Towards a fast and accurate AI-integrated ocean wave model

A neural surrogate for the nonlinear four-wave interaction source term

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Why ocean wave matter

Wave attacks in Dawlish, Devon, UK in 2014
Rail link breakage: 3-month service suspension

Spectral wave model

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Action balance equation for wave forecast

$$\boxed{\frac{\partial F(k,f,\theta,x,t)}{\partial t} = S_{tot} = S_{in} + S_{ds} + S_{nl} + \cdots}$$

- **order of 10^4 more expensive**
- **not operationally feasible**

Solution: crude approximation (DIA, 1985)

Millions of resonance interactions $\longrightarrow$ One set

Error compensated by tuning other terms

Describe temporal and spatial evolution of wave energy spectrum $\boldsymbol{F(k,f,\theta,x,t)}$

S_{tot}: all physical processes affect energy transfer

S_{in}: energy input from wind

S_{ds}: dissipation due to wave breaking

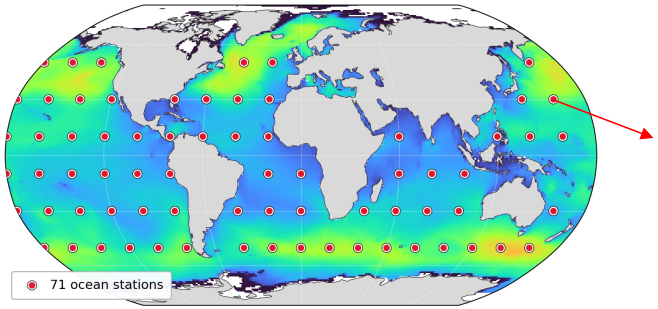
S_{nl}: Nonlinear interaction between spectral component

well-known theory and accurate integral description developed in 1962 (64 years ago)

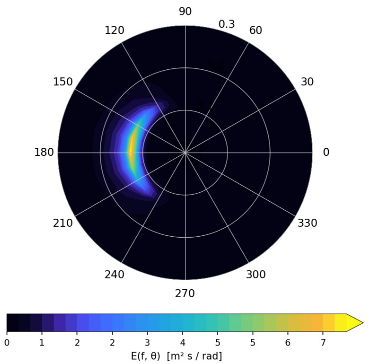
$$\boxed{\frac{\partial n_1}{\partial t} = \iiint G(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3, \boldsymbol{k}_4)\big(n_1 n_3 (n_4 + n_2) - n_2 n_4 (n_1 + n_3)\big)\delta(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k}_3 - \boldsymbol{k}_4)\delta(\omega_1 + \omega_2 - \omega_3 - \omega_4)\, d\boldsymbol{k}_2 d\boldsymbol{k}_3 d\boldsymbol{k}_4}$$

Dataset

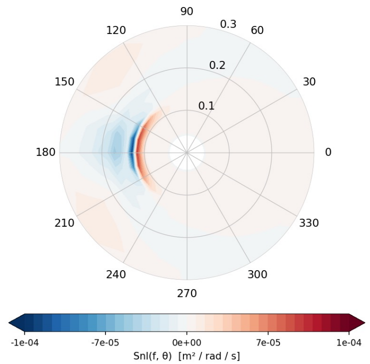
ECMWF ERA5 reanalysis dataset



Input: Spectrum
(downloaded from ERA5)



Target: S_{nl} (WRT)
(recalculated from WW3)



Training data: 2019-01-01 to 2020-01-01 at 6-hour intervals

- 120,000 sets of deep-water 2D wave spectra downloaded from ECMWF ERA5
  https://cds.climate.copernicus.eu/datasets/reanalysis-era5

- Corresponding nonlinear 4-wave interaction recalculated from the WAVEWATCH III source package

Method

Per simulation hour globally
(1° resolution, explicit scheme)

36,000 gird × ~60 timestep

= 2 million S_{nl} runs

Data transformation and postprocessing:

