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SMC multi-grid global model for UKMO future wave forecasting

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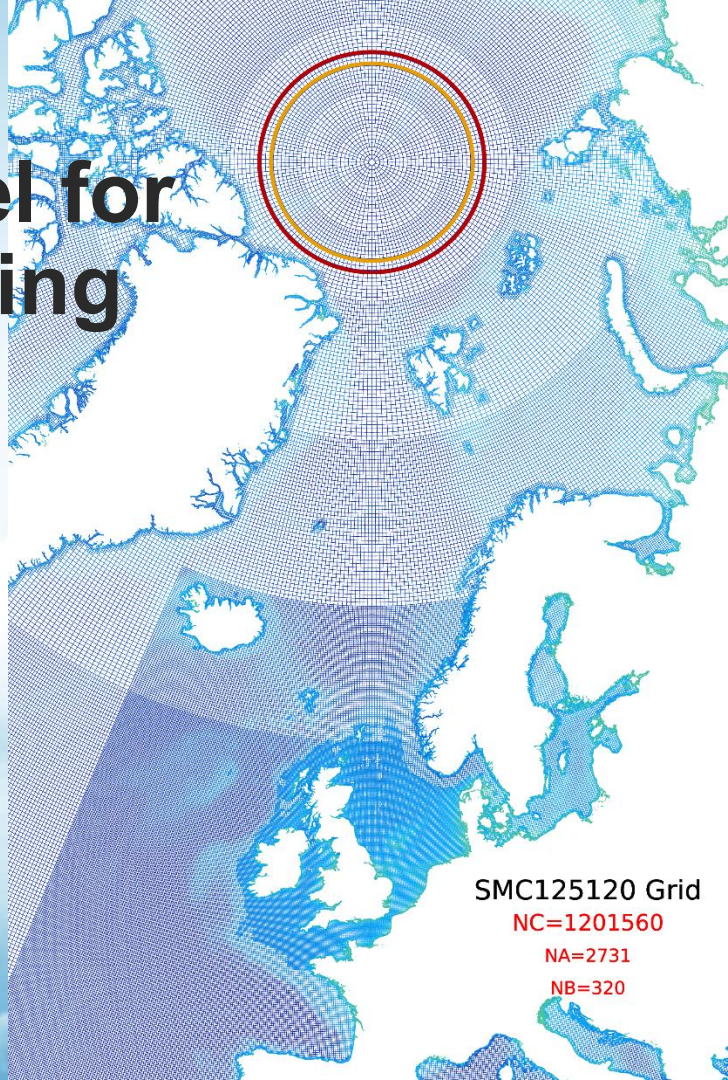

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Three parts in this presentation

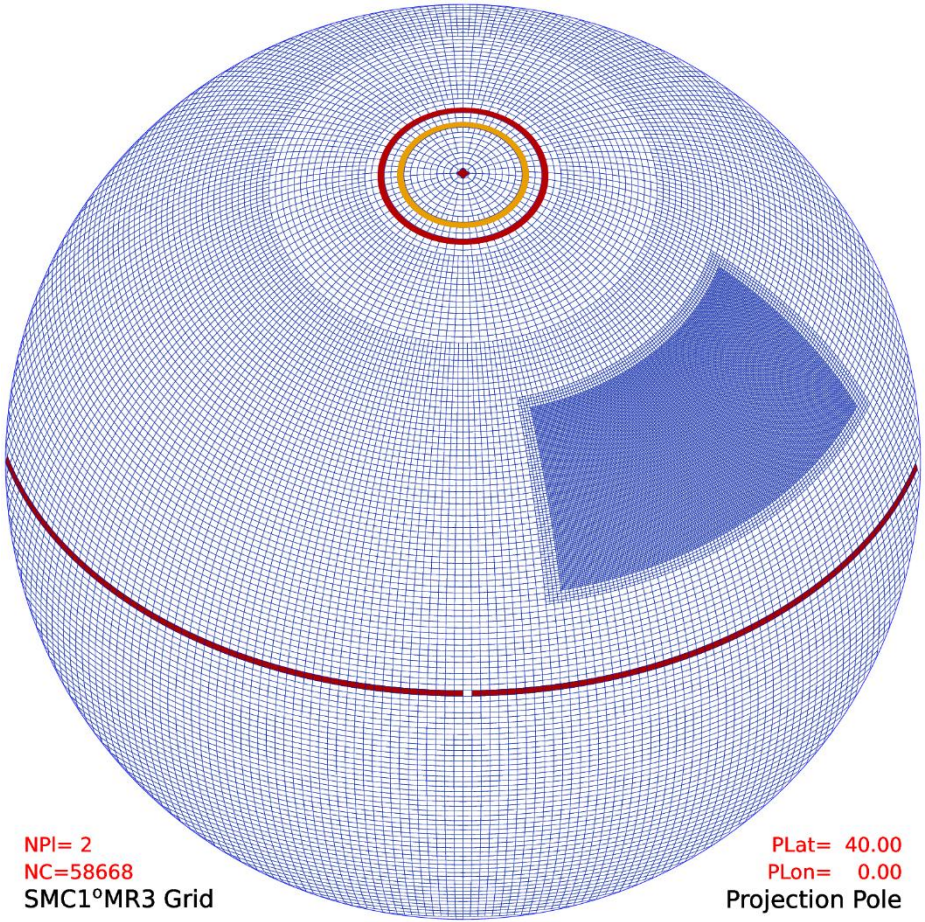
1. SMC multi-grid hybrid parallelization in WW3 model
2. Planned UK Met Office multi-grid global wave model
3. GitHub tools package for generating and testing SMC grids
   https://github.com/ww3-opentools/SMCGTools/

Spherical Multiple-Cell grid

- Unstructured grid with rectangular cells, like a latitude-longitude grid.
- Merged cells at high latitudes to relax CFL time step limit, like a reduced grid.
- Use fixed reference direction to define vector components in polar regions for valid scalar assumption.
- Round polar cells at poles to avoid polar singularity.
- Multi-resolution levels with refined cells.

Li, J.G. 2011: *Mon. Wea. Rev.*, **139**, 1536-1555.

Li, J.G. 2018: *Q. J. Royal Meteoro. Soc.*, **144**, 1-12.



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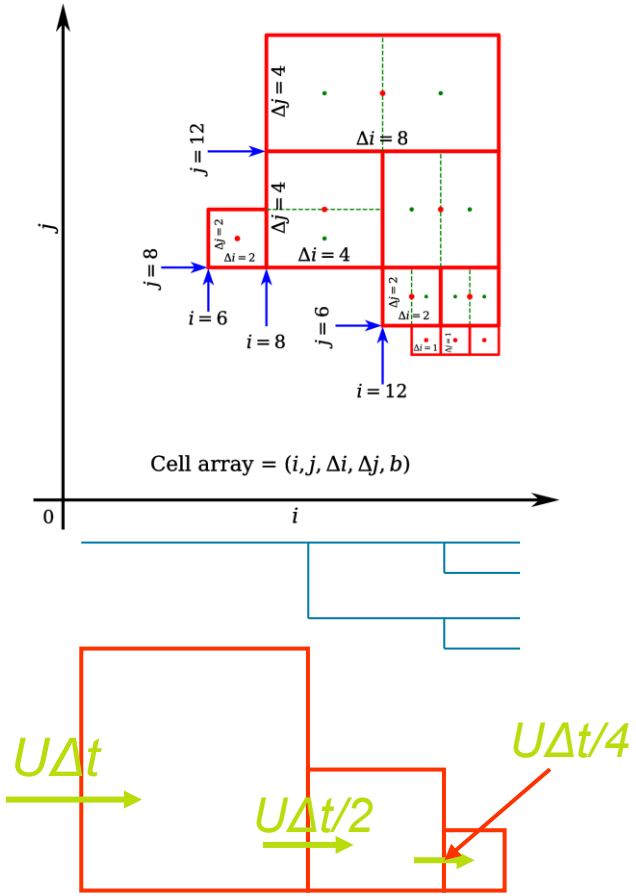
SMC grid with multi-resolution cells and pointer-oriented sub-loops

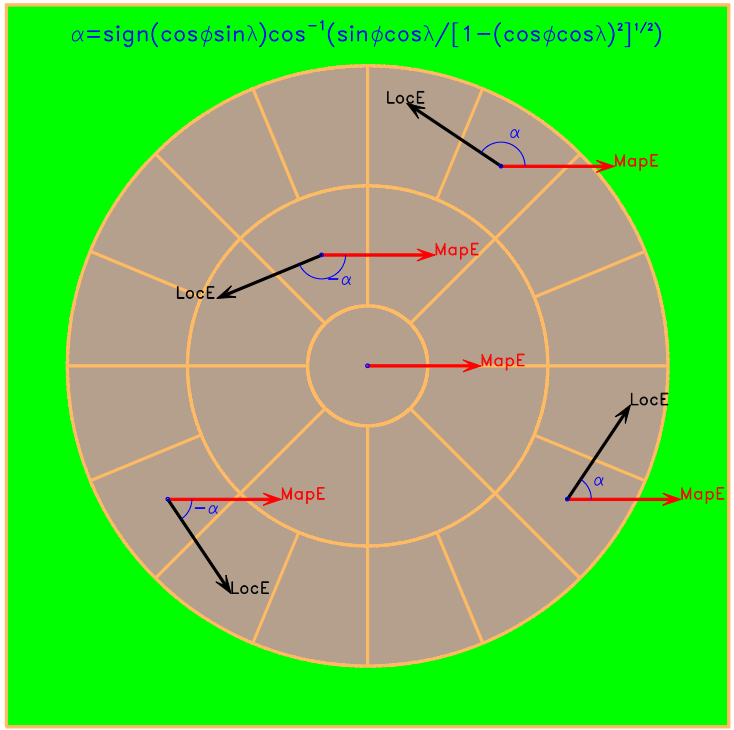
- Cells are defined by location and size indexes and multi-resolution by refinement.
- Transport fluxes are calculated with the aid of face-array in pointer-oriented loops.
- Sub-time-steps are used for refined cells in sub-loops for efficiency.
- One-dimensional array loop convenient for parallelization.

• Li, J.G. 2012: *J. Comput. Phys.*, **231**, 8262-8277.



Map-east reference direction — Vector polar problem

- SMC grid uses merged cells at high latitudes to relax CFL limit on time step like a reduced grid.
- Local east changes rapidly from cell to cell in polar regions, rendering the scalar assumption of vector component invalid.
- Defining vector components with fixed reference direction --- the map-east, instead of the rapidly changing local east in polar regions, solves the polar problem.

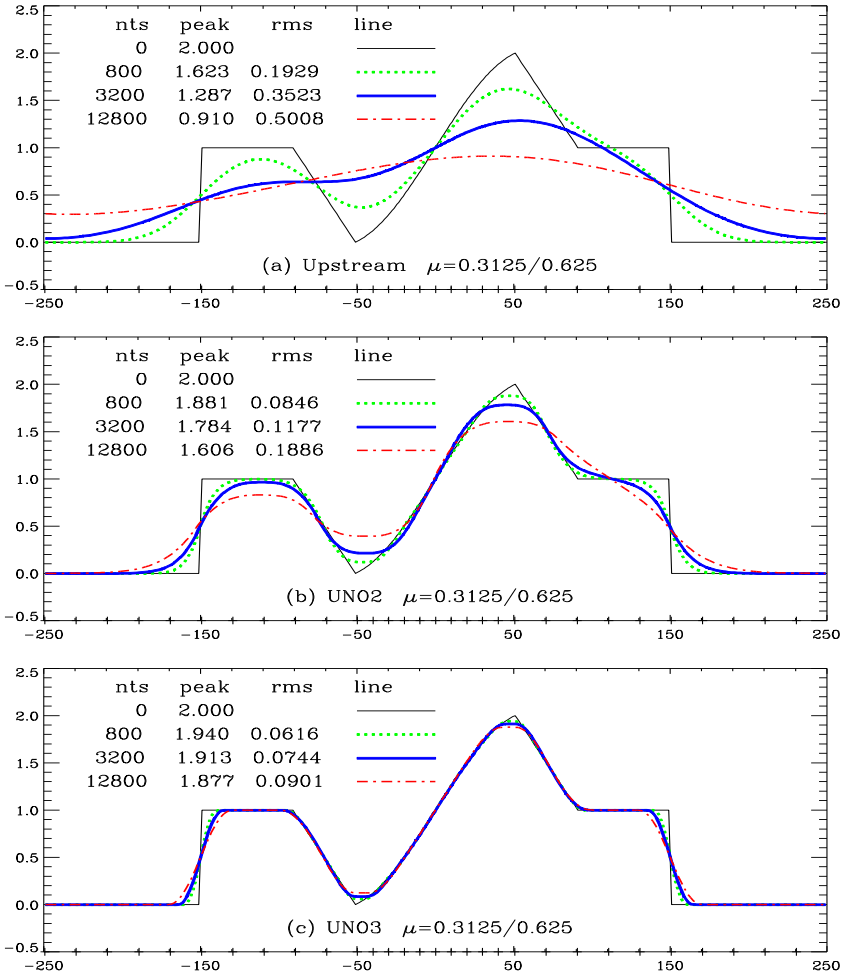


Li, J.G. 2016: *Ocean Dynamics*, **66**, 989-1004.

Upstream Non-Oscillatory advection schemes

- Choice of 2nd or 3rd order UNO advection schemes on SMC grid.
- Recommend the 2nd order UNO2 scheme for wave and atmospheric models, fast and accurate enough.
- SMC grid was implemented in WW3 V4.18 model in 2014 and updated in WW3 V7.

