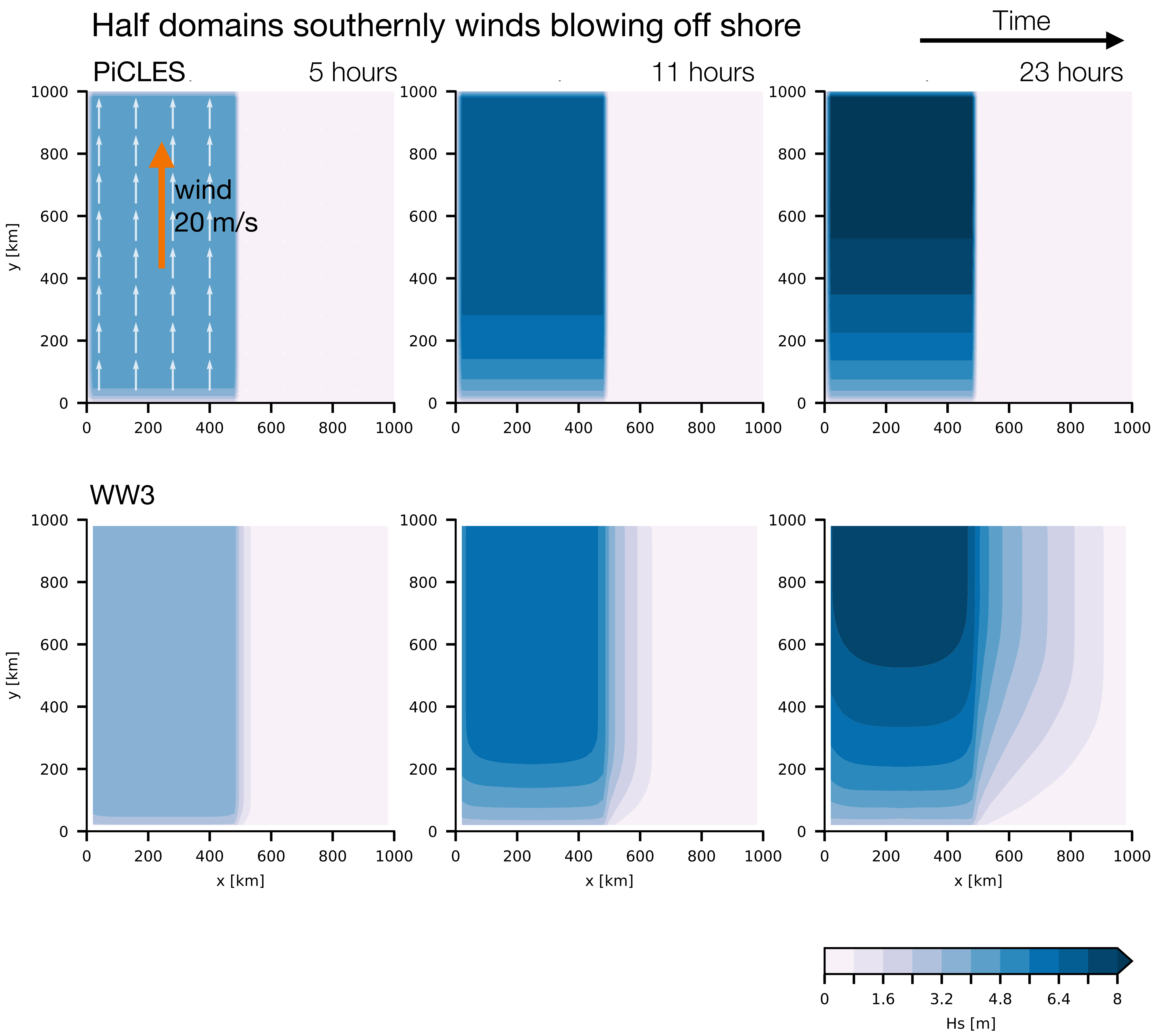
The general model structure works well, but

- Lagrangian equations and PiCLES **reproduce wave-growth rates well** (to be optimized later)
- Regrinding scheme is **conservative and non-dispersive**