Reconstruction based on DIA: $S_{nl} \propto f^{11} \cdot F^3$

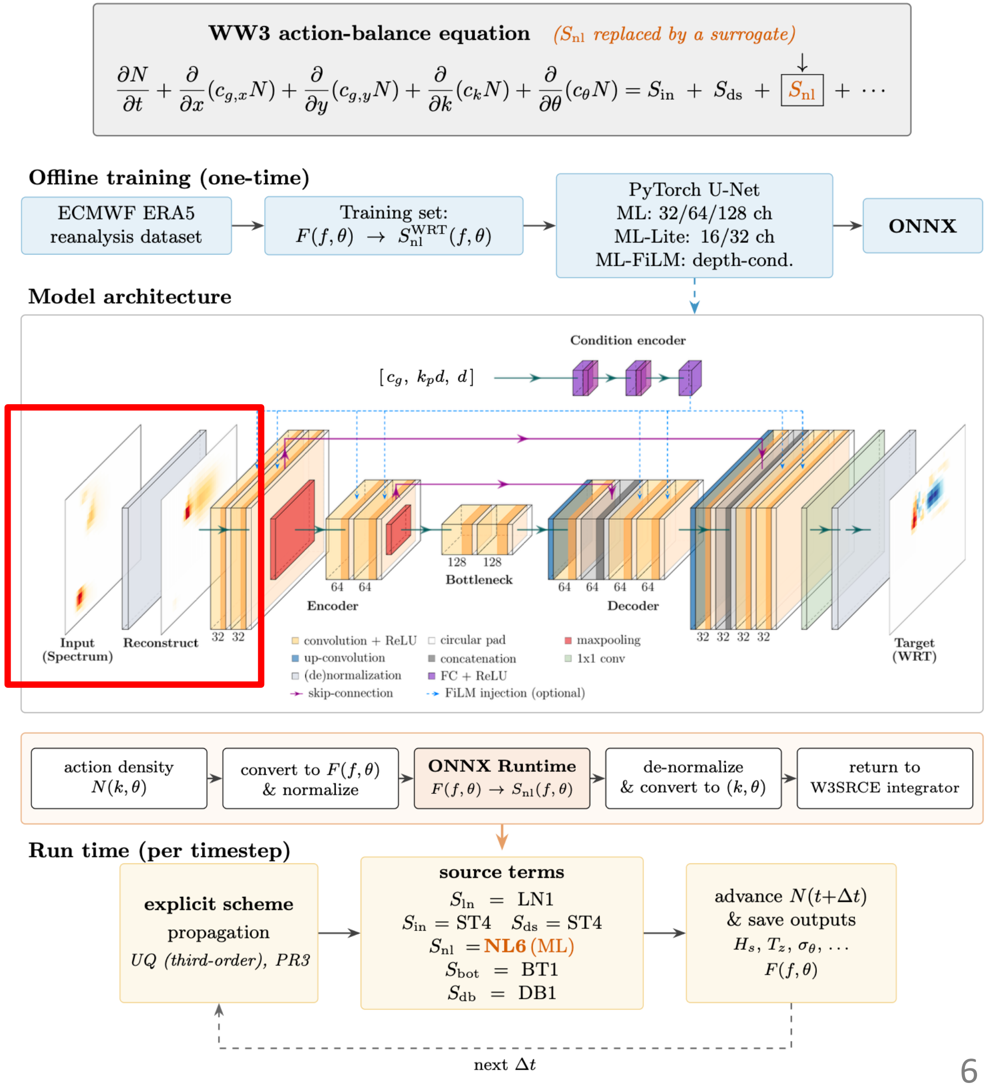
$$\begin{pmatrix} \delta S_{\mathrm{nl},1} \\ \delta S_{\mathrm{nl},3} \\ \delta S_{\mathrm{nl},4} \end{pmatrix} = \begin{pmatrix} -2 \\ 1 \\ 1 \end{pmatrix} Cg^{-4} f_1^{11} \left[F_1^2 \left(\frac{F_3}{(1+\lambda)^4} + \frac{F_4}{(1-\lambda)^4} \right) - \frac{2F_1F_3F_4}{(1-\lambda^2)^4} \right]$$

Shallow water condition:

Depth scaling: $R = 1 + \frac{5.5}{k_p d}\left(1 - \frac{5}{6} k_p d\right) \exp\left(-\frac{5}{4} k_p d\right)$

or FiLM injection in architecture:

$\boldsymbol{c} = \left[\ln(1{+}C_{g,1}), \ldots, \ln(1{+}C_{g,40}),\ \ln(1{+}k_p d),\ \ln(1{+}d)\right] \in \mathbb{R}^{42}$



Method

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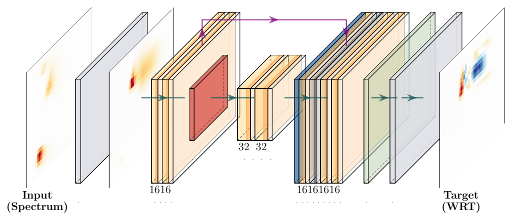
Lightweight model for fast inference



	ML ($C_b = 32$)		ML-Lite ($C_b = 16$)	
Component	channels	params	channels	params
Encoder DC$_1$	1→32→32	9,568	1→16→16	2,480
Encoder DC$_2$	32→64→64	55,424	–	–
Bottleneck	64→128→128	221,440	16→32→32	13,888
Up + DC (mid)	128→64	118,976	–	–
Up + DC (final)	64→32	29,792	32→16	7,472
Conv 1×1 head	32→1	33	16→1	17
Total		~435,233		~23,857

