Hybrid multi-grid parallelisation of WAVEWATCH III model on Spherical Multiple-Cell (SMC) grids

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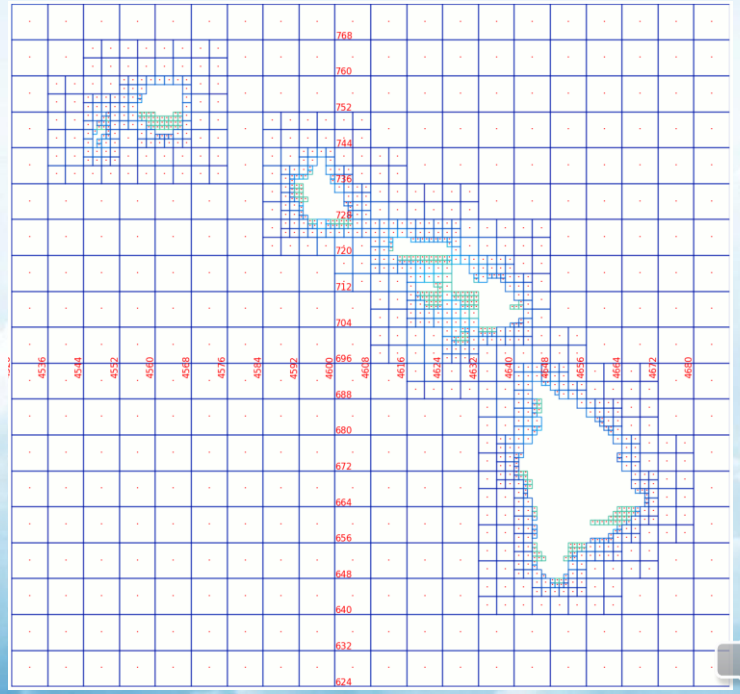

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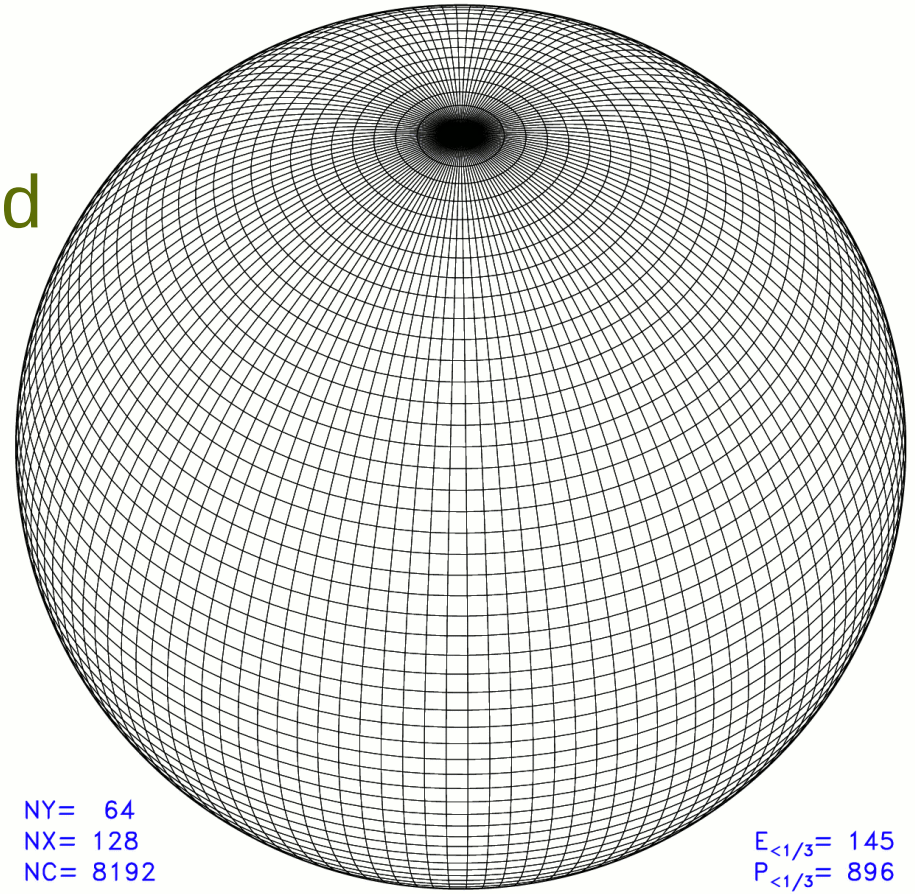
Three parts in this presentation

1. Spherical Multiple-Cell (SMC) grid --- a brief introduction.
2. Hybrid (MPI-OpenMP) parallelization in WAVEWATCH III (WW3).
3. Multi-grid option for SMC grid in WW3.

Polar problems in lat-lon grid

1. Severe CFL restriction on Eulerian advection time step at high latitudes.
2. The Pole is a singular point and flow has to go around it, not crossing it.
3. Scalar assumption of vector components becomes invalid near the Poles due to increased curvature of the longitude circles.