Li, J.G. 2008: *Mon. Wea. Rev.*, **136**, 4709- 4729.

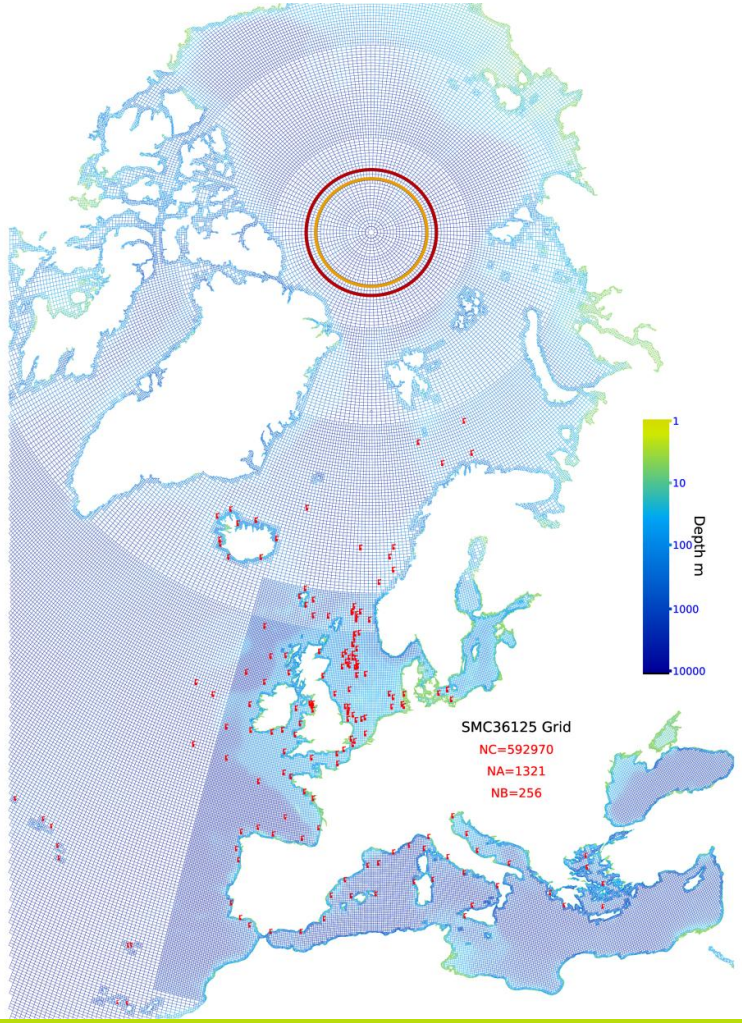


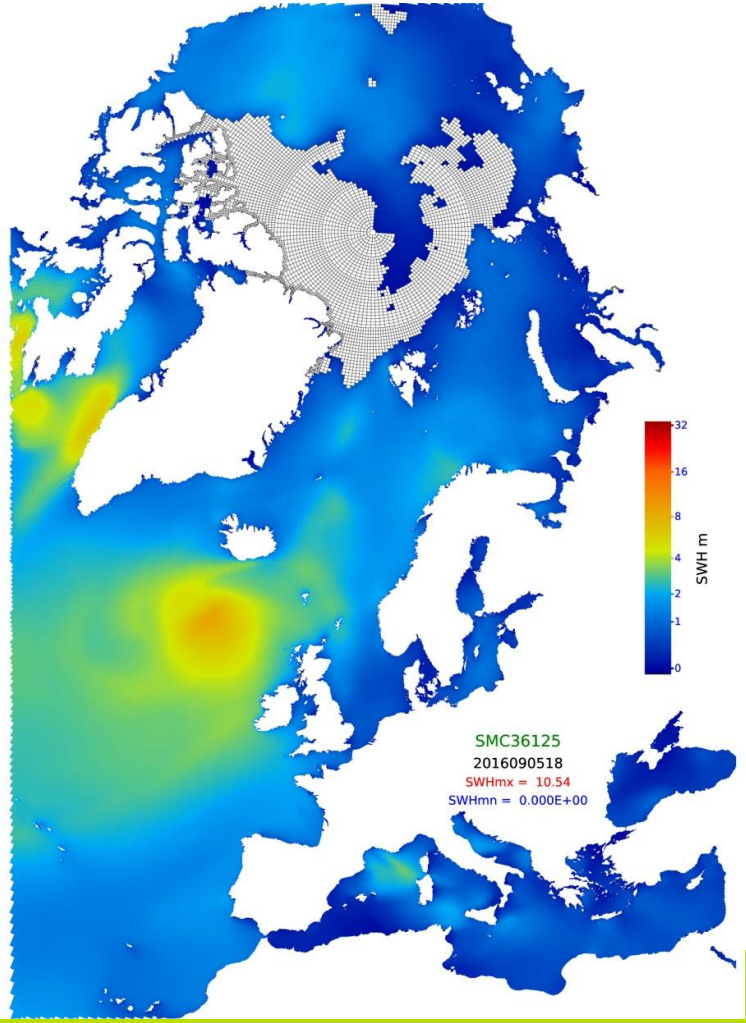
UKMO global 3-6-12-25 km wave model

Operational wave model since 2016 as Arctic sea ice retreat demands polar extension.

Improved forecast accuracy thanks to refined resolutions.

Li, J.G., A. Saulter, 2014:. *Ocean Dyn.*, **64**, 1657-1670.



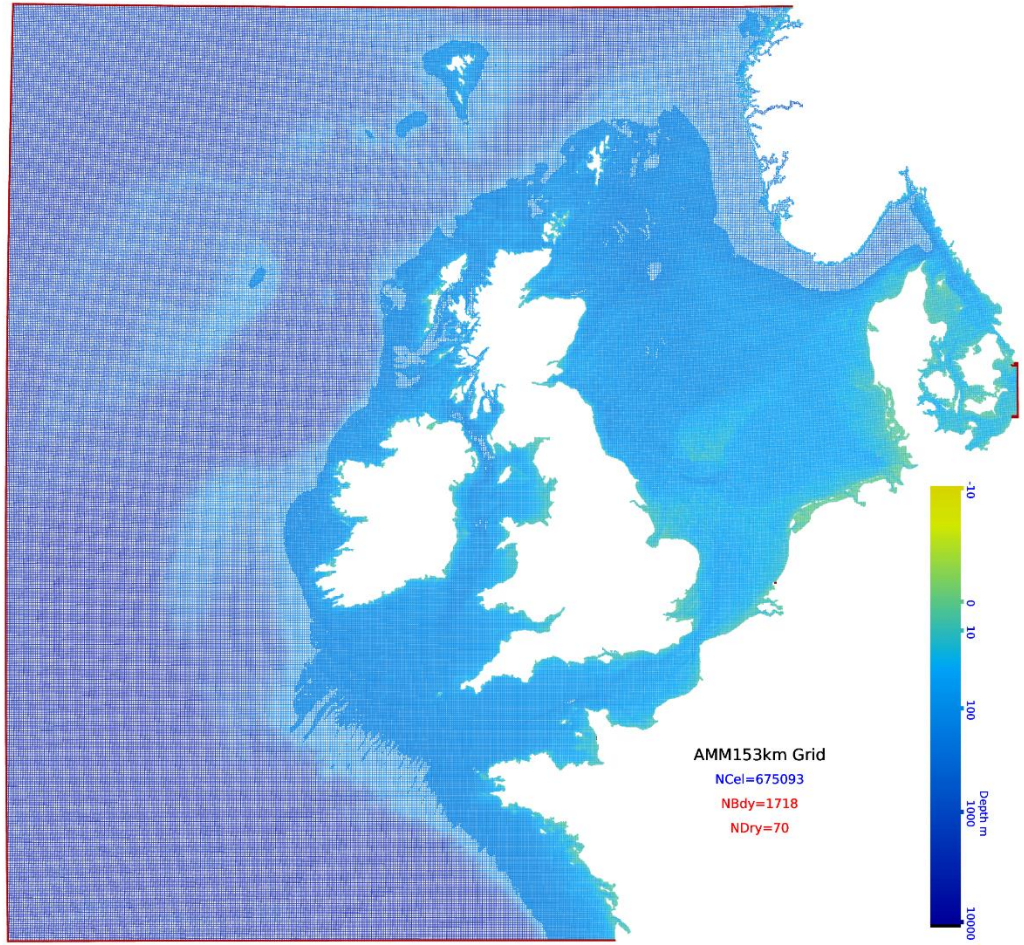


UKMO AMM 1.5-3 km wave model 2016

The Atlantic Margin Model (AMM) is a regional ocean model at 1.5 km resolution on a rotated grid. A wave model matching the same domain at 2-level 1.5-3 km is used for wave forecasting and coupled system for climate studies (AMM153).

The 1.5 km cells cover all shallow water area < 150 m deep and other water surface is covered by 3 km cells.

The AMM153 wave model is also used in NOC Liverpool and NEA Singapore coupled climate systems.

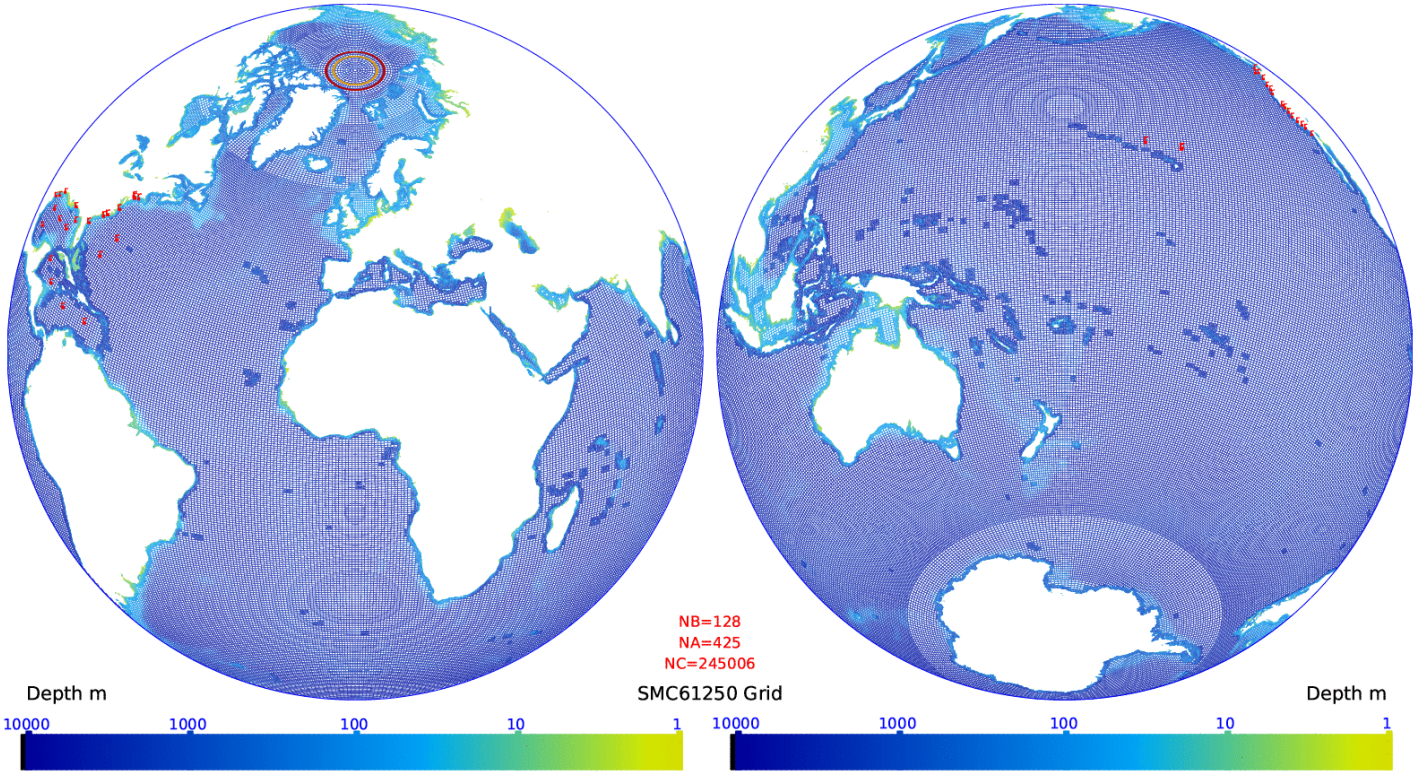


Singapore NEA 4-level global wave climate model

SMC 4-level at 6-12-25-50 km

Whole Arctic is included for possible ice-free scenario.

Also used in UKMO coupled climate system



Kumar, R., G. Lemos, A. Semedo, J.G. Li, 2025: *Ocean Modelling*, **197**, 102566, 23pp.

