

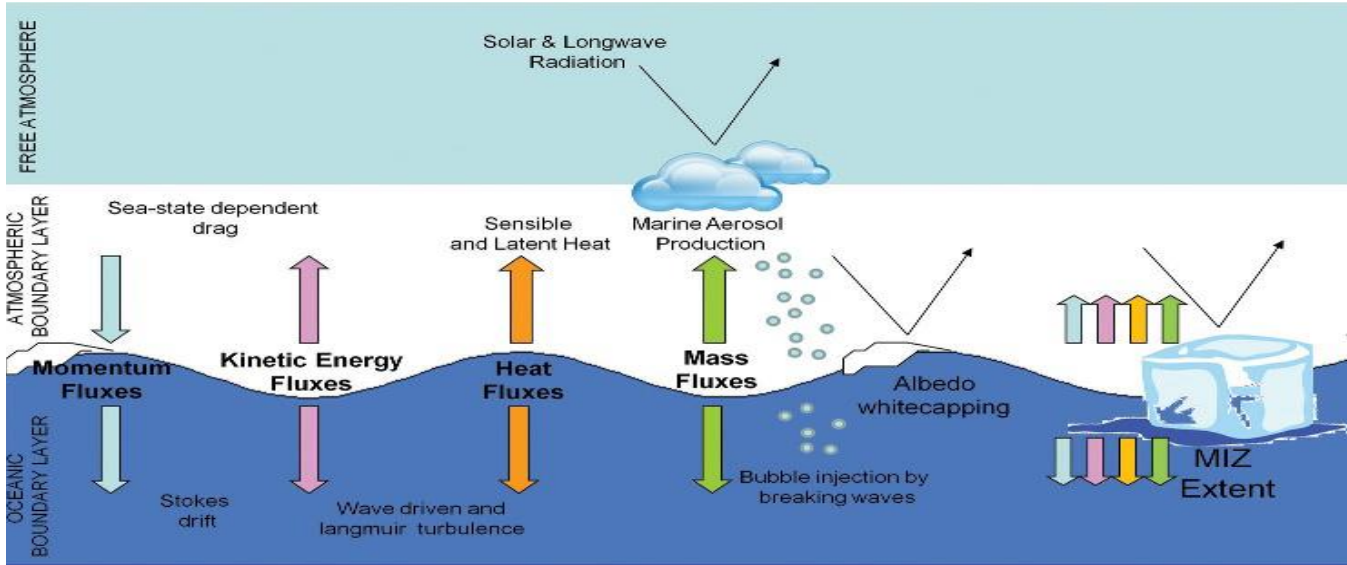
# AI for Ocean Surface Wave Emulation

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# WHY CARE ABOUT OCEAN WAVES?



- Wind waves: key interface process in the coupled earth system.

**Yahoo**  
<https://www.yahoo.com/lifestyle/massive-waves-bre...>

**Massive Waves Break at Offshore SoCal Oil Rig (Watch)**  
Dec 24, 2024 — Surfers score Oil Rig Platform Esther, 1.5 miles off Seal Beach, during XXL California swell.

**ABC News**

**California storm turns deadly as waves wreak havoc in coastal communities**  
A powerful storm pummeling the West Coast churned up waves as high as 60 feet, killing one man, sweeping another out to sea and prompting multiple rescues.

**Yahoo News**  
<https://news.yahoo.com/big-waves-impact-local-sports...>

**Big waves impact local sports fisheries in Morro Bay**  
Jan 4, 2024 — Speaking to a group of conservative Italian politicians, Elon Musk on Saturday called for a

Accurate wave prediction is crucial for protecting offshore infrastructure and coastal communities.

$$\frac{DF(f, \theta)}{DT} = S_{tot} = S_{in} + S_{nl} + S_{ds} + S_{xx}$$

$S_{in}$  – Wind input;  $S_{ds}$  – Dissipation;  $S_{nl}$  – **Nonlinear wave interactions**  
 $S_{bot}$  – wave-bottom interactions;  $S_{ice}$  – wave-ice interactions

F - spectrum energy often represented as action density,  $N = \frac{F}{\sigma}$ ,  $\sigma$  is the relative frequency

- **Nonlinear interactions** drive energy transfer and shape wave evolution.

$$\frac{\partial n_1}{\partial t} = \iiint G(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) \delta_{\kappa} \delta_{\sigma} \times [n_1 n_3 (n_4 - n_2) + n_2 n_4 (n_3 - n_1)] d\mathbf{k}_2 d\mathbf{k}_3 d\mathbf{k}_4$$

$k$  - wavenumber,  $\sigma$ - radian freq and  $G$  is a coupling coefficients (Herterich and Hasselmann 1980)

**Webb-Resio-Tracy method (WRT) - van Vledder (2006)**

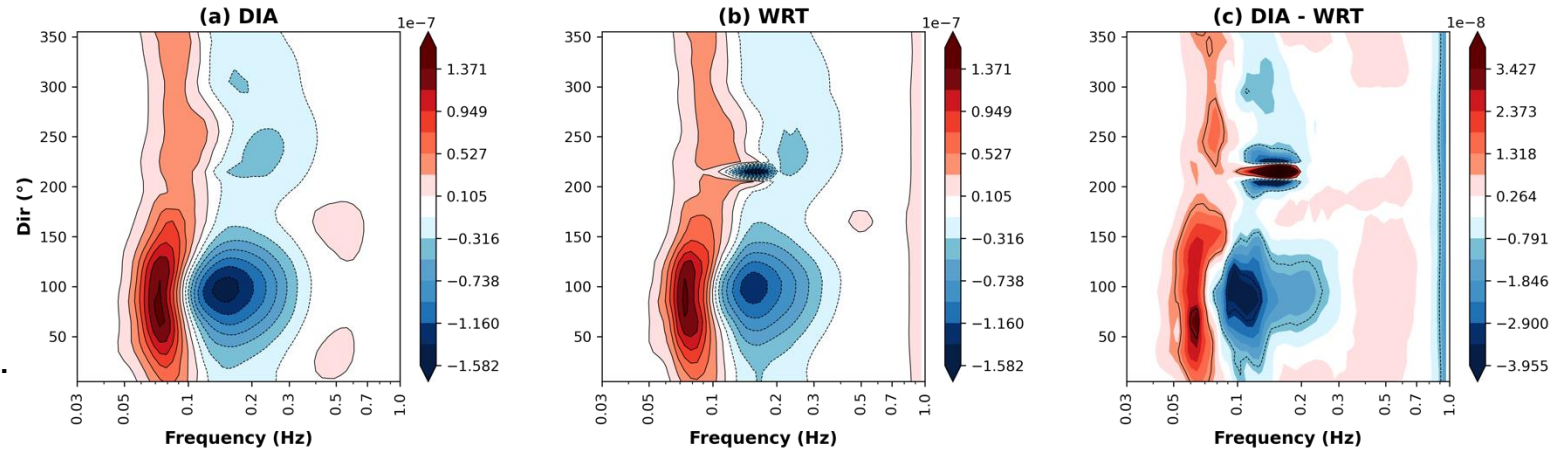
**~100X more expensive than the rest on the wave model due to the 6D Boltzmann integral.**