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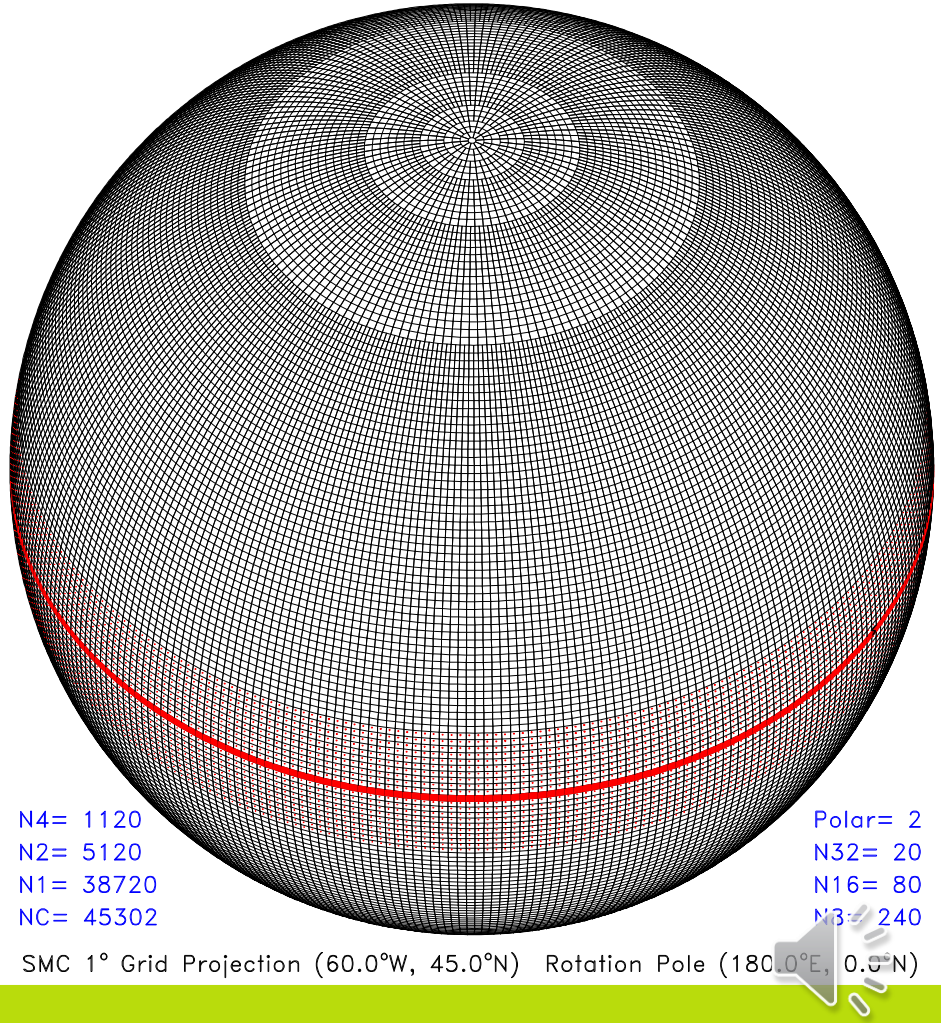
Spherical Multiple-Cell grid

- Merged cells at high latitudes to relax CFL limit on time step, like a reduced grid.
- Round polar cells with integral equation to avoid polar blocking and singularity.
- Use fixed reference direction to define vector components in polar regions.

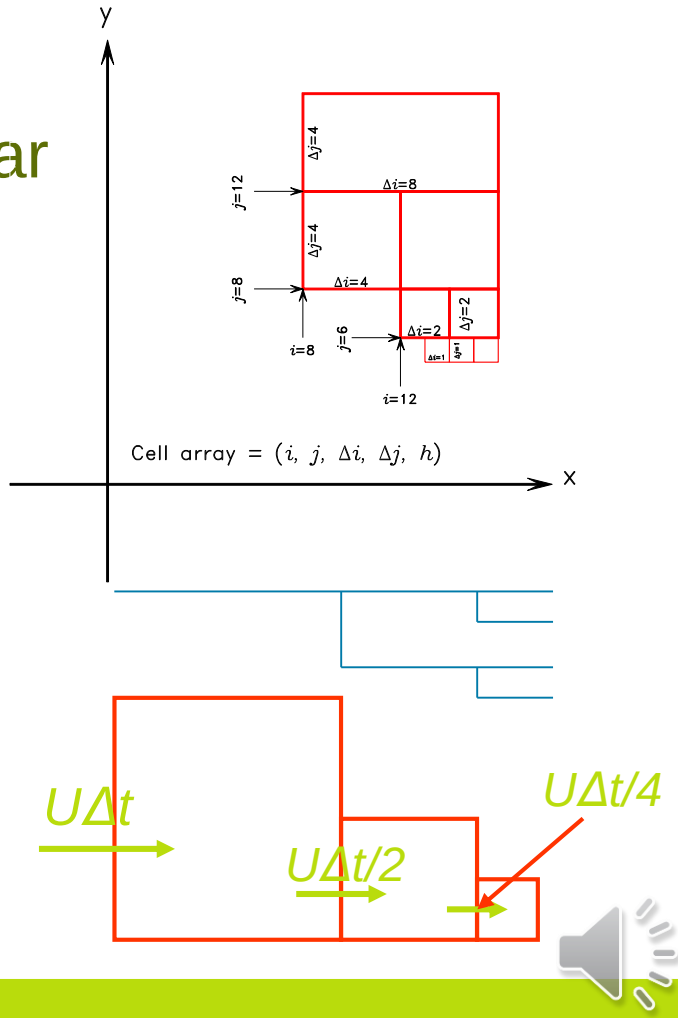
- Reference: Li, J.G. 2011: *Mon. Wea. Rev.*, **139**, 1536-1555.



