A wave model for efficient sea-state and swell estimates in coupled models

Particle-In-Cell for Efficient Swell *PiCLES*

Momme C. Hell[1], Baylor Fox-Kemper[1], and Bertrand Chapron[2]

[1]Brown University, Providence, RI, USA, [2]Ifremer, CNRS, IRD, Univ. Brest/LOPS, IUEM, Brest, France

The need for a wave model in Earth System Models (ESMs)

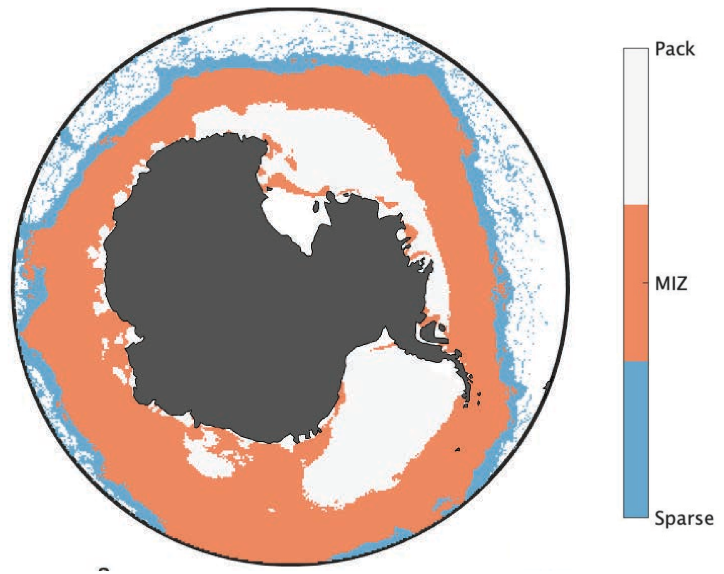
Ocean surface waves have emergent importance for coupled earth system models. They fracture sea ice, control atmosphere-ocean momentum transfer, and impact mixed-layer depth through Langmuir turbulence.

Third-generation spectral wave models are too expensive for global coupled modeling. Here we present an alternative wave model for coupled systems that provides dominant frequency, direction, to parameterize wave-interaction processes.

targets for a semi-lagrangien wave model:

1. Non-local swell impact on the MIZ
2. Gradients in the wave field on scales O(Roatm) effect drag, white capping, sea spray, …
3. Wave-current interaction on scale < 20km may effect Langmuir turbulence

