



Norwegian  
Meteorological  
Institute

**MET**report

No. 05/2026  
ISSN 2387-4201  
Open

# **MakingWaves' wave diagnostic and visualization tool for WAVEWATCH III**

Clio Michel, Ana Carrasco, and Jens B. Debernard





Norwegian  
Meteorological  
Institute

# METreport

<b>Title</b> Wave diagnostic tool for WAVEWATCH III	<b>Date</b> May 11, 2026
<b>Section</b> HAV/OM and HAV/HI	<b>Report no.</b> 05/2026
<b>Author(s)</b> Clio Michel, Ana Carrasco, and Jens Boldingh Debernard	<b>Classification</b> <input checked="" type="radio"/> Free <input type="radio"/> Restricted
<b>Client(s)</b>	<b>Client's reference</b>
<b>Abstract</b> This Python-based diagnostic and visualisation tool can be applied to raw daily mean outputs of the wave model WAVEWATCH III (WW3) from the Norwegian Earth System Model (NorESM). The outputs of our wave model are on a tripolar grid and are first regridded to a regular $1^{\circ} \times 1^{\circ}$ grid before performing the calculations. This tool was developed during the MakingWaves project funded by the Research Council of Norway in order to provide a diagnostics package of the wave component which was absent in NorESM. The outputs of the tool are png figures and a html webpage where the figures are displayed.	
<b>Keywords</b> waves, climate, diagnostics	

Øyvind Sætra

Øyvind Breivik

---

Disciplinary signature

---

Responsible signature

## Abstract

This Python-based diagnostic and visualisation tool can be applied to raw daily mean outputs of the wave model WAVEWATCH III (WW3) from the Norwegian Earth System Model (NorESM). The outputs of our wave model are on a tripolar grid and are first regridded to a regular  $1^\circ \times 1^\circ$  grid before performing the calculations. This tool was developed during the MakingWaves project funded by the Research Council of Norway in order to provide a diagnostics package of the wave component which was absent in NorESM. The outputs of the tool are png figures and a html webpage where the figures are displayed.

# Contents

<b>1</b>	<b>Introduction</b>	<b>5</b>
<b>2</b>	<b>Variables and diagnostics</b>	<b>7</b>
2.1	Variables given by WW3 . . . . .	7
2.2	New variables calculated . . . . .	8
2.3	Diagnostics . . . . .	11
<b>3</b>	<b>Regridding</b>	<b>13</b>
3.1	Special handling of directional fields . . . . .	14
3.2	Special handling of undefined points . . . . .	14
<b>4</b>	<b>Usage and practicalities</b>	<b>16</b>
<b>5</b>	<b>Webpage</b>	<b>19</b>

# 1 Introduction

*MakingWaves: Wave-mediated atmosphere-ocean-sea-ice interactions and their climatic impacts in the Nordic Seas and eastern Arctic* is a project funded by the Research Council of Norway (project nr. 325654) aiming at understanding the impact of wind waves on the global climate. This is done by implementing for the first time a wave component, with WAVEWATCH III<sup>1</sup> (WW3), in the Norwegian Earth System Model (NorESM). With it we perform several experiments coupling the wave to the atmosphere, ocean and sea ice components. Therefore, various experiments have been performed and are compared to each other with our diagnostic and visualisation tool in order to understand how the different configurations of the experiments impact the waves climate. The experiments can also be compared with a reference dataset, here the ECMWF reanalysis ERA5 (*Hersbach et al.*, 2020). The comparisons are represented with three-panel figures displaying the diagnostic for the variable of interest for the two experiments in the first two panels and their comparison (difference plot) in the third panel (see example in Fig. 1). Moreover, there is also the possibility to run the tool for just one experiment. Such a tool is already available for other components of NorESM, such as the ocean, atmosphere and ice, but for the wave component a diagnostic tool did not exist. We describe here below the various variables and diagnostics performed as well as give examples of the outputs.