- $S_{nl}$  is being approximated as Discrete Interaction Approximation (*DIA*) - **fixed wavenumber configuration**

$$\begin{aligned}
 k_1 = k_2 = k, \quad k_3 = k(1 + \lambda), \quad k_4 = k(1 - \lambda) & \quad \frac{\partial}{\partial t} \begin{pmatrix} N \\ N_+ \\ N_- \end{pmatrix} = \begin{pmatrix} -2 \\ +1 \\ +1 \end{pmatrix} Cg^{-8} f[N^2(N_+ + N_-) - 2NN_+N_-] \Delta k \\
 \lambda = 0.25 \quad \theta_3 = 11.5^\circ, \quad \theta_4 = -33.6^\circ & \quad \text{Hasselmann et al. (1985)}
 \end{aligned}$$

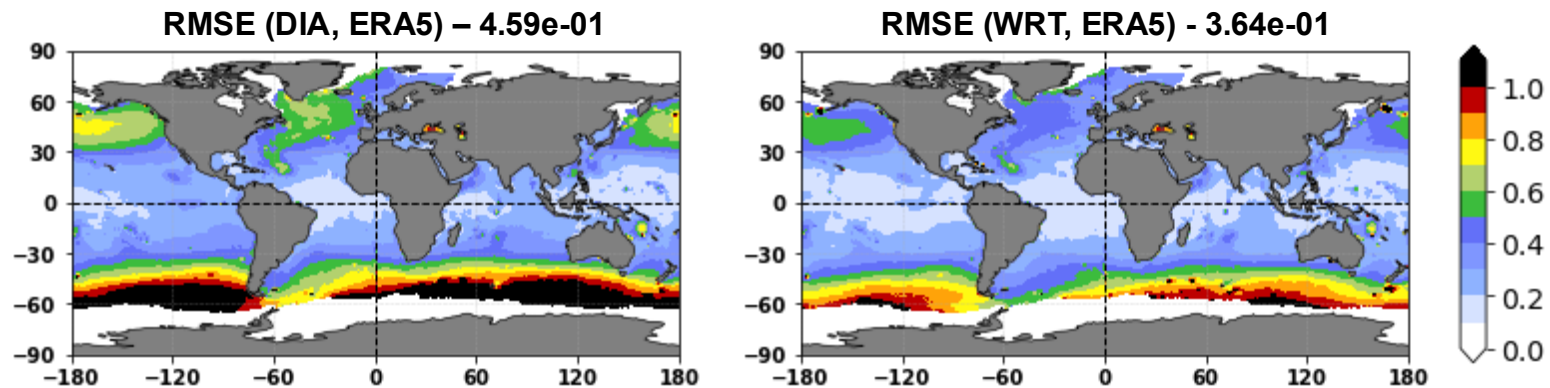
# Expensive accuracy: Bottleneck of nonlinear wave interactions

- **Approx.** formulation - Discrete Interaction Approximation (*DIA*) **sacrifices accuracy for speed**
- Efforts to replace DIA with accurate methods often come at the cost of its speed advantage.



The global mean of the nonlinear interactions

**Objective:**  
Our goal is to develop a neural network emulator that achieves the accuracy of the **WRT** and the speed of **DIA**.



2010 global RMSE patterns of significant wave height (m)

# Past ML Efforts

## 2001/2002

*Krasnopolsky et al. (2001, 2002)*

- First emulator using math basis function expansion
- A single hidden layer with 30 neurons
- 2× more accurate than DIA, 3× more expensive
- Trained on deep-water spectra only, not model-integrated

## 2005

*Tolman et al. 2005*

- EOFs
- 4.7× more accurate & ~4.7x costly than DIA
- Most of the time spent on EOF decomposition and reconstruction
- Single-peaked spectra only, leading to instability in model integration

## 2009

*Wahle et al. 2009*

- Direct mapping of spectra to  $S_{nl}$
- Trained on multi-peaked spectra from a wave model in the North Atlantic
- 3 hidden layers - 80, 39, & 80 neurons
- Accurate but no cost/integration results

*Tolman et al. 2009*

- Added Quality Control (QC) during online integration
- Stable but often revert to the exact method
- Computationally expensive as exact methods

## 2014

*Puscasu 2014*

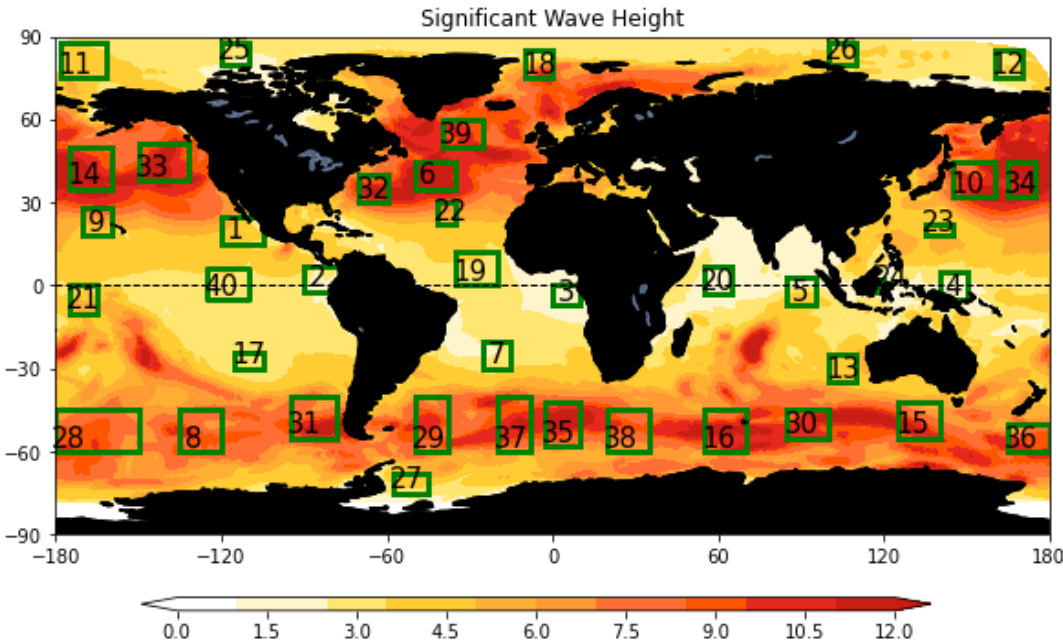
- Real-case NNIA in WW3 (Lake Michigan)
- Tested over 75 days, but performance on unseen data uncertain