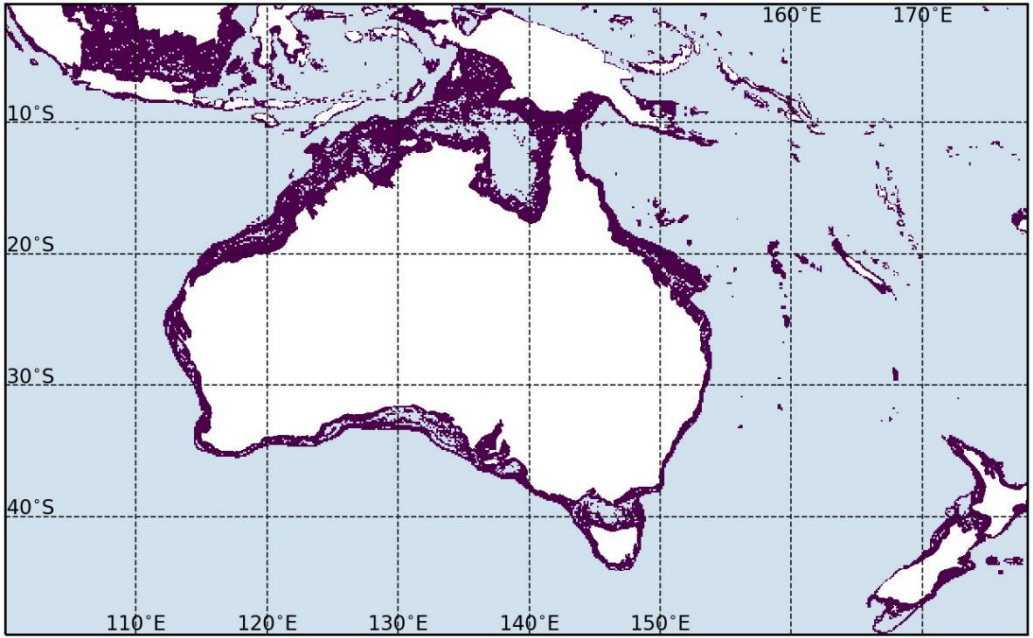
Australia BoM wave forecasting model

- Courtesy of **Dr Stefan Zieger, Bureau of Meteorology, Australia**

Base resolution of 1/8°,

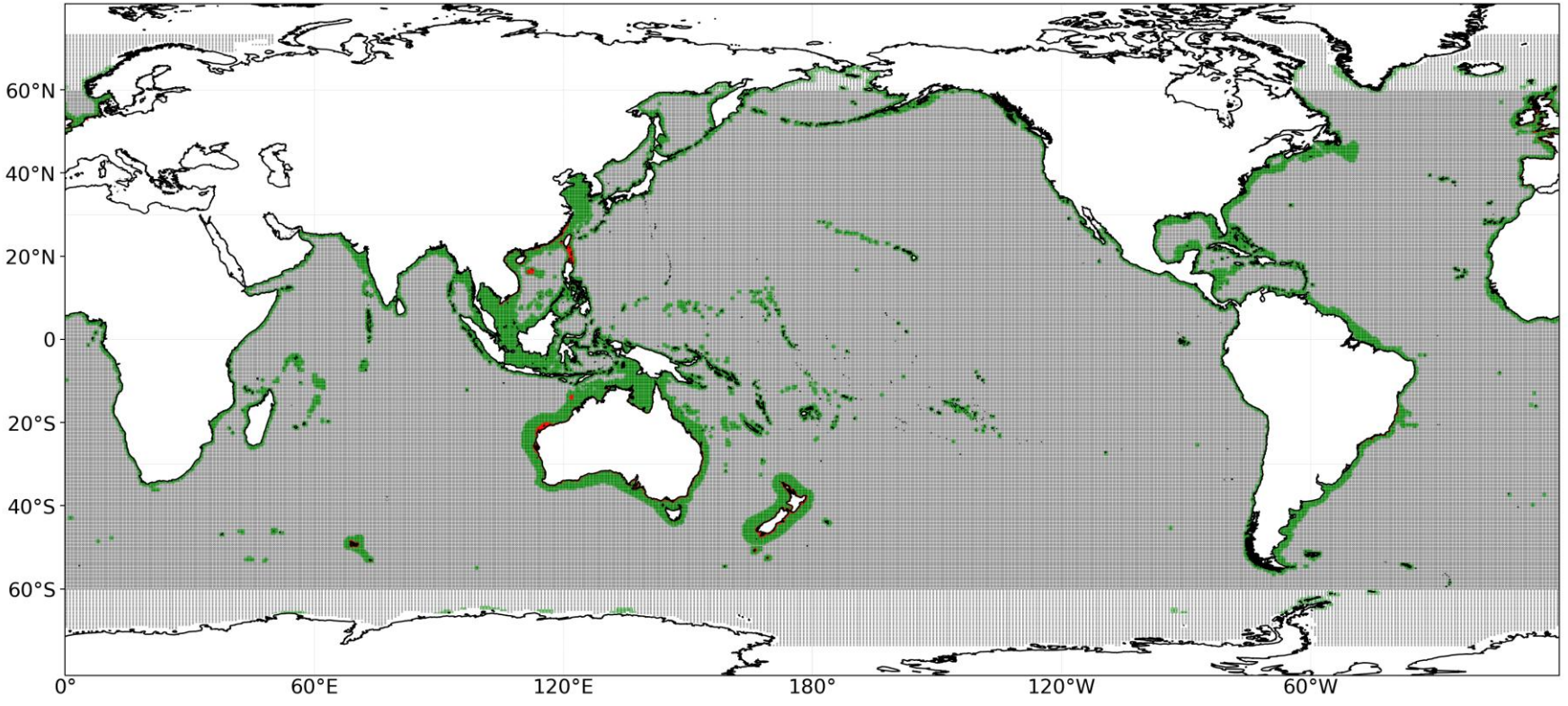
Increase to 1/16° around islands or in shallow waters (< 350 m)

Zieger, S., D.J.M. Greenslade, 2021: AUSWAVE-G3. *Bureau Res. Report* **51**. 74pp.



MetOcean Solutions (NZ) wave forecasting model

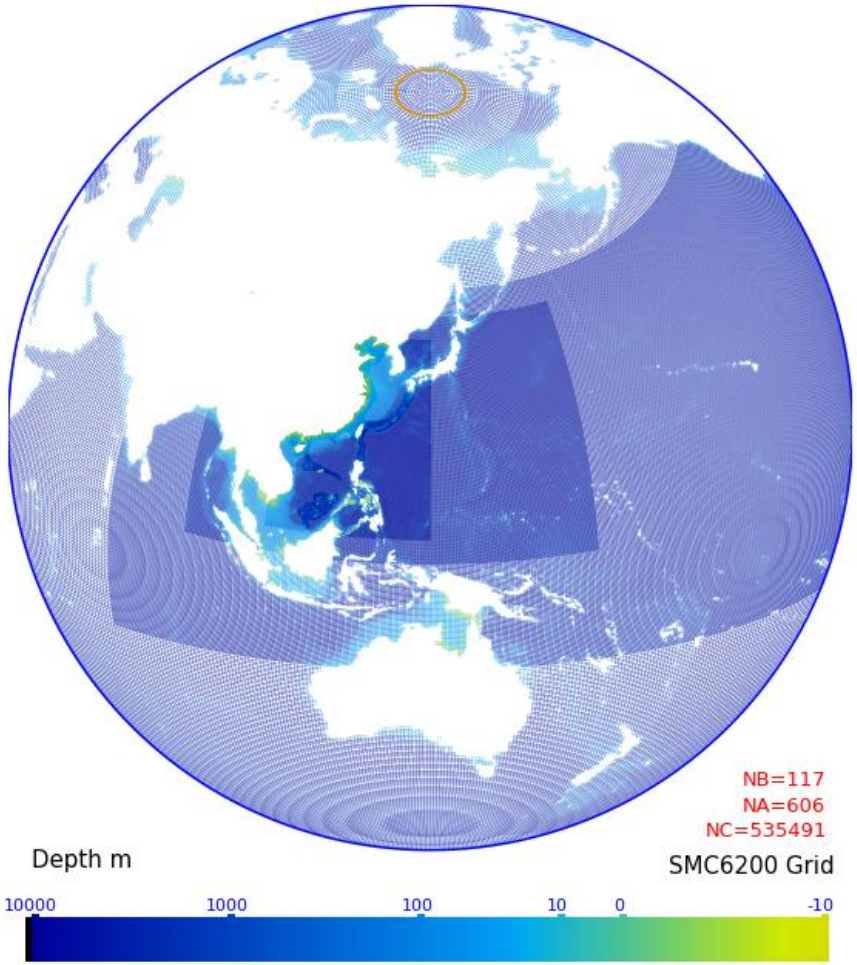
- Courtesy of **Dr Emilio Echevarria, MetOcean Solutions, New Zealand** **40-20-10 km**



China NMEFC 6-level wave forecasting model

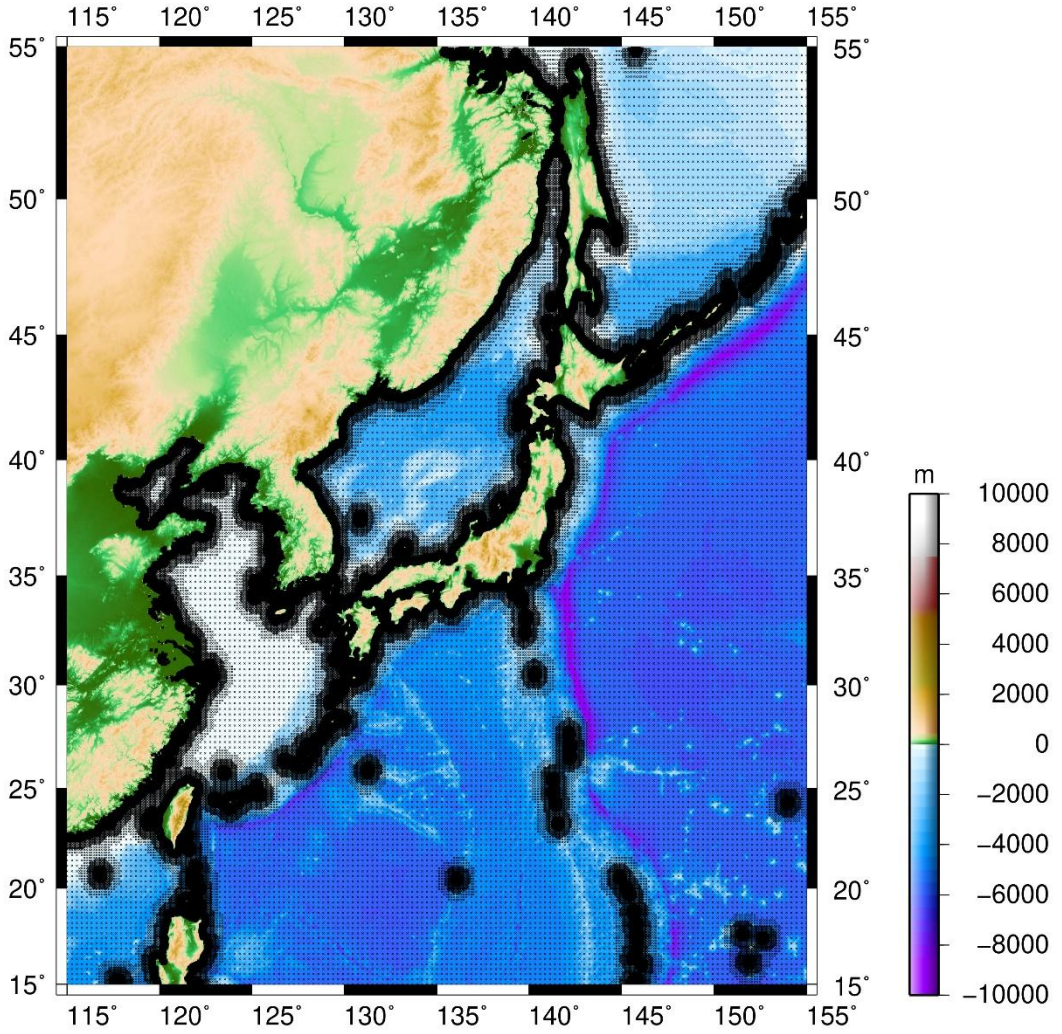
- Six-level SMC grid at 50-25-12-6-3-1.5 km refined from global down to Chinese coastlines like nested grids, except for last 2 levels near coastlines.

- Hou F, Gao Z, Li JG, Yu F, 2022: *Acta Oceano. Sinica*, 41(5), 41-50.



JMA 5-level global wave model with refined Japan coastal waters

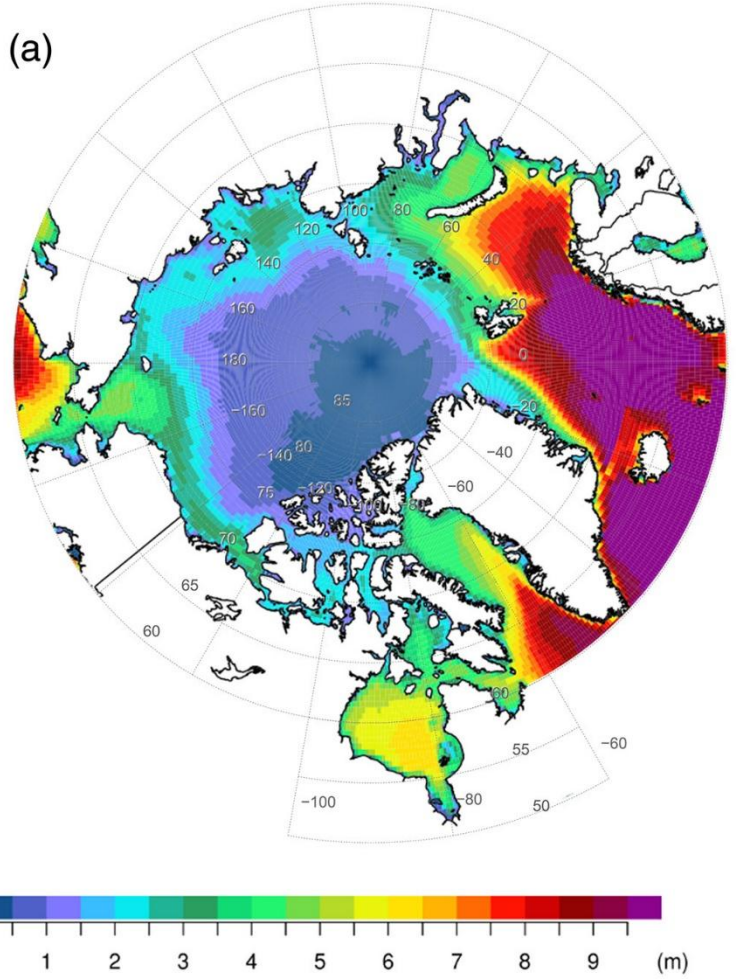
- Courtesy of Dr Nadao Kohno, Japan Metero. Agency (JMA)
- 5-level at 1-2-4-8-16 min by distance from coast greater than 0-20-30-40-60 km, respectively.
- Wave Spectrum 25 frq x 36 dir = 900 components.