---

<sup>1</sup><https://github.com/NOAA-EMC/WW3/releases/tag/6.07.1>

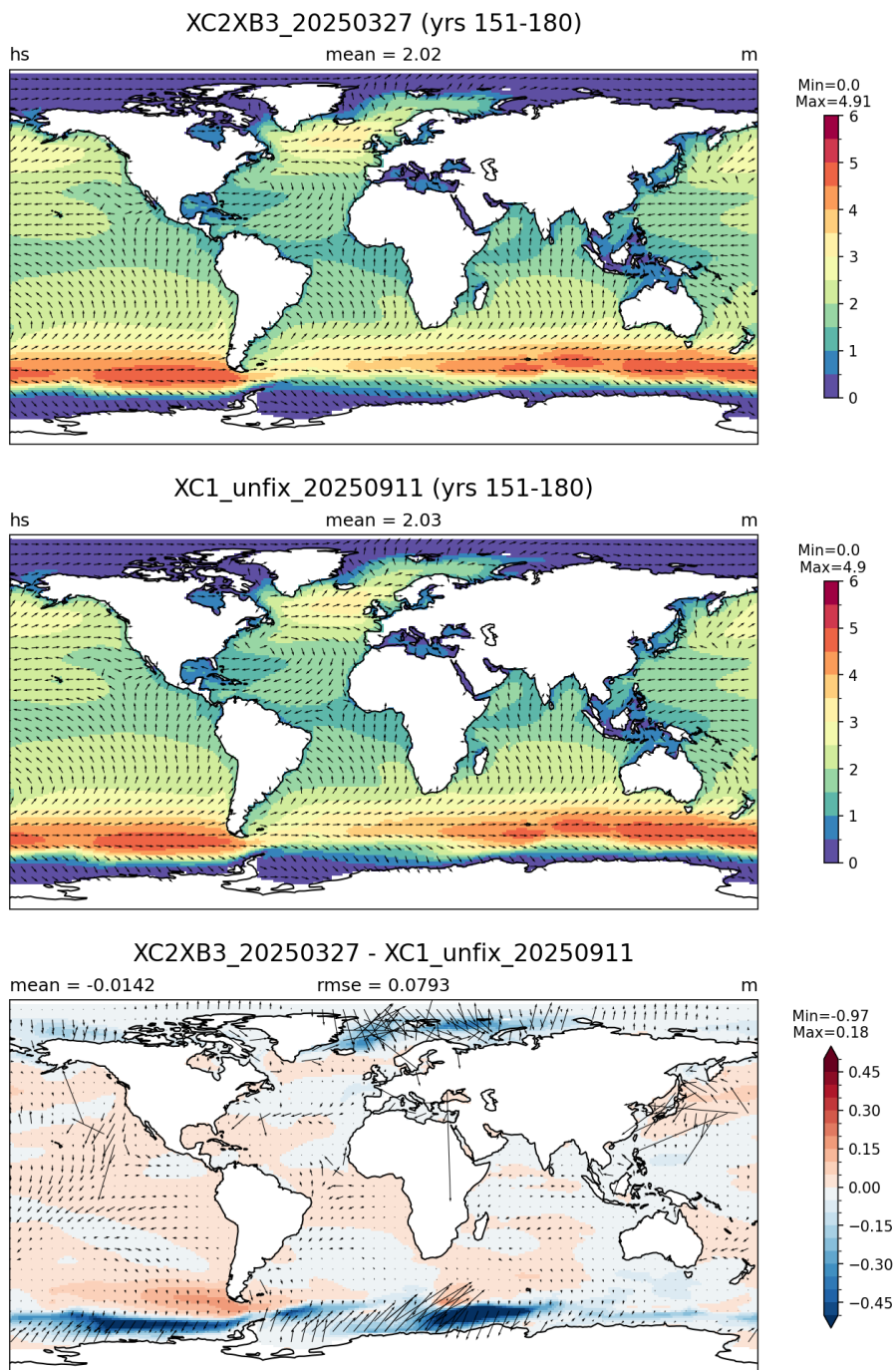


Figure 1: Example of figure performed by the tool in comparison mode. The titles of the top and middle panels give the names of the experiments that the panel represents along with the years used and the title of the bottom panel states that the difference between these two experiments is represented. Above the top and middle panels, one can find the short name of the field represented on the left, the value of the global mean in the middle, and the unit of the field on the right. Above the bottom panel, the global mean, the global root mean square error (rmse), and the unit of the field are given from left to right. Above each colorbar, are shown the minimum and maximum values of the field displayed.

## 2 Variables and diagnostics

### 2.1 Variables given by WW3

In this wave model, the variables' names take the general form *wavImp\_Sw\_VAR\_avg* with *VAR* being the variable's name. Table 1 lists all variables given by the model that we use in the diagnostics and to calculate new variables that are described in the next section.

Table 1: List of the variables output by WW3 that are used in the tool.

Model variable	Unit	Short description
hs	m	Significant wave height ( $H_{tot}$ )
phs0	m	Wind-sea significant wave height ( $H_{ws}$ )
phs1	m	Swell significant wave height ( $H_{sw}$ )
Tm1	s	Mean wave period ( $T_{m1}$ )
pTm10	s	Wind-sea mean wave period ( $T_{m1,ws}$ )
pTm11	s	Swell mean wave period ( $T_{m1,sw}$ )
thm	rad	Mean wave direction
pdir0	rad	Wind-sea mean wave direction
pdir1	rad	Swell mean wave direction
u,v	$\text{m s}^{-1}$	Zonal and meridional wind components
ustokes,vstokes	$\text{m s}^{-1}$	Zonal and meridional Stokes drift
tusx,tusy	$\text{m}^2 \text{s}^{-1}$	Zonal and meridional Stokes transport
tauicex,tauicey	$\text{m}^2 \text{s}^{-2}$	Wave-to-ice stress
cu,cv	$\text{m s}^{-1}$	Ocean surface currents
tm02	s	M2 period
fp0	$\text{s}^{-1}$	Peak frequency
lamult	-	Langmuir number
foc	$\text{W m}^{-3}$	Wave-to-energy flux
faw	$\text{W m}^{-3}$	Wind-to-wave energy flux
charn	-	Charnock parameter
ifrac	-	Sea ice concentration
thick	m	Sea ice thickness