**Unstable**

**Shallow ML model**

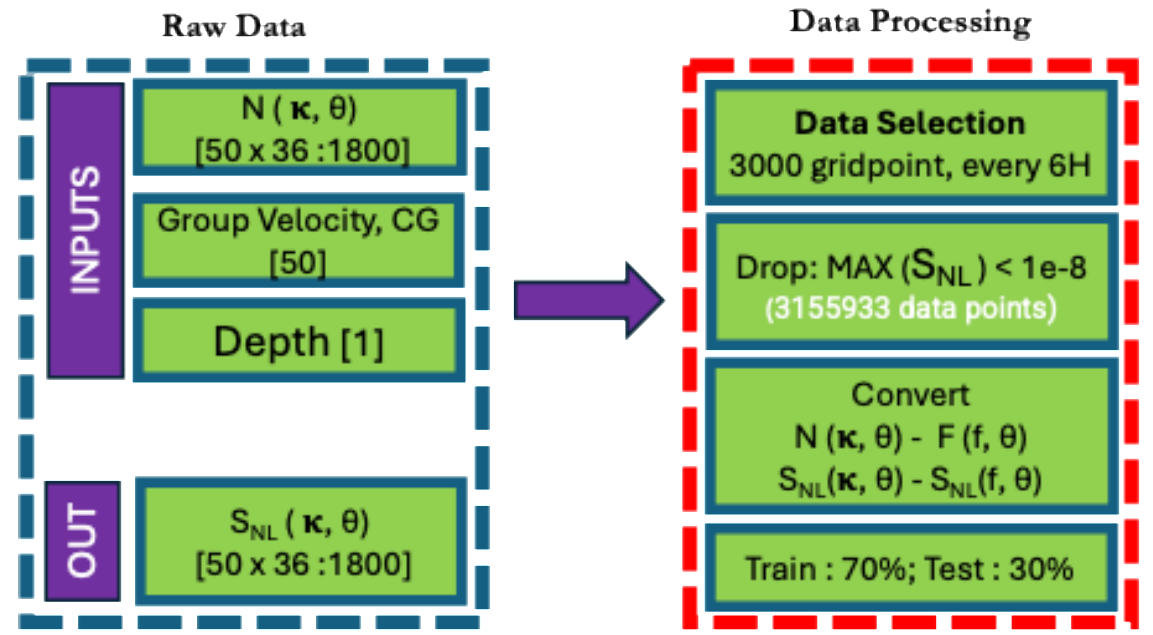
**No global training dataset and limited temporal coverage**

# Training and Validation Data



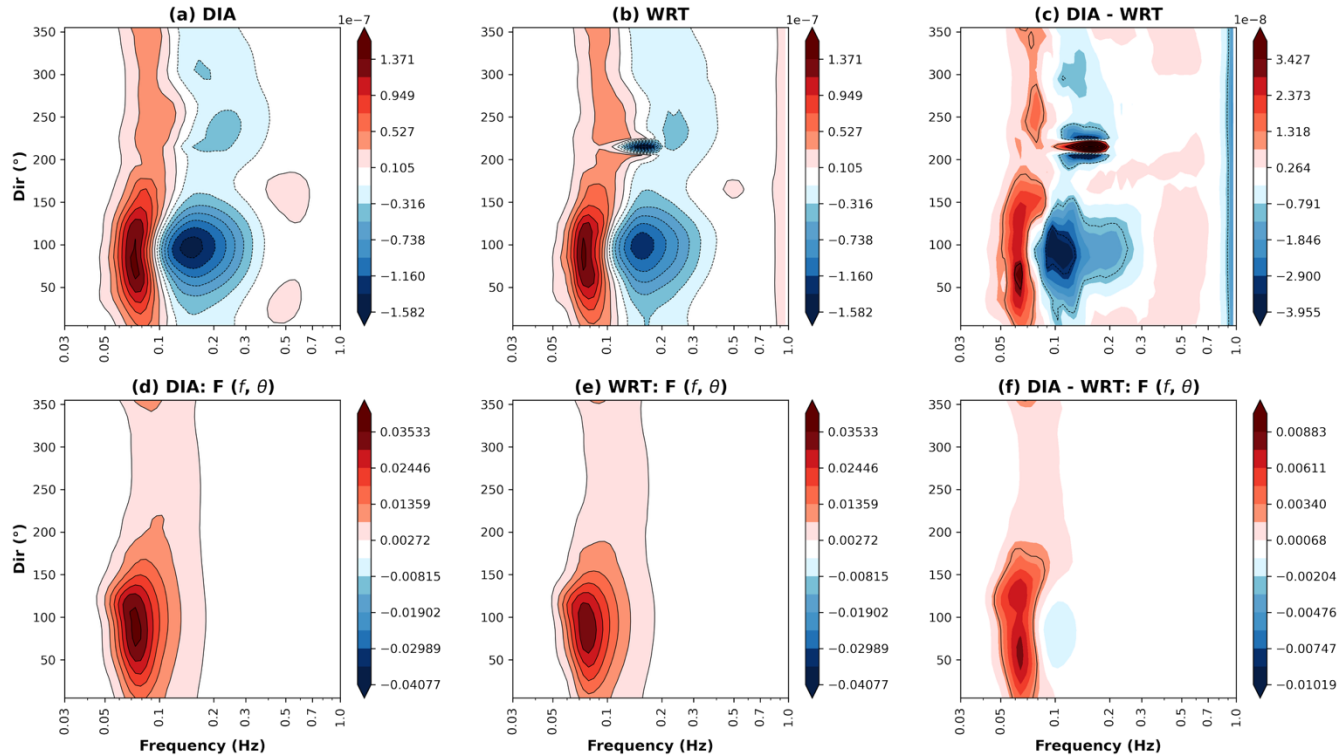
Randomly selected data locations shown as boxed regions over areas of high and low wave activity.

- Data from WW3**
- Unstructured mesh (56K gridpoints)
  - 50x36 spectral resolution
  - Waves only (2010 & 2020) simulations with DIA/WRT
- ERA5 wave reanalysis ( $H_s$  &  $T_p$ )**
- Uses DIA & satellite observations



- Additional inputs
- Sensitivity tests
- Converted  $N(\mathbf{k}, \theta) \rightarrow F(\mathbf{f}, \theta)$
- Normalization strategy:

$F(\mathbf{f}, \theta, j)$  – per frequency-direction bin [1800]  
 $CG(\mathbf{f}, j)$  - CG[1]; Depth - Depth[1]



The global mean of nonlinear interaction source terms and wave spectral energy for the year 2010

## ERROR METRICS

$$\epsilon_S(f, \theta) = \left\{ \frac{1}{N} \sum_{j=1}^N [Y_j(f, \theta) - \hat{Y}_j(f, \theta)]^2 \right\}^{1/2}$$