Unstructured SMC grid with rectangular cells and pointer-oriented loops

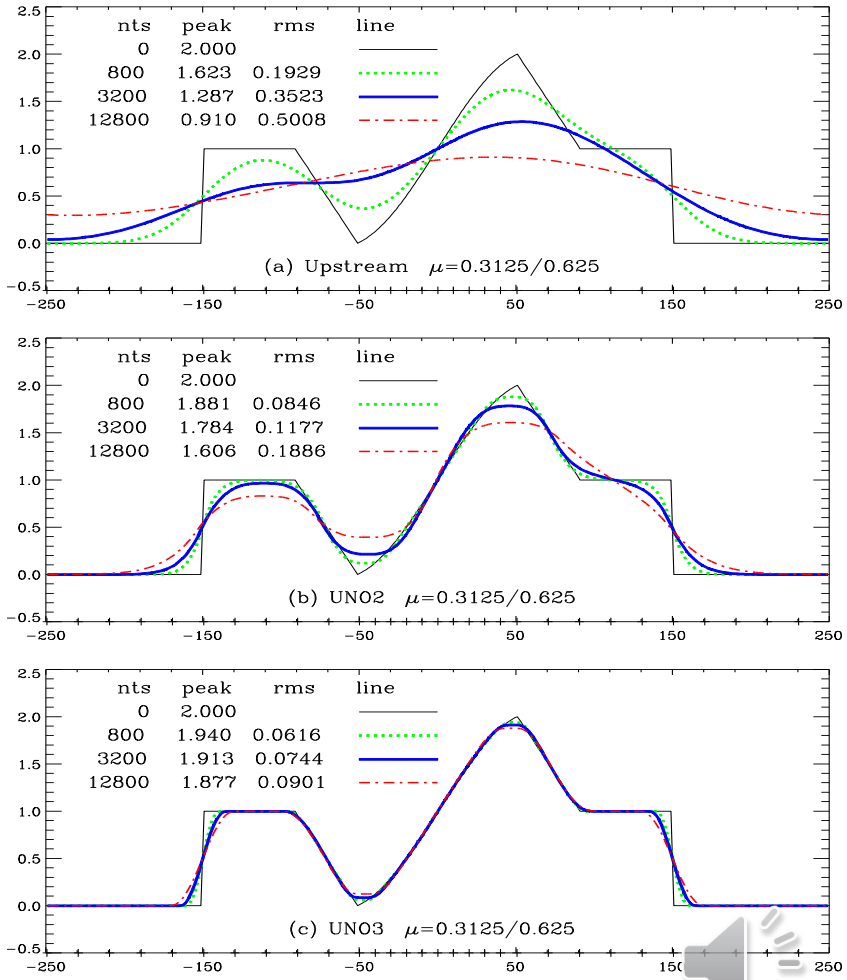
- Cells are defined by location and size indexes and multi-resolution by refinement.
- Transport fluxes are calculated with face-array or pointer-oriented loops.
- Sub-timesteps are used for refined cells in sub-loops for efficiency.
- One-dimensional array loop convenient for parallelization.

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



Upstream Non-Oscillatory advection schemes

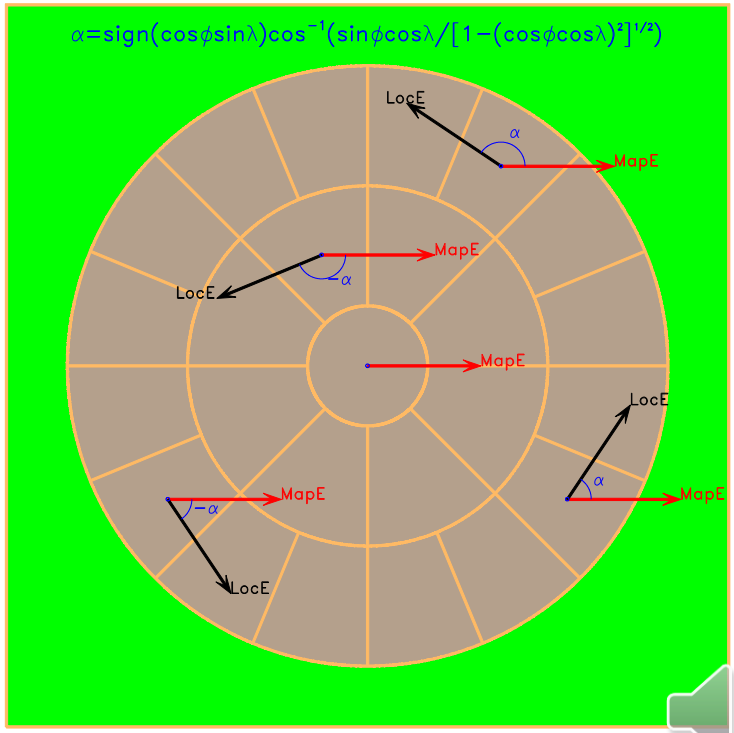
- Choice of 2nd and 3rd order UNO advection schemes are available on SMC grid.
- Recommend the 2nd order UNO2 scheme for wave models, fast and accurate enough.



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

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 scalar assumption of vector component invalid.
- Define vector components with fixed reference direction --- the map-east, instead of the rapidly changing local east in polar regions.