Environ. Canada Arctic models and Ocean Univ. China climatic studies

- Courtesy of **Dr Mercè Casas-Prat** Environment Canada and **Dr LI, Jinkai**, Ocean University of China

- Casas-Prat et al 2018: *Ocean Modelling*, **123**, 66-85.
- Li, J., Y. Ma, Q. Liu, W. Zhang, C. Guan, 2019: *Cold Regions Sci. Techn.* **164**, 102790.

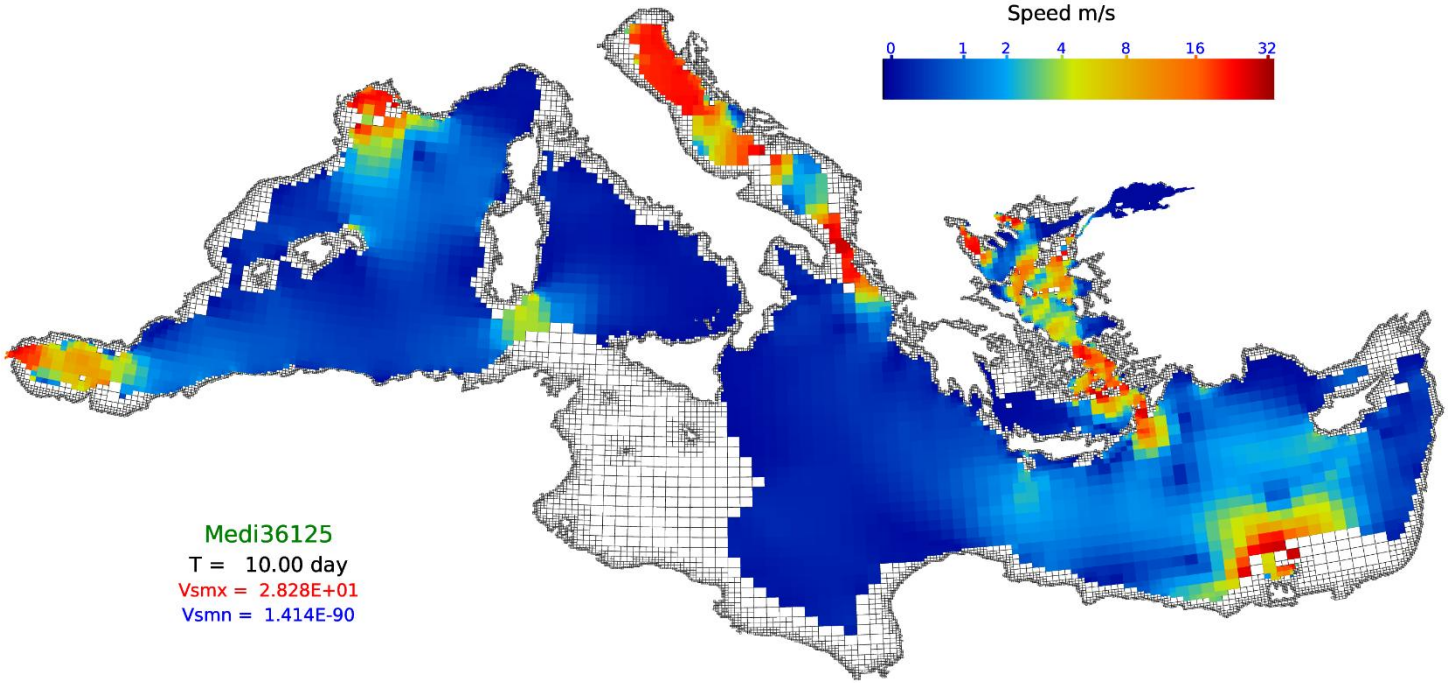


Shallow water equations on SMC grid for tsunami

Mediterranean Sea SWEs model on 4-level 3-6-12-25 km

Filling ocean test water speed after 10 days filling an empty Medit. Sea.

Global 4-level 2.5-5-10-20 km tsunami model is tested.



Li, J.G. 2021: Filling oceans on a spherical multiple-cell grid. *Ocean Modelling*, **157**, 101729, 13pp.

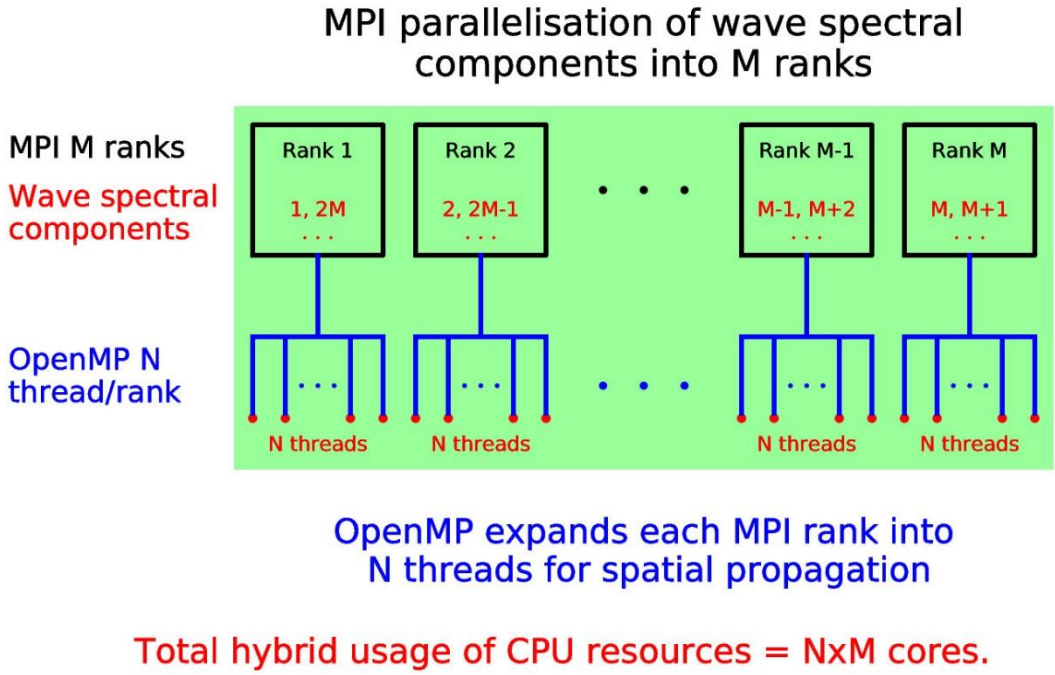
Li, J.G., P. Wang, 2024: Global tsunami modelling on a SMC grid. *Ocean Modelling*, **192**, 102461, 24pp.

WW3 parallelization schemes, CD method

• MPI M ranks store whole spectra for selected sea points, ready for parallelization of source terms.

•Whole domain propagation for a single spectral component is calculated on one MPI rank --- Component Decomposition, limited by 30x36=1080 ranks.

• Hybrid (MPI+OpenMP): 1 MPI rank is expanded to N OpenMP threads within shared memory.



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Multi-grid option for SMC grid in WW3, DD+CD

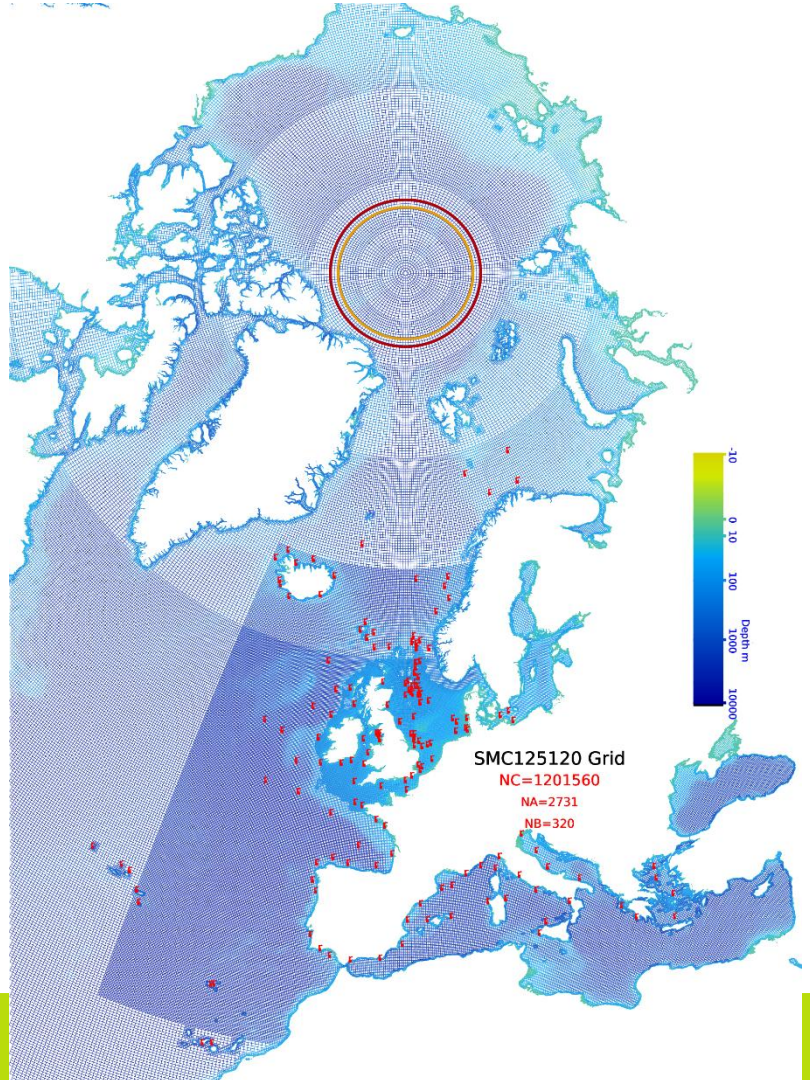
- WW3 model has a multi-grid option mainly for regular lat-lon grid (Tolman, 2002). It allow sub-grids to run in parallel like Domain Decomposition (DD), while keeping each sub-grid parallelised with the CD method. Very limited applications due to restrictions of online rectangular DD.
- SMC grid in WW3 is updated to use the multi-grid option (Li, 2022) with pre-calculated, well balanced sub-grids, not splitting grid online each run.
- Boundary cells are also pre-calculated with 1-1 corresponding spectral exchange. No interpolation is needed, differ from lat-lon multi-grids.
- Two, 3 and 4 sub-grids are tested and validated against spectral buoys.

Tolman, H. L. 2002: *Parallel Computing*, **28**, 35-52.

Li, J.G. 2022: *J. Parallel Distributed Computing*, **167C**, 187-198.

Planned UK Met Office SMC 1.25-2.5-5-10-20 km grid

- European regions is refined to 10 km and shallow waters around UK is refined to 5 km, in addition to coastal refinement to 2.5 and 1.25 km or size-1 resolution (0.017578125°, 0.0125°).
- The rest of world oceans are resolved with 2.5-5-10-20 km 4-level resolutions. Total ~1.2M sea-points (present ~0.6M on SMC36125 grid).
- Sub125120 multi-grid is created by splitting this global grid into 3 sub-grids.