## 2.2 New variables calculated

**Correlation between wind speed and significant wave height** The correlation between the wind speed and the significant wave height indicates whether the waves are linked to the wind or not. When the correlation is close to 1, the waves height is mostly linked to the wind whereas when the correlation is close to 0, the waves height is not due to the wind is most probably due to swell. This diagnostic is taken from *Stopa et al.* (2013). The climatology of the correlation between the wind speed and the significant wave height for one of the experiments performed is displayed in Fig. 2a. The pattern and values are in good agreement with Fig. 8 in *Stopa et al.* (2013).

**Unitary dot product of surface Stokes drift versus Stokes transport** Following the method by *Carrasco et al.* (2014), we take the cosine of the angle between the Stokes drift direction and the Stokes transport direction. When the Stokes drift and Stokes transport are aligned, the unitary dot product equals 1 whereas if they have opposite directions, the unitary dot product equals -1. The regions where the two directions are identical are known as regions where the waves are influenced by the wind ("wind-driven wave regime") and the regions where they do not align mean that the waves influence the wind ("wave-driven wind regime"). The climatology of the unitary dot product of surface Stokes drift versus Stokes transport for one of the experiments performed is displayed in Fig. 2b. The Stokes drift and Stokes transport are mainly misaligned around 30°S and in the eastern tropical part of the North Pacific. This is in relative good agreement with Fig. 8 in *Carrasco et al.* (2014) who used the ERA40 reanalysis.

**Stokes depth** The Stokes depth (in m) gives the height of the water column over which the Stokes drift has an impact.

$$SD(t, \lambda, \varphi) = \frac{g}{2} \left( \frac{T_{m1}}{2\pi} \right)^2 \quad (1)$$

where  $g = 9.80665 \text{ m s}^{-2}$  is the gravity constant and  $T_{m1}$  the mean wave period (in s). The climatological Stokes depth for one of the experiments performed is displayed in Fig. 2c. It shows that the Stokes drift impact is largest along the sea ice edges and along the eastern side of the Pacific Ocean.

**Degree of crossing** *Breivik and Christensen* (2020) decompose the Stokes drift velocity in a component due to swell ( $sw$ ) and a component due to wind-sea ( $ws$ ) and calculates the