20-60% of the Southern Ocean ice extent is MIZ



.. and CMIP6 models disagree about the MIZ

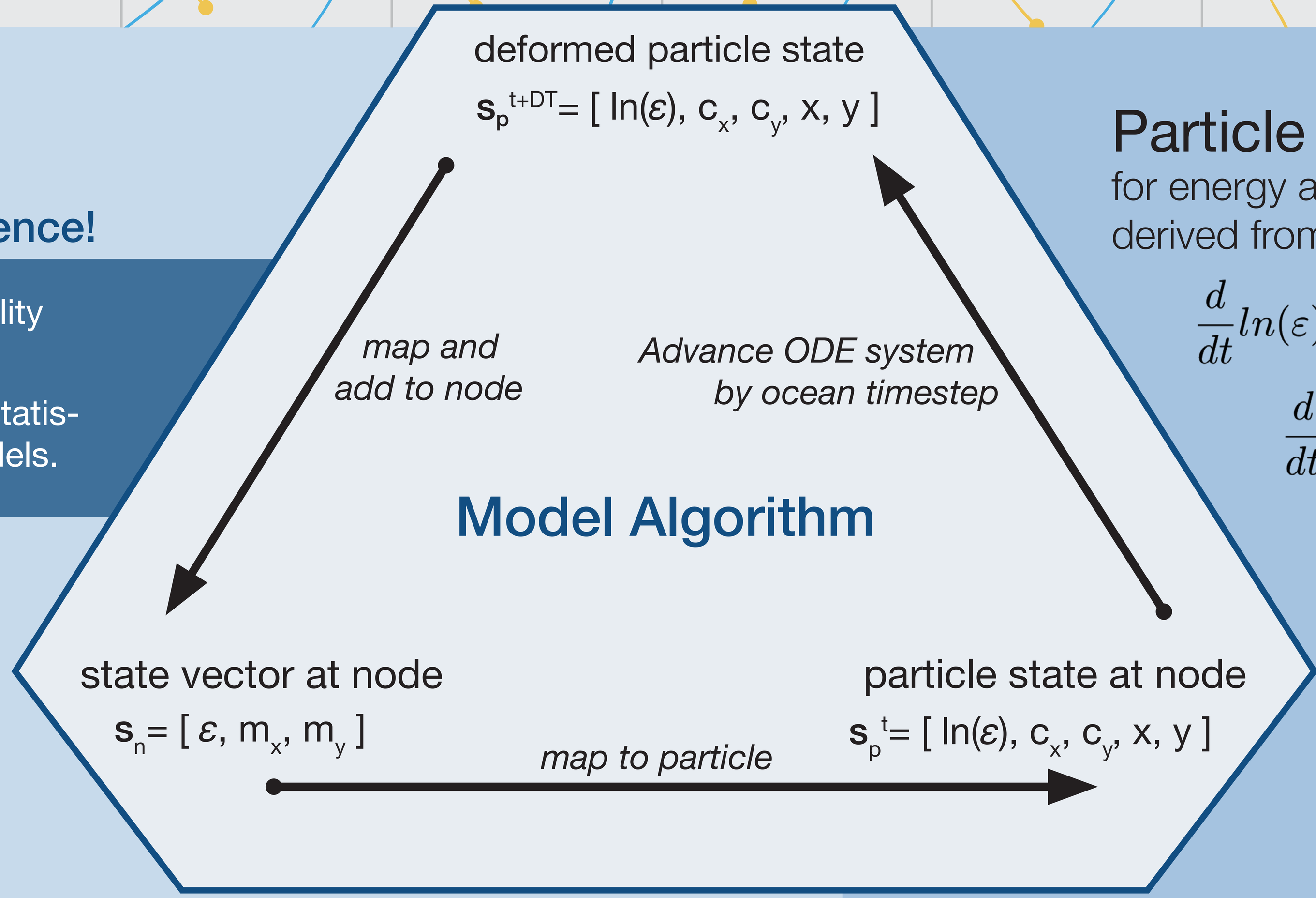
PiCLES main objetives

Trade accuracy for speed and convenience!

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

Requirements:

- Minimize particle interaction
- Designed to be parallel on GPUs
- Partition between wind sea and swell
- Written in julia
- Focus on open-ocean waves



Particle equations

for energy and energy-weighted group velocity c_g, derived from wave action, no currents *(Kudryavt et al. 2021)*

$$\frac{d}{dt} \ln(\varepsilon) = -\bar{c}_g G_n + \frac{r_g}{\omega_p} S^{cg} + S^{\varepsilon},$$

$$\frac{d}{dt} \bar{c}_{g,i} = [-\bar{c}_{g,2}, \bar{c}_{g,1}] \frac{1}{\omega_p} S^{dir} - \bar{c}_{g,i} \frac{r_g}{\omega_p} S^{cg}$$

$$\frac{d}{dt} x_i = \bar{c}_{g,i}.$$

- Each particle equation is solved on its own timestep
- parametrized wave-wave interaction along the trajectories and on nodes for across term interaction