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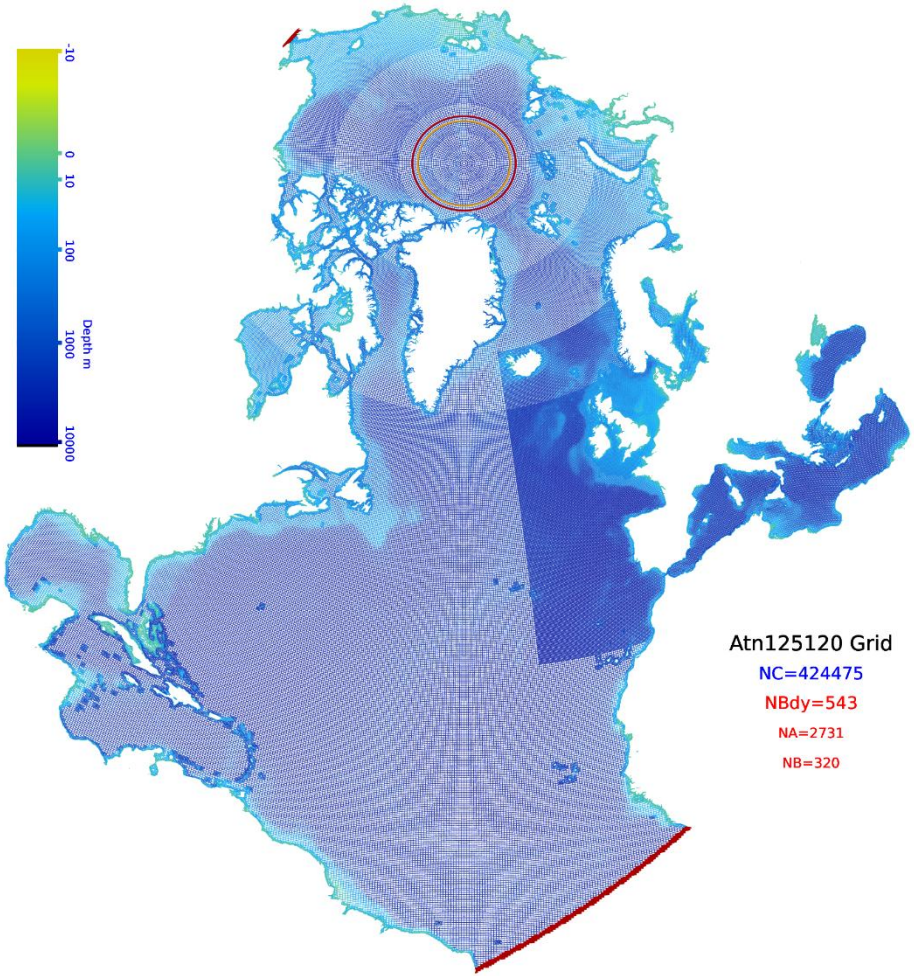
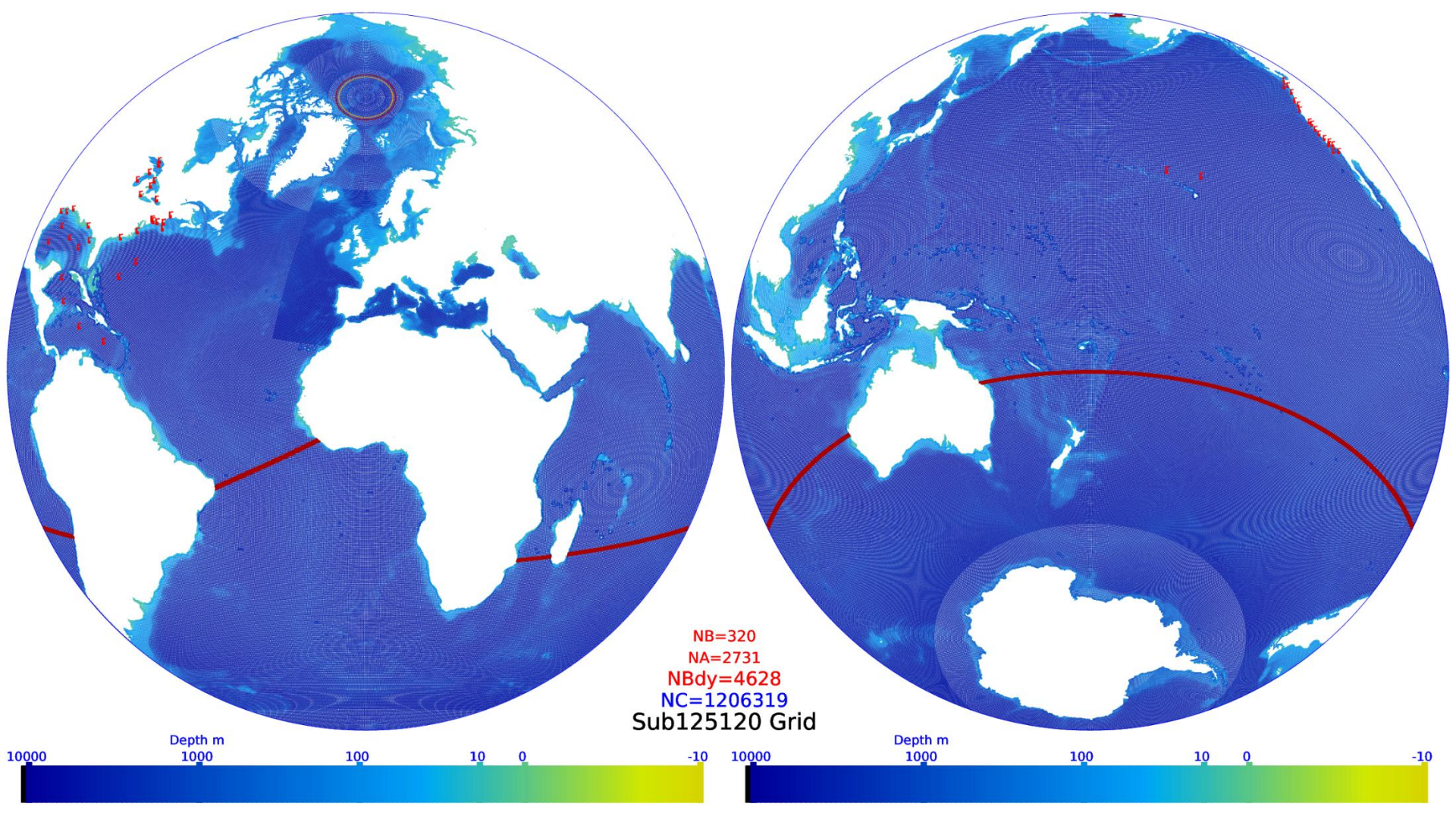
Atlantic sub-grid 1.25-20km

- Includes main wave forecasting area of European and UK waters. Most of our forecasting products could be processed with this sub-grid model output, instead of using full global one.
- Covers all fetch area of N. Atlantic with only 543 boundary cells input. Could be run as an independent model for UKMO ensemble forecasting.
- Has ~425 thousands cells (~1/3 of 1.2M).

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NC=1206319
Sub125120 Grid
Depth m
10000
1000
100
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Depth m
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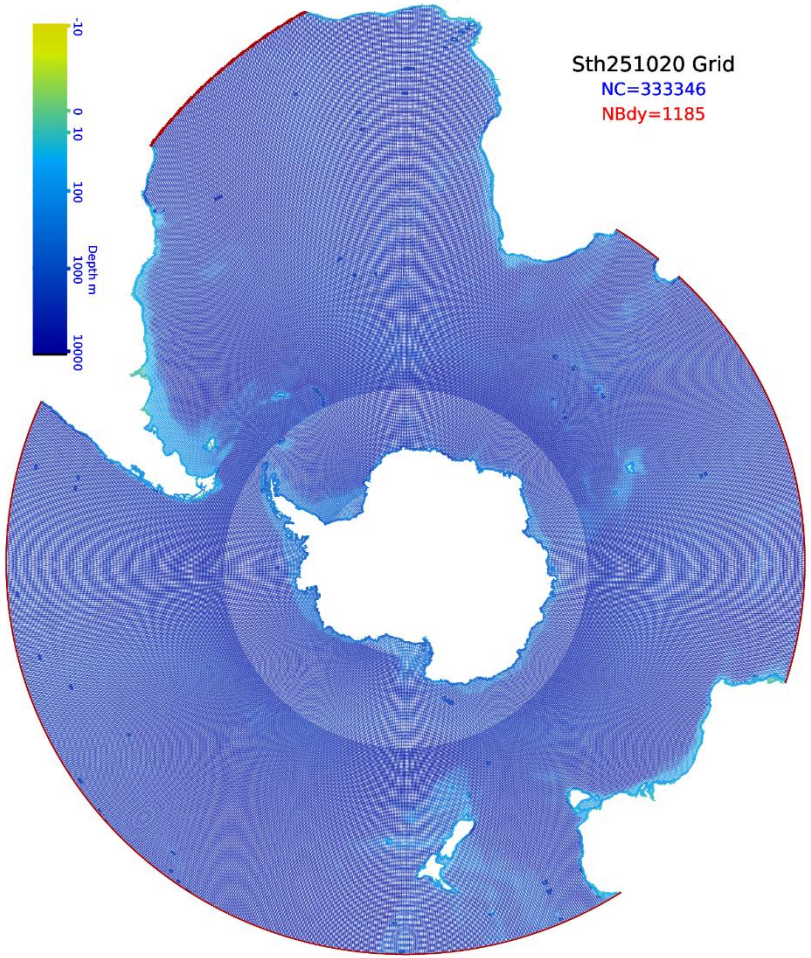
Southern Ocean grid 2.5-20 km

Keeps Southern Ocean circulation within one grid which is one of the main sources of ocean swell.

Total ~333 thousands cells and 1185 boundary points, the smallest among the 3 sub-grids.

Pacific grid 4-level 2.5-20 km

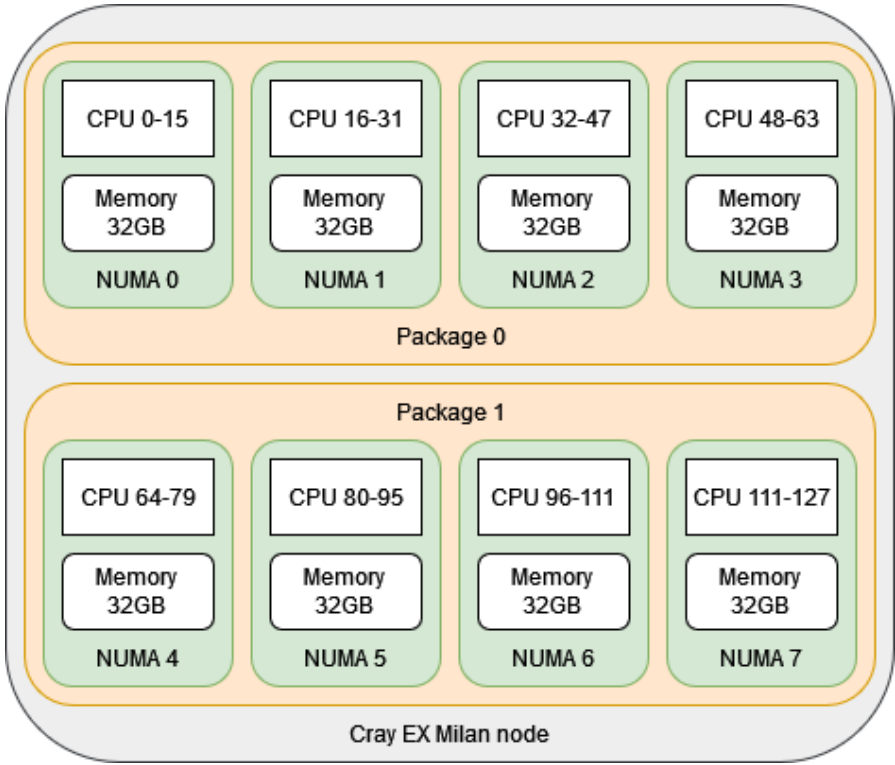
Cover the rest of ocean surfaces, including Indian and Pacific Oceans, the Great Lakes and Caspian Sea. Total ~448 thousands cells, 2900 boundary points.



Hybrid parallelization of UKMO models

- UKMO old Cray XC40 has 36 cores 128 GB per node, ~ 10,000 nodes.
- WW3 MPI optimised: 360 ranks (3 out of 1080 spectral components per rank).
- Hybrid: 60 nodes, 6 threads per rank.

- UKMO new Cray EX system has 128 cores 256 GB memory per node, best OpenMP usage:16 cores in one unit.
- Optimised hybrid: 544 ranks 8 threads.
- Multi-grid model: 1440 ranks among 3 sub-grids (360:544:544) on 90 nodes (11520 cores) with 8 threads.



16 cores per unit shares fast 32Gb mem.