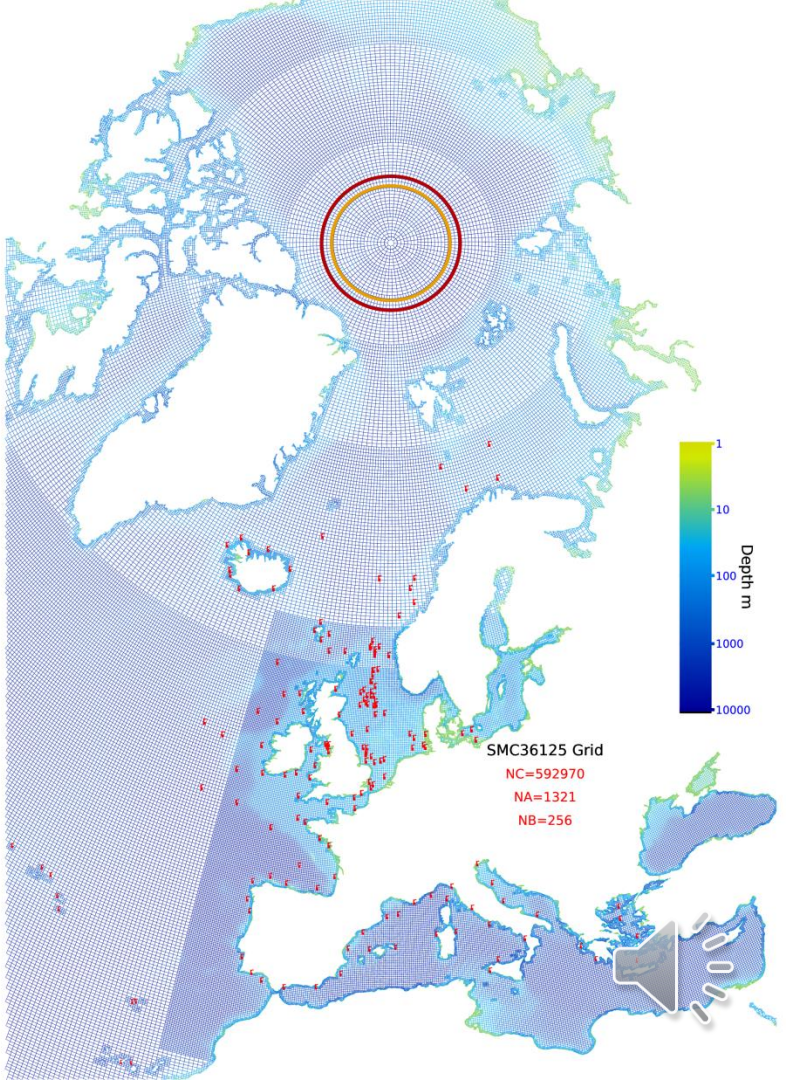


Li, J.G. 2016: *Ocean Dynamics*, **66**, 989-1004.

WW3 SMC update in PRV6 and MO SMC36125 wave model

- SMC grid has been implemented in WW3 since 2014 V4.18 and updated 2019 PRV6.
- MO started operational use from 2016 with a 3-6-12-25 km SMC grid global wave model.
- Refined 3, 6, 12 km European region to replace old European 8 km wave model.
- The global model is driven by 25 km regular wind at present and MPI parallelization on 10x36 PEs.

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



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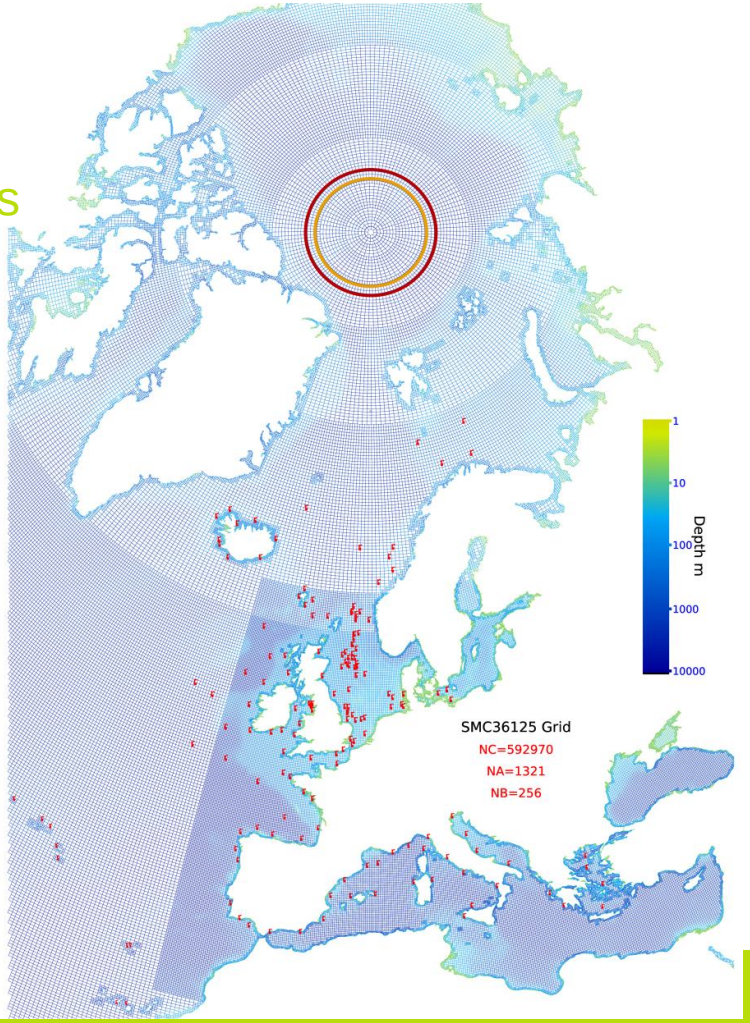
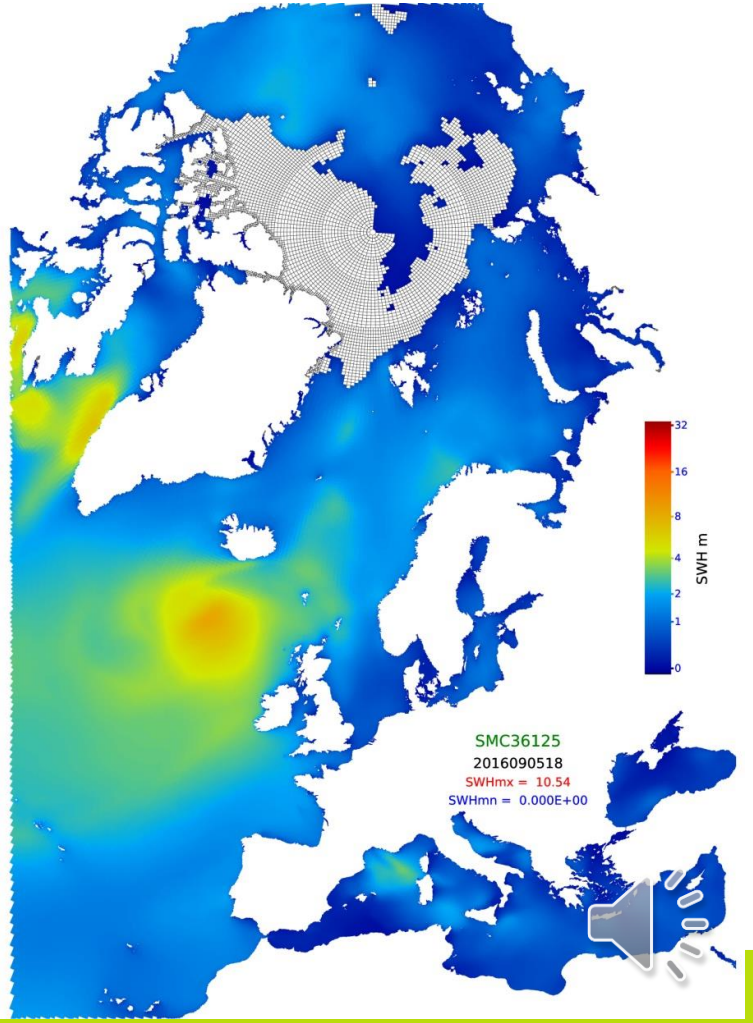
Arctic sea ice retreat demands polar extension