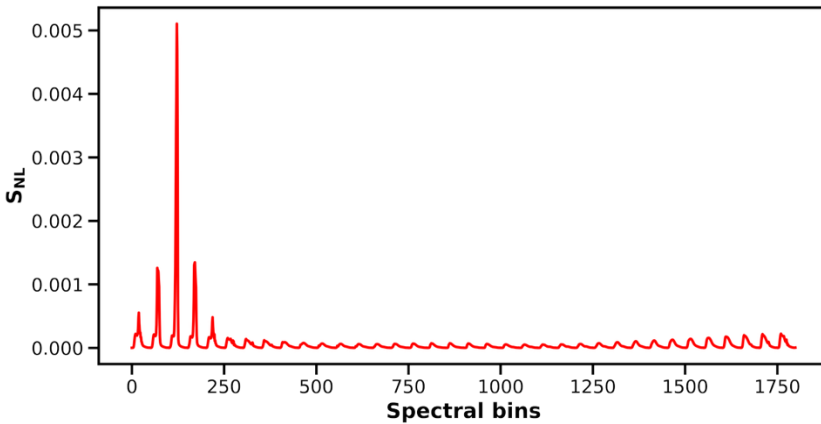
$$\bar{\epsilon}_S = \int \int \epsilon_S(f, \theta) df d\theta.$$

### Mean Wave Parameters

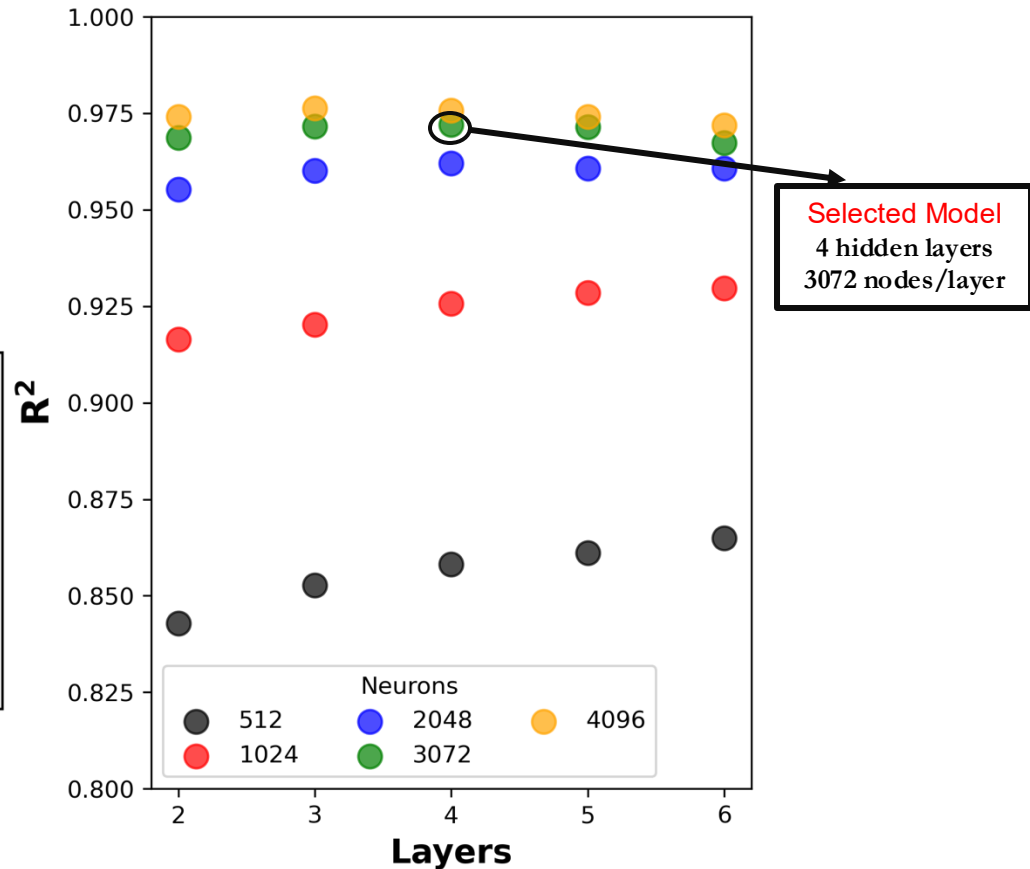
$$\epsilon_W = \sqrt{\sum_1^n [W - W_{NN}]^2}$$

## Customized Loss Function

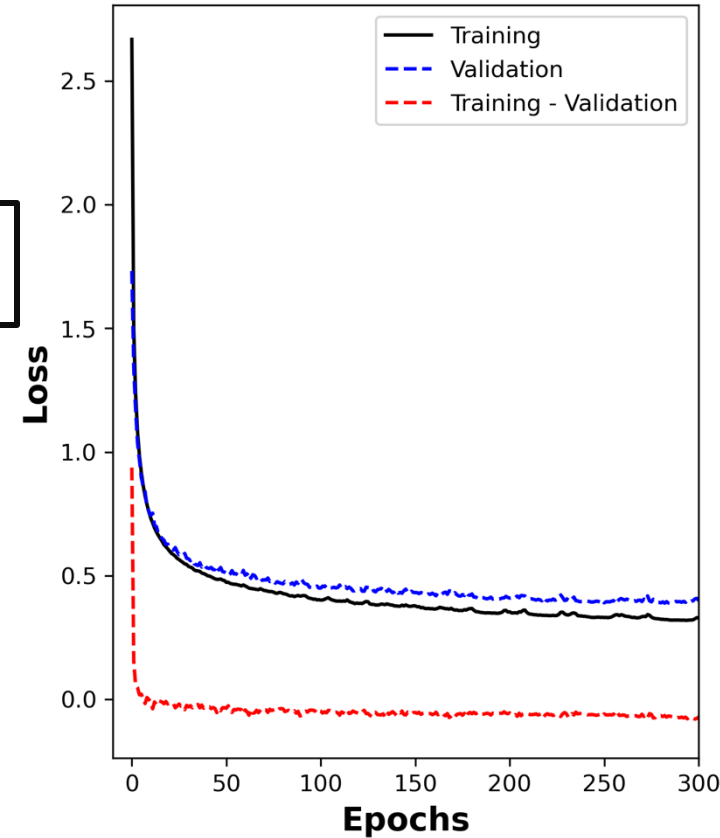
$$\frac{1}{N} \sum_{i=1}^N |Y_i - \hat{Y}_i| \times \text{stdev}(\mathbf{Y})_i$$