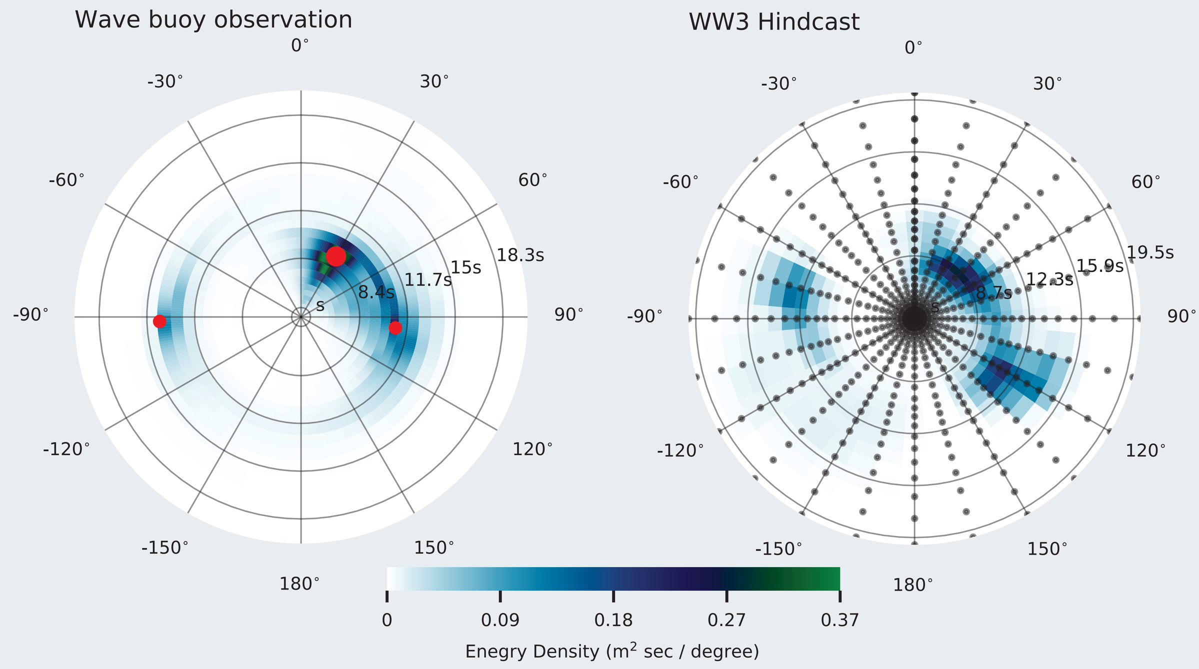
Representation of directional wave spectra

Typical wave observations

- Wind sea & 1-3 Swels (red dots)
- Each of these have a direction, peak frequency, and energy
- The total wave spectrum can be approximated by **9 variables**

Spectral wave model (WW3)

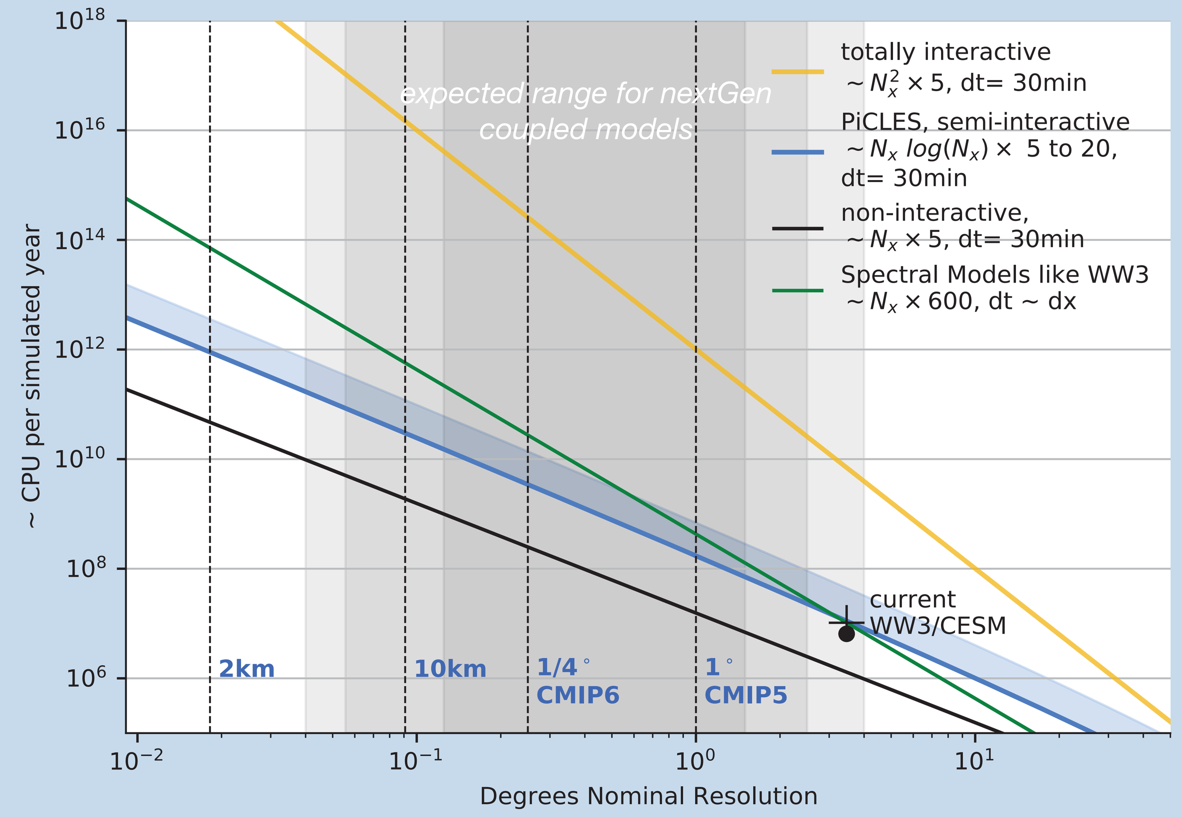
- discretize the wave action in frequency and direction
- needs about **600 variables** to describe nearly the same information (**black dots**)