Pipeline optimized
Operationally deployable

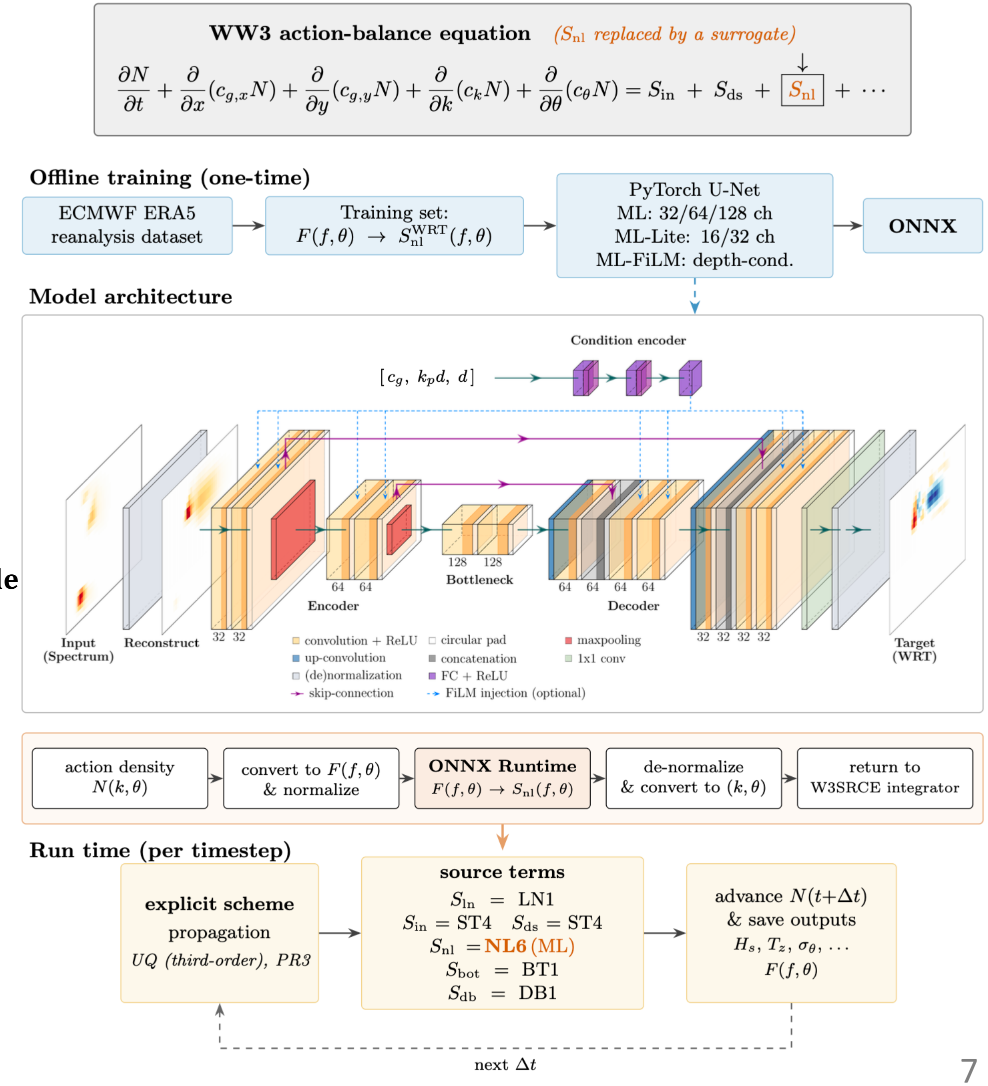
switch
data/model/exe/

NOGRB DIST MPI
PR3 UQ FLX0 LN1
ST4 **NL1** BT1 DB1...

MLLite.onnx

w3snl6md_mllite.F90
onnx_models/

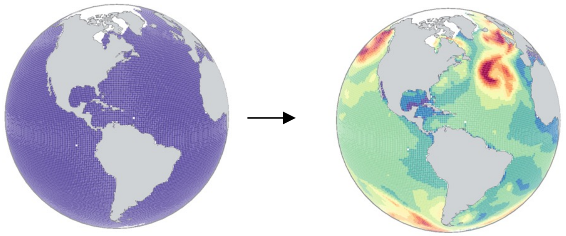
NOGRB DIST MPI
PR3 UQ FLX0 LN1
ST4 **NL6** BT1 DB1...



Results

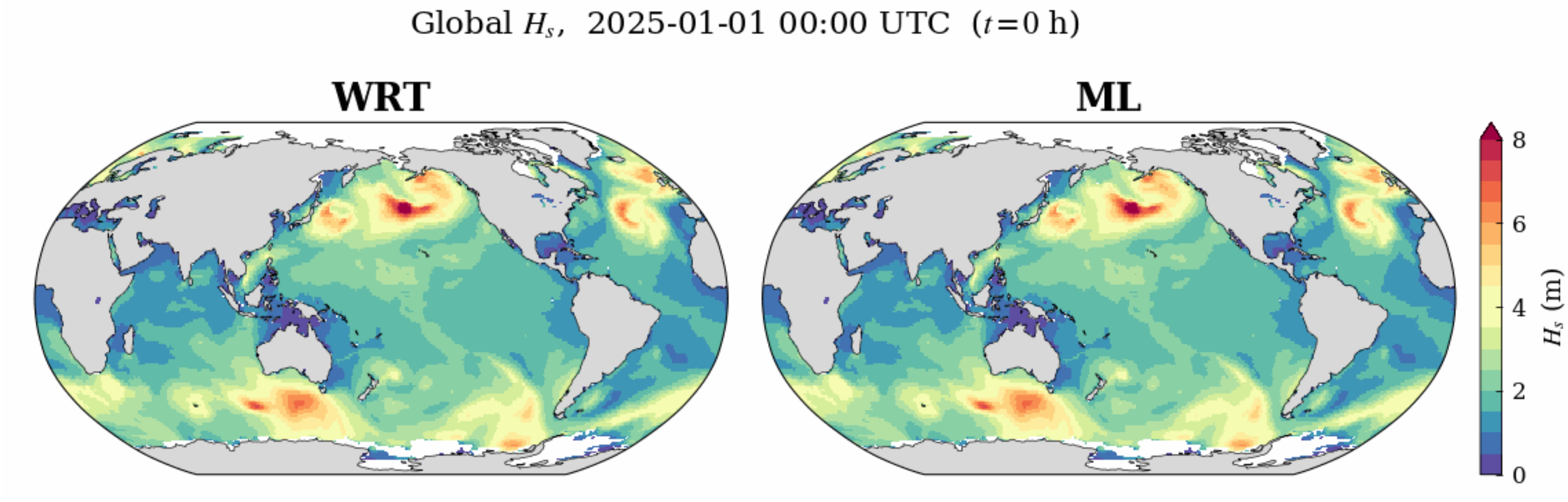
- **Direct mapping validation**
- **Duration-limited growth at a single grid**
  - Added time evolution
- **Fetch-limited growth at wave basin**
  - Added spatial propagation
- **Regional simulation (Lake Victoria)**
  - Added real wind data
  - Added real bathymetry
- **Global simulation**
  - Standard operational settings