## Hyperparameter Optimization



## Loss Curve

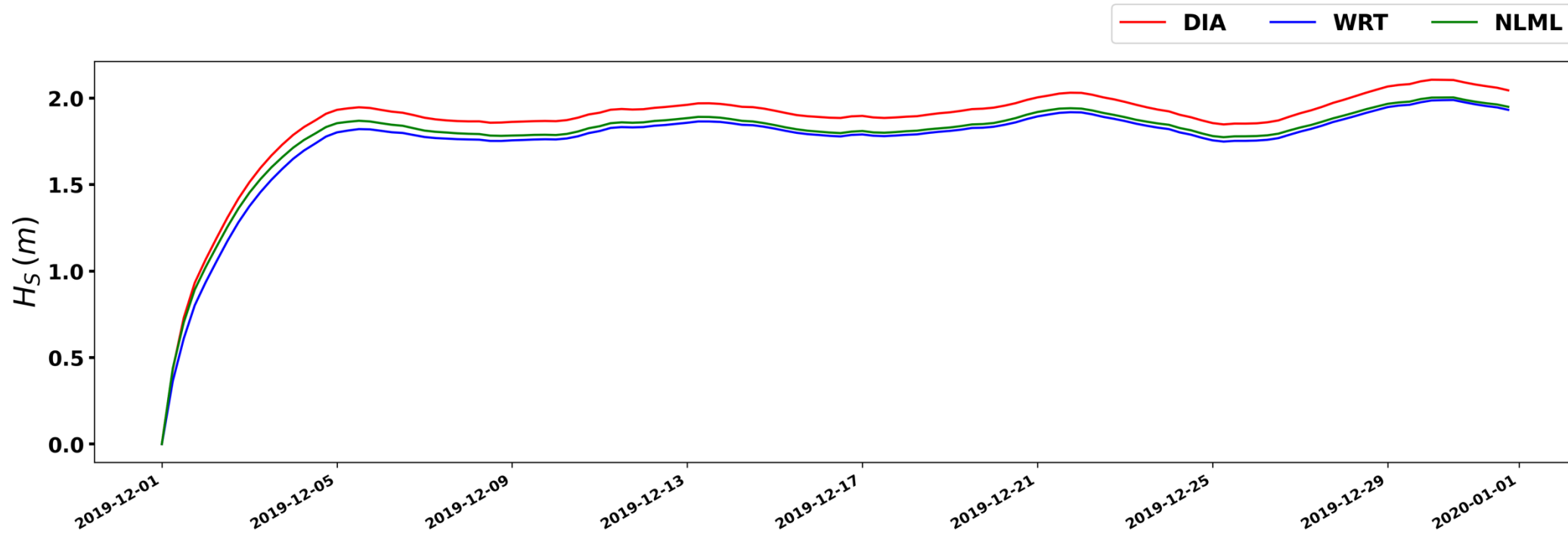


### WW3-ML integration

- FTorch: For online inference
- Online inference: 2020

6 Hours training time on  
one NVIDIA A100 GPU

# Model Stability and Spin-Up Performance

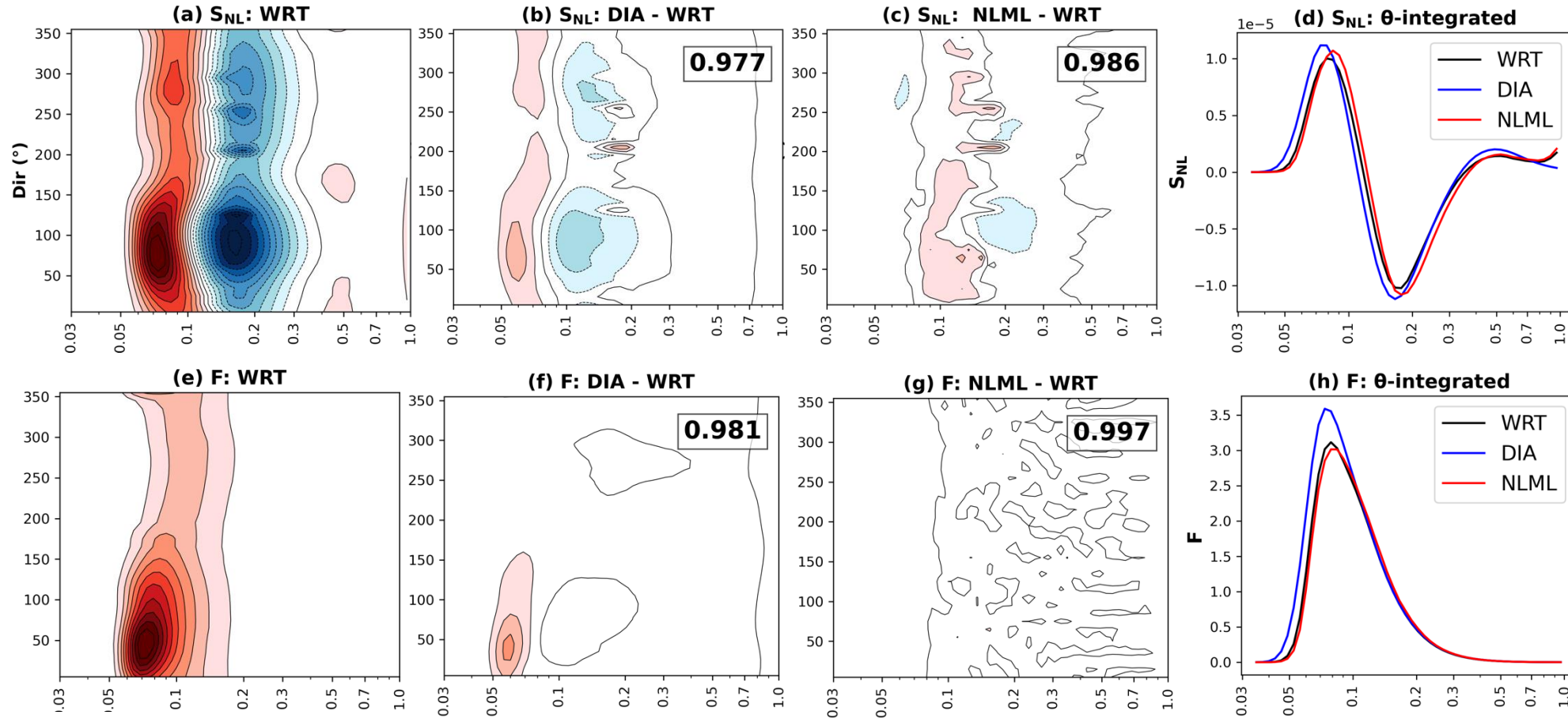


Time series of global mean HS during the first month of each simulation

**NLML is stable without employing any additional constraints**

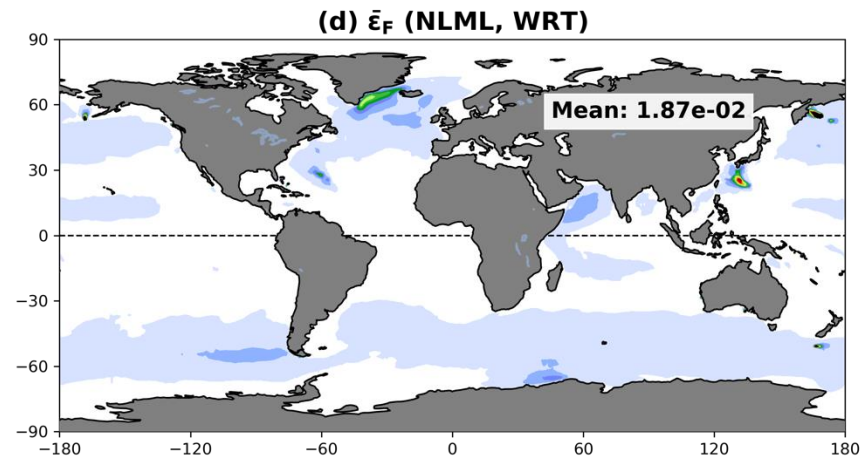