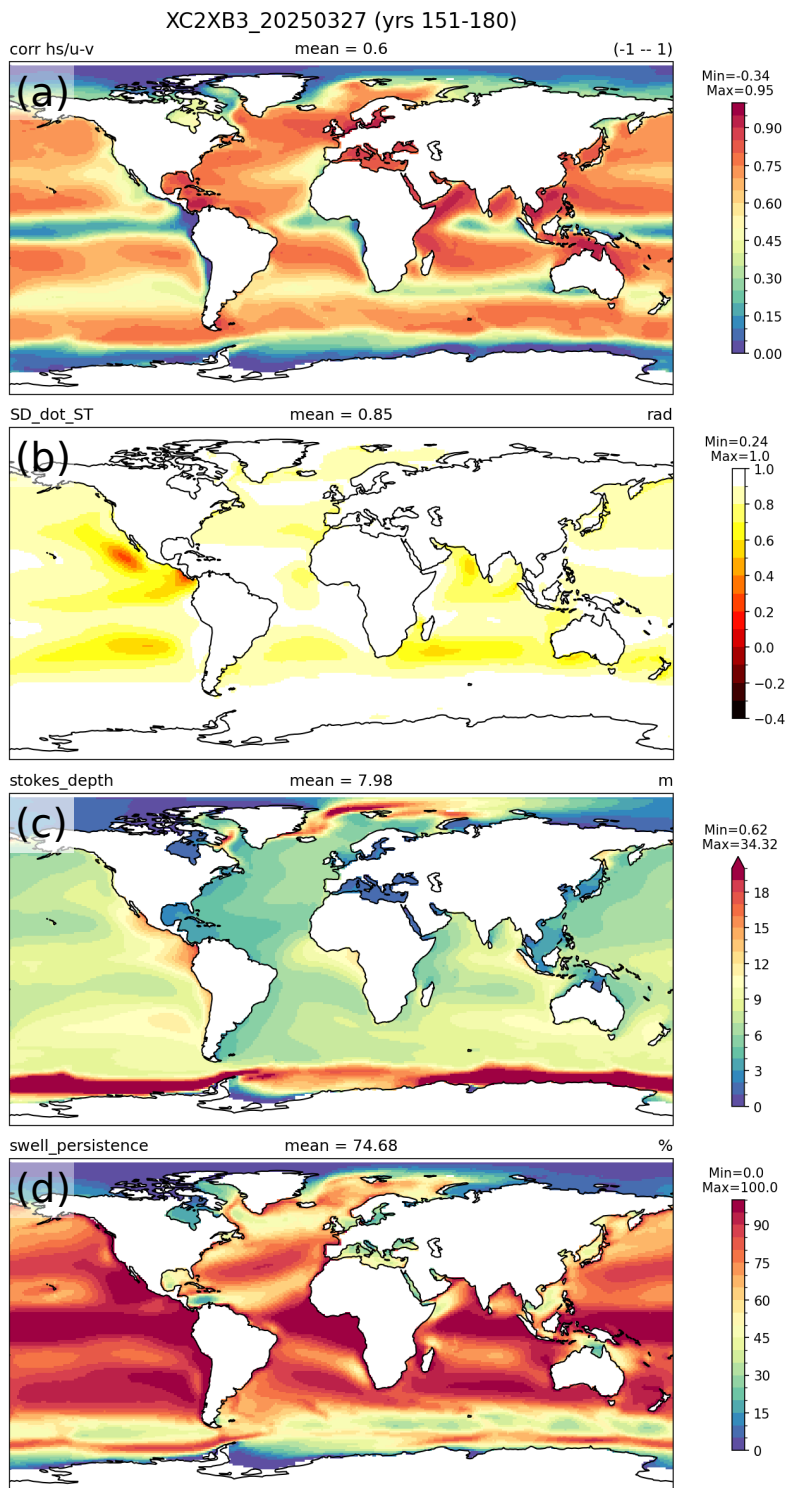


Figure 2: Some of the new variables calculated for the experiment XC2XB3 as an example: (a) Correlation between wind speed and significant wave height, (b) the unitary dot product of Surface Stokes drift versus Stokes transport, (c) the Stokes depth, and (d) the swell persistence.

Stokes transport due to both components. The cross product of the swell component with the wind-sea component over the total surface Stokes drift gives an indication of relative transport of both components.

$$r_{\times} = \frac{MSD_{ws}MSD_{sw}}{MSD_0^2} \sin(\theta_{ws} - \theta_{sw}) \quad (2)$$

where  $MSD_{ws}$  and  $MSD_{sw}$  are the magnitude of the surface Stokes drift due to the wind sea and to swell, respectively, and  $MSD_0$  is the magnitude of the total surface Stokes drift. As  $MSD_0$  sometimes equals 0, a minimum threshold is chosen and set to  $0.0028 \text{ m s}^{-1}$ .  $\theta_{ws}$  and  $\theta_{sw}$  are the directions of the Stokes drift due to wind sea and swell, respectively. The magnitude of the surface Stokes drift due to wind sea is given by

$$MSD_{ws} = \frac{8\pi^2}{g T_{m1ws}^2} V_{ws} \quad (3)$$

where  $g = 9.80665 \text{ m s}^{-2}$  is the gravity constant,  $T_{m1}$  the mean wind-sea wave period (in s), and  $V_{ws}$  is the magnitude of the wind-sea Stokes transport (in  $\text{m}^2 \text{ s}^{-1}$ ):

$$V_{ws} = \frac{2\pi}{16} \frac{H_{ws}^2}{T_{m1ws}}, \quad (4)$$

with  $H_{ws}$  being the wind-sea significant wave height (in m).

The same formula can be derived for the magnitude of the surface Stokes drift due to swell:

$$MSD_{sw} = \frac{8\pi^2}{g T_{m1sw}^2} V_{sw} \quad \text{with} \quad V_{sw} = \frac{2\pi}{16} \frac{H_{sw}^2}{T_{m1sw}}. \quad (5)$$

**Swell persistence** Following *Björkqvist et al. (2021)*, the swell persistence is defined as the probability (in percent of the time) of the squared ratio of the swell significant wave height over the total significant wave height to be larger than 0.5:

$$\text{Probability} \left[ \left( \frac{H_{sw}}{H_{tot}} \right)^2 > 0.5 \right]. \quad (6)$$

The climatological swell persistence for one of the experiments performed is displayed in Fig. 2d. The swell persistence is the largest close to the equator and around  $30^\circ\text{S/N}$ .

**Surface Stokes drift speed over currents speed** This is the ratio of the Stokes drift speed over the surface currents speed. When the ratio equals 1, the Stokes drift and currents are equal. When the ratio is positive (negative), the Stokes drift is greater (lower).