Spectral wave models are ineffcient in ESMs. Semi-lagrangien modes have a state vector (~5) that is much closer to the information needed

Scaling of the computational effort

A semi-interactive wave model is more efficient on resolutions of current and future Earth System Models



PiCLES perks:

- small state vector
- runs on the ocean grid and time step (no strict CFL condition)
- expected to scale with N log(N)
- designed to be highly parallel with minimal overhead
- for CMIP6, we expect it about an order of magnitude faster then WW3

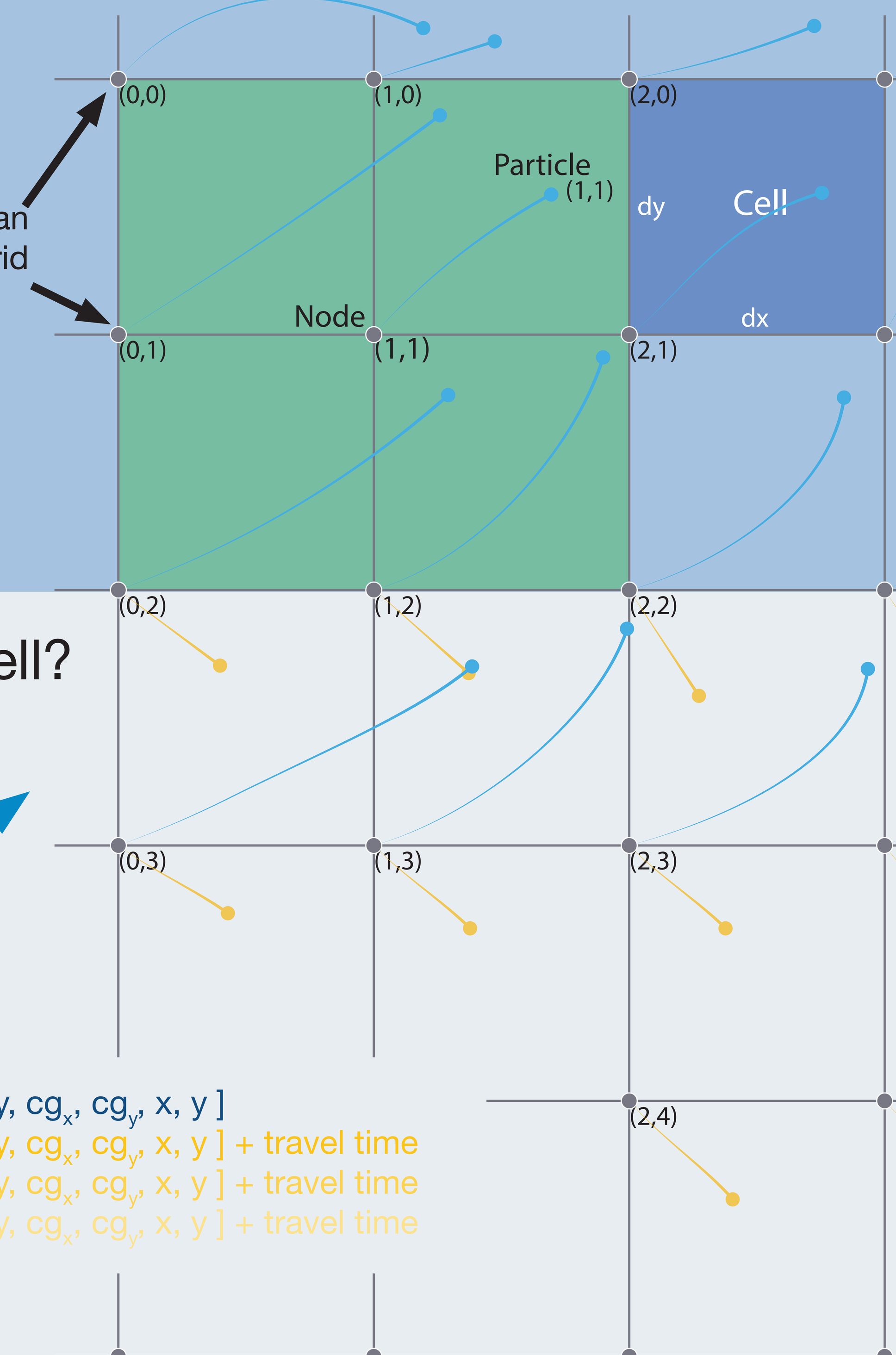
Re-meshing based on Particle-in-Cell

- re-meshing conserves energy and momentum
- only additive operation to minimize particle interaction
- can model strong gradients and shocks well