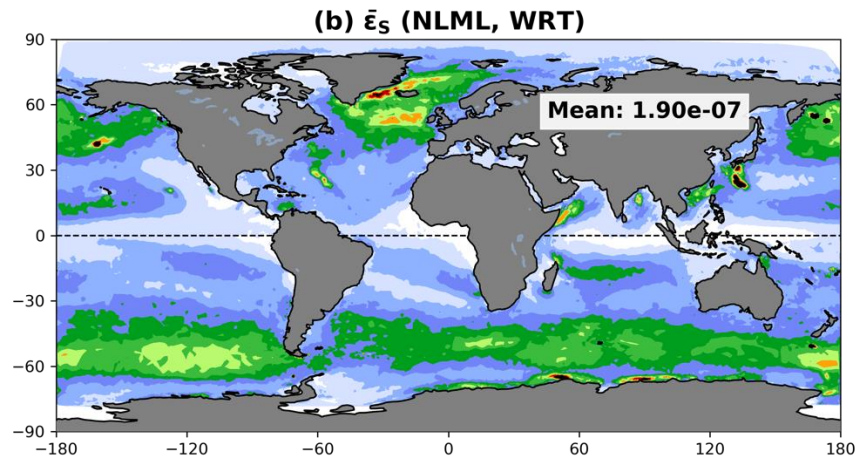
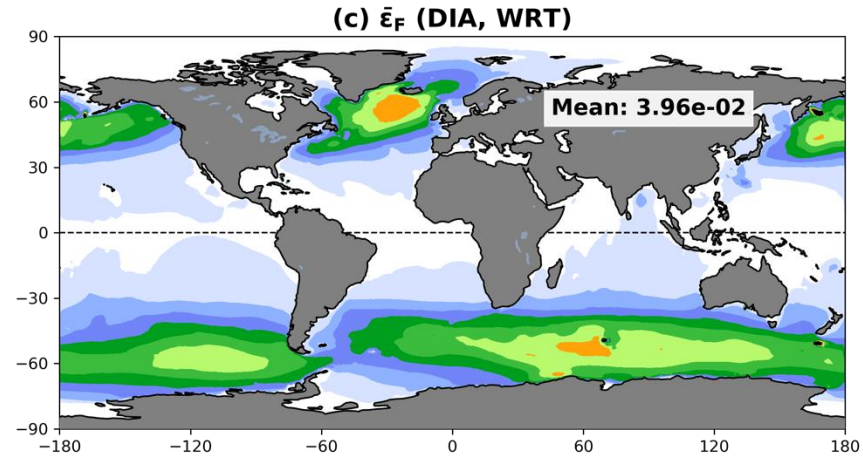
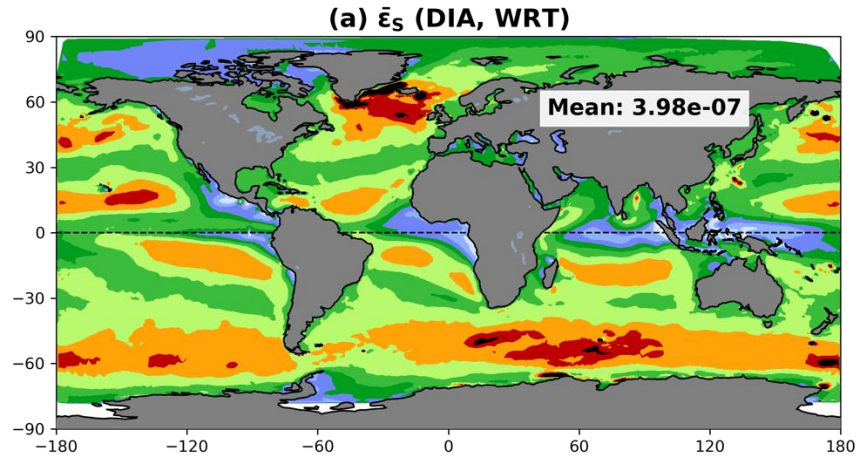
**In training, we excluded the spin-up period (December 1 to 31, 2010)**

# Online Performance: MEAN

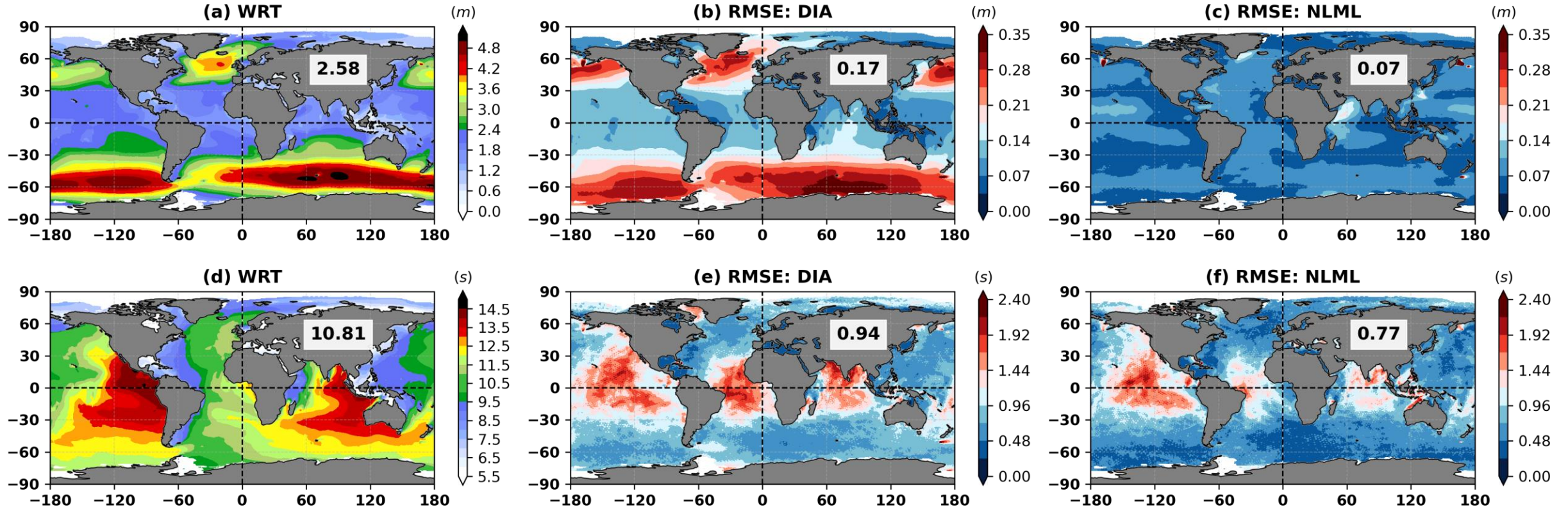


The global spatiotemporal mean for year 2020. The numbers in the boxes indicate the spatial correlation in frequency-direction.