Global wave model settings (WW3)

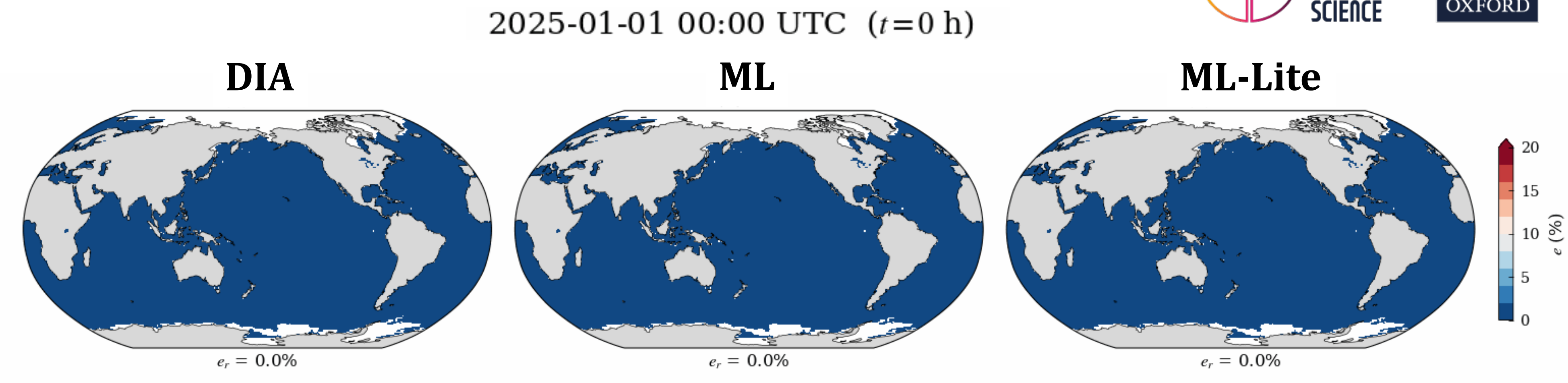


DIST, MPI	Distributed-memory parallelization (MPI)
PR3, UQ	Third-order propagation, ULTIMATE QUICKEST scheme
LN1	Linear wind input (Cavaleri & Malanotte-Rizzoli, 1981)
ST4	Generation and dissipation (Ardhuin et al., 2010)
BT1	Joint North Sea Wave Project (JONSWAP) bottom friction (K. Hasselmann et al., 1973)
DB1	Depth-limited breaking (Battjes & Janssen, 1978)
WNT1, WNX1	Wind interpolation in time and space
NL1	Discrete Interaction Approximation (DIA) for quadruplets (S. Hasselmann et al., 1985)
NL2	Full Boltzmann Integral (Webb–Resio–Tracy, WRT) (Tracy & Resio, 1982; D. Resio & Perrie, 1991)
NL6	Machine-learning S_{nl} surrogate, `W3SNL6MD` (this study)