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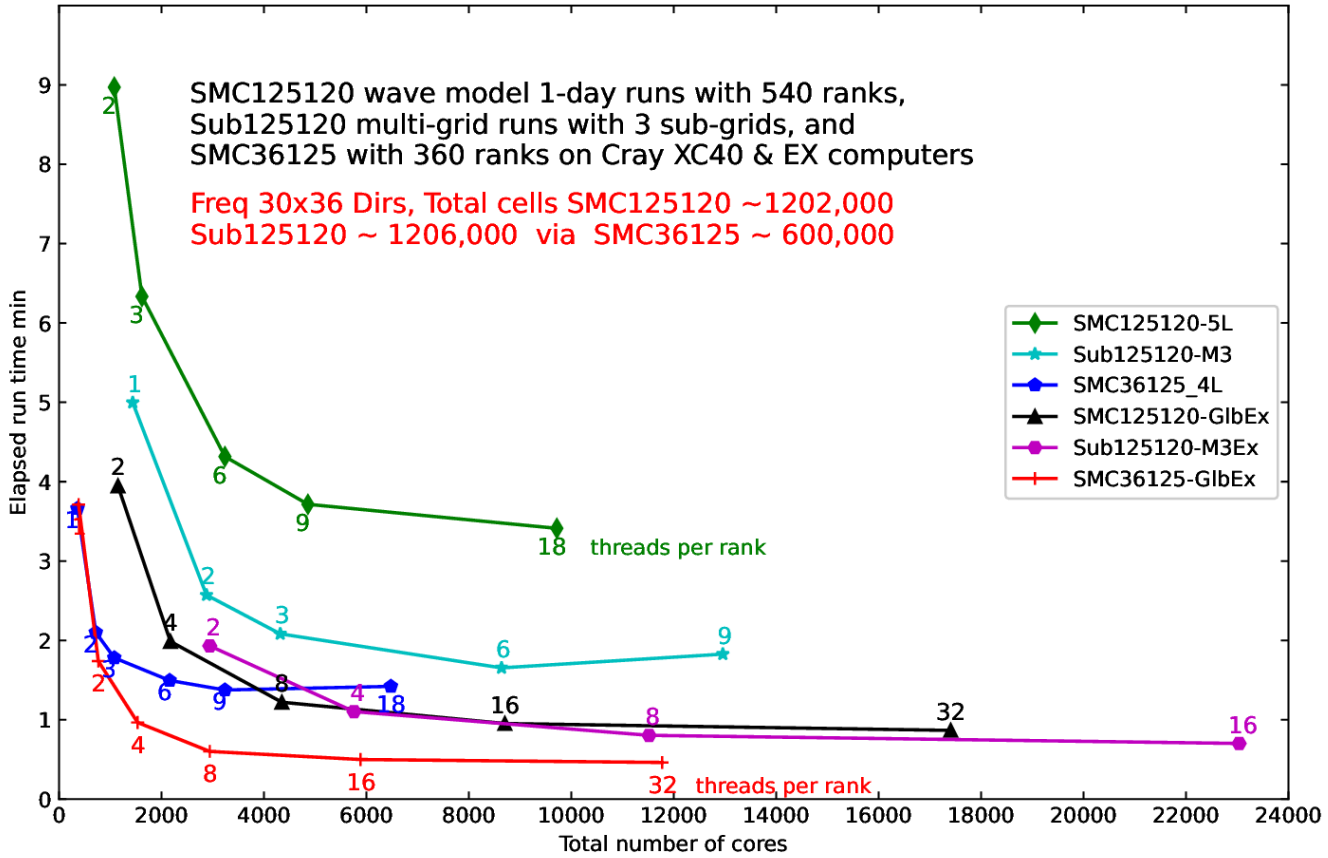
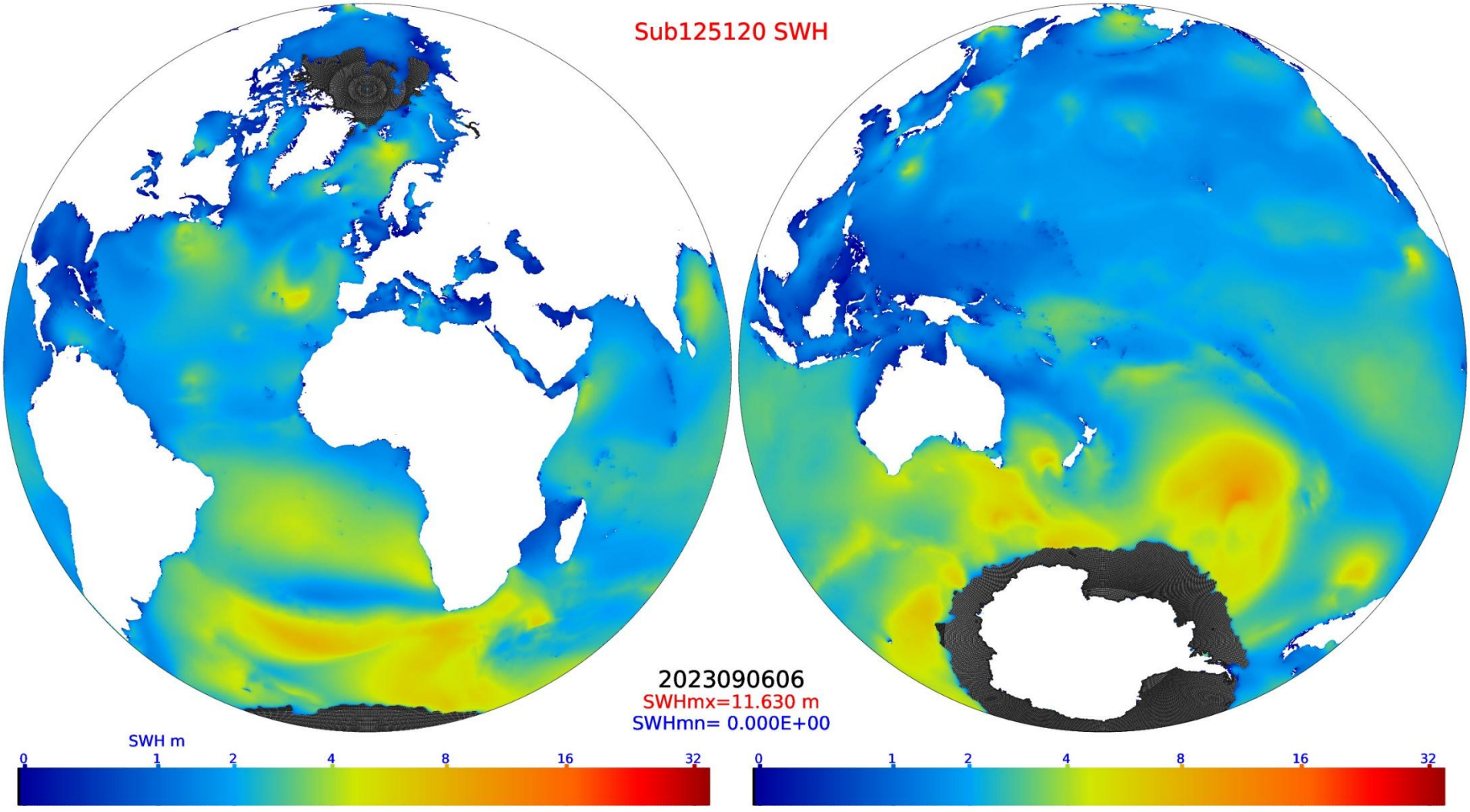
Timing results

- Scalability flattens after 360/540 ranks for MPI runs
- Hybrid runs most efficient for OMP threads within one unit (6/8 threads).
- Best runtime ~1 min per model day.

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SWHmn= 0.000E+00
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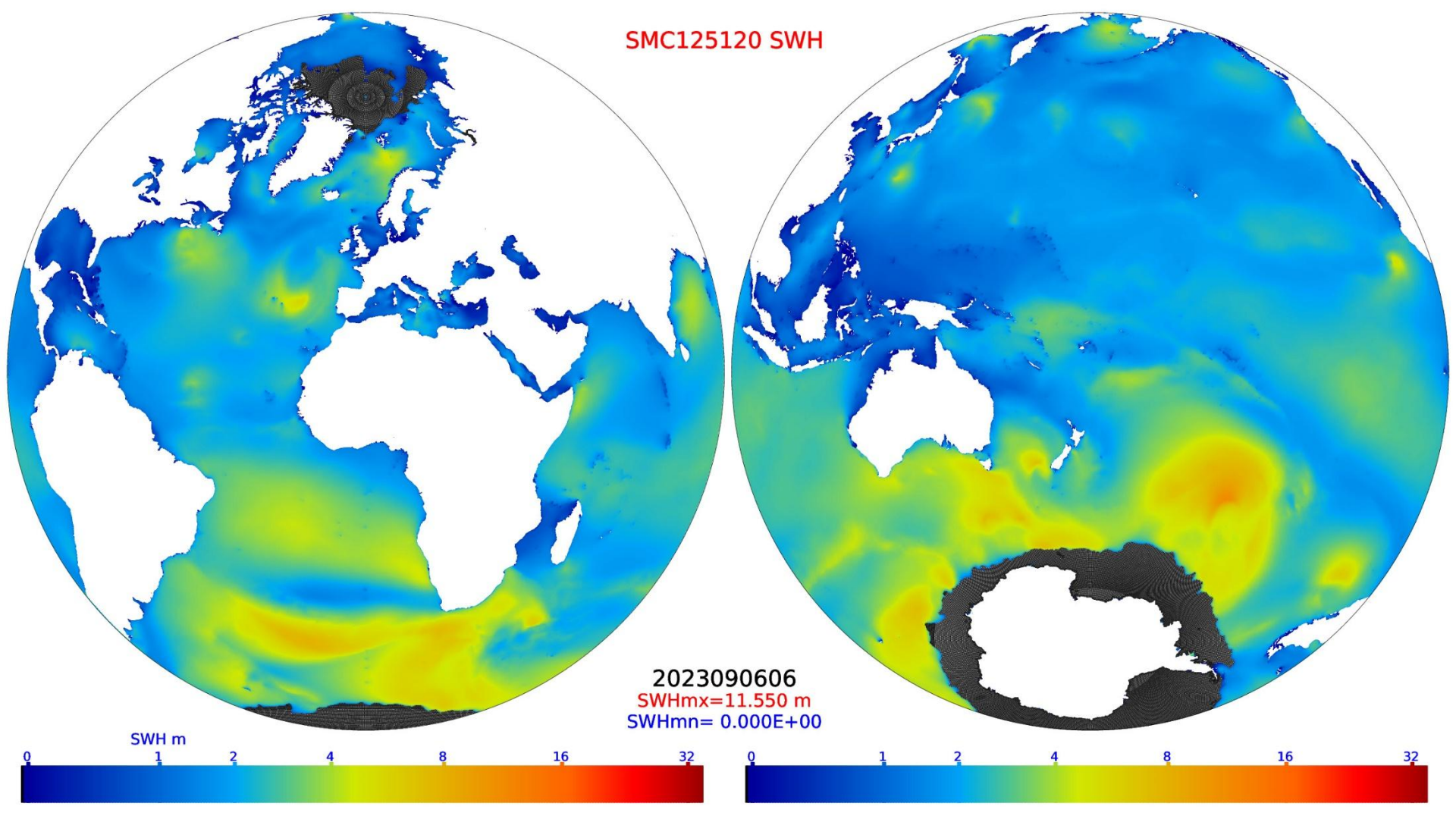
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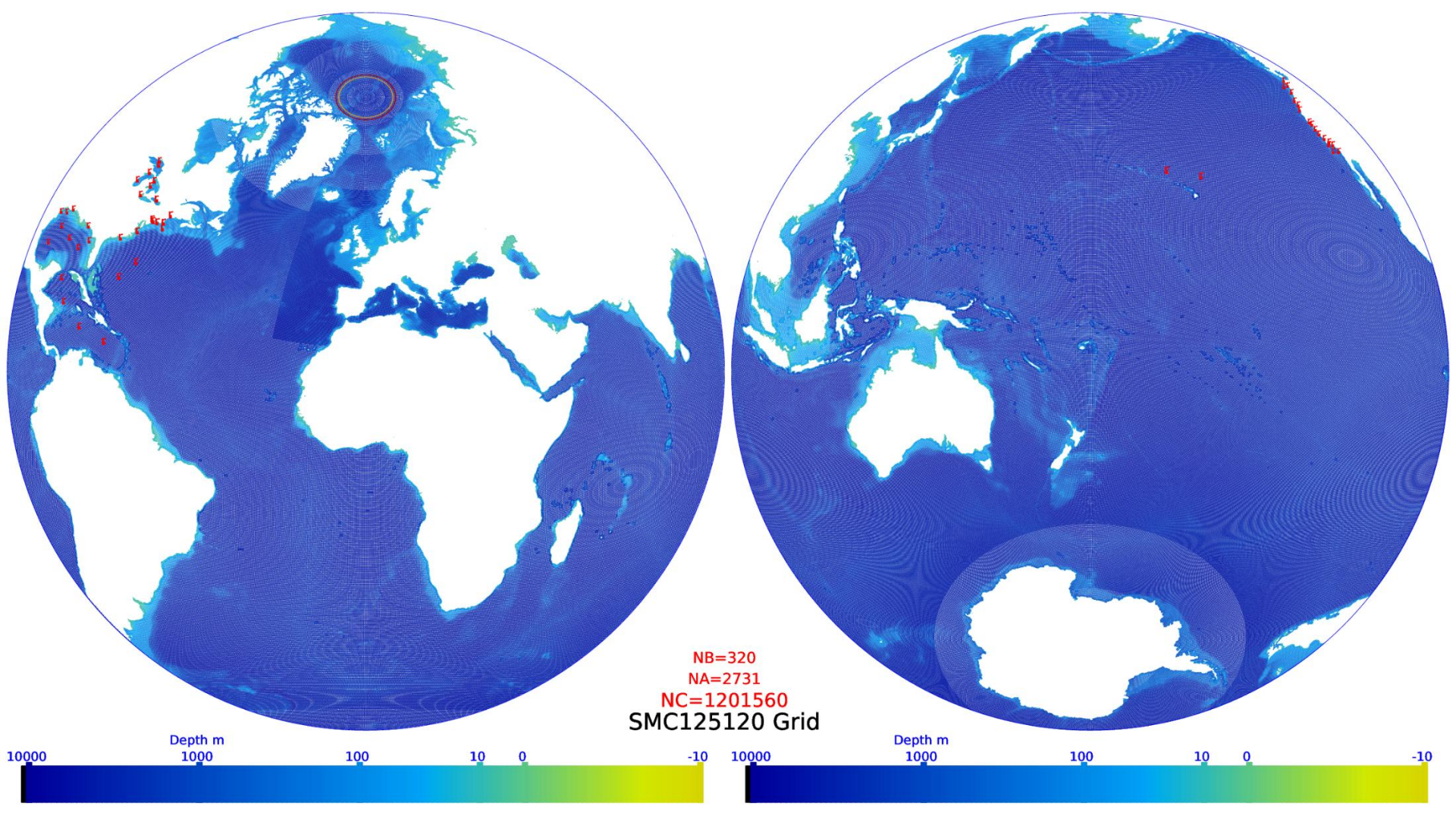
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SMC125120 Grid
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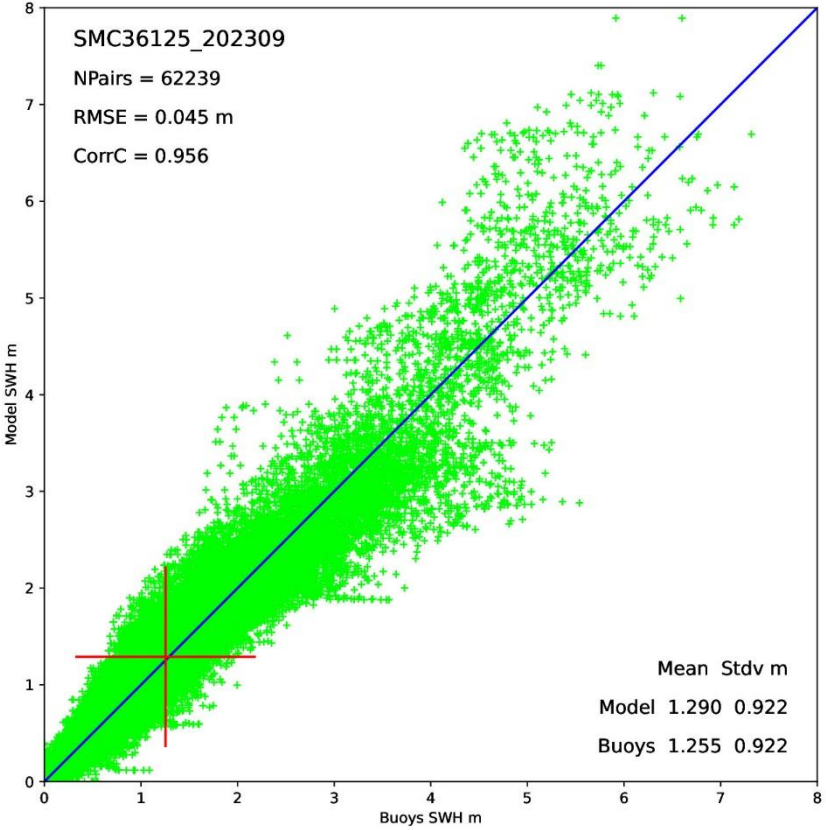
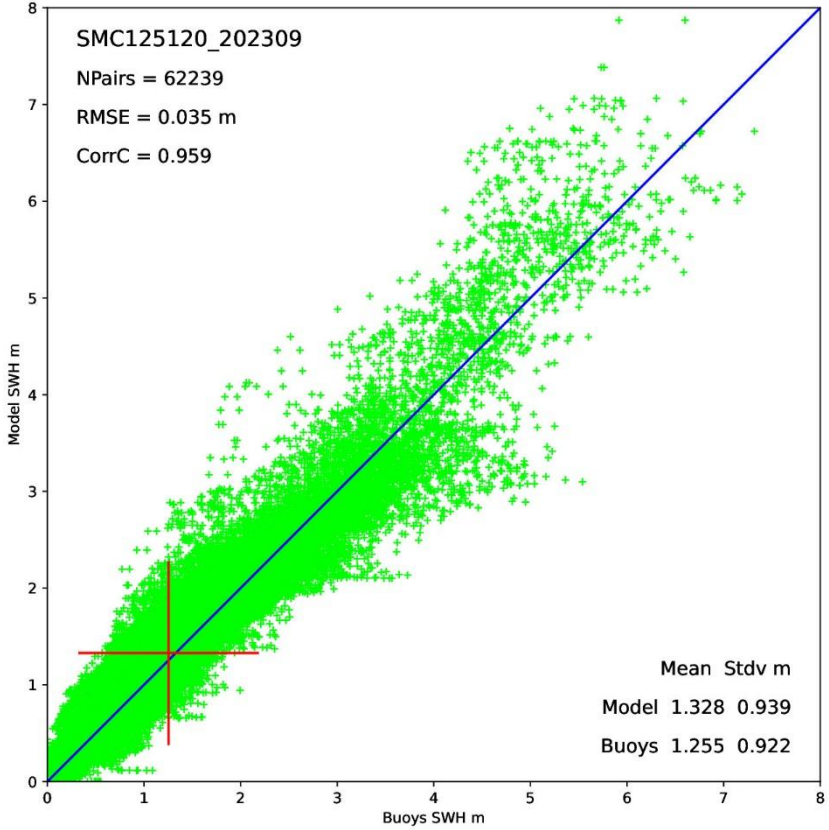
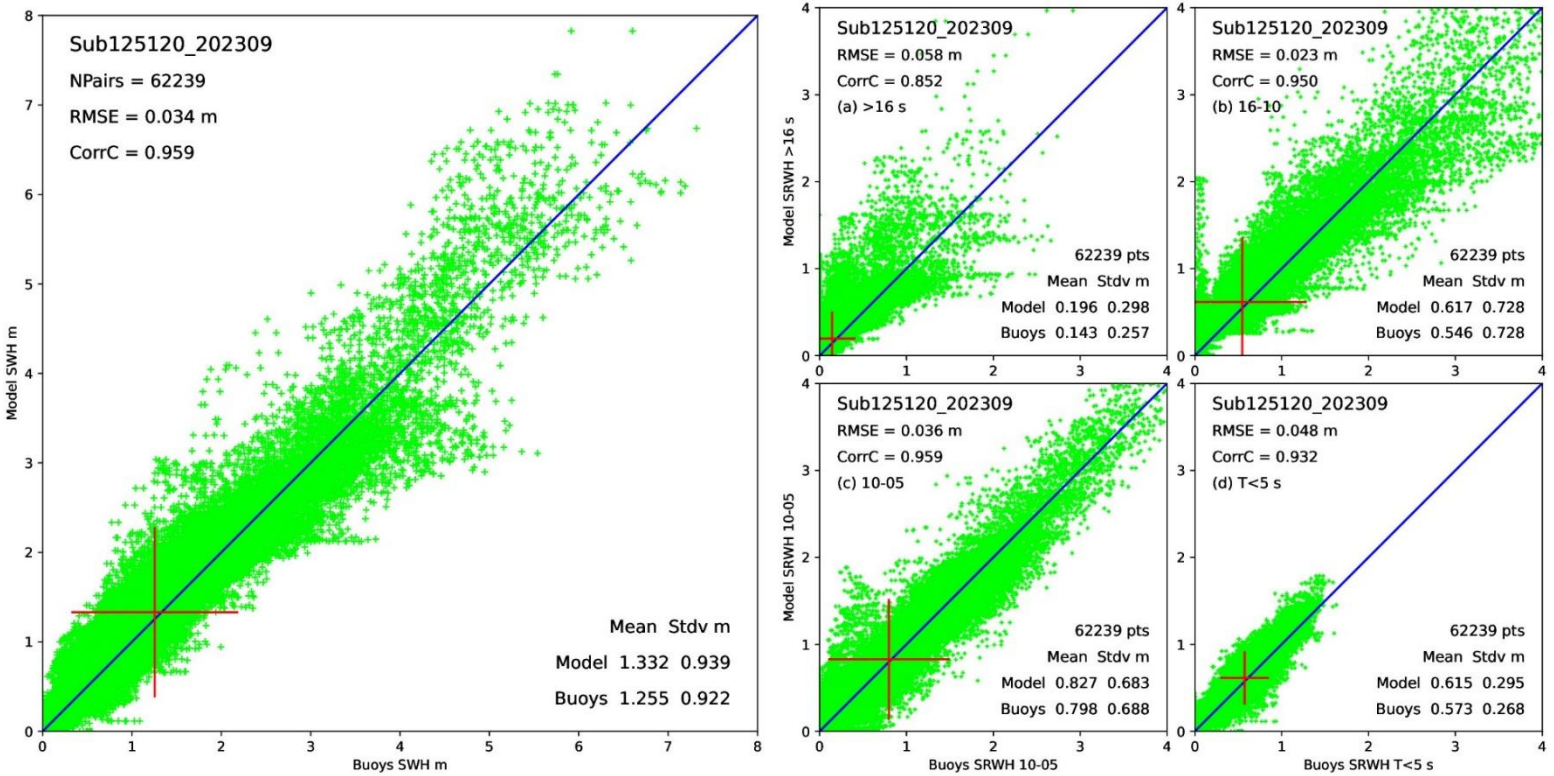
Comparisons SMC36125 and SMC125120 via sp. buoys