- originally developed in Los Alamos *(Evans 57, Harlow, Brackbill et al. 86, 88, …)*
- widely used in plasma physics, electro-magnetics, and geophysical applications

$$\hat{m} = \sum_n^N w_n m_n,$$

$$\hat{e} = \sum_n^N w_n e_n,$$

Particle-In-Cell weighting function



A hierarchy of surface wave models

back to the future of wave 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, SWOM, SWAN can model non-linear interactions, but often parametrizes them *Susan Hasselman & Hasselmann, 1985*

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

BACK TO THE FUTURE

2nd generation+

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

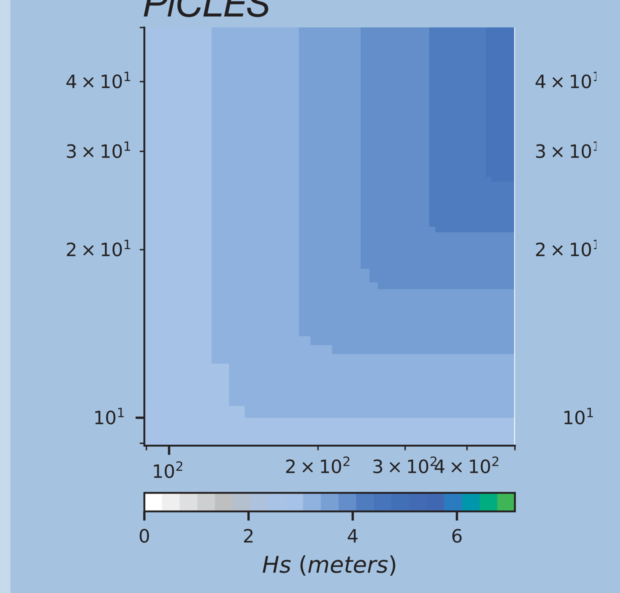
2nd generation wave models - Fetch relation
Pierson-Moskowitz, GONO, HYPA, UKMO, JONSWAP, ..
Parameterized non-linear interactions

