Recent developments in ocean wave modelling at ECMWF

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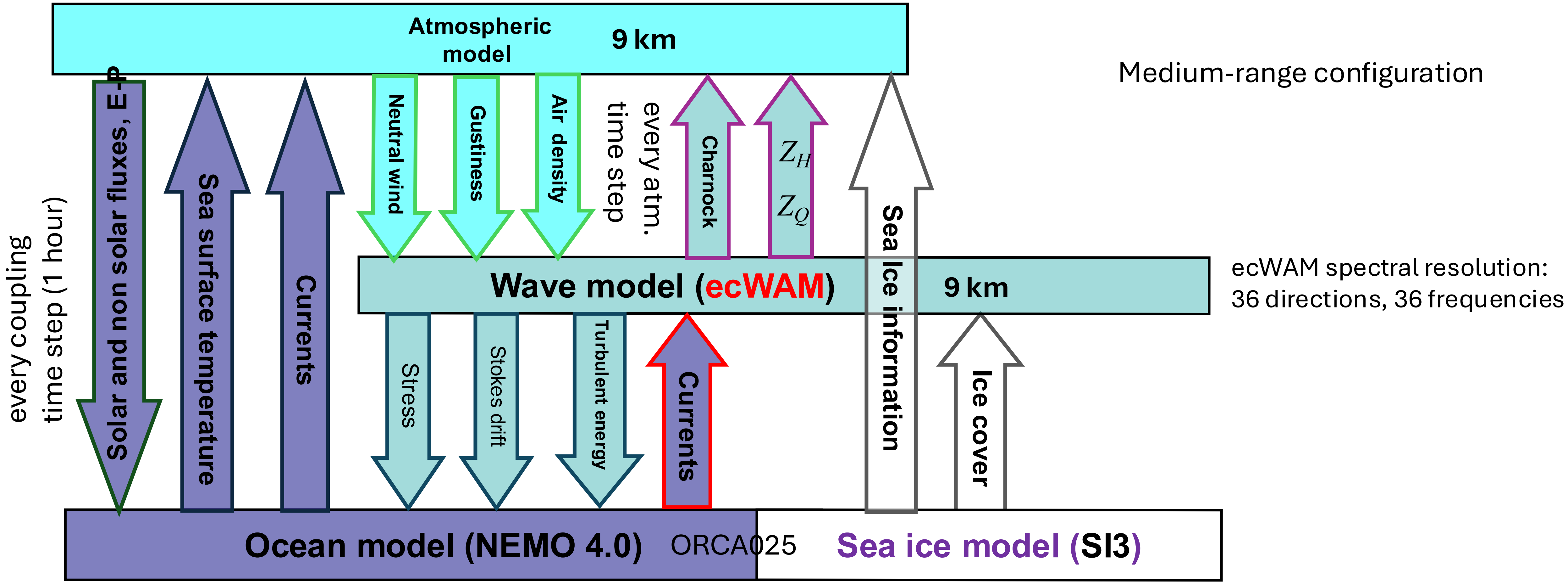
Introduction:
Wave model role
for Numerical Weather Prediction.

ECMWF Earth System Model (Cy50r1, 12 May 2026)

In the context of its Earth System Model, the wave model plays an active role in many exchanges between atmosphere and ocean in ECMWF Earth System Model.



Sea state dependent surface stress.

Atmosphere- ocean wave system

Atmospheric model

Neutral wind

Roughness

$$\mathbf{U}_{10N} = \frac{\vec{\mathbf{u}}_*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right)$$

z = 10 m

Every
IFS
time step

Charnock relation

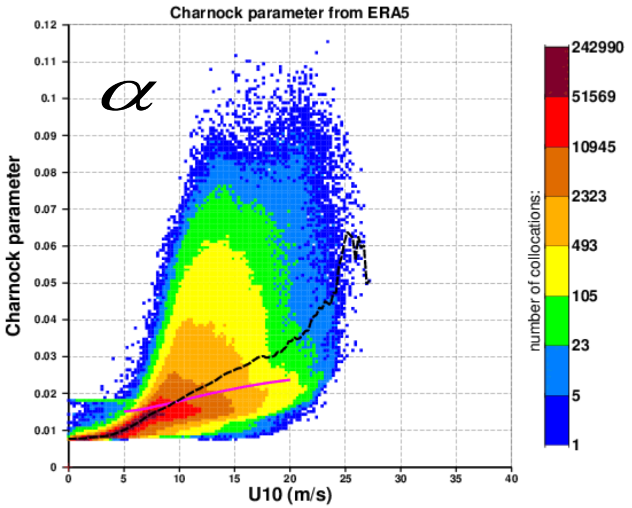
$$z_0 = \frac{\alpha\, \mathbf{u}_*^2}{g}$$

as in ERA5

Model as of 2016

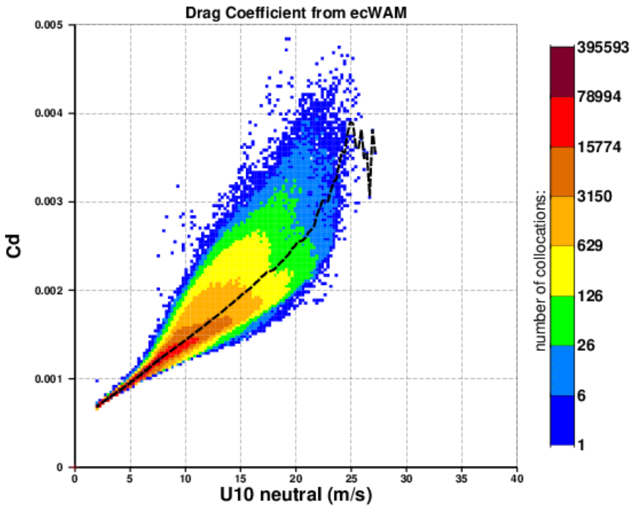
Wave model (ecWAM)

Charnock for all ocean points



Analysis data from stream oper, class ea, expver 0005, all Sea points with sea ice cover <= 0.3
from 20260222 12 UTC to 20260224 0 UTC

Cd within ecWAM for all ocean points



Forecast data from stream wave, class ea, expver 0005, all WAM sea points with no sea ice cover
from 20260222 12 UTC to 20260224 0 UTC

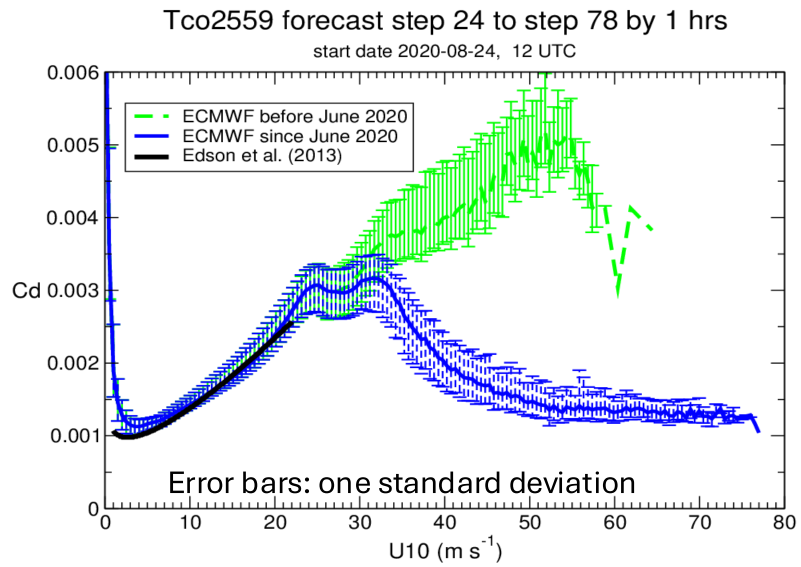
Specific wave model developments

- Over the years, we have implemented changes in ecWAM that have resulted in a better control of the drag coefficient for strong winds (IFS documentation, part VII, ECMWF, 2024).

1. Cy43r3, November 2016 : a cap on the maximum spectral steepness (Magnusson et al. 2019).
2. **Cy46r1**, June 2019 : the wind input and whitecap dissipation source terms of Ardhuin et al. (2010).
3. Cy47r1, June 2020 : a capping of the Charnock coefficient for tropical cyclones winds above 33 m/s (Majumdar et al. 2023, ECMWF, 2024).
4. **Cy49r1**, November 2024: a model for the role of gravity-capillary waves on the surface stress and the inclusion of a nonlinear wind input growth rate (Janssen and Bidlot, 2023), ECMWF 2024). Sea state dependent heat and moisture fluxes (Janssen and Bidlot, 2018).