## 2.3 Diagnostics

The list of diagnostics:

- Climatology
- Monthly climatology
- Seasonal climatology
- 95th percentile
- Mean annual variability
- Inter-annual variability
- Time series of the yearly area-averaged significant wave height in four regions

**Mean annual variability** The mean annual variability (MAV) is defined by *Stopa et al.* (2013) as the average over all years of the yearly standard deviation over the yearly mean. It is multiplied by 100 to give a percentage.

$$MAV = \left( \frac{1}{NY} \sum_{Y=1}^{NY} \frac{\sigma_Y}{\mu_Y} \right) \times 100 \quad (7)$$

where  $\mu_Y$  is the mean of variable  $x$  for year  $Y$

$$\mu_Y(\lambda, \varphi) = \frac{1}{N_d} \sum_{t=1}^{N_d} x(t, \lambda, \varphi) \quad (8)$$

and  $\sigma_Y$  is the standard deviation of variable  $x$  for year  $Y$

$$\sigma_Y(\lambda, \varphi) = \sqrt{\frac{1}{N_d} \sum_{t=1}^{N_d} (x(t, \lambda, \varphi) - \mu_Y(\lambda, \varphi))^2} \quad (9)$$

supposing that there are  $NY$  years and  $N_d$  days per year. MAV highlights the areas where the intra-annual variability, that is the variability within a year, is the largest in average.

**Inter-annual variability** The inter-annual variability (IAV) is defined by *Stopa et al.* (2013) as the standard deviation of the yearly mean over the total mean over all years (climatology)

$$IAV = \frac{\sigma(\lambda, \varphi)}{\mu_c(\lambda, \varphi)} \times 100 \quad (10)$$

where  $\mu_c$  is the climatological mean

$$\mu_c(\lambda, \varphi) = \frac{1}{N} \sum_{t=1}^N x(t, \lambda, \varphi) \quad (11)$$

and  $\sigma$  is the standard deviation of the yearly means

$$\sigma(\lambda, \varphi) = \sqrt{\frac{1}{ny} \sum_{Y=1}^{ny} \mu_Y(\lambda, \varphi) - \mu_c(\lambda, \varphi)} \quad (12)$$

IAV gives a measure of where the inter-annual variability, that is the variability from one year to another, is large.

**Time series of the area-averaged significant wave height** We have chosen five boxes of interest to calculate the area averages and the 95th percentile of the significant wave height for winter (December-January-February) and summer (June-July-August). The boxes are located in the North Atlantic (32°N-42.5°N / 287°E-338°E), the North Pacific (30.5°N-46°N / 173.5°E-235°E), the Equatorial Pacific (21°S-5.5°S / 180°E-244°E), the warm pool (0°-15°N / 124.5°E-180°E), the South Pacific (54°S-43°S / 180°E-237.5°E), and the northern North Atlantic (55°N-78.5°N / 325°E-35°E) as shown in Fig. 3.

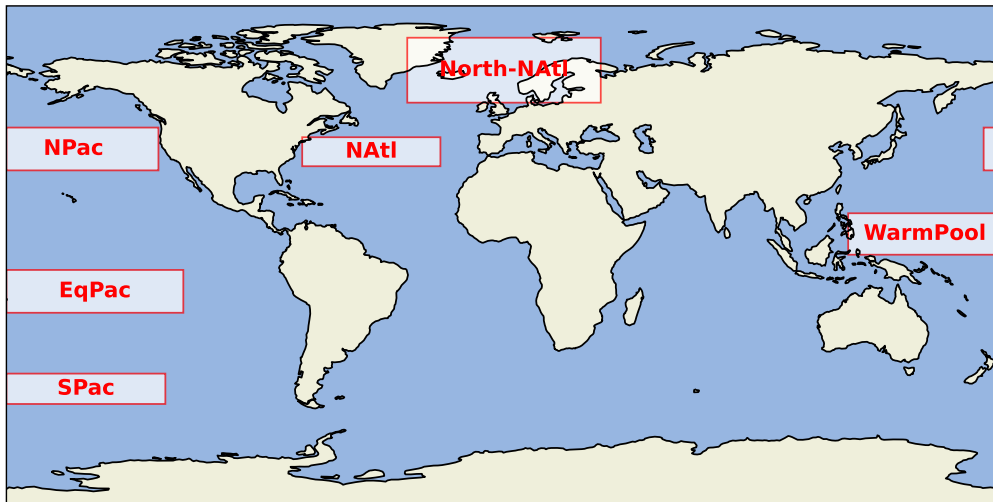


Figure 3: Map showing the six regional boxes in which we take the yearly area average and 95th percentile time series refer in the text.

### 3 Regridding

In NorESM, WW3 runs on either a regular curvilinear or a general unstructured grid. For visualisation and comparison with observations, the model results are regridded to grids that are more similar to data products, such as ERA5. In the setup described here, the fields are regridded to a regular  $1^\circ \times 1^\circ$  latitude-longitude grid. The data shown in this report originate from runs where the wave model uses the same grid as the ocean and sea ice components of NorESM, that is a curvilinear tripolar grid as depicted in Fig. 4.