Results



Results

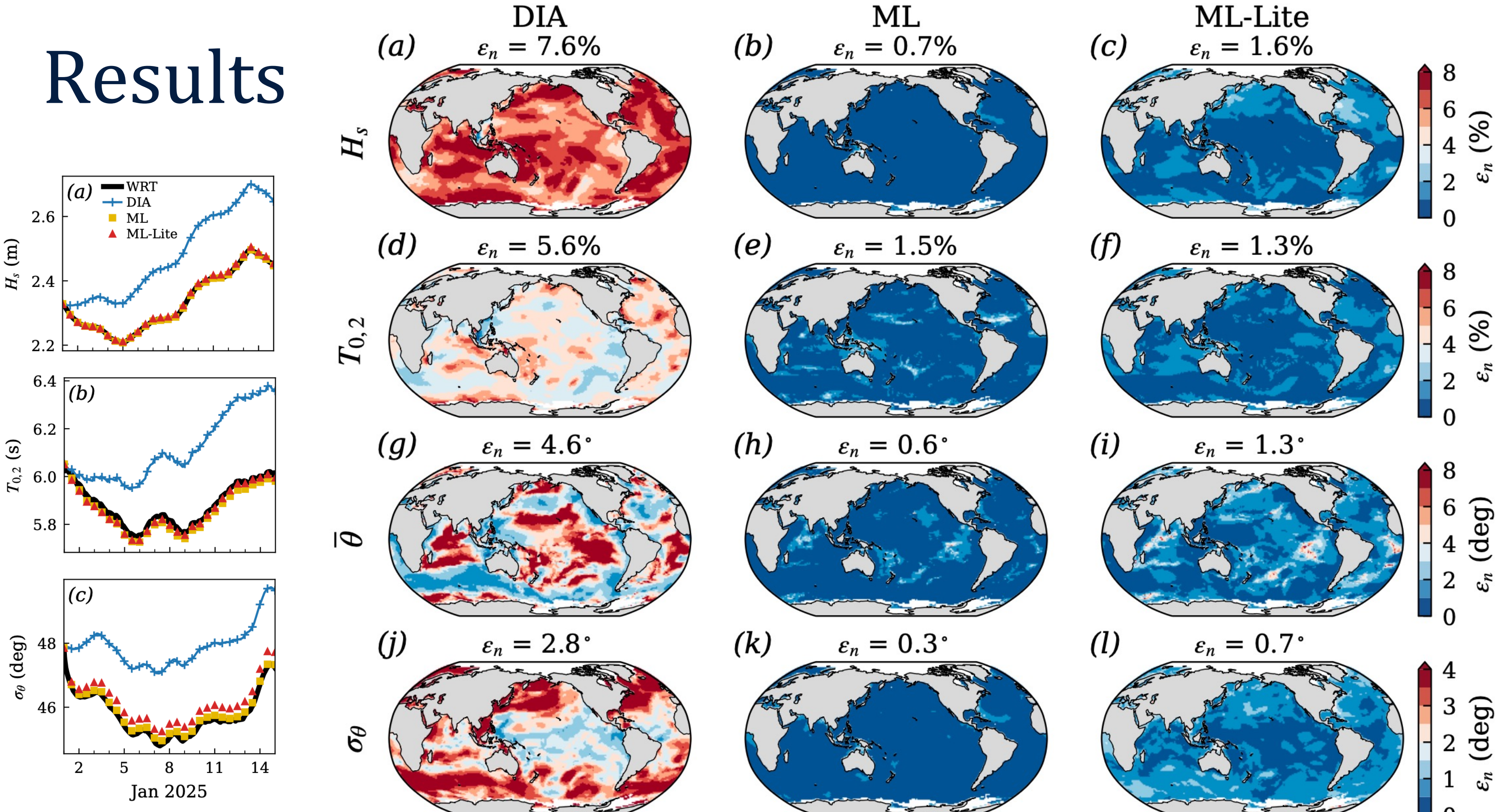


Computational cost for global simulation:

- **WRT:** 134 times slower than DIA.
- **ML:** 12.8 times slower than DIA.
- **ML-Lite:** 2.5 times slower than DIA, 54 times faster than WRT

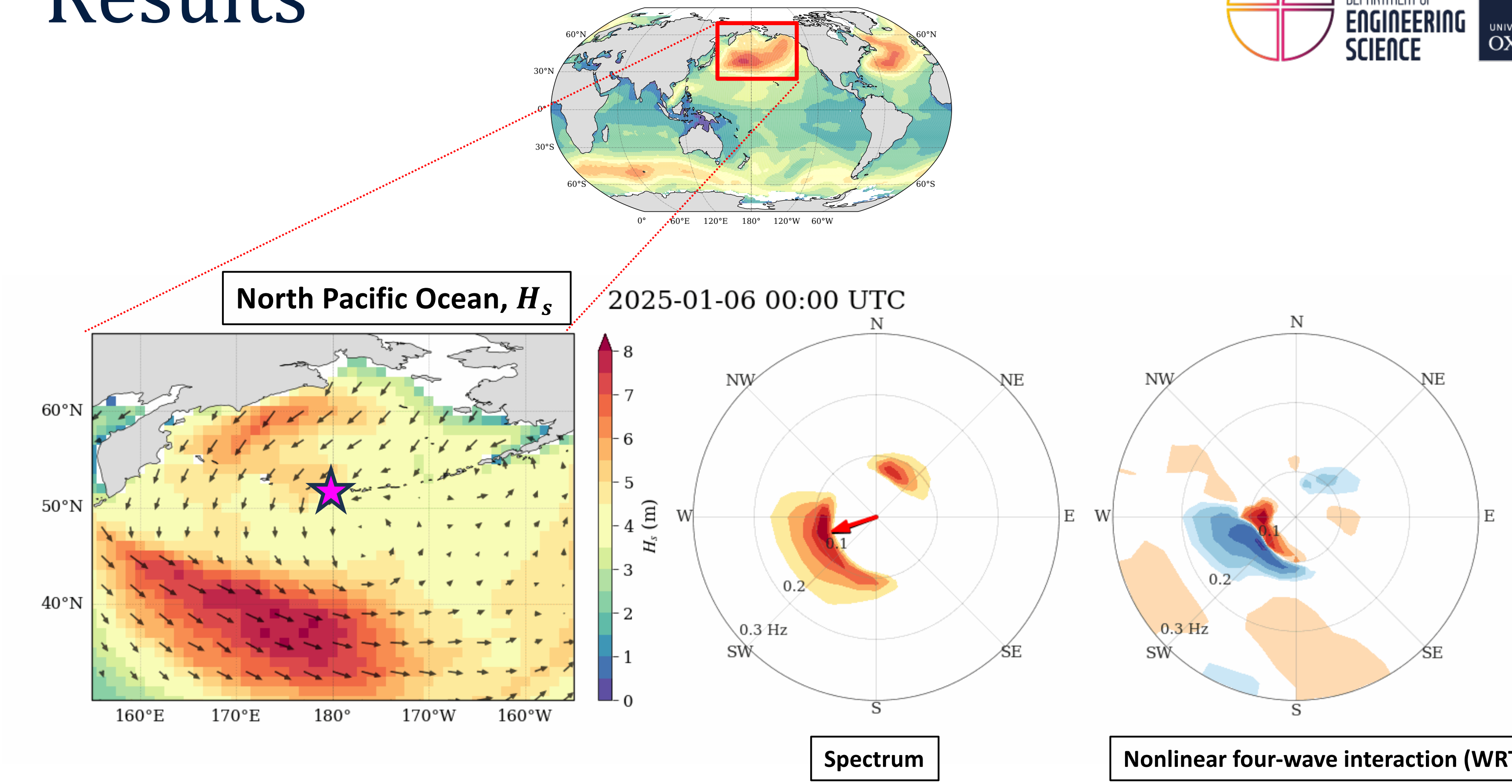
11th Gen Intel Core i9-11900K CPU (8 cores, 16 threads), 128 GB of system memory