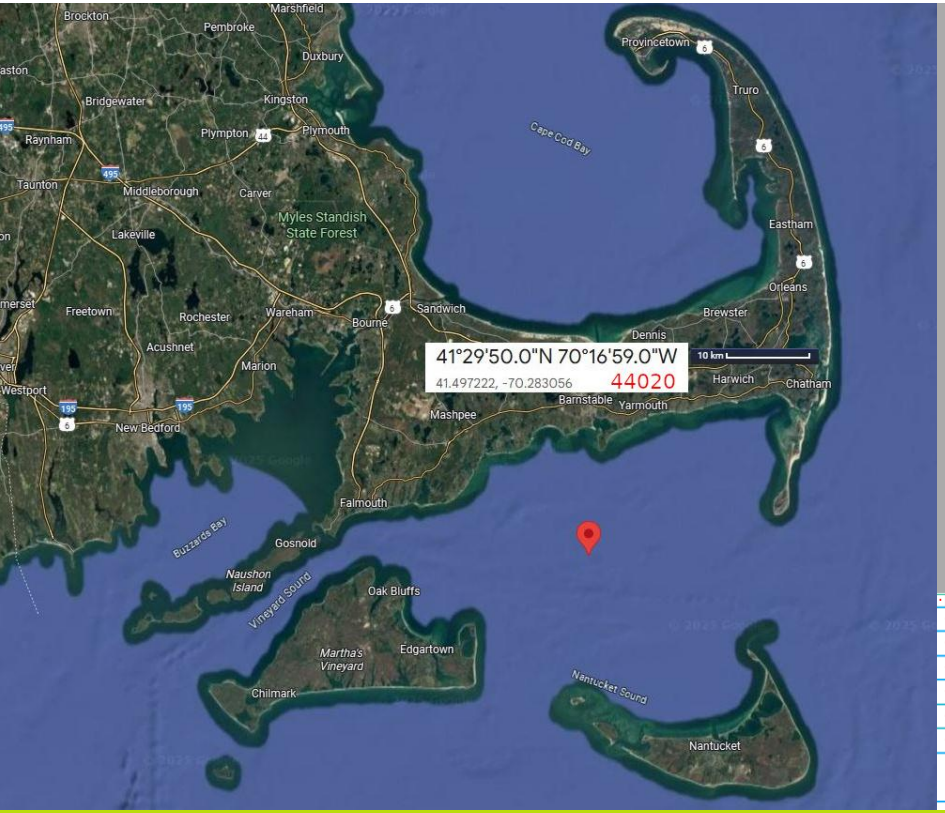


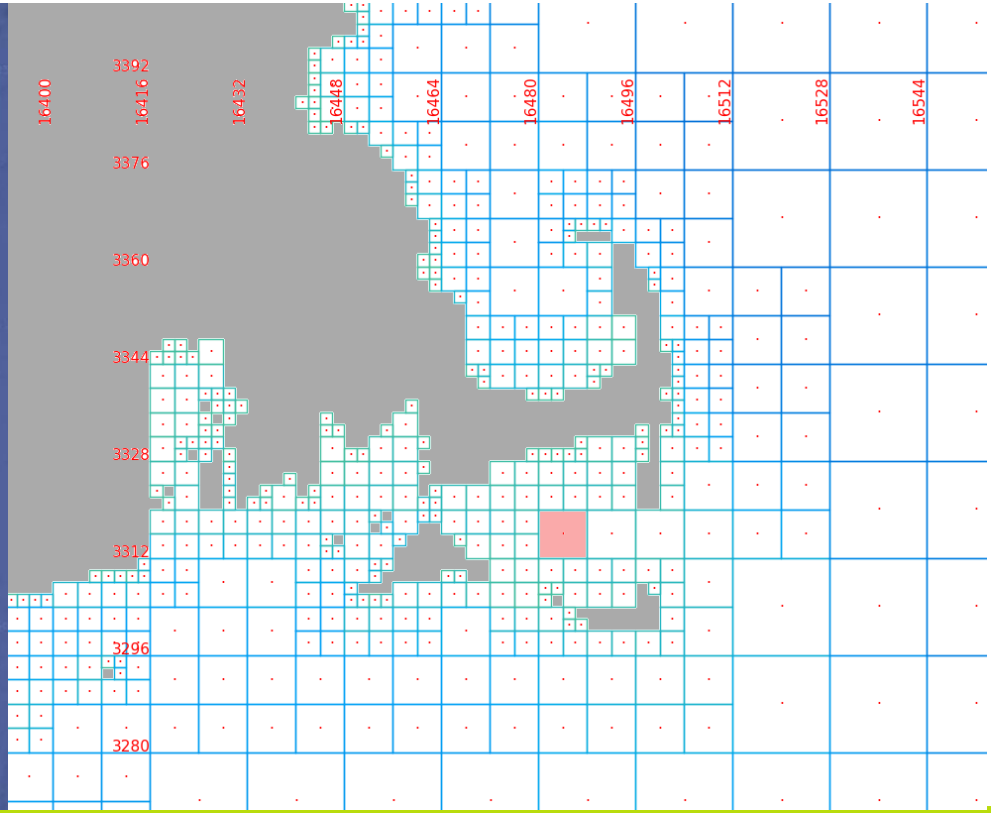
Sub125120 SWH and 4-bin SRWH comparison with sp. buoys