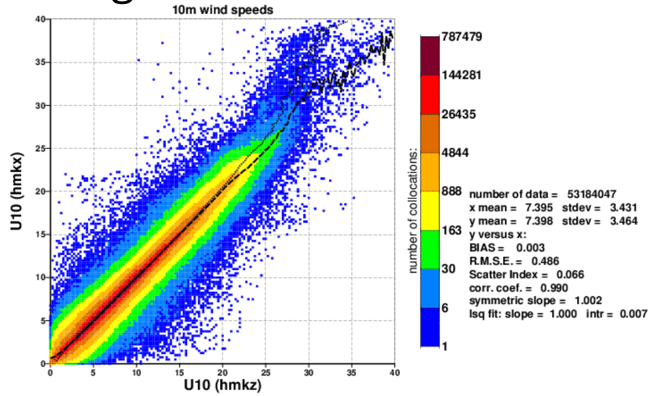
Drag coefficient v 10m wind speed:

During Hurricane Laura, 27 August 2020



Higher surface winds:

new



Forecast data from all sea points with sea ice cover <= 0.0 (on native grid) from 20201225 00UTC to 20201230 12UTC, for steps from 24 to 24 by 6

control

Atmosphere- ocean wave system

Atmospheric model

$$\mathbf{U}_{10N} = \frac{\vec{\mathbf{u}}_*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right)$$

z = 10 m

Neutral wind

Every
IFS
time step

Roughness

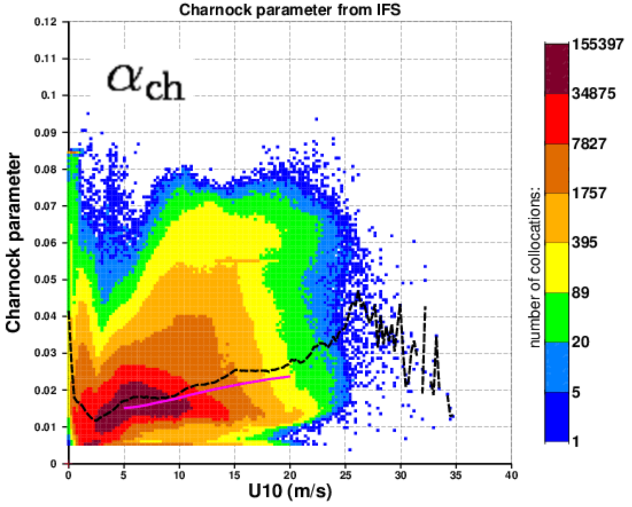
Charnock relation

$$z_0 = \alpha_M \frac{\nu}{u_*} + \alpha_{ch} \frac{u_*^2}{g}$$

as in latest version to be part of ERA6

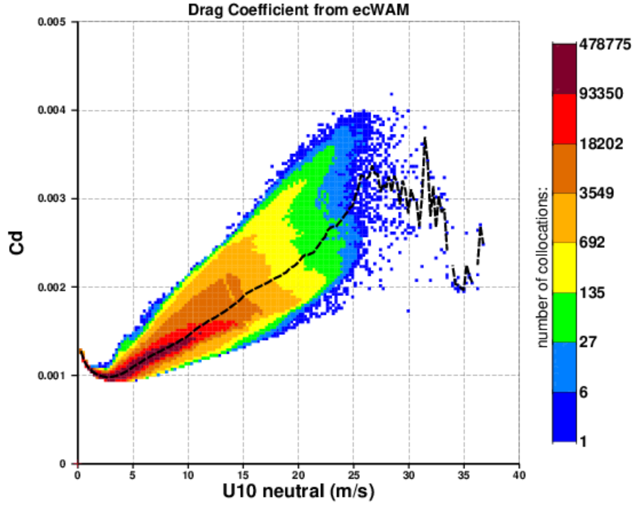
Wave model (ecWAM)

Charnock for all ocean points



Forecast data from stream oper, class rd, expver j2os, all Sea points with sea ice cover <= 0.3
from 20260222 12UTC, for steps from 1 to 36 by 1

Cd within ecWAM for all ocean points



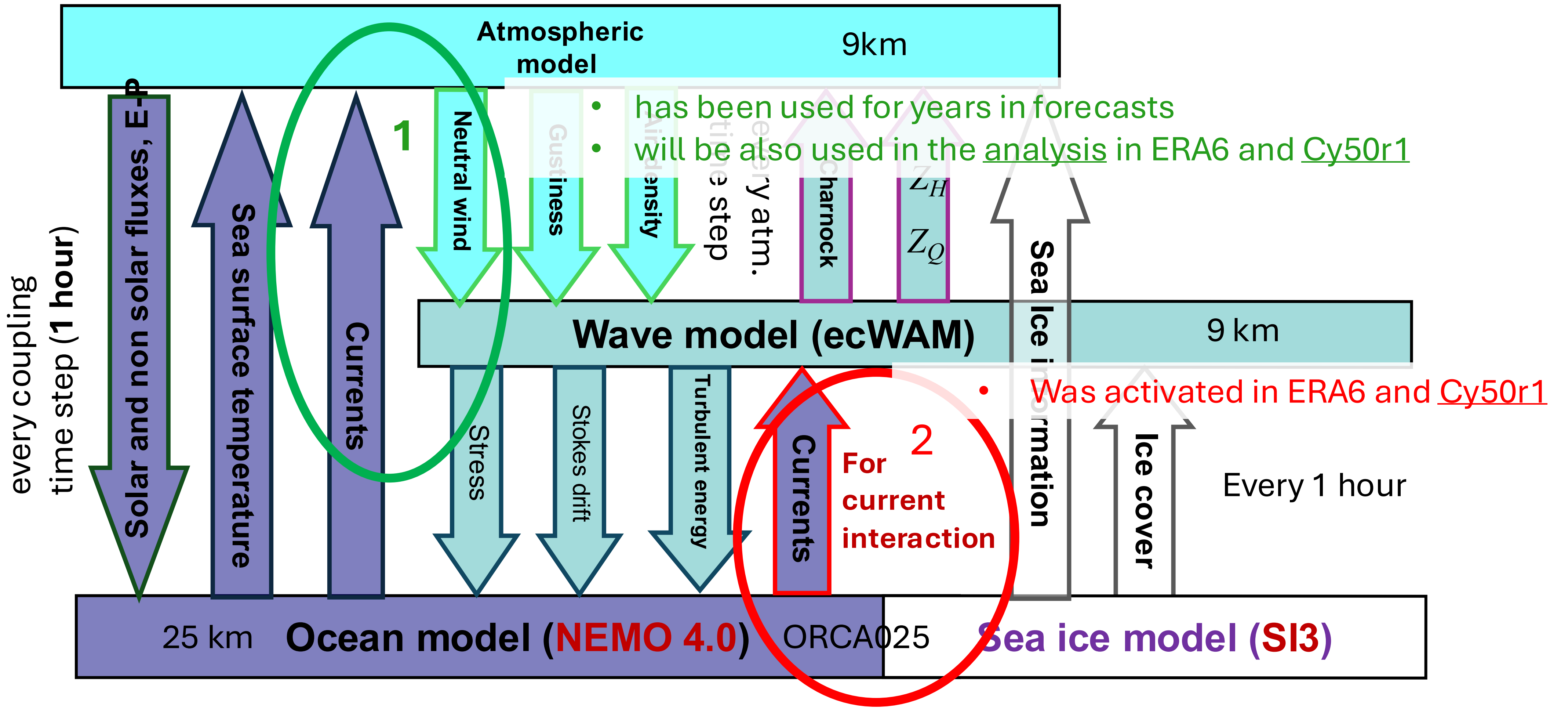
Forecast data from stream wave, class rd, expver j2os, all WAM sea points with no sea ice cover
from 20260222 12UTC, for steps from 1 to 36 by 1

Surface ocean current effects on wind and waves.