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

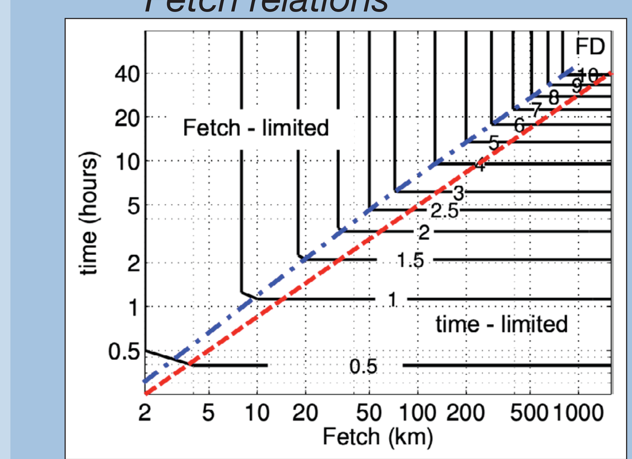
First tests in 1D

Static Fetch

PiCLES



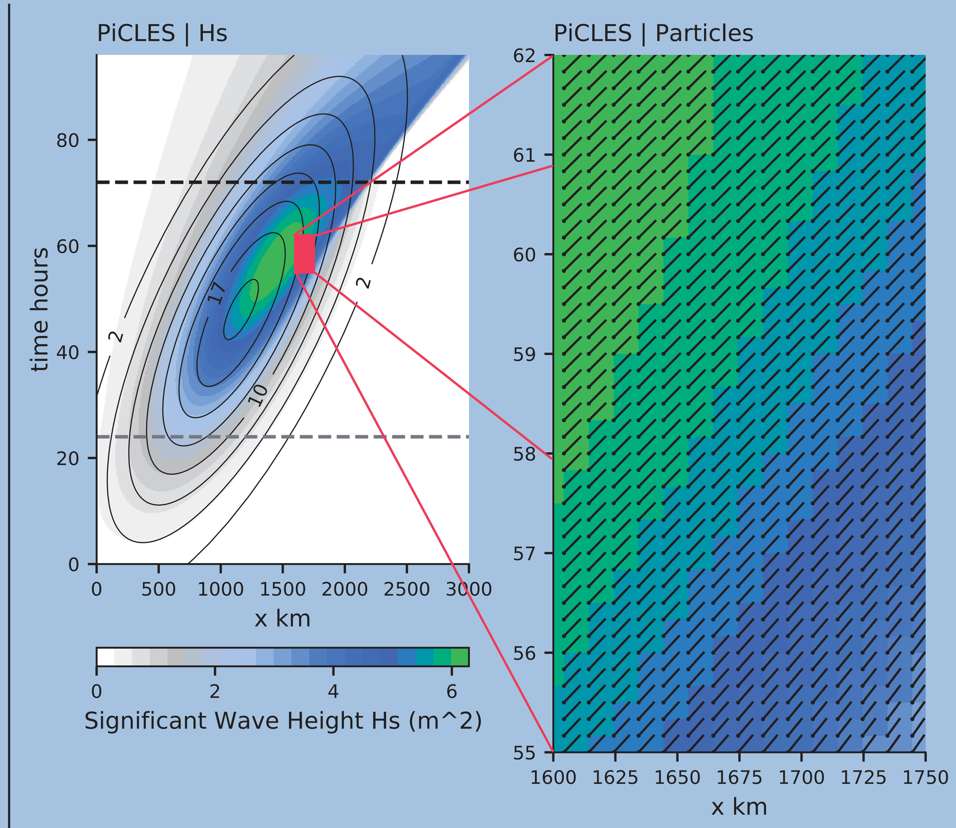
Fetch relations



(Ardhuin and Filipot, *Ocean waves in geoscience*, Book)

Dynamical Fetch

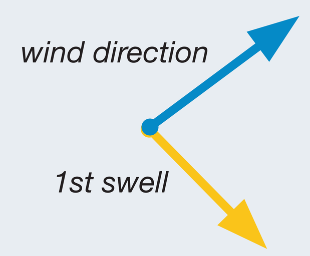
Qualitatively reproduces results from Hell et al 2021



- highest wave speeds and energy ahead of the high-test wind speeds
- non-local effects under wave-growth conditions
- frequency and geometric dispersion are not included

What about swell?

We take the model x 4!



Wind Sea: 1 x 5 [energy, c_{gx}, c_{gy}, x, y]
Swell I: 1 x 5 [energy, c_{gx}, c_{gy}, x, y] + travel time
Swell II: 1 x 5 [energy, c_{gx}, c_{gy}, x, y] + travel time
Swell III: 1 x 5 [energy, c_{gx}, c_{gy}, x, y] + travel time

Future work

- Implement swell propagation and dispersion
- Test against WW3
- Test against observations and optimize
- Implement in ESMs

References

Kudryavtsev, V., M. Yurovskaya, and B. Chapron, 2021: 2D Parametric Model for Surface Wave Development Under Varying Wind Field in Space and Time. Journal of Geophysical Research: Oceans, 126

Hell, M. C., A. Ayet, and B. Chapron, 2021: Swell Generation Under Extra-Tropical Storms. Journal of Geophysical Research: Oceans, 126

Kudryavtsev, V., P. Golubkin, and B. Chapron, 2015: A simplified wave enhancement criterion for moving extreme events. Journal of Geophysical Research: Oceans, 120, 7538–7558

Ardhuin, F., T. H. C. Herbers, and W. C. O'Reilly, 2001: A Hybrid Eulerian–Lagrangian Model for Spectral Wave Evolution with Application to Bottom Friction on the Continental Shelf. Journal of Physical Oceanography, 31, 1498–1516.