Commercial shipping lines across Arctic in summers are in sight.

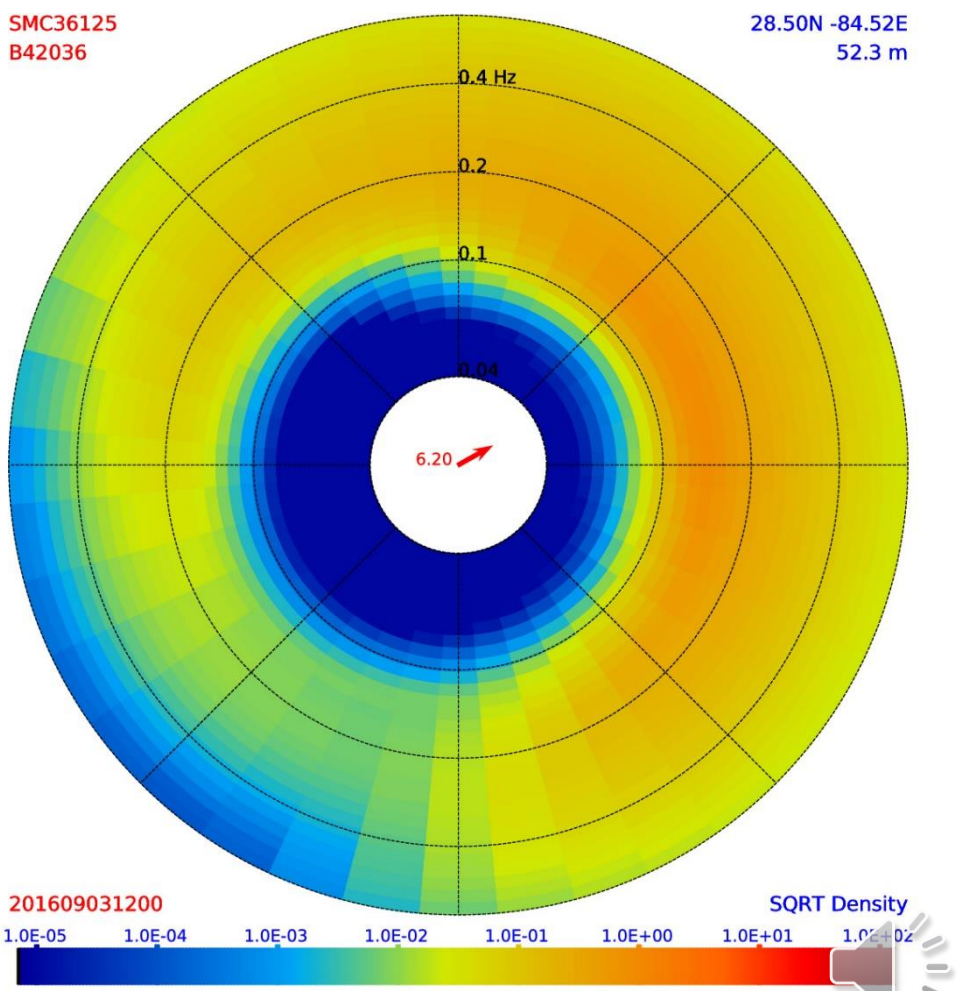
Oil industry is also aiming at extracting the oil reservoir underneath.





Wave model spectrum

- Ocean surface wave model solves for 2-D wave spectrum, which usually has 36 directions and 30 frequency bins or 36x30 = 1080 spectral components at each point.
- Its memory demand is comparable to a 3-D ocean model.
- Its physics is complicated, including spatial propagation of each spectral component and source terms on the whole spectrum.