Dimensionless Energy $\tilde{E}$

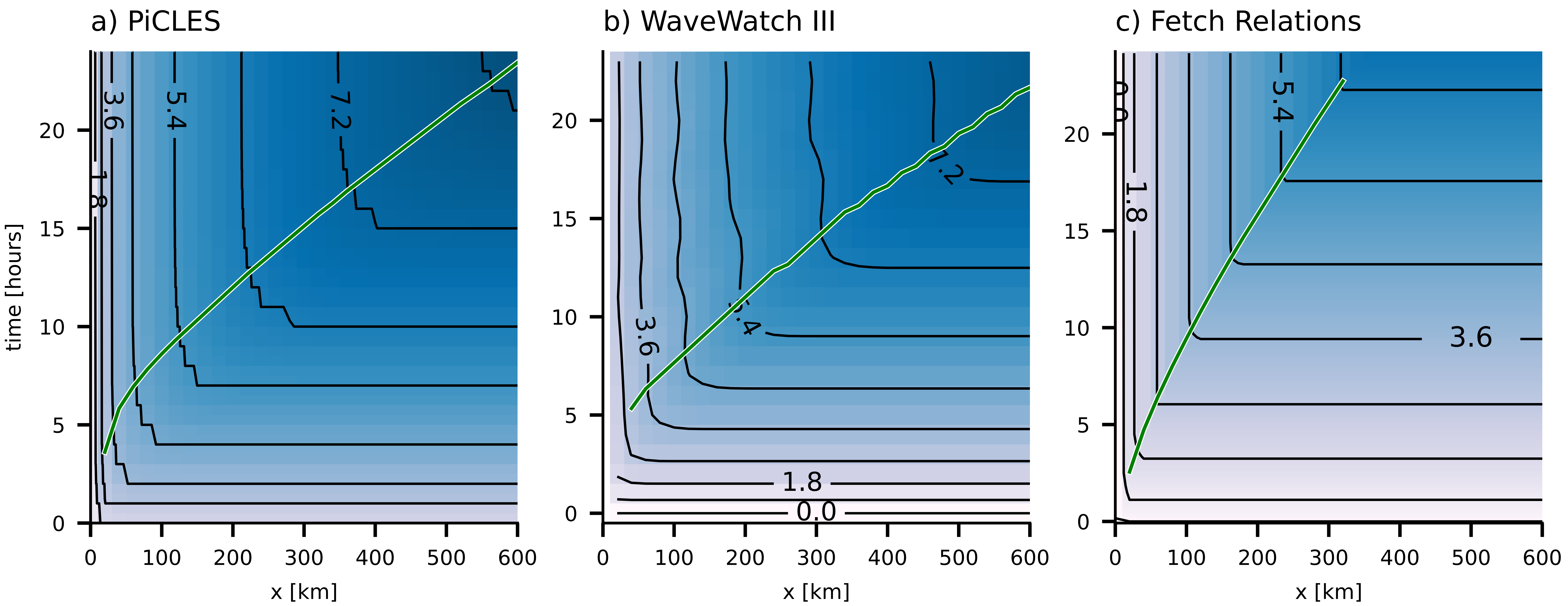


Half domains southernly winds blowing off shore



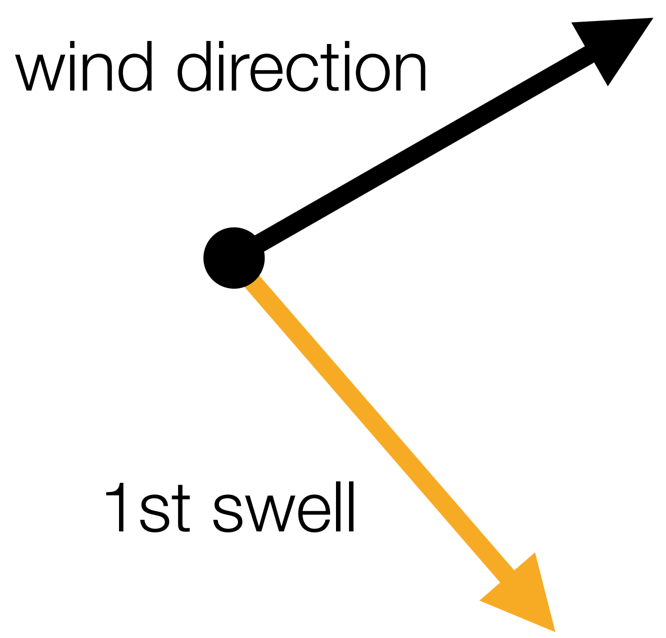
Accuracy: Comparing to WW3