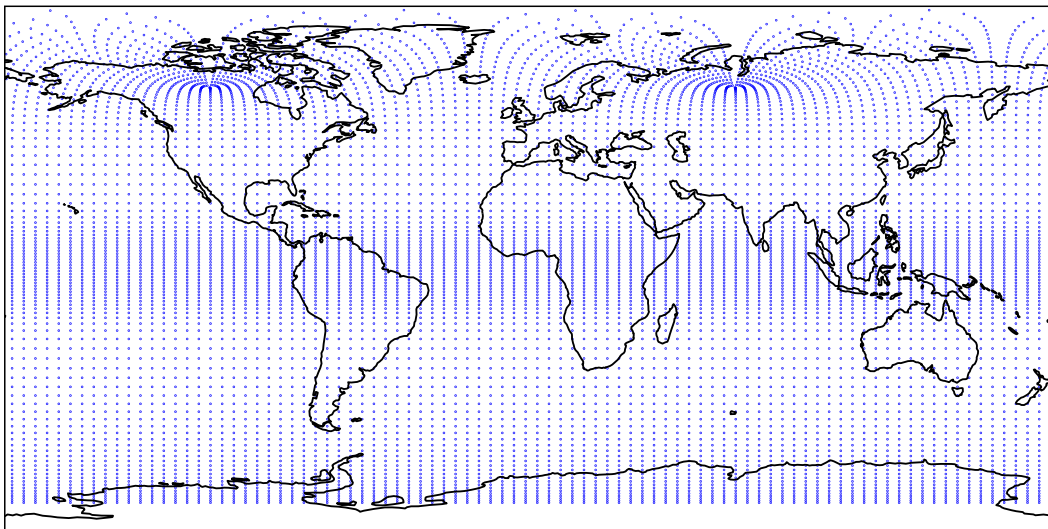


Figure 4: Illustration of the tripolar grid on which WW3 is run. There are two poles in the Northern Hemisphere over Canada and Russia and the third pole is the South Pole. For better readability, only one point out of four is plotted.

Regridding is done using a copy of the `Regrid_esmf_ww3` package available at [https://github.com/JensBDebernard/Regrid\\_esmf\\_ww3](https://github.com/JensBDebernard/Regrid_esmf_ww3). This package is designed for efficient regridding of the WW3 output fields by using the Python interface to the Earth System Modeling Framework (ESMF, <https://earthsystemmodeling.org/>) regridding routines. The package incorporates special handling of directional quantities and temporary varying missing points in the wave data. The regridding tool supports bilinear and first-order conservative regridding. Bilinear interpolation is used in the default setup, which is appropriate when the resolution of the destination grid and source grid are similar and as long as area-integrated conservation of properties is of less importance.

The regridding package is very efficient as it can handle a large number of files. It uses the ESMF ability to store and read regrid-weights from disk, such that these are only made once for a given combination of grids. In addition, each wave model output file, also called history file, can be processed independently, in parallel. This is achieved by giving the `-np` flag together with the required number of parallel processes as argument to the regridding script.

Different destination and source grids can be easily added. Here, it is most relevant to add different wave output grids. The grid definition file should be the ESMF-mesh file used by NorESM to define the coupler interphase between the model components. We refer to documentation of NorESM3 for this.

### 3.1 Special handling of directional fields

Wave directions in the model output are given by angles, measuring the anticlockwise angle between the wave propagation direction and geographical East, such that an angle of 0 is Eastward, and the angle  $\frac{\pi}{2}$  is Northward. To regrid the direction, the East and North components of the unit directional vector are regridded to the new grid, and then the direction angle is re-calculated based on the new vector. The 'units' attribute for the variables in the model history file is used to select angle quantities, where values like 'radians' or 'degrees' imply angle quantities.

### 3.2 Special handling of undefined points

Some model fields such as wind sea direction and swell direction are only defined when the wave energy for the frequencies are above a small threshold value. This can give points in the model field without a physical value and these are flagged as undefined in the history file. These points should not be used in the regridding.

Given a source field  $F_{S_l}$  covering all points  $l$  in the source grid, and a destination field  $F_{D_k}$  covering all points  $k$  in the destination grid, the interpolation methods used here are written as a matrix-vector product

$$F_{D_k} = a_{k,l} F_{S_l}, \quad (13)$$

where the remapping weight matrix  $a_{k,l}$  is given by the regrid method, the grid geometries of both the source and destination grids, and the mask of the source grid. For bilinear and conservative regridding, only a few points from the source grid influence a given grid point in the destination grid, and therefore the weight matrix is sparse. This sparse

matrix-vector product is calculated very efficiently by the underlying routines in ESMF. For a given mask and grid geometry, the matrix is constant in time, and it is reused for all the calculations.

If some points  $F_{s_m}$  are marked as undefined, they should not be part of the calculation in Eq. (13). To avoid the expensive process of recalculating  $a_{k,l}$  without the influence of the time varying points  $m$ , we introduce a special handling of this cases with a time varying mask vector. Let the vector  $ws_l$  on the source grid be ‘zero’ for all undefined points, and ‘one’ in all other cases. Remapping this vector to the destination grid

$$wd_k = a_{k,l} ws_l, \quad (14)$$

gives the mask weights  $0 \leq wd_k \leq 1$ .

Using a redefined source field  $\hat{F}_{s_l}$  where undefined points is given the value ‘zero’, the remapped special field is given by

$$Fd_k = (a_{k,l} \hat{F}_{s_l}) / wd_k \quad (15)$$

for  $wd_k > 0$ . In the special case where  $wd_k = 0$ ,  $Fd_k$  is undefined.