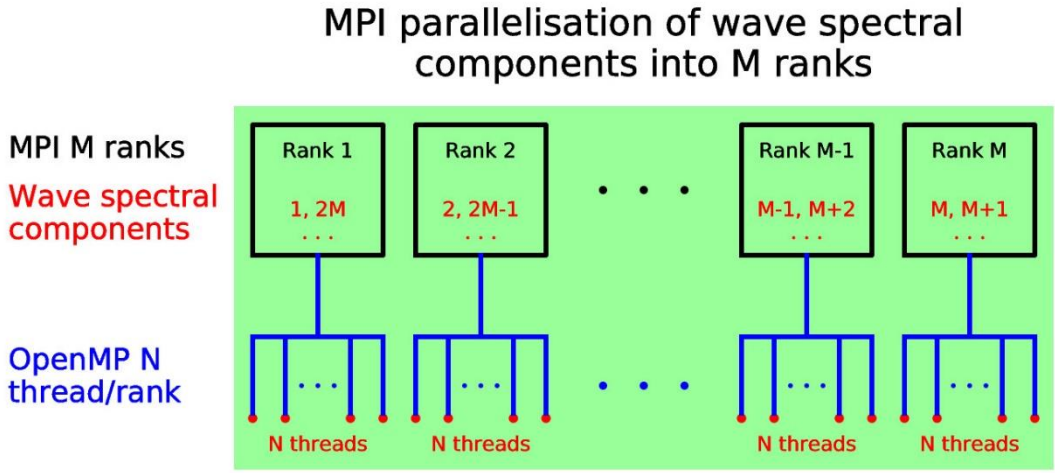


WW3 parallelization schemes, CD method

• 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.

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



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Hybrid parallelization in WW3 SMC grid

- Supercomputer Cray XC40 in Met Office, 36 PEs per node, ~ 10,000 nodes

- WW3 MPI parallelization uses, at most, 36*30 = 1080 PEs or 30 nodes, but optimised at 1080/3 = 360 ranks (10 nodes) due to different wave speed.

- Hybrid parallelization may extend to 30*N nodes, but most efficient near 360 MPI ranks or 10*N nodes.

- Spatial propagation of 1 spectral component on SMC grid is parallelized with OpenMP on N-threads. Simple OpenMP directives are inserted as SMC grid uses 1-D loops.

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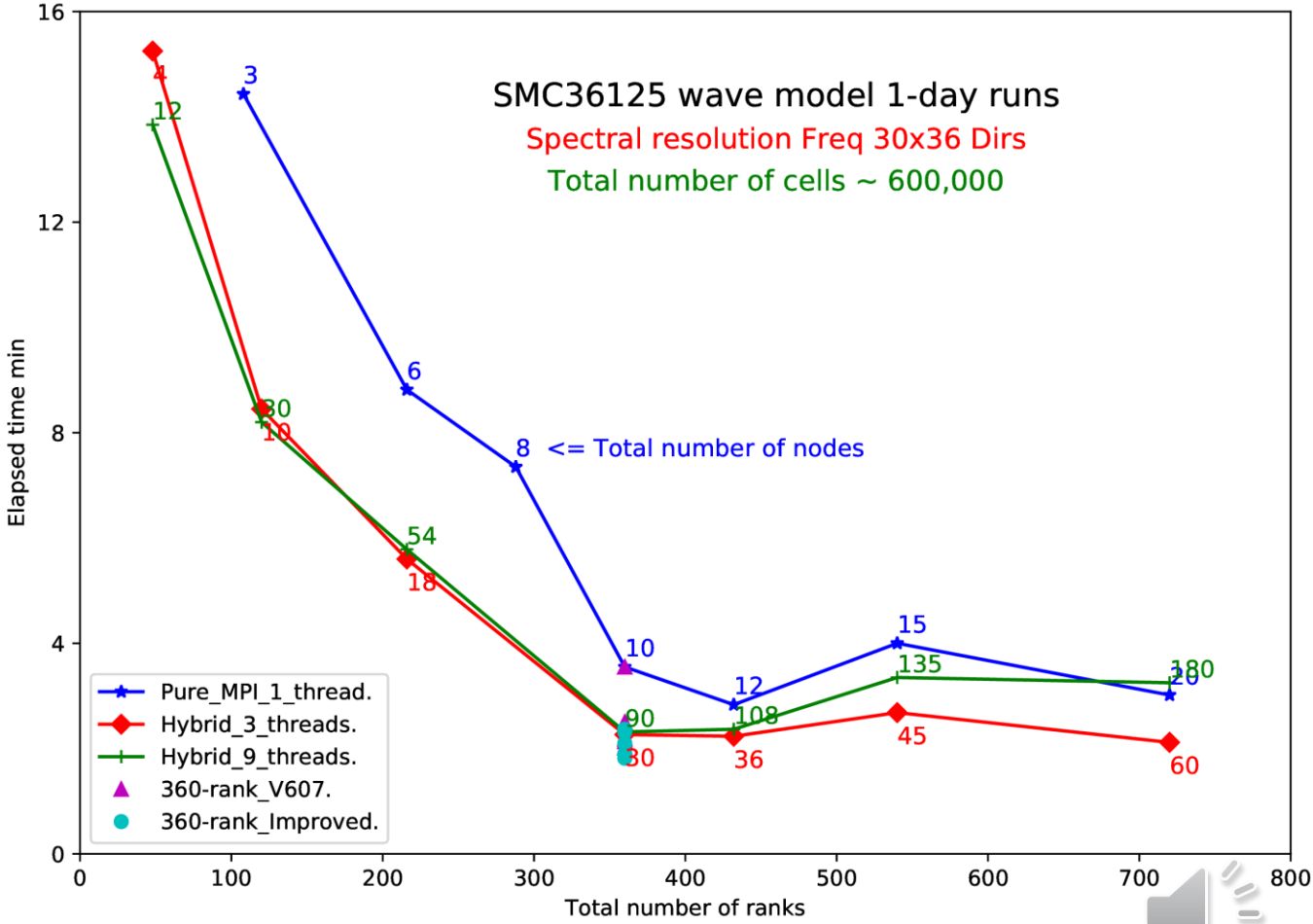
Timing results

Scalability flattens after 360 ranks for both MPI & Hybrid runs, due to load balance of different spectral components at different speed.