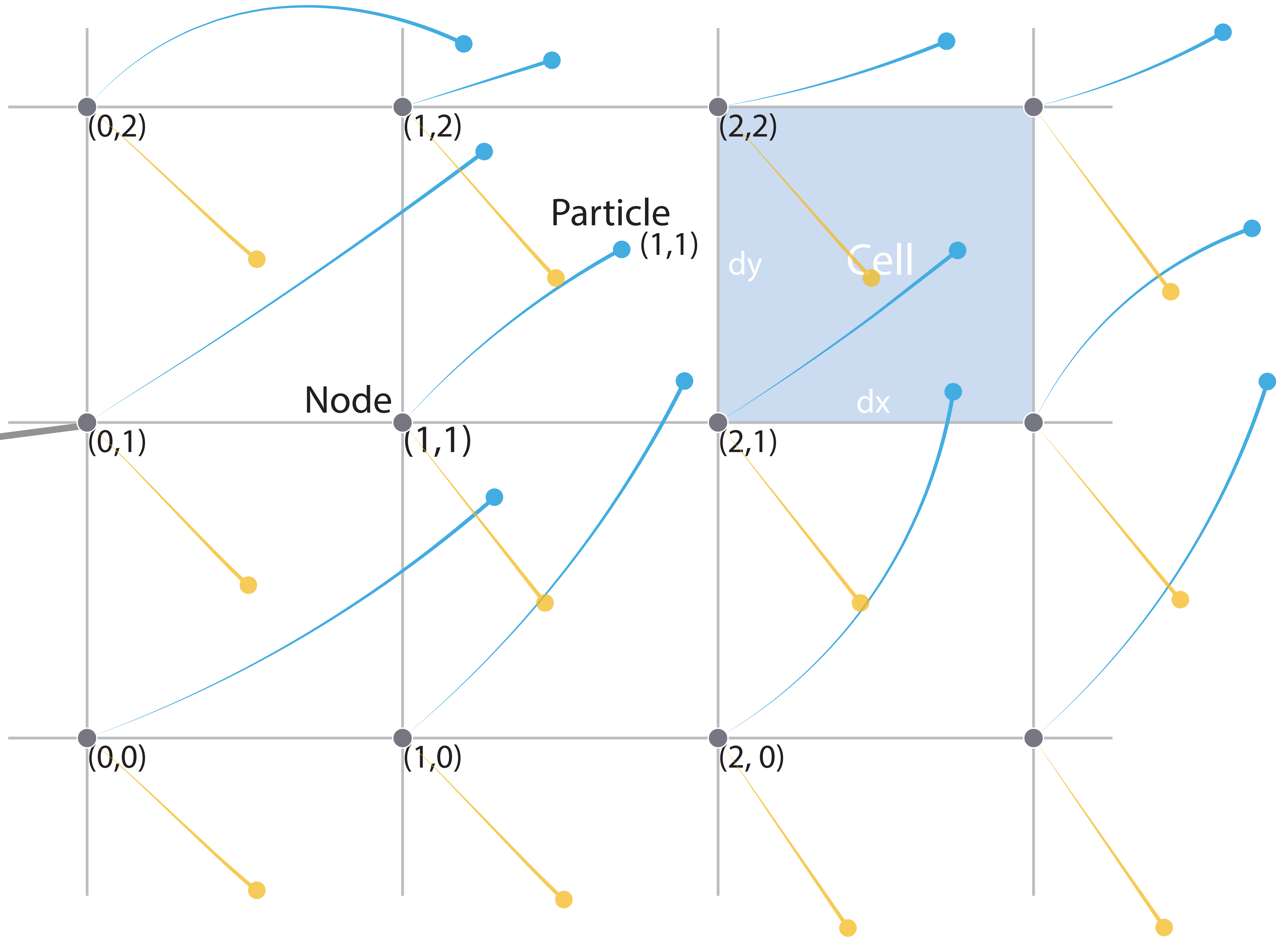
- Fetch- and time-limited cases are comparable to WW3 or static Fetch-relations



Propagating swell

How? We take the model x 4!