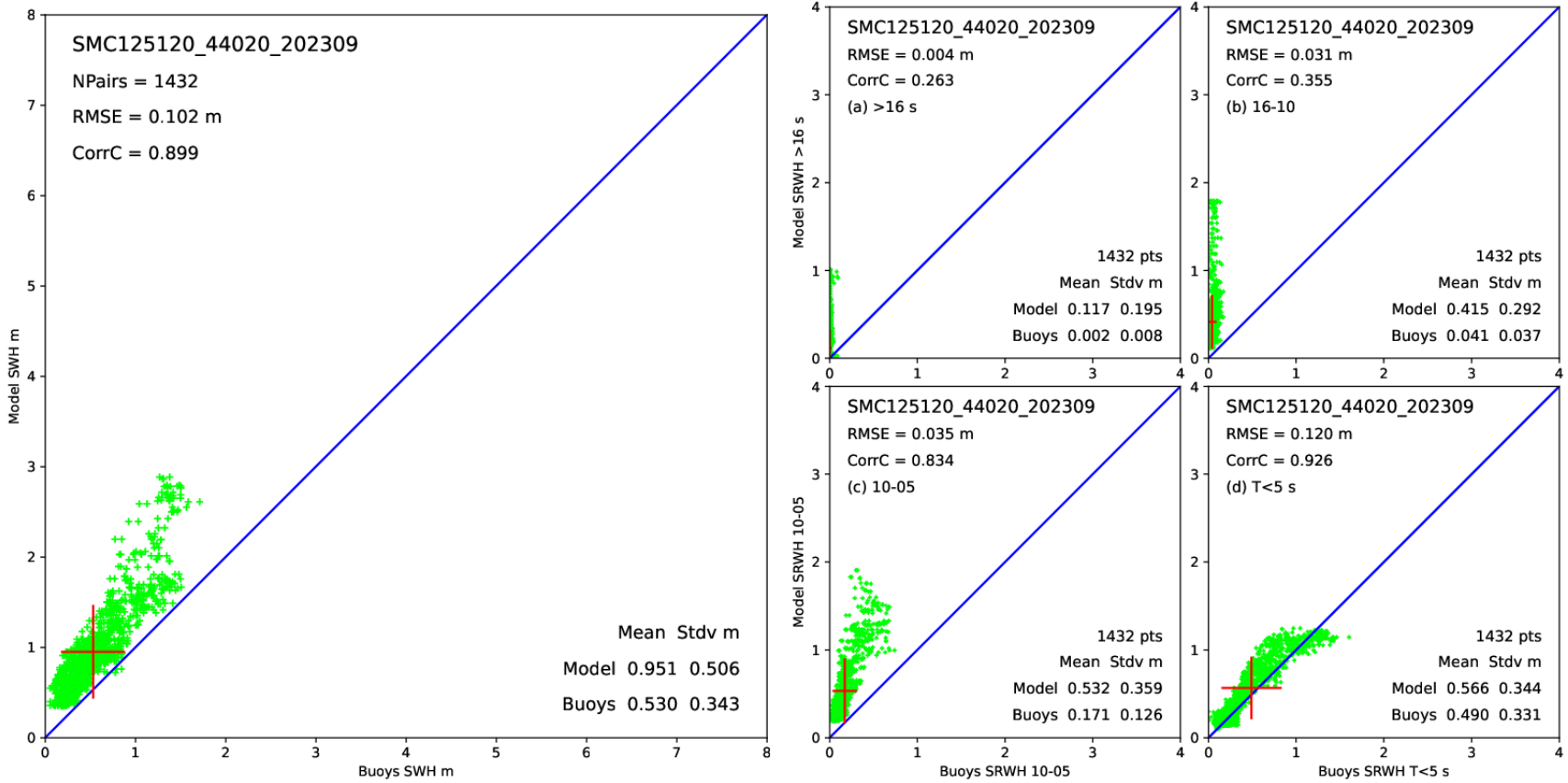
Li, J.G., A. Saulter 2012: Remote Sensing Environment, **126**, 72-83.

SMC 2.5-5-10-20 km cells near buoy 44020 site





SMC125120 SWH & 4-bin SRWH comparison with buoy 44020



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SMC Grid Tools on Github

- Some SMC grid generating and testing tools have been developed and uploaded on Github for public use. The package can be downloaded from the web site:
  https://github.com/ww3-opentools/SMCGTools

- Three guide documents on the SMCGTools web site:

1. SMC_Grids_Guide.pdf introduces SMC grid, the best starting point for new users.
2. SWEsonSMC_Guide.pdf details of Shallow Water Equations (SWEs) model on SMC grids.
3. SMCGTools_Guide.pdf contends instructions to use the SMC grid tool package.

- Three sub-directories contend Fortran, Python and Linux files:

1. F90SMC - Face generating, Propagation test, and SWEs model F90 programs.
2. PySMCs - Bathymetry preparation, SMC grid generating and visualization programs.
3. Linuxs - Linux scripts to sort cell/face arrays, split/trim grids, and run F90/Python programs.

- Comments and suggestions for improvements are welcome.

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Summary and conclusions

- The SMC grid module in WAVEWATCH III® has been updated with improved hybrid parallelisation and multi-grid option.
- Hybrid parallelisation with optimised MPI ranks expanded by OpenMP threads may reduce model runtime by 50% in comparison with MPI runs.
- Multi-grid parallelisation with same ranked SMC sub-grids allows expanded use of computing resources and may reduce model runtime as well.
- Planed UKMO global multi-grid wave forecasting model at 1.25-2.5-5-10-20 km resolutions has been developed and validated. It doubles sea-points of the present global wave model (~600K) to about 1.2 M and improves wave forecast.
- The best averaged runtime of the 5-level wave model on the Cray EX system is about 1 min for one model day, using about 5 to 10 thousand cores.
- Hybrid multi-grid option creates room for higher spatial and spectral resolutions and possible reduced post-processing time with sub-grids.

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Thanks! Questions?

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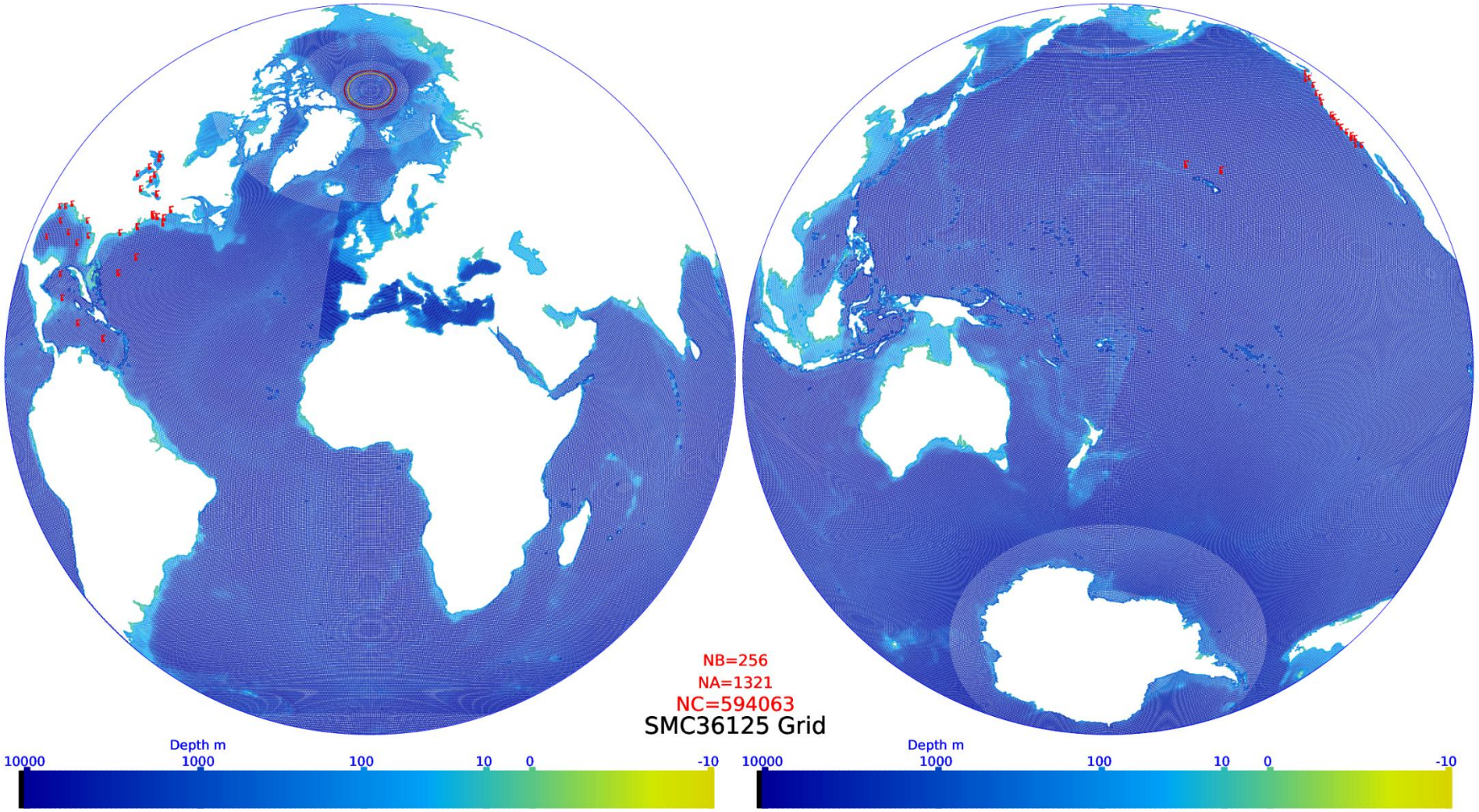
Sea point wind via regular wind in WW3

- Wind forcing is on a rectangular grid for lat-lon grid in WW3 though its wave spectra are stored for sea points only.
- SMC grid has introduced an option to use sea-point only wind forcing.
- MO global wave model is forced by 17 km regular wind from our atmospheric model.
- Regular wind input for the wave model is at the base resolution (17->25 km) and interpolated to multi-resolution sea points inside the model (25 km -> 12/6/3 km).
- Sea-point only wind interpolates the raw 17 km wind directly to the multi-resolution sea points (17 km -> 25/12/6/3 km). So differences are restricted near coastlines.
- The difference is in refined (12/6/3 km) cells which have wind interpolated either from 25 km (regular wind) or 17 km (sea point wind). For computation load the two options differ at the extra spatial interpolation for regular wind and reduced file sizes in sub-grids for sea-point only wind.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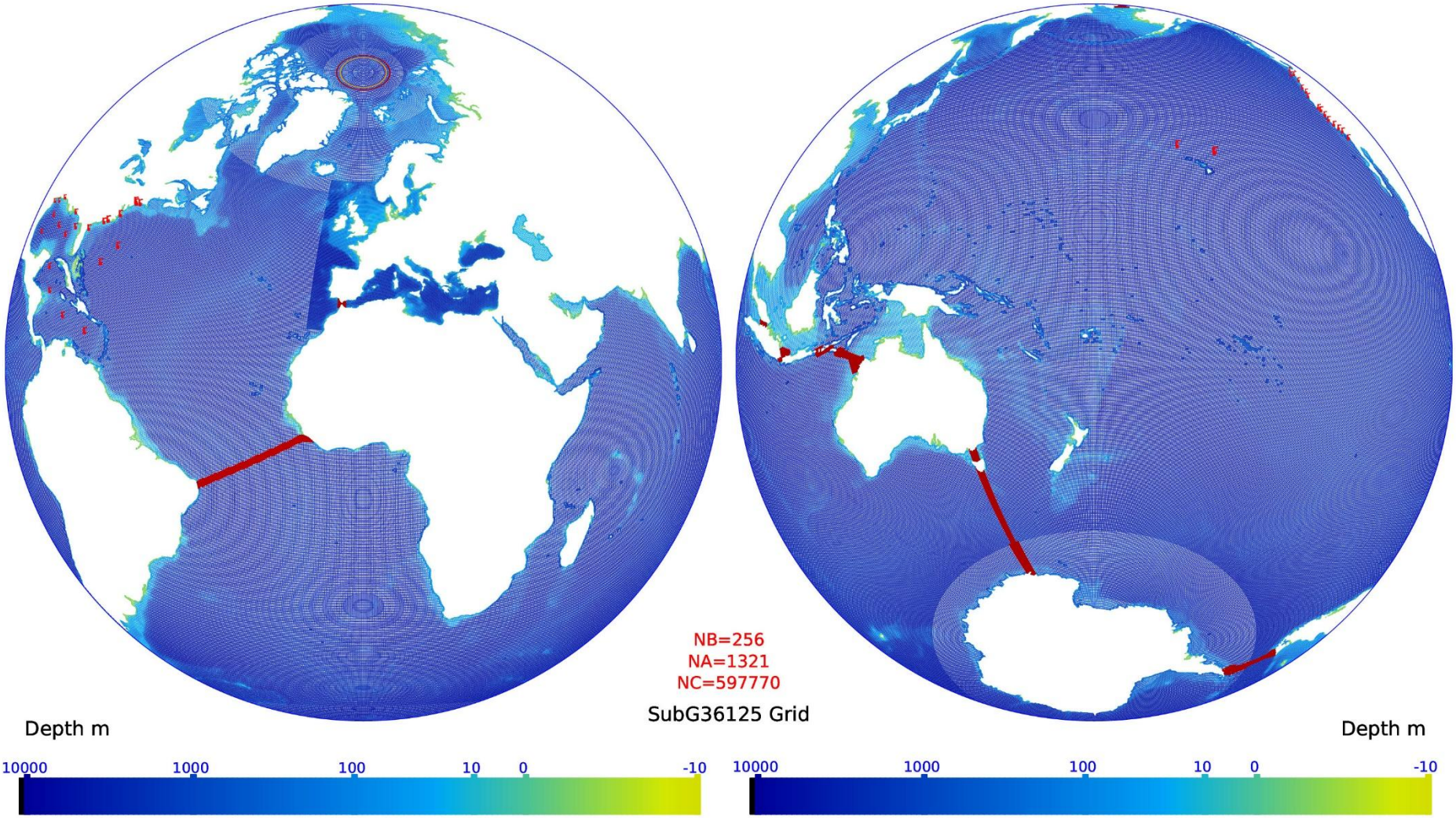
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SubG36125 Grid
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