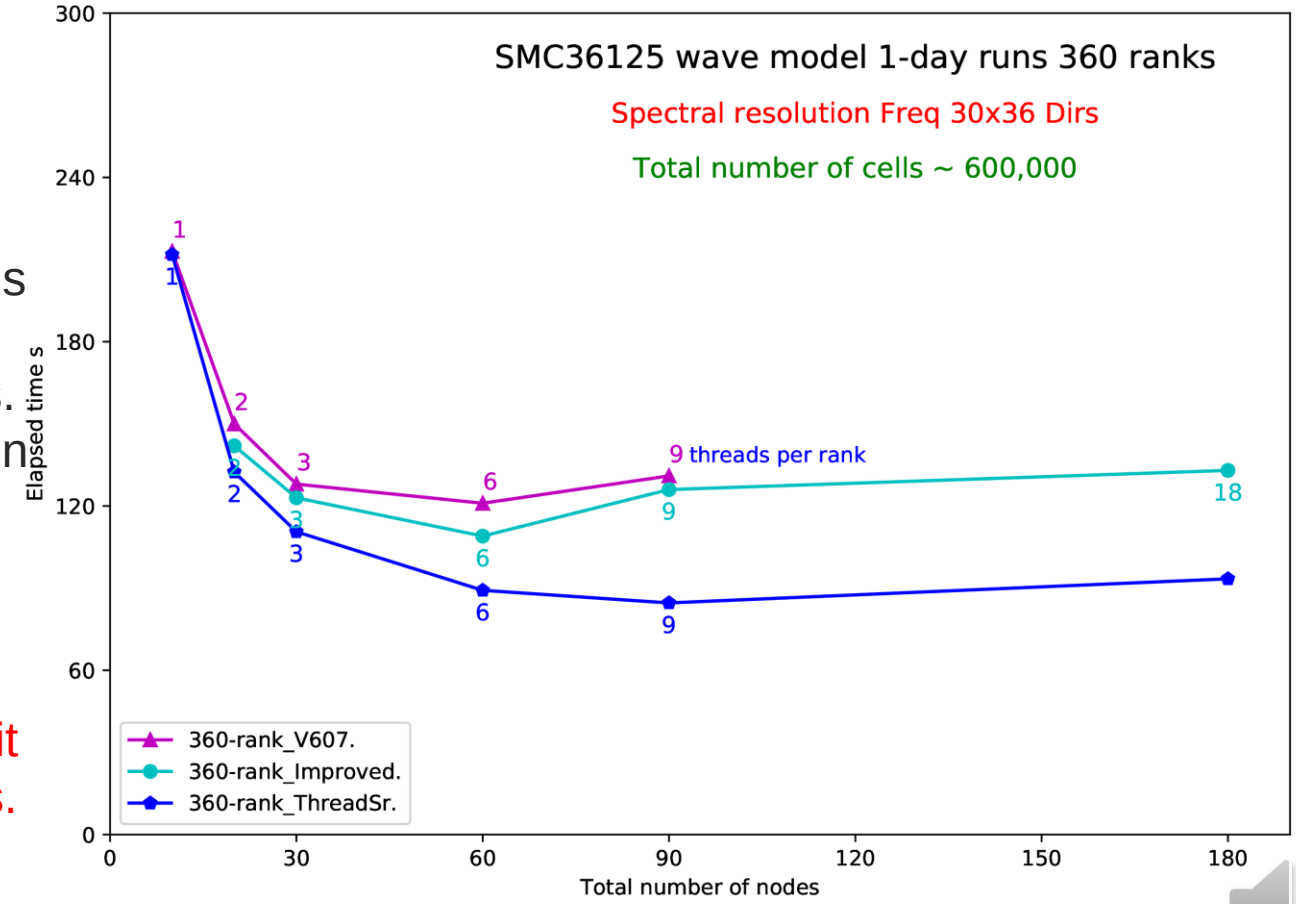
CD methods has a limit to use as many MPI ranks as 1/3 of spectral components.



Timing results

Hybrid OpenMP flattens after 3 threads and quickest at 9 threads for 360 ranks. Most efficient run is on 90 nodes, ~ 50% reduction of elapsed time.