Each node has multiple particles

Wind sea:	1 x 5	energy, cg_x, cg_y, x, y
Swell I:	1 x 5	energy, cg_x, cg_y, x, y, + travel time
Swell II:	1 x 5	energy, cg_x, cg_y, x, y, + travel time
Swell III:	1 x 5	energy, cg_x, cg_y, x, y, + travel time

Weak Scaling Tests I Out-running WW3

PiCELS will enable routine use of waves for air-sea coupling in high-resolution Earth System Models

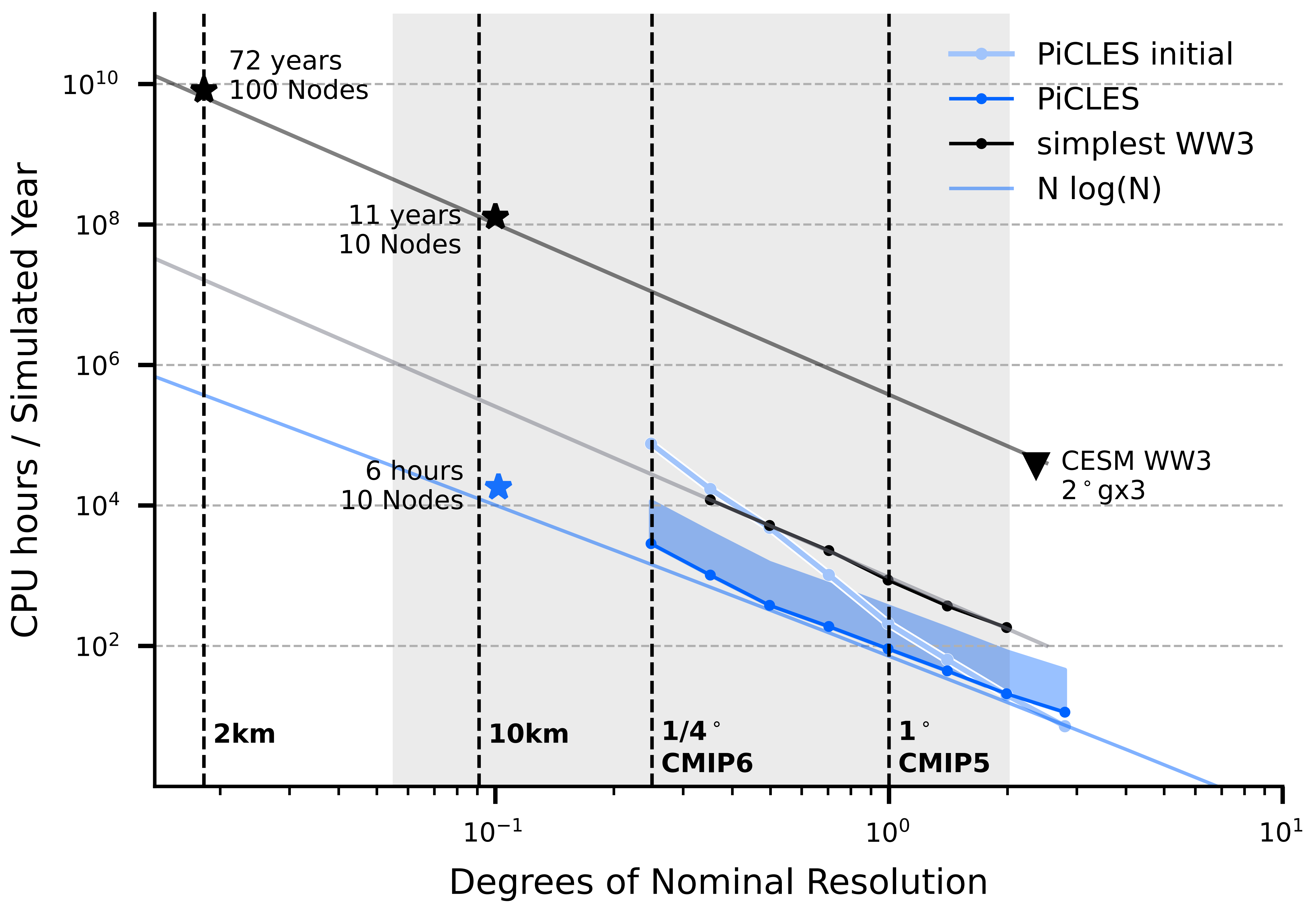
Spectral Models in ESMs

- Large state vector (~600)
- coupling has likely large overhead
- S_{nl} is expensive
- WaveWatch III resolution in CESM is currently reduced to 3°

PiCLES:

- small state vector (about 5 - 20)
- runs with ocean grid and time step
- can be well optimized for GPUs