ECMWF Earth System Model

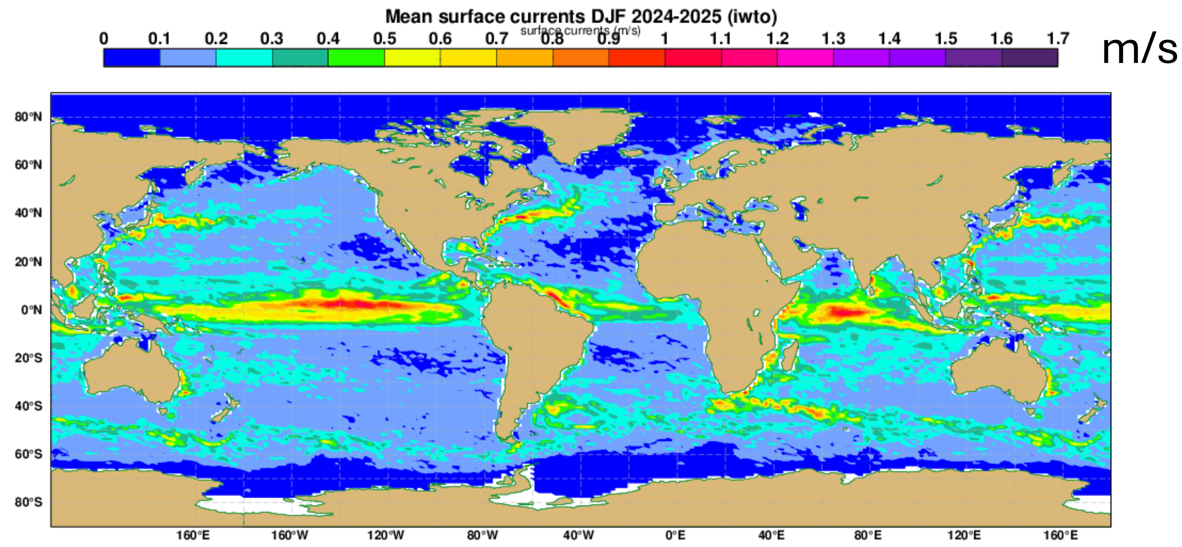
Surface currents from NEMO directly impact the waves through:

1. Their impact on the wind profile and hence the stress passed to ecWAM and NEMO.
2. Impact of the wave propagation properties (current refraction and Doppler shift).

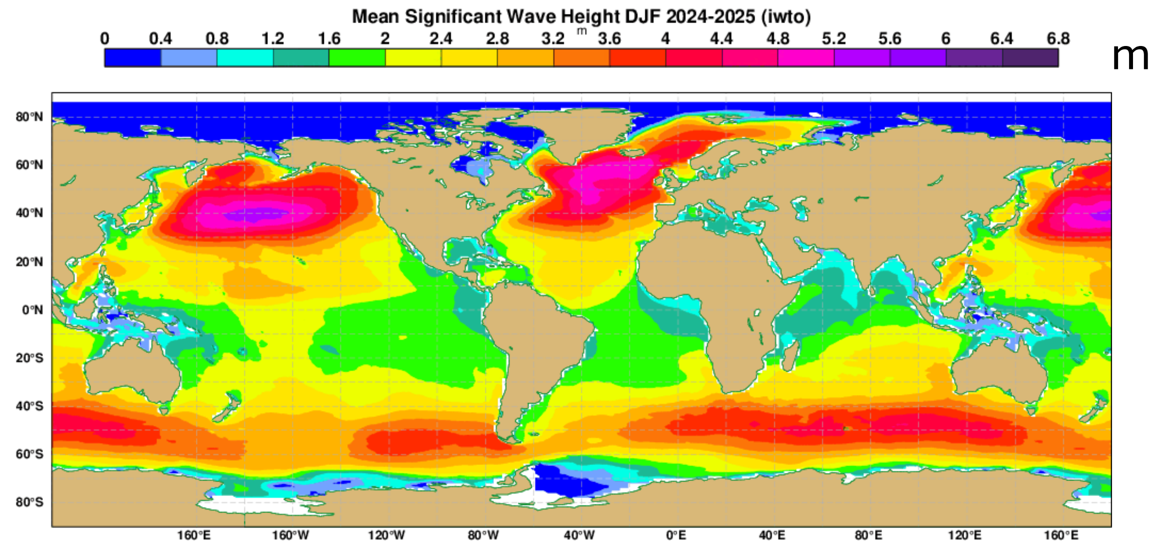


Impact of currents on the winds: currents – no currents, Significant Wave Height

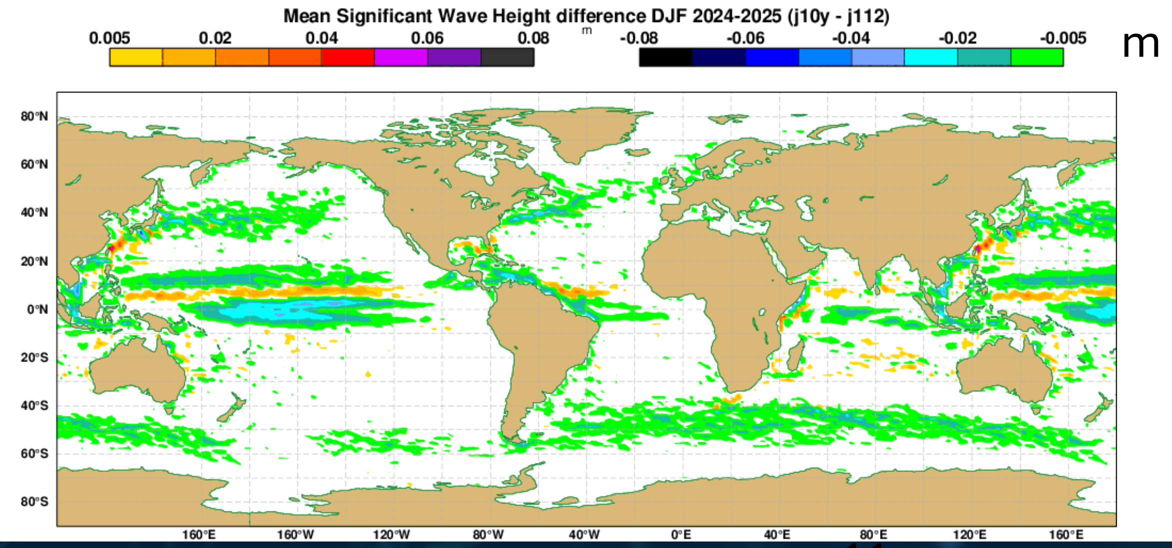
Mean surface current speed (DJF 202402025)



Mean analysis Significant Wave Height (DJF 2024-2025)

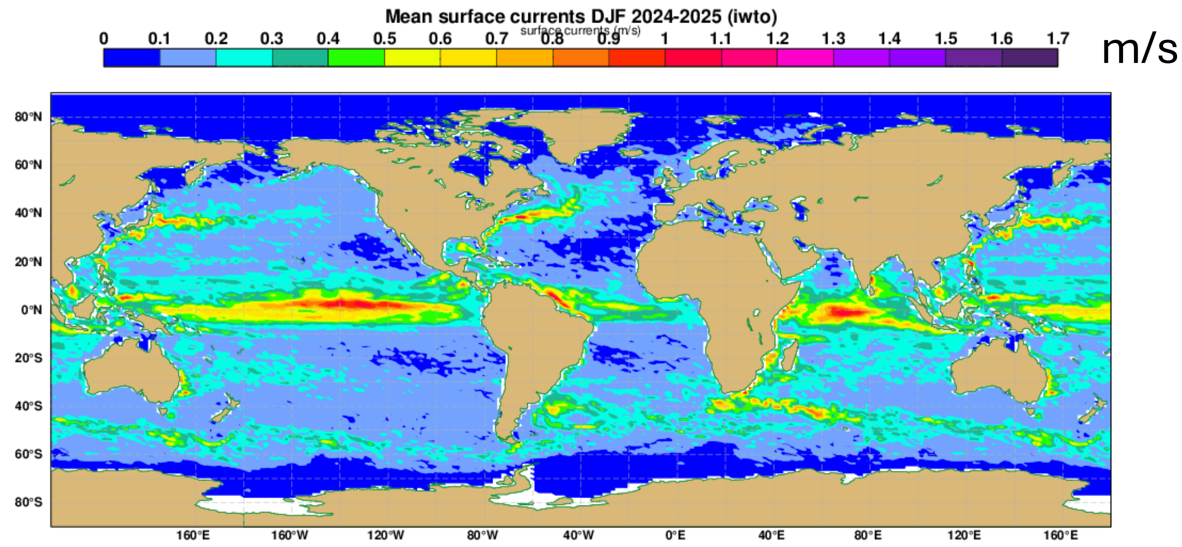


Mean difference in analysis significant wave height:

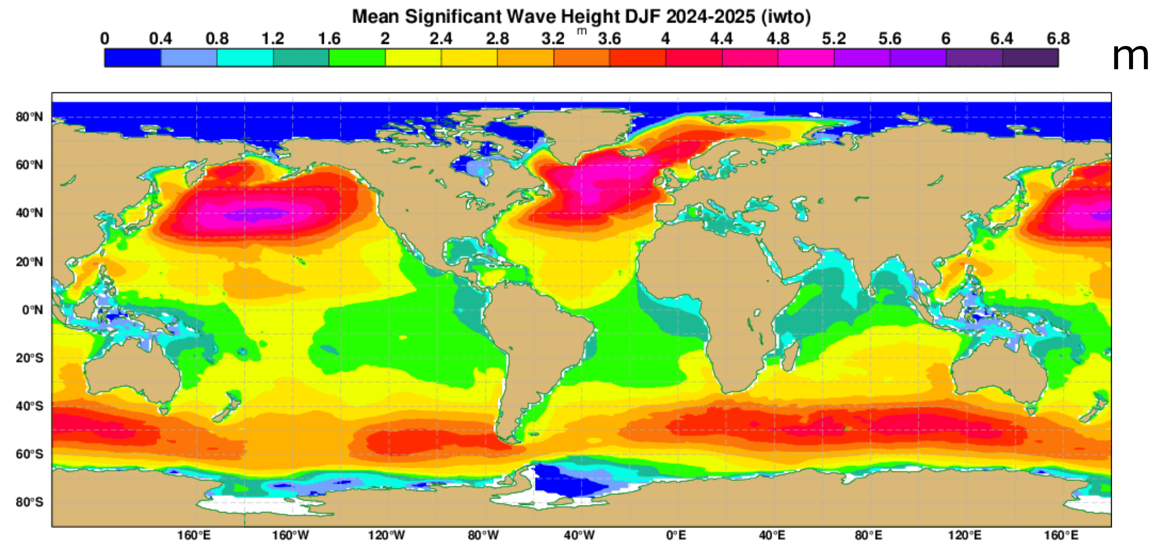


Impact of currents on the wave propagation: currents – no currents, SWH

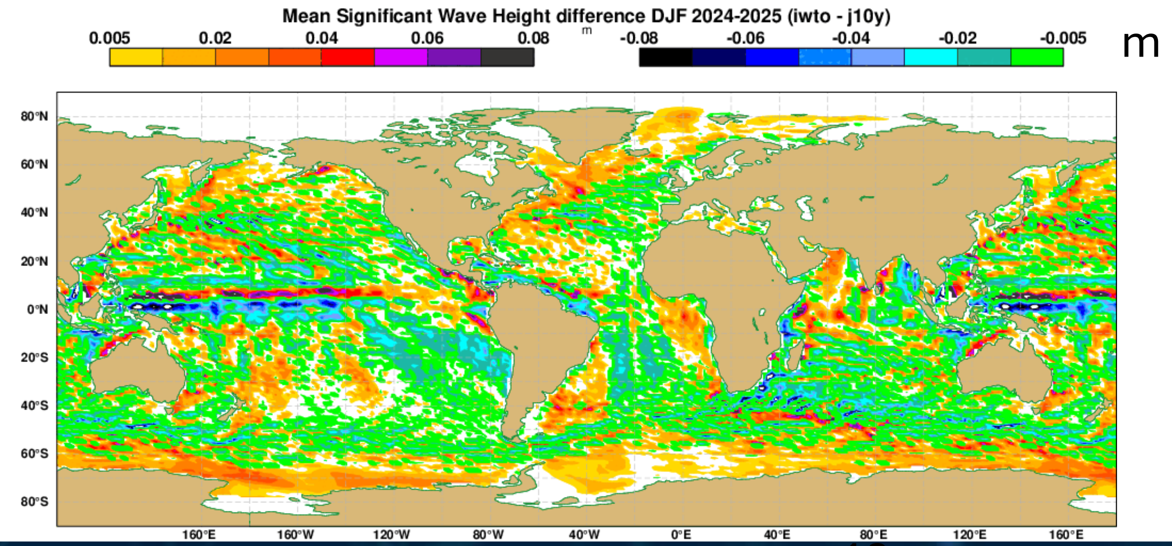
Mean surface current speed (DJF 202402025)



Mean analysis Significant Wave Height (DJF 2024-2025)



Mean difference in analysis significant wave height:



ERA6: the next global reanalysis.

ERA6 will benefit from an additional 8 years of R&D at ECMWF & improved compute capacity

Configuration: **75** years of reanalysis, to be maintained close to real time once completed, based on IFS Cy49r2

- Higher **horizontal resolution of 14km (TCo799) for all components** (ERA5 31km for atmosphere, 40km for waves)
- Uncertainty estimate at 28km (TCo399) from 11-member ensemble (63km for ERA5)

Science :

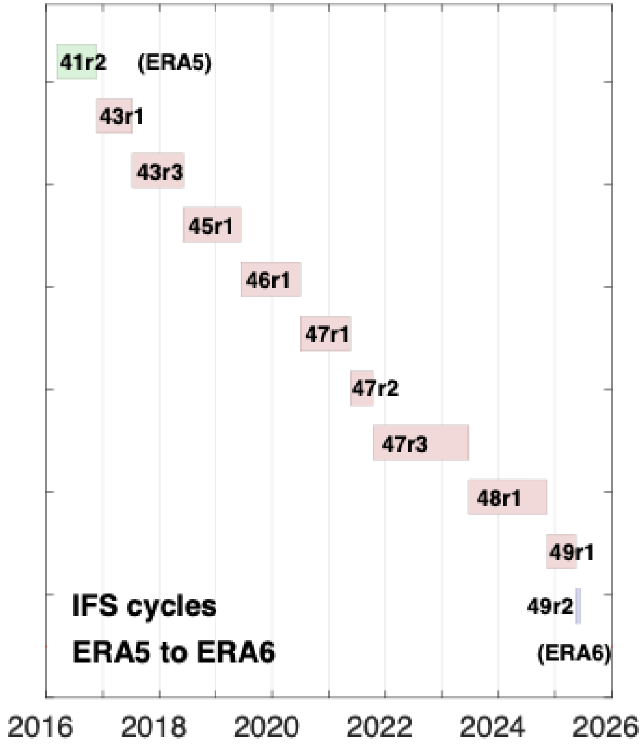
- 8 years of additional R&D at ECMWF (10 model cycles)
- **Ocean** model (NEMO4) fully coupled in DA trajectories

Ingest the best observations:

- Satellite+ in-situ reprocessing and data rescue. (e.g. ESA sea state CCI)

Products: based on user requirements

- 3D+2D **ocean parameters**
- **Height levels** for the lowest part of the atmosphere
- Hourly, for extended list of (new) parameters (2d wave spectra will again be available)
- **Daily** in addition to monthly **precalculated statistics**
- **GRIB2**



6. Comparison with in-situ observations: yearly Scatter Index

Hindcast without data assimilation.

+ Using altimeter wave height assimilation (DA).