# Online Performance: SPECTRA ERRORS



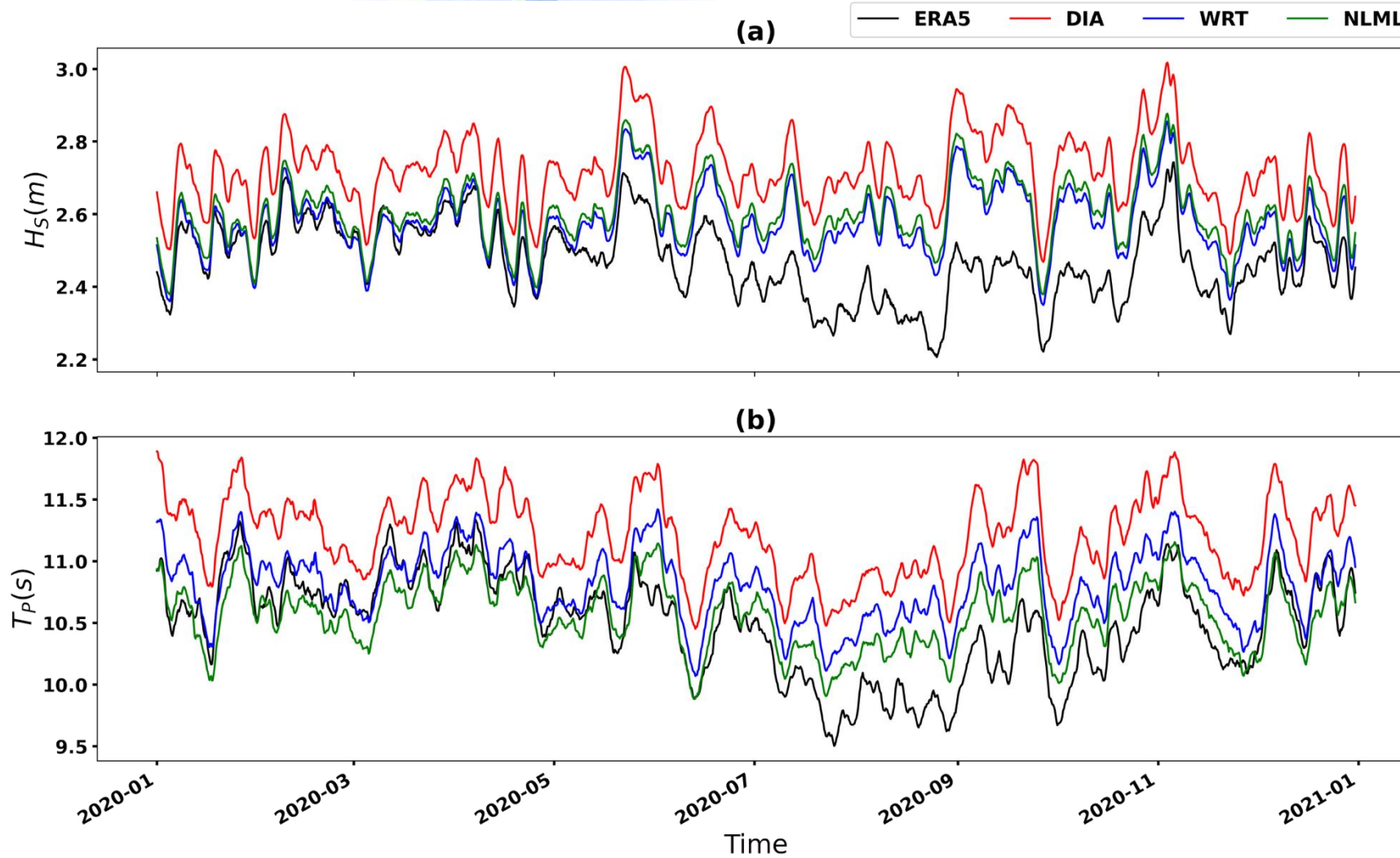
The global pattern of the integrated spectra errors



2020 annual mean HS & TP for WRT

Global RMSE pattern of HS & TP relative to WRT. The numbers in the white boxes indicate the global mean.

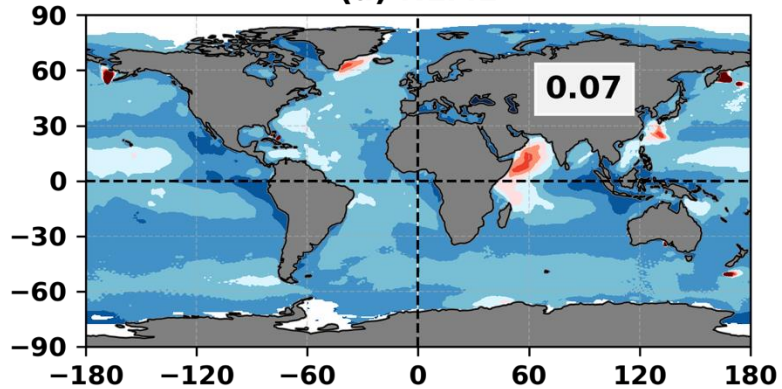
# Online Performance: ERA5



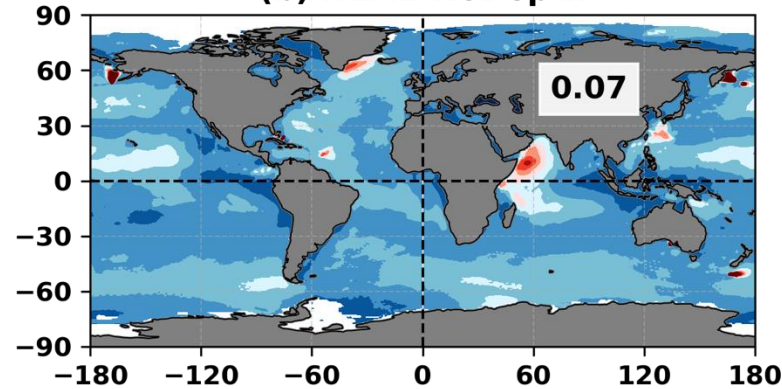
Time series of the 2020 global mean  $H_s$  and  $T_p$ , comparing simulations with reanalysis data (ERA5)