Results



DIA
ML
ML-Lite
(a) ε_n = 7.6%
(b) ε_n = 0.7%
(c) ε_n = 1.6%
(d) ε_n = 5.6%
(e) ε_n = 1.5%
(f) ε_n = 1.3%
(g) ε_n = 4.6°
(h) ε_n = 0.6°
(i) ε_n = 1.3°
(j) ε_n = 2.8°
(k) ε_n = 0.3°
(l) ε_n = 0.7°
H_s
$T_{0,2}$
$\bar{\theta}$
σ_θ
ε_n (%)
ε_n (deg)
WRT
DIA
ML
ML-Lite
H_s (m)
$T_{0,2}$ (s)
σ_θ (deg)
Jan 2025

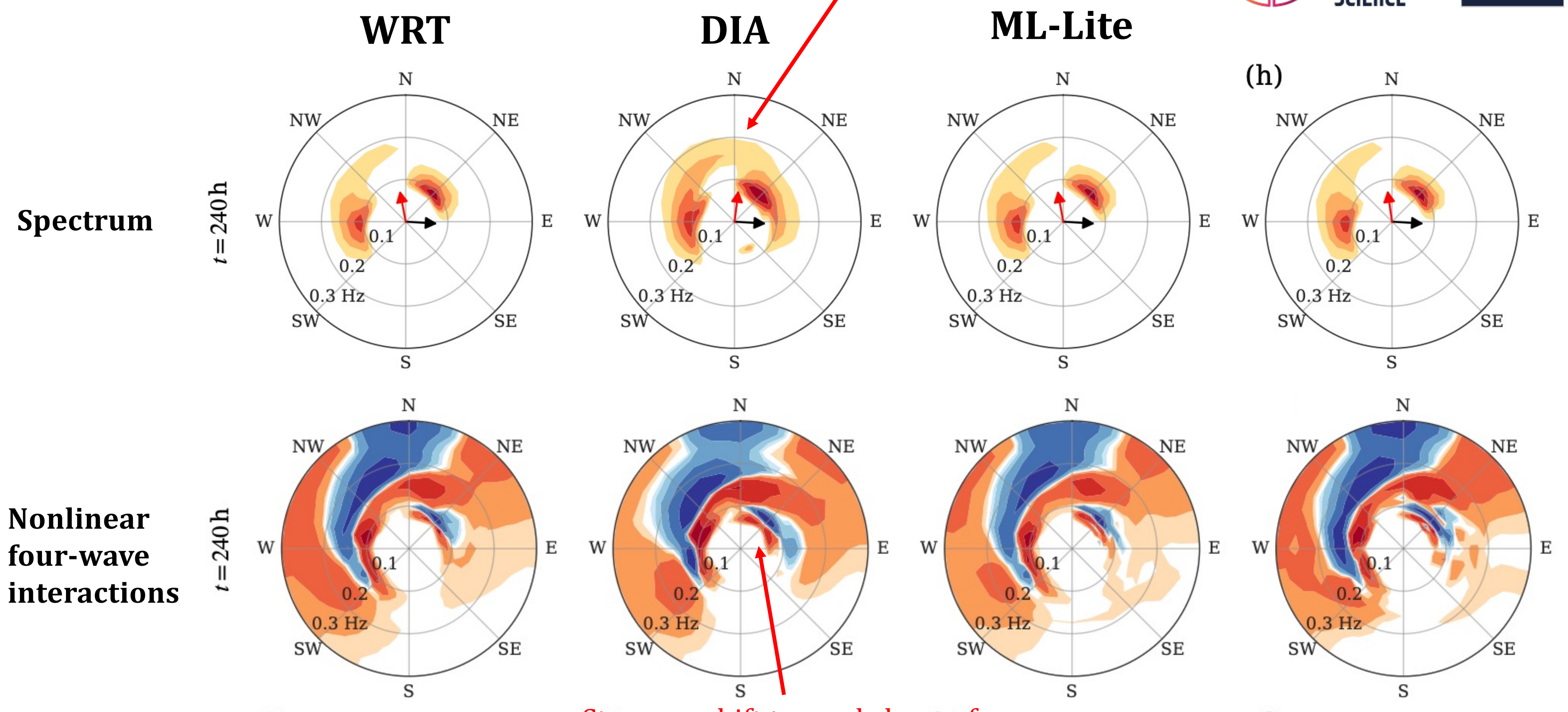
Results



North Pacific Ocean, H_s
2025-01-06 00:00 UTC
60°N
50°N
40°N
160°E
170°E
180°
170°W
160°W
H_s (m)
0 1 2 3 4 5 6 7 8
N
NE
E
SE
S
SW
W
NW
0.1
0.2
0.3 Hz
Spectrum
Nonlinear four-wave interaction (WRT)

Results

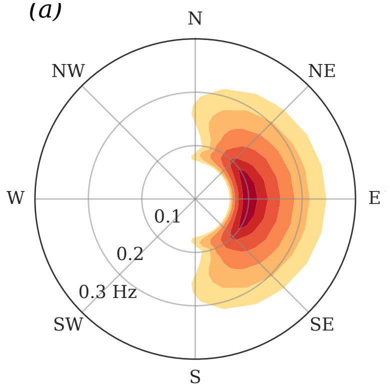
- Broader directional distribution