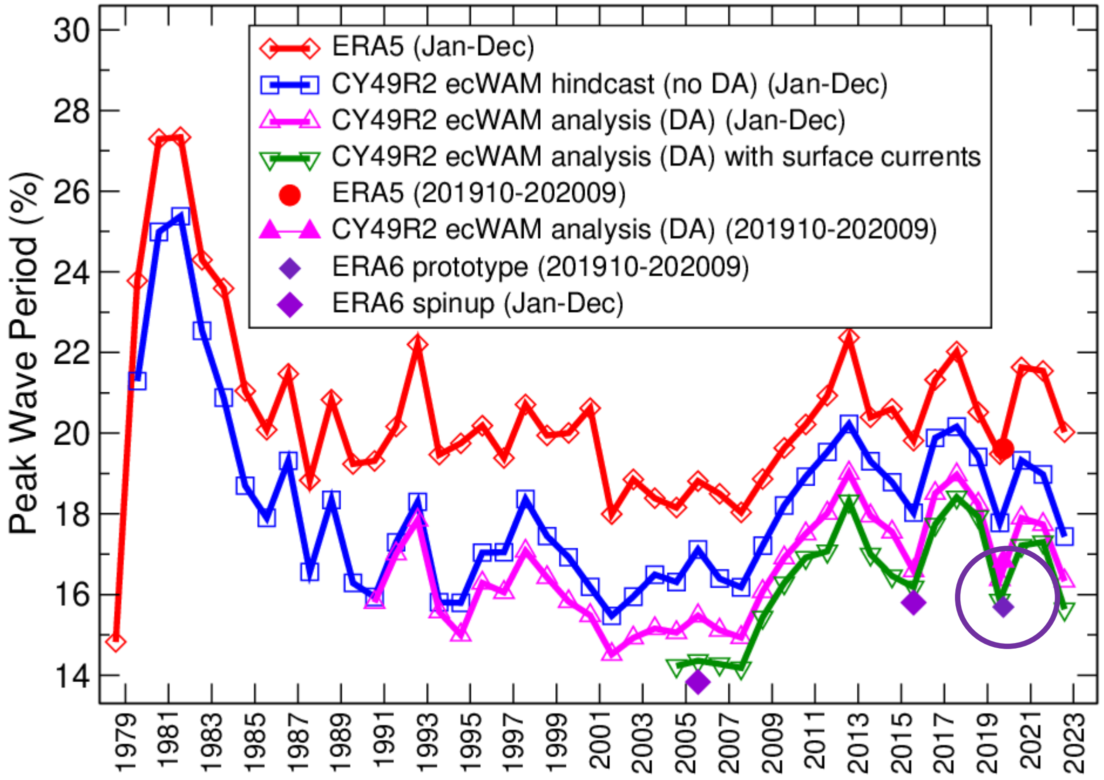
+ Using ocean surface current from ORAS6 for wave-current interaction.

Compared to ERA5.

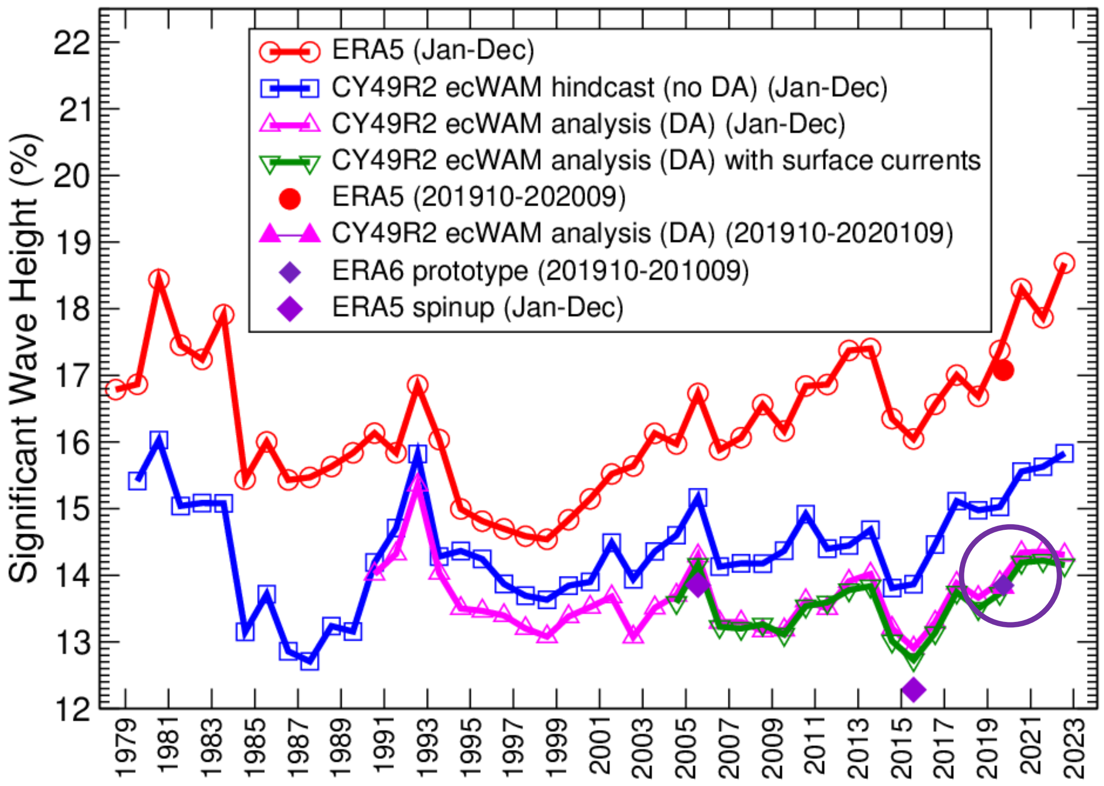
The one-year ERA6 prototype which has used CY49R2 + Altimeter DA + Ocean surface currents is also shown

ERA6 spin-up years (2006 and 2016)

Annual Scatter Index against in-situ observations



Annual Scatter Index against in-situ observations



Scatter Index: standard deviation of the difference normalized by the mean of the observations

Status of ERA6, summary/outlook

ERA6 is coming

Production has started

Expect 2007 onwards public by start of 2027.

- ✓ Higher resolution 14km
- ✓ Additional 8 years R&D
- ✓ Ocean component
- ✓ More and better use of observations
- ✓ Ensure 49r2 also works well back in time
- ✓ Resolve several ERA5 issues

More products:

- ✓ Ocean fields, height levels
- ✓ GRIB2 format
- ✓ Daily/monthly statistics

ERA5T will be maintained for the time being

Wave-sea ice interactions.

Sadly, not in ERA6

Attenuation

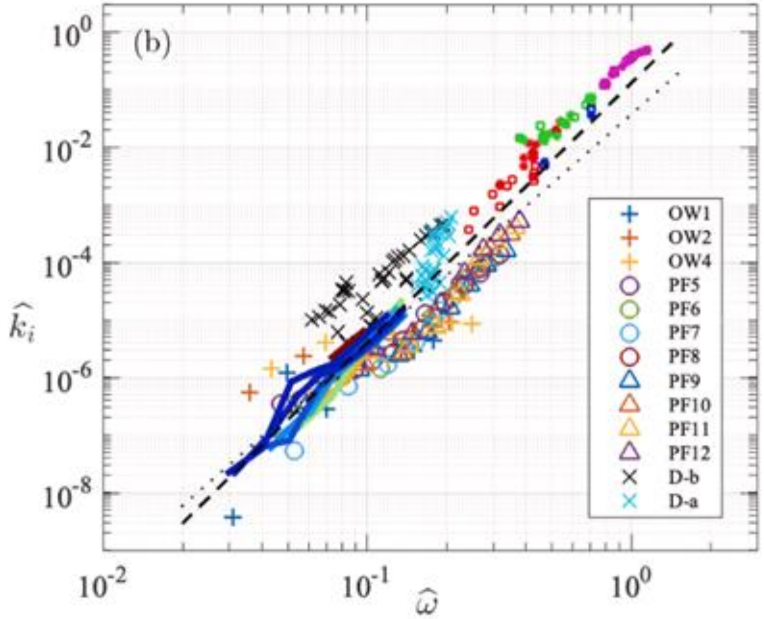
attenuation of waves by sea ice

- Waves are attenuated in the sea ice due to processes such as scattering, under-ice friction, in-ice friction, …

- Attenuation of waves by sea ice is generally represented as

$$S_{ice} = -2C_g k_i E$$

$$k_i(f) \propto f^n$$



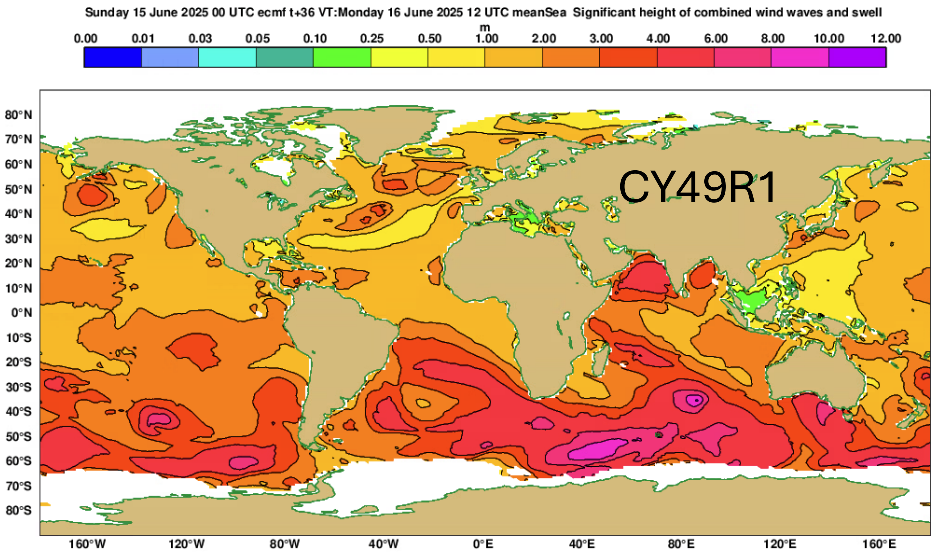
A new method for parameterization of wave dissipation by sea ice