CPU hours per simulated year for a given ocean grid

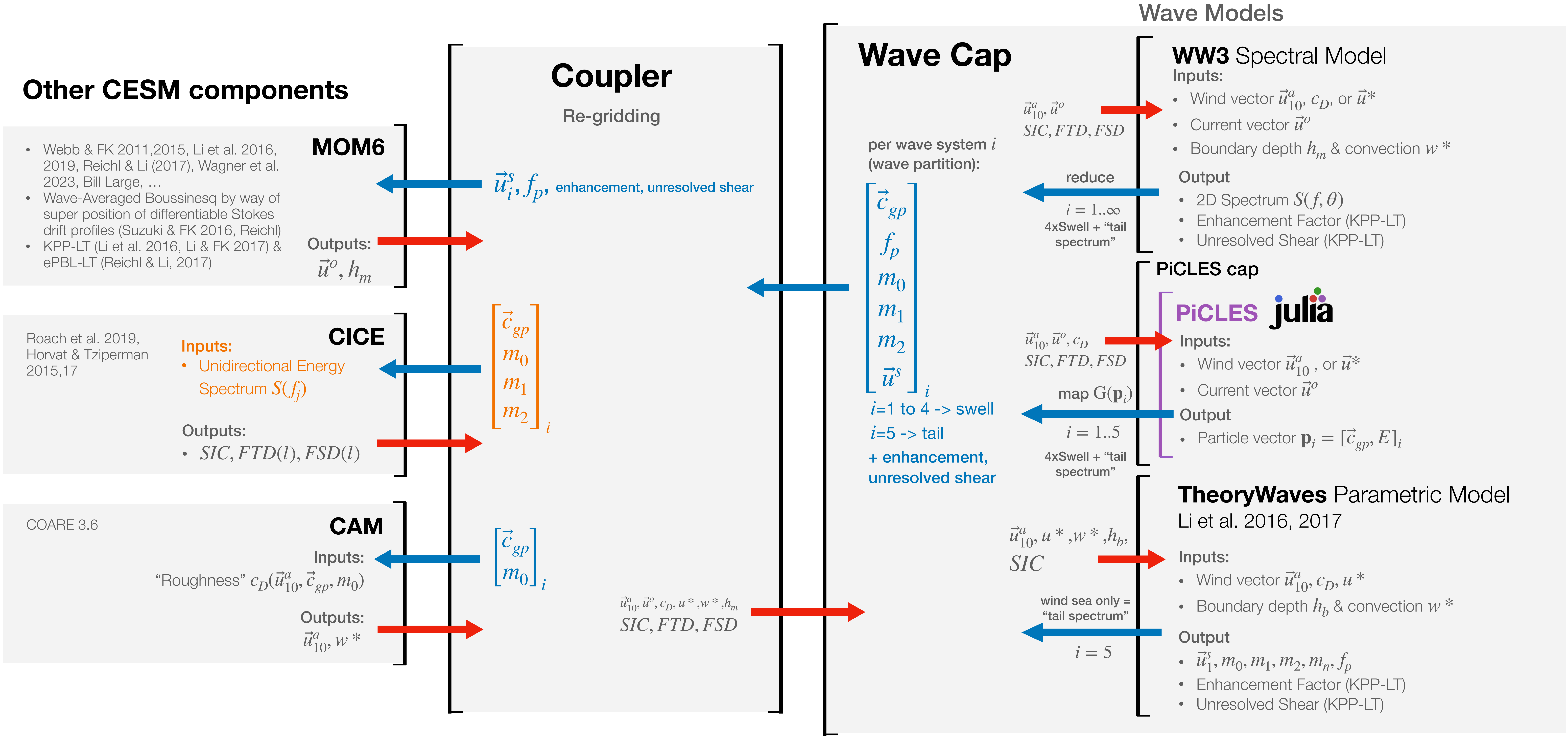


Performance

- *current* PiCLES is $\mathcal{O}(10)$ faster then **WW3** ***without overhead***
- PiCLES is about $\mathcal{O}(10^4)$ faster then **WW3** ***with overhead*** and coupling
- for CMIP6-class models, we expect PiCLES at least run $\mathcal{O}(10)$ faster then WW3

Towards a standard, unified wave-coupling in CESM

Enabling better physics and a basis for machine learning



Outlook

Steps towards a stand-alone wave model

1) Dispersion, Diffusion, and Refraction
2) Multi-layer & Merging rules
3) Optimize allocations
4) Determine time stepping limits

Implementation into CESM

towards the routine use of waves in coupled models for prediction and climate integrations

- Unify implementation of (any) wave-model in CESM
- Fortran <—> C <—> Julia interface

Toward an ML-driven model for air-sea exchange

- **cheap and adjustable wave-information for ML-driven parametrizations** in an ML-native language
- An improved representation of the interface

Time-varying wind sea