- Error in mean wave direction



Stronger shift towards lower frequency

Preliminary results

JONSWAP Spectrum



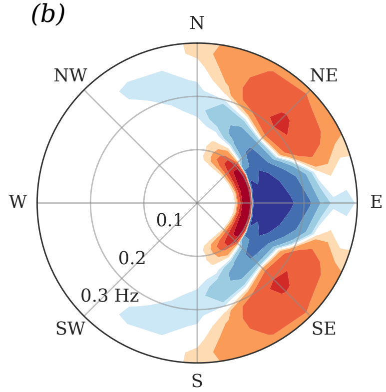
Depth scaling for shallow case:

$$R = 1 + \frac{5.5}{k_p d}\left(1 - \frac{5}{6}k_p d\right)\exp\left(-\frac{5}{4}k_p d\right)$$

Scaled only

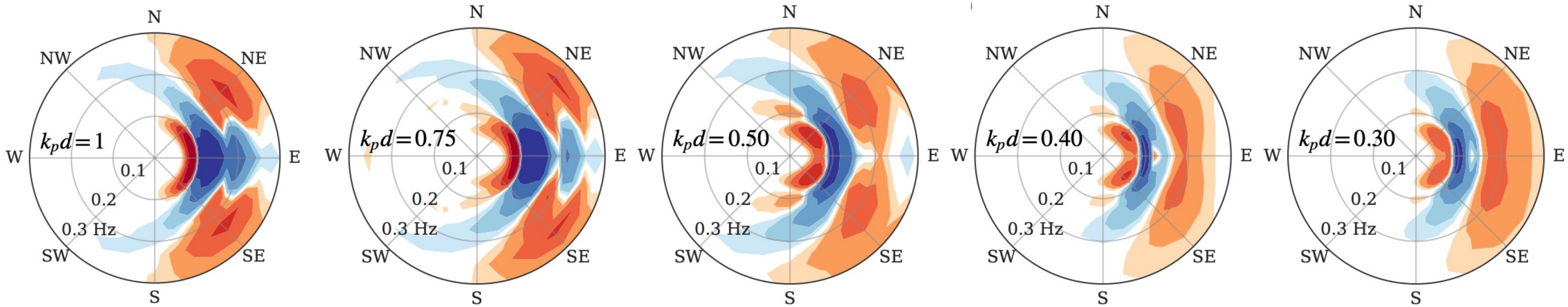
Only magnitude change

Scaled WRT

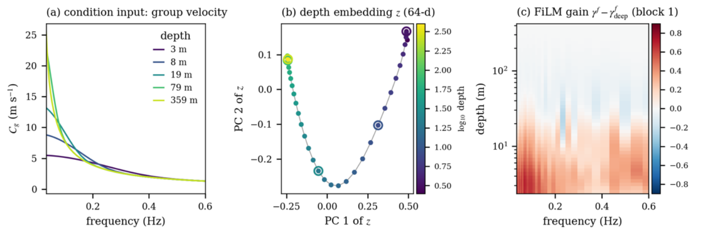


Deep to shallow

Directly evaluated, but with computational and memory cost



FiLM injection: $\boldsymbol{c} = \left[\ln(1{+}C_{g,1}), \ldots, \ln(1{+}C_{g,40}),\ \ln(1{+}k_p d),\ \ln(1{+}d)\right] \in \mathbb{R}^{42}$