## 4 Usage and practicalities

### Where to get the codes?

All codes can be downloaded from the following GitHub repository: <https://github.com/clio-met/WW3-DT-Making-Waves/>.

### How to run the tool?

The tool is run with a one-line command as follows:

- To perform the figures for one experiment only, one should use:

```
./diag-wave --x1 name_exp --y1 year1 --y2 year2  
--p1 /path/to/data/ -r mesh_grid_file.nc
```

- To perform the comparison figures between for two experiments, one should use:

```
./diag-wave --x1 name_exp1 --x2 name_exp2  
--y1 year1 --y2 year2  
--p1 /path/to/data1/ --p2 /path/to/data2/  
-r mesh_grid_file.nc
```

The arguments are:

- `--x1 name_exp1`, `--x2 exp_name2`: they are the names of the experiments' re-gridded files (netCDF) and should be given without `'.nc'`. This argument is mandatory. For a comparison with ERA5, `ERA5_WAVE` is the file name to use here.
- `--y1 year1`, `--y2 year2`: they are the first and last years of the period considered and are used in the re-gridding step if more years are present in the original data folder. Both experiments must cover the same period of time. These arguments are mandatory.
- `--p1 /path/to/data1/` `--p2 /path/to/data2/`: they are the paths to the original data folders. These arguments are not mandatory, but are required if the original data must be re-gridded.
- `-r mesh_grid_file.nc`: this is the name of the ESMF mesh grid file which defines the model grid used in the re-gridding. This argument is not mandatory, but is required if the original data must be re-gridded. The grid file must be placed in

`./regridding/Regrid_esmf_mw_sigma2/grids/` before running the tool. The grid file that corresponds to our tripolar grid is named `wtnx1v4nw_20230917_cdf5_ESMFmesh.nc`.

Note that options `--p1`, `--p2`, `-r` can be discarded if the files have already been re-gridded and are present in the folder `./regridded/`.

To perform the comparison with ERA5, the command line should be as follows:

```
./diag-wave --x1 name_exp1 --x2 ERA5_WAVE
            --y1 year1 --y2 year2
```

where `year1` and `year2` are the first and last years present in `name_exp1`.

Mandatory steps to follow before using `diag-wave`:

- 1) The Python environment `waves_env` must be installed using the following command `conda env create -f environment_mw.yaml` or `mamba create -f environment_mw.yaml`.
- 2) If the input files are already re-gridded on a regular latitude/longitude grid, the netCDF files must be placed in the folder `./regridded/`. There should be one file per experiment. If re-gridding is needed, the path to the input files must be given along with the new grid file in netCDF format that should be placed in `./regridding/Regrid_esmf_mw_sigma2/grids/`. For this step, there may be several files per experiments.

### **Other considerations to be aware of**

The wave output from NorESM is time averaged and written by the NorESM coupler. Time averaged fields get the time stamp when the file is written to disk, thus, at the end of the average period, meaning that the daily average from, e.g., January 1st has the time stamp of 2 January at 00UTC. Therefore, our tool first shifts the data one day backward before any analysis to simplify the calculation of the statistics. See lines

```
# Shift time one day backwards
f1=shift_time_coords(f1)
f2=shift_time_coords(f2)
```

in the scripts `main_script.py` and `main_script_1exp.py`.

The experiments have daily time resolution and the program does not support other time resolutions.

The file ERA5\_WAVE.nc contains the climatologies (total, monthly, seasonal) of the following variables: total significant wave height (hs), wind-sea significant wave height (phs0), swell significant wave height (phs1), mean wave period (tm1), wind-sea mean wave period (ptm10), swell mean wave period (ptm11), peak wave period (pp1d), mean wave (M2) period (tm02), the zonal and meridional components of the mean, wind-sea mean, and swell mean wave directions (thm\_x, thm\_y, pdir0\_x, pdir0\_y, pdir1\_x, pdir1\_y), the wind speed (wind) as well as its zonal and meridional components (u, v), sea ice concentration (frac), Stokes drift intensity (stokes) as well as its zonal and meridional components (ustokes, vstokes).