# Online Performance: FEATURE IMPORTANCE

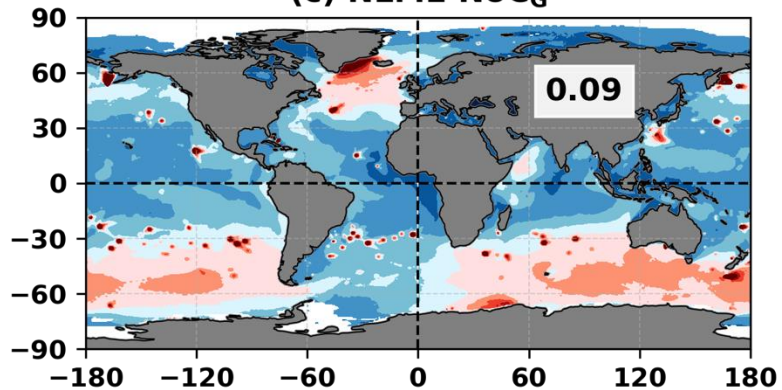
(a) NLML



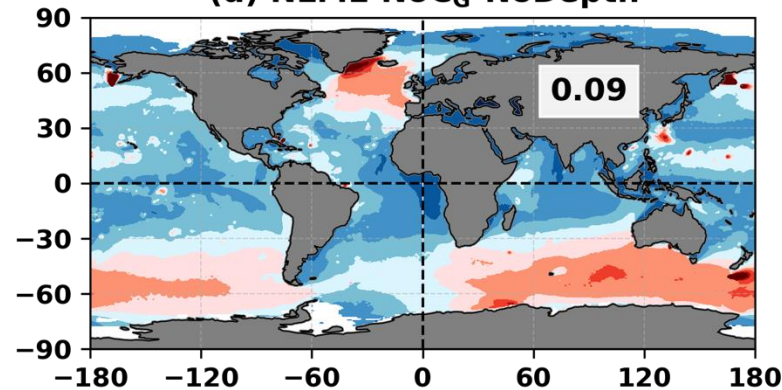
(b) NLML-NoDepth



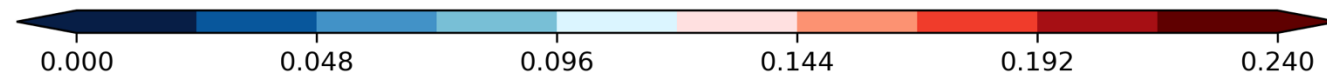
(c) NLML-NoC<sub>G</sub>



(d) NLML-NoC<sub>G</sub>-NoDepth

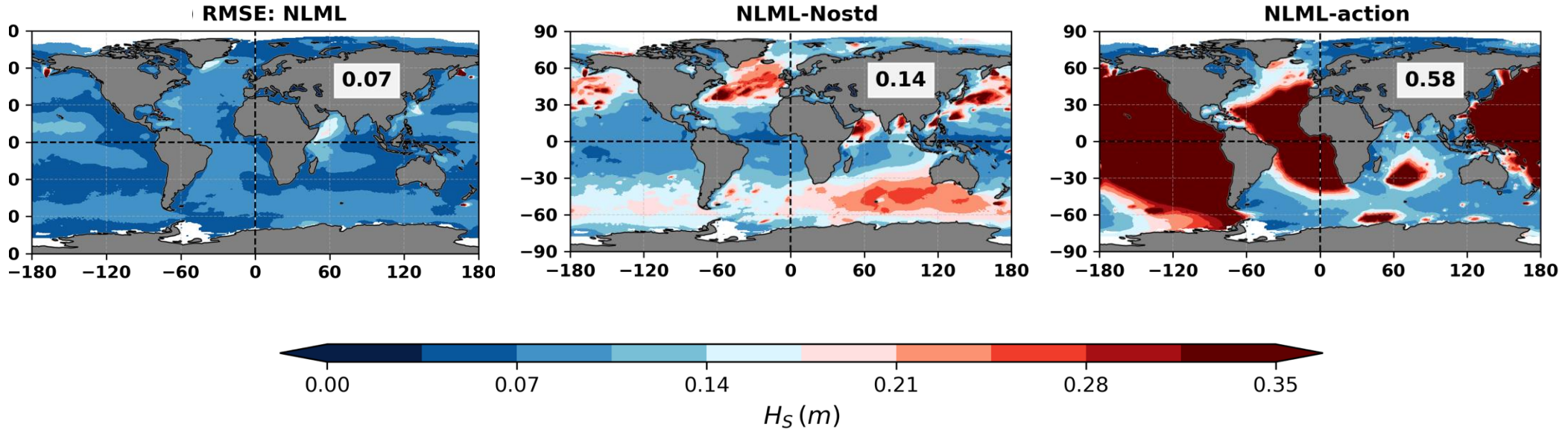


- The removal of depth shows no significant difference
- CG improves model performance
- The removal of either CG, D, or both does not lead to model instability




$H_S$  (m)  
Global RMSE pattern of HS


# Online Performance: FEATURE IMPORTANCE



Global RMSE pattern of HS in NLML-Nostd and NLML-action relative to WRT

  $\frac{1}{N} \sum_{i=1}^N |Y_i - \hat{Y}_i| \times \text{stdev}(\mathbf{Y})_i$

Customized loss improves model

 Converted  $N(k, \theta) \rightarrow F(f, \theta)$

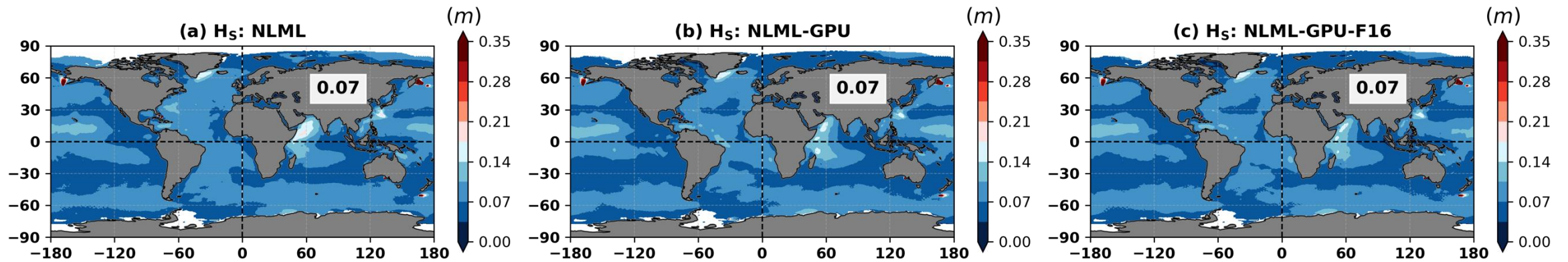
NLML-action becomes unstable

# COMPUTATIONAL PERFORMANCE

**MISSION  
ACCOMPLISHED**

Our ML emulator matches closely the accuracy of the exact method at the cost of the faster approximate method

Nonlinear Interactions	Relative Time
DIA	1.00
WRT	<b>142.00</b>
NLML-cpu	3.20
NLML-gpu	1.09
NLML-gpu-F16	<b>1.04</b>



RMSE of NLML, NLML-GPU, and NLML-GPU-FP16 relative to WRT for HS and TP

- We develop a stable, deep and wide ML emulator (*NLML*) for the exact (*WRT*) nonlinear interaction in a wave model to address the limitations and deficiencies of the Discrete Interaction Approximation (*DIA*).
- Trained on <10% of global modeled spectra, yet generalizes across all spectrum types.
- Inclusion of group velocity (CG) significantly improves *NLML* accuracy.
- *NLML* achieves 2x better accuracy in global wave spectra energy and mean wave parameters than *DIA*, with up to 7x higher accuracy in some regions.
- By leveraging advanced GPU computing with FP16 capabilities, we achieved substantial speedups, up to 136x faster than the *WRT* and only a modest 1.04x slowdown relative to *DIA*.
- Our new ML parameterization bridges the gap between accuracy and efficiency, offering a promising alternative for improving wave modeling in operational settings and research purposes