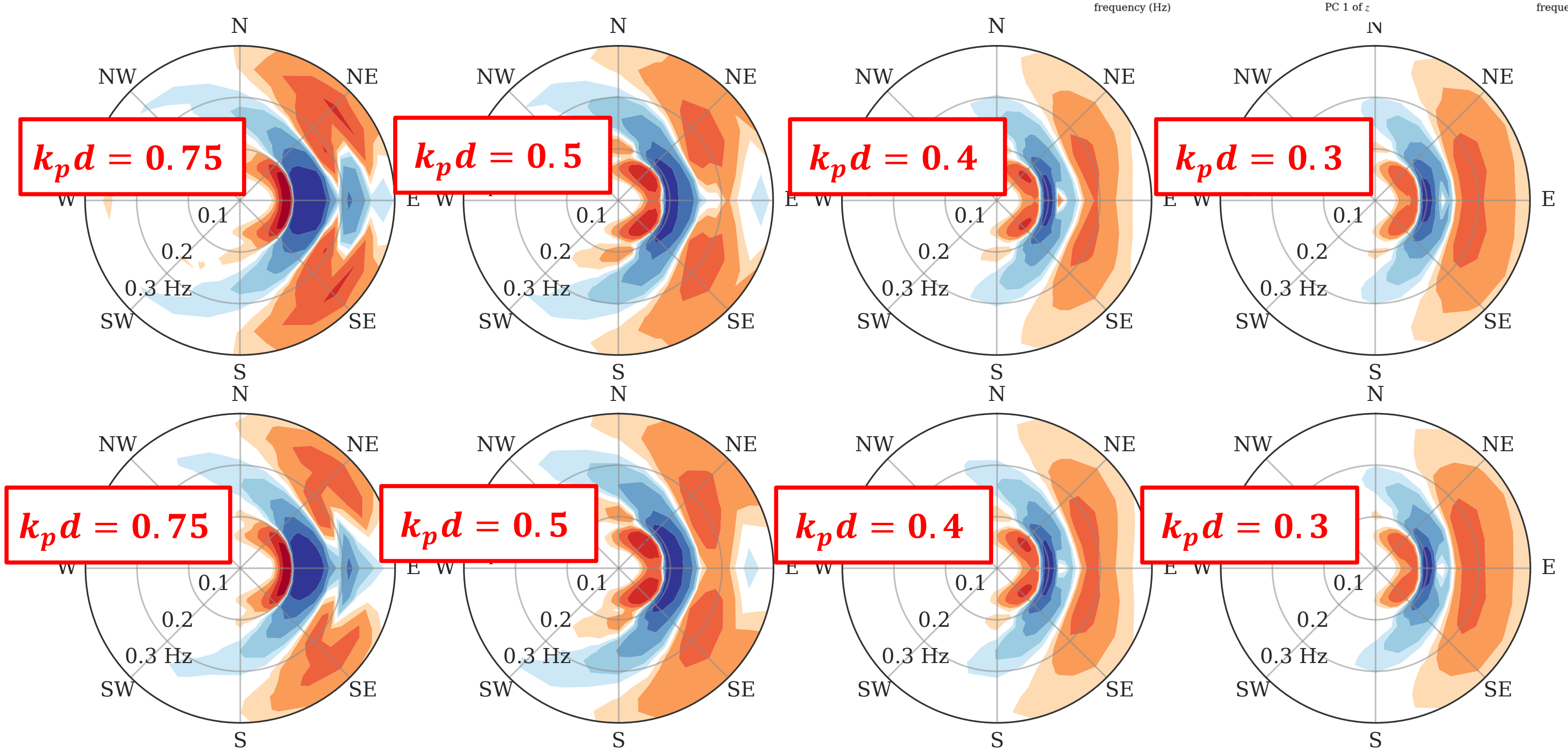


Preliminary results

Deep to shallow

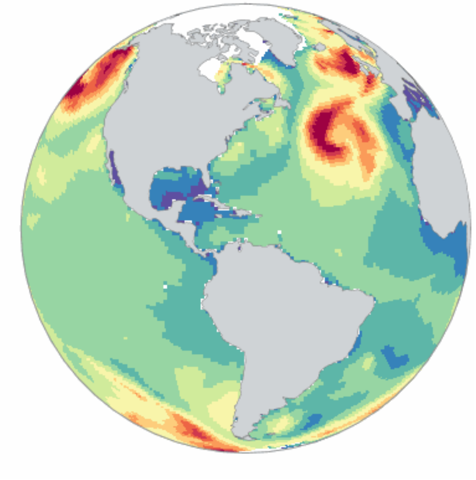
WRT finite

ML-FiLM



Summary

- Fast ML surrogate for S_{nl} and can be further extended to finite depth with FiLM-based architecture
- Embedded in WAVEWATCH III as a new source-term module
- Stable across full global run with WRT-level accuracy
- Only **2.5×** slower than DIA and **54×** faster than WRT – operational viable



Ongoing work:

- Further investigation in hurricane cases
- Calibration needed for other source terms

Acknowledgements

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