Jie Yu *, W. Erick Rogers, David W. Wang
Naval Research Laboratory, Stennis Space Center, MS 39529, USA

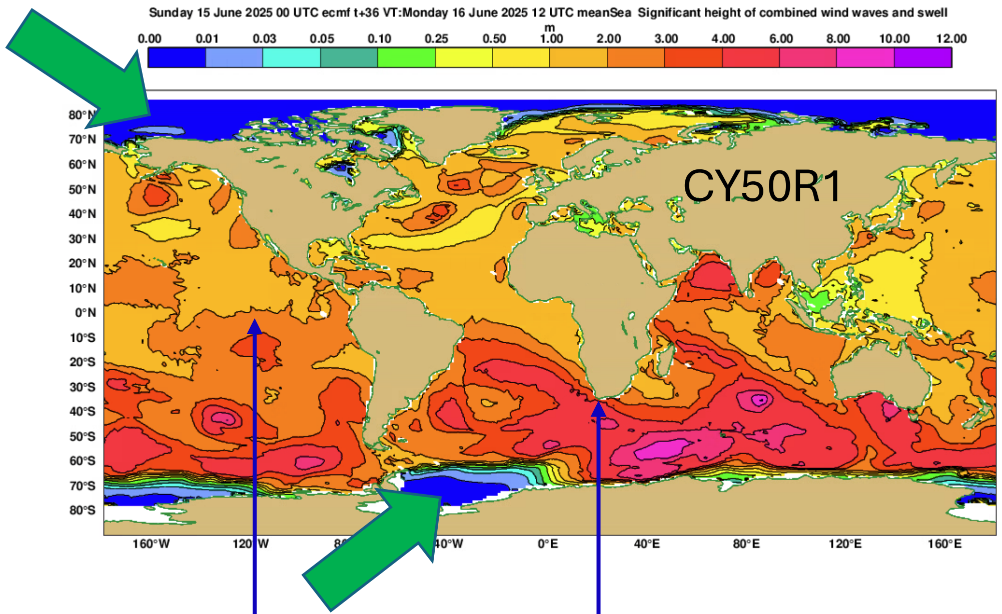
$$k_i = C h_{ice}^{1.25} f^{4.5}, \quad \text{where} \quad C = 0.1274\left(2\pi/\sqrt{g}\right)^{4.5}$$

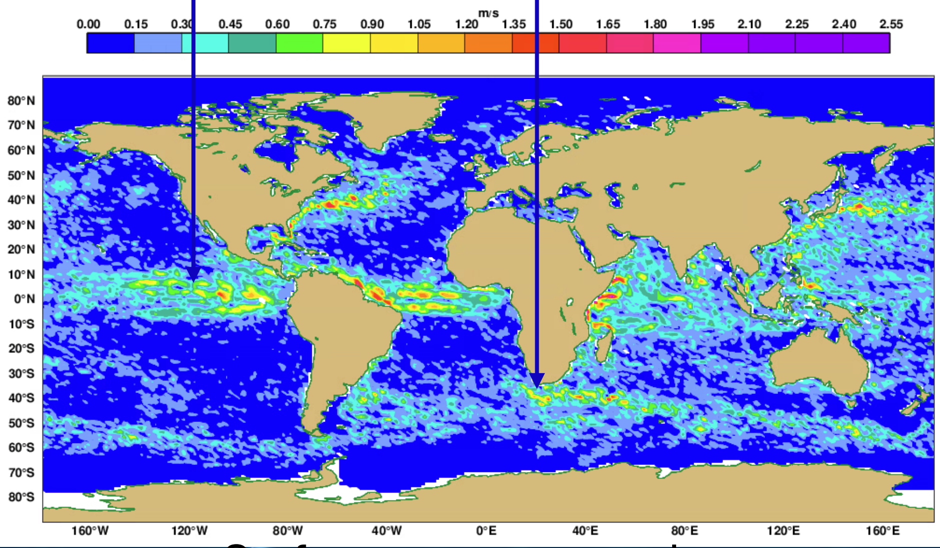
Latest upgrade (Cy50r1, May 12, 2026):

waves in sea ice and 'less' smooth contours due to current refraction



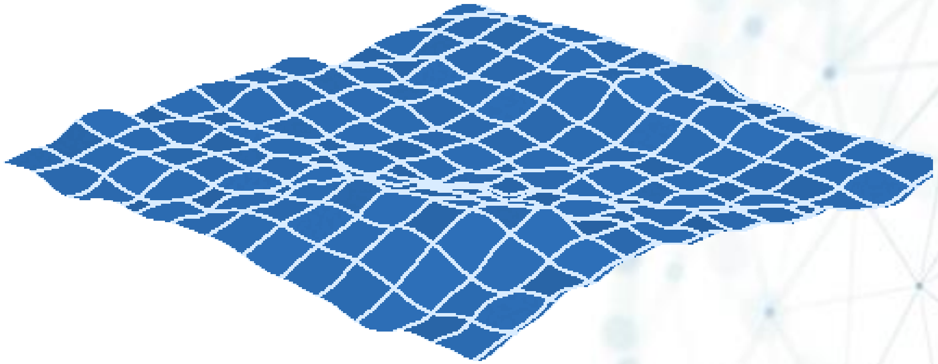
Significant Wave Height (m)





Surface current speed

Complex Sea States.

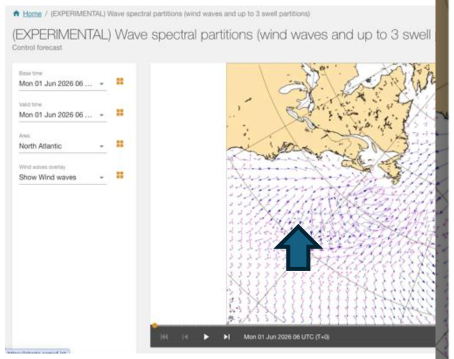


Product Development

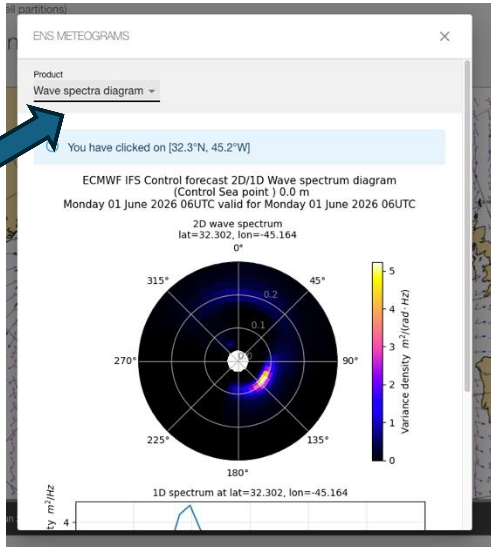
- Experimental products released with Cy50r1 on the 12th of May 2026. Feedback welcome.