## 5 Webpage

The Python script generates a HTML file that looks like this:

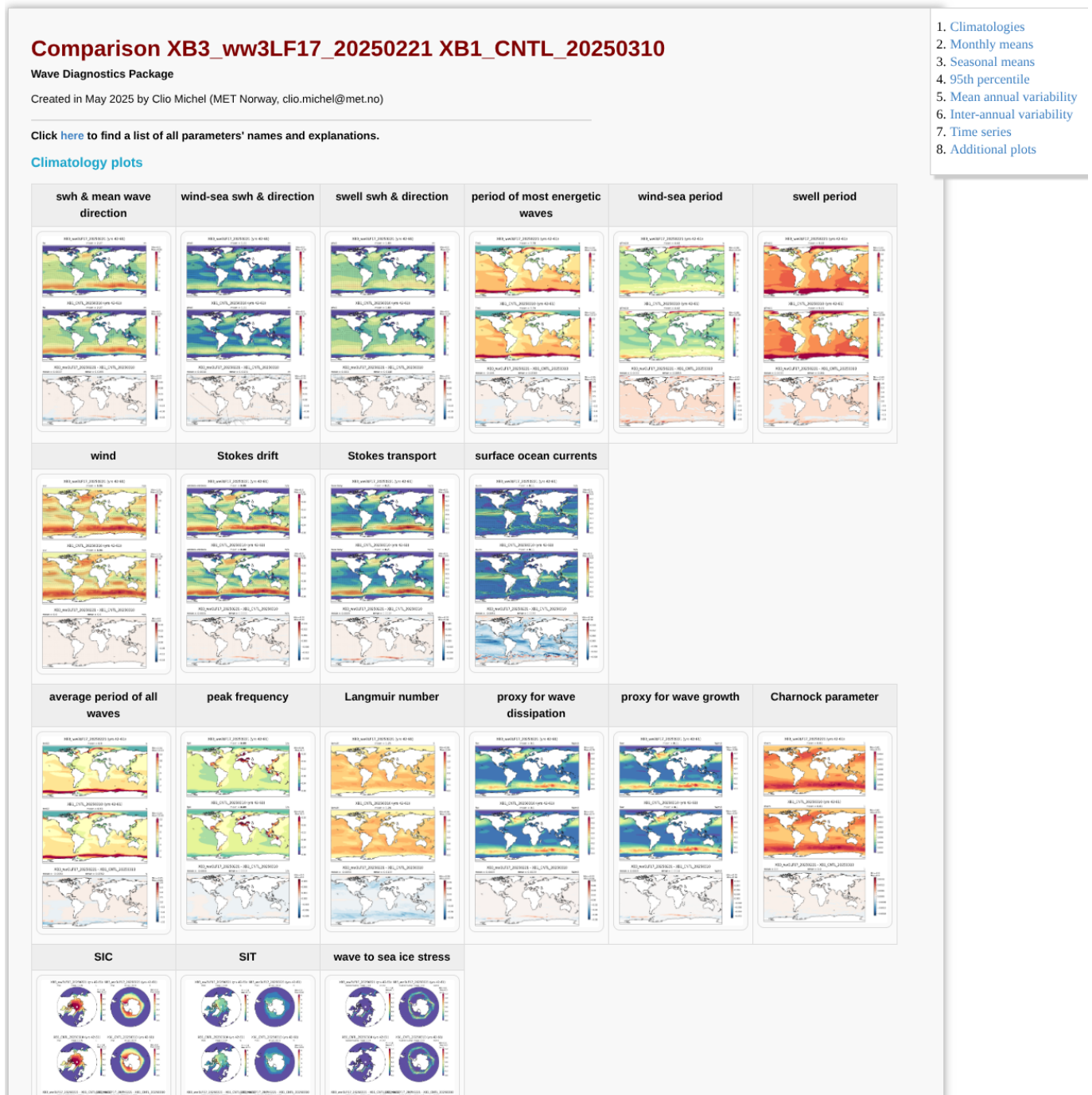


Figure 5: Example of the html file generated by the Python script when opened in an internet browser.

## Acknowledgments

This work was carried out during the project MakingWaves nr. 325654 funded by the Research Council of Norway. The development of the diagnostic tool along with the simulations used by the tool were performed on resources provided by Sigma2 - the National Infrastructure for High-Performance Computing and Data Storage in Norway (projects NS8015K and NN8015K).

## References

- Björkqvist, J.-V., S. Pärt, V. Alari, S. Rikka, E. Lindgren, and L. Tuomi (2021), Swell hindcast statistics for the Baltic Sea, *Ocean Sci.*, *17*, 1815–1829, doi:10.5194/os-17-1815-2021.
- Breivik, Ø., and K. H. Christensen (2020), A combined Stokes drift profile under swell and wind sea, *J. Phys. Oceanogr.*, *50*, 2819–2833, doi:10.1175/JCLI-D-18-0435.1.
- Carrasco, A., A. Semedo, P. E. Isachsen, K. H. Christensen, and Ø. Saetra (2014), Global surface wave drift climate from ERA-40: the contributions from wind-sea and swell, *Ocean Dynamics*, *64*, 1815–1829, doi:10.1007/s10236-014-0783-9.
- Hersbach, H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. D. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R. J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. de Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut (2020), The ERA5 global reanalysis, *Quart. J. Roy. Meteor. Soc.*, *146*, 1999–2049, doi:10.1002/qj.3803.
- Stopa, J. E., K. F. Cheung, H. L. Tolman, and A. Chawla (2013), Patterns and cycles in the Climate Forecast System Reanalysis wind and wave data, *Ocean Modelling*, *70*, 207–220, doi:10.1016/j.ocemod.2012.10.005.