ECMWF Open Charts

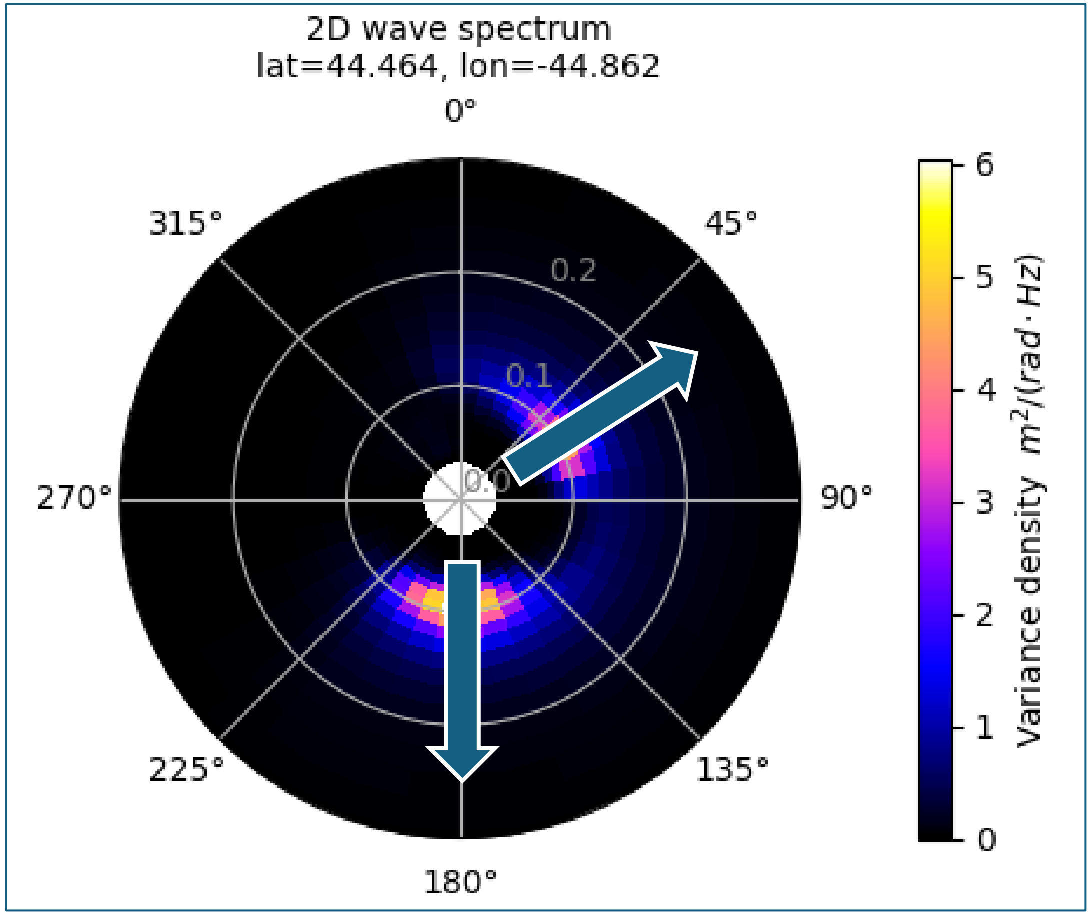
Accessible to all

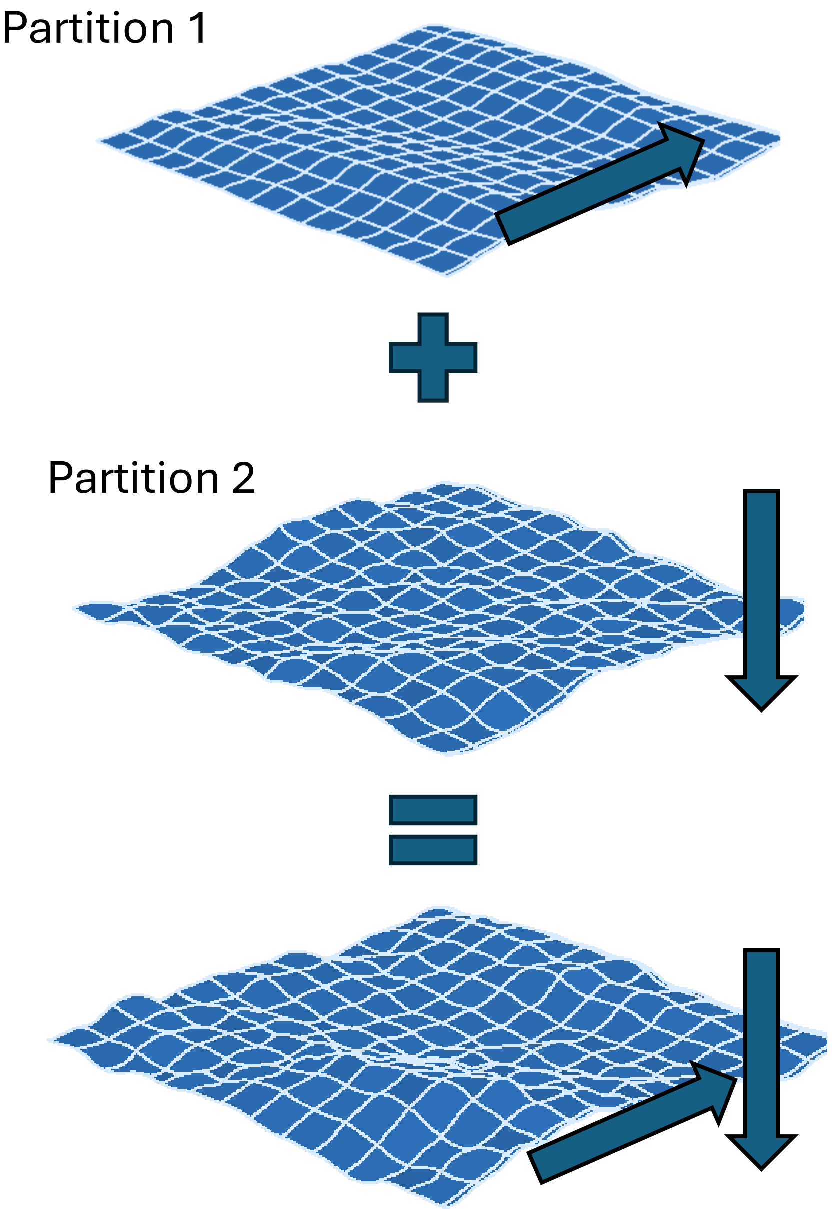


Click on any map

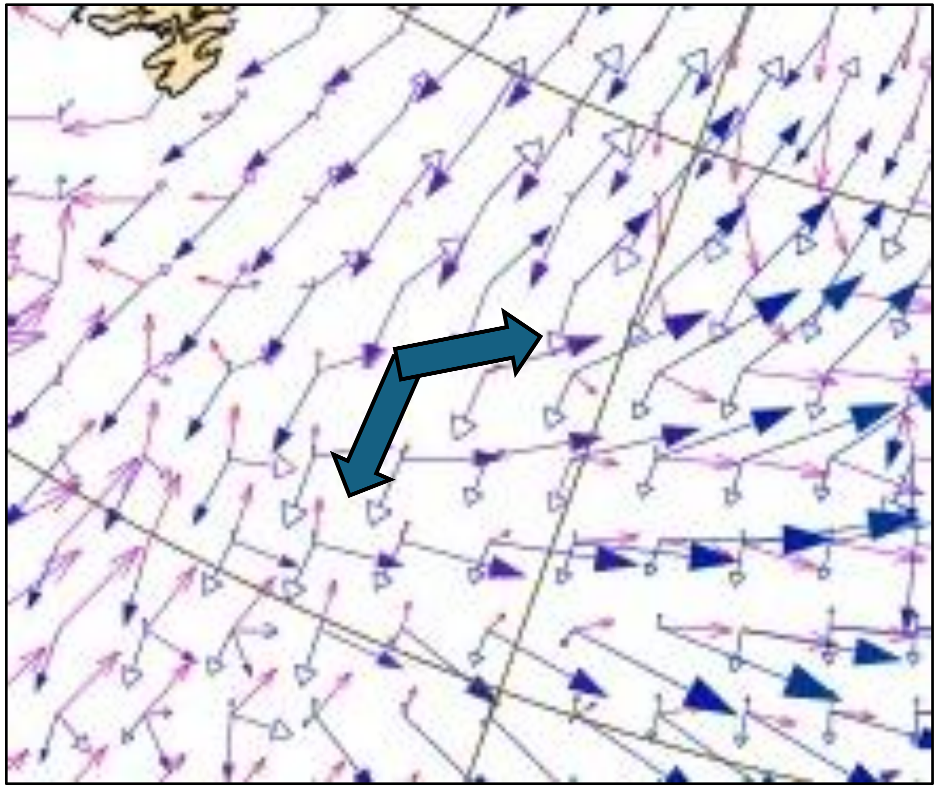


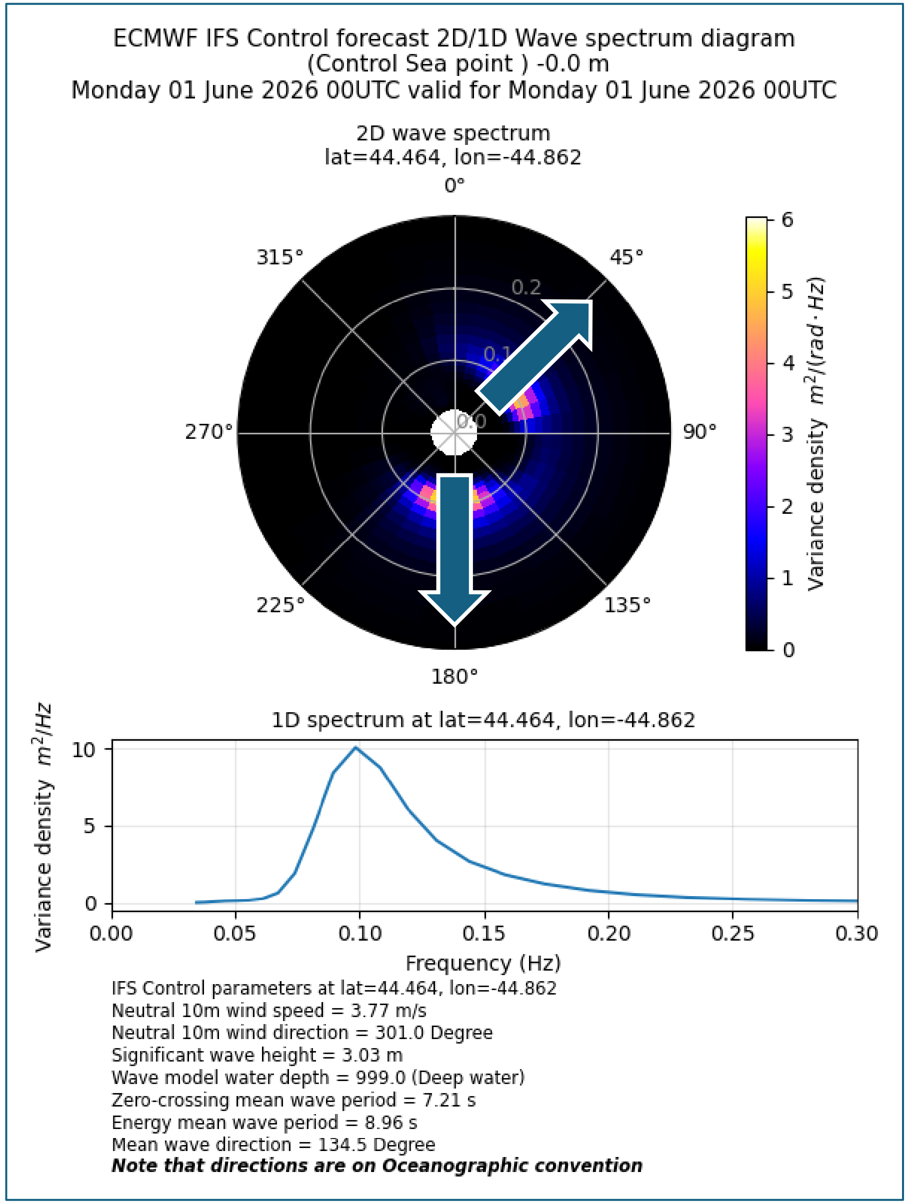
The Wave Spectrum: Partitions





The Wave Spectrum: Partition Quivers





ECMWF's
Artificial Intelligence Forecasting System AIFS v2.

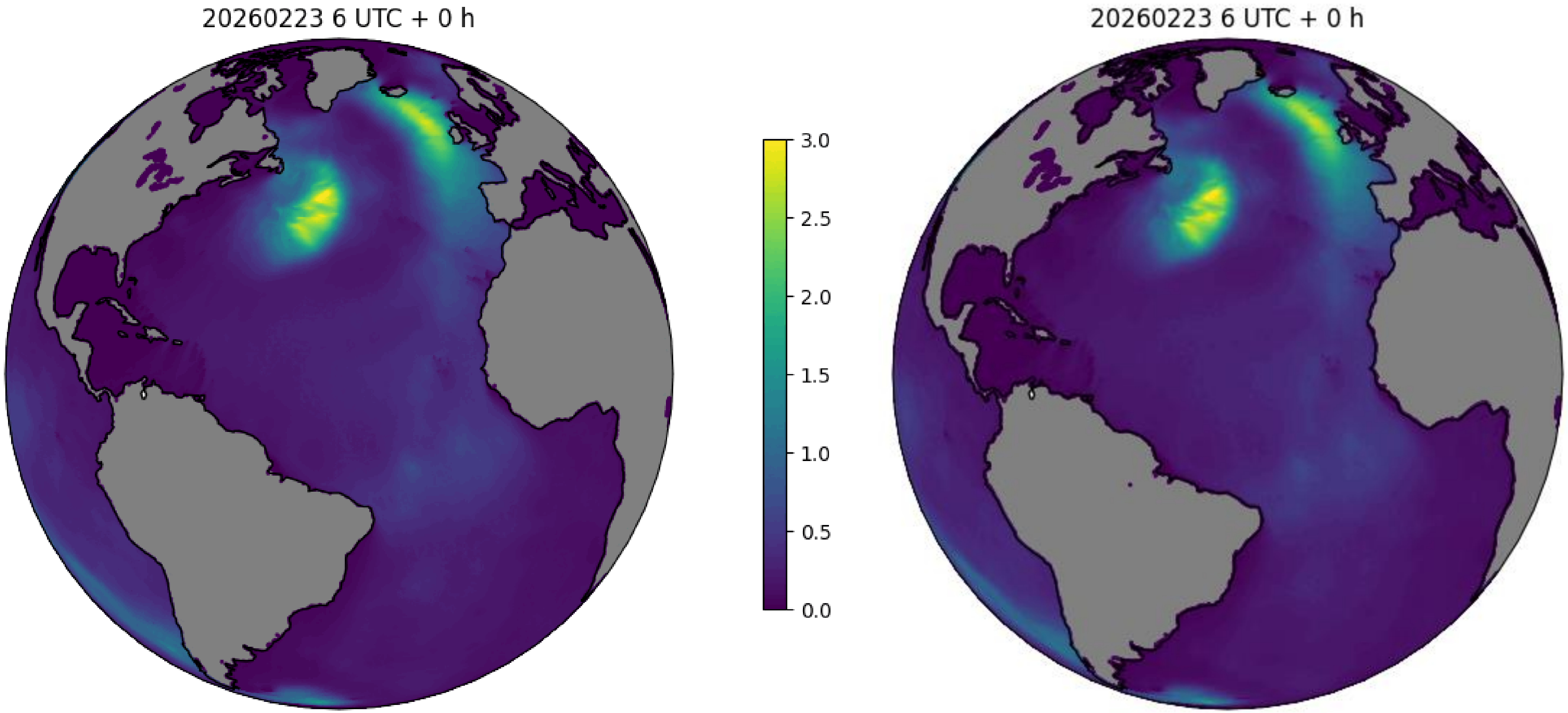
Wave component in AIFS Single 2.0

- Joint modelling approach for wave component.
- Represent additional variable in AIFS Single 2.0
    - **Significant wave height**
    - **Mean wave period**
    - **Mean wave direction**
    - **Coefficient of drag with waves**
- Forcing:
    - Bathymetry
- Training data:
    - Bulk: Cy50r1 wave hindcasts forced by ERA5.
    - Fine tuning: but with recent operational forcing.

- Additional:
    - Significant wave height in several period bins
        - **H1012**
        - **H1214**
        - **H1417**
        - **H1721**
        - **H2125**
        - **H2530**
    - *Significant wave height of all waves with periods within the inclusive range from XX to YY seconds*

Representation of Long Period Swell in Data-driven Forecast

Significant Wave Height for waves with **periods 17 ≤ T < 21s** (North American Blizzard Feb 2026)



Operational AIFS Single v2

Operational wave model ecWAM (50r1)

Conclusions

Conclusions

- Ocean waves are an active component of ECMWF Earth System Model.
- ECMWF has been using sea state information for surface exchange for years.
- Waves effects are also interacting with the ocean model.
- Surface currents affect both winds and waves.
- ERA6 will benefit from 10 years of R&D and should be a major improvement on ERA5.
- May 12, 2026:
  - new operational physics-based model (Cy50r1) with waves in sea ice and surface currents effects.
  - AIFS v2 has wave variables.
  - New graphical product for complex sea states.

Thank You

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Open Charts

ecWAM

- ecWAM is open source:

https://github.com/ecmwf-ifs/ecwam

ecwam

References

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Hahner et al., 2026: Representing the Surface Ocean in ECMWF's data-driven forecasting system AIFS. Submitted https://arxiv.org/abs/2604.25559