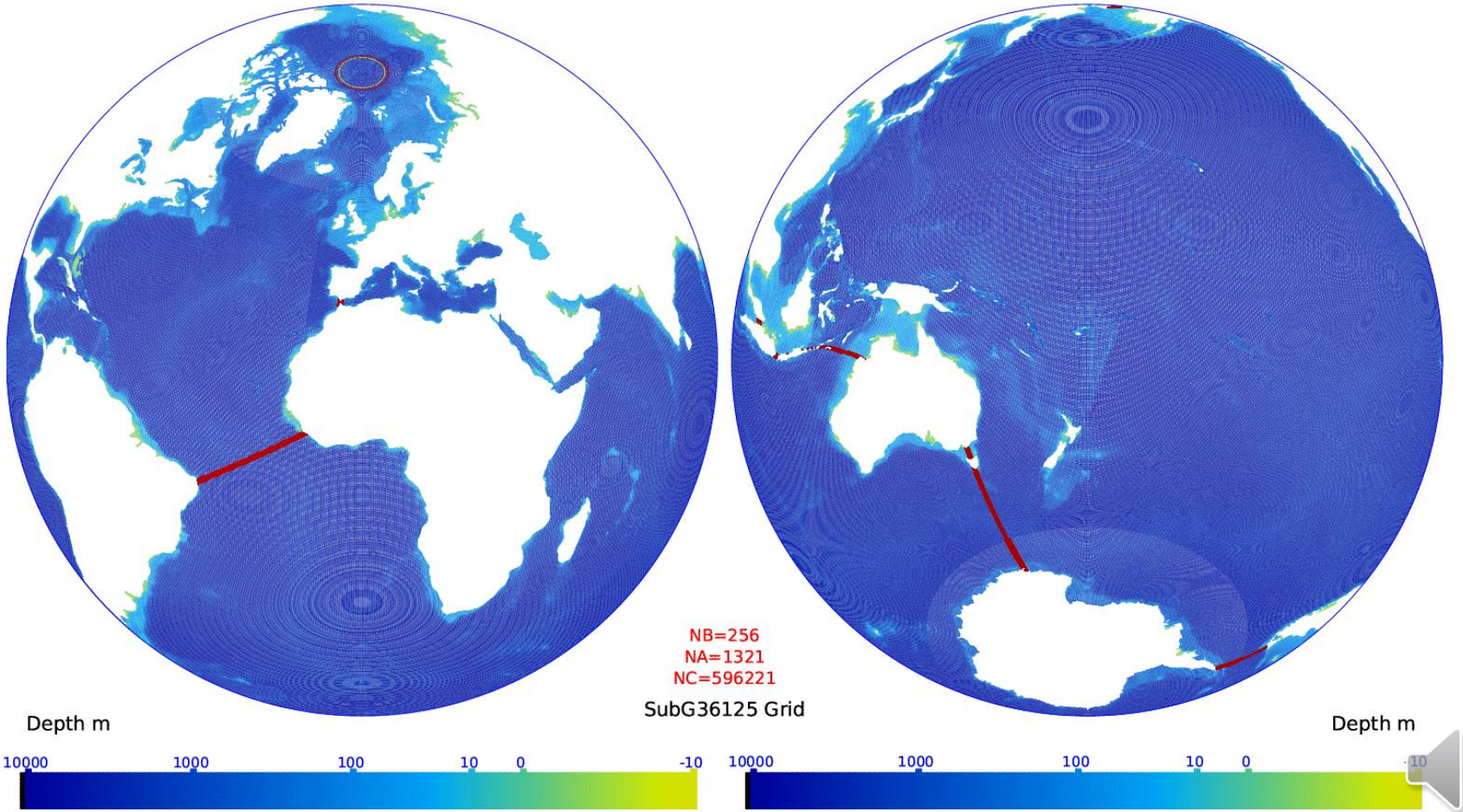
Hybrid also has a limit of 9 OpenMP threads.



Multi-grid option for SMC grid in WW3

- WW3 model has a multi-grid option mainly for regular lat-lon grid (2002). It allow sub-grids to run in parallel like Domain Decomposition (DD), while keeping each sub-grid parallelised with the CD method.

- Multi-grid option not only allows the combined CD-DD parallelization, it also creates room for higher resolutions.
- SMC grid in WW3 is now updated to use the multi-grid option (2020).
- Boundary exchange is simplified as 1-1 corresponding spectral exchange.
- Two, 3 and 4 grids are tested so far and validated against spectral buoys.


NB=256
NA=1321
NC=596221
SubG36125 Grid
Depth m
10000
1000
100
10
0
-10
Depth m
10000
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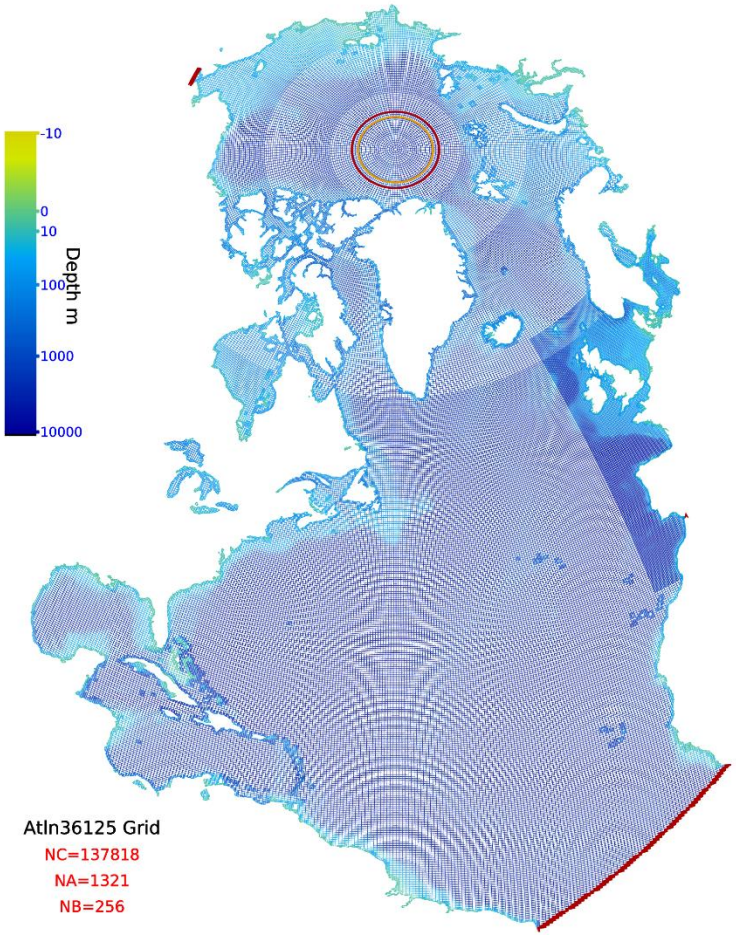
-10
0
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Depth m
AtIn36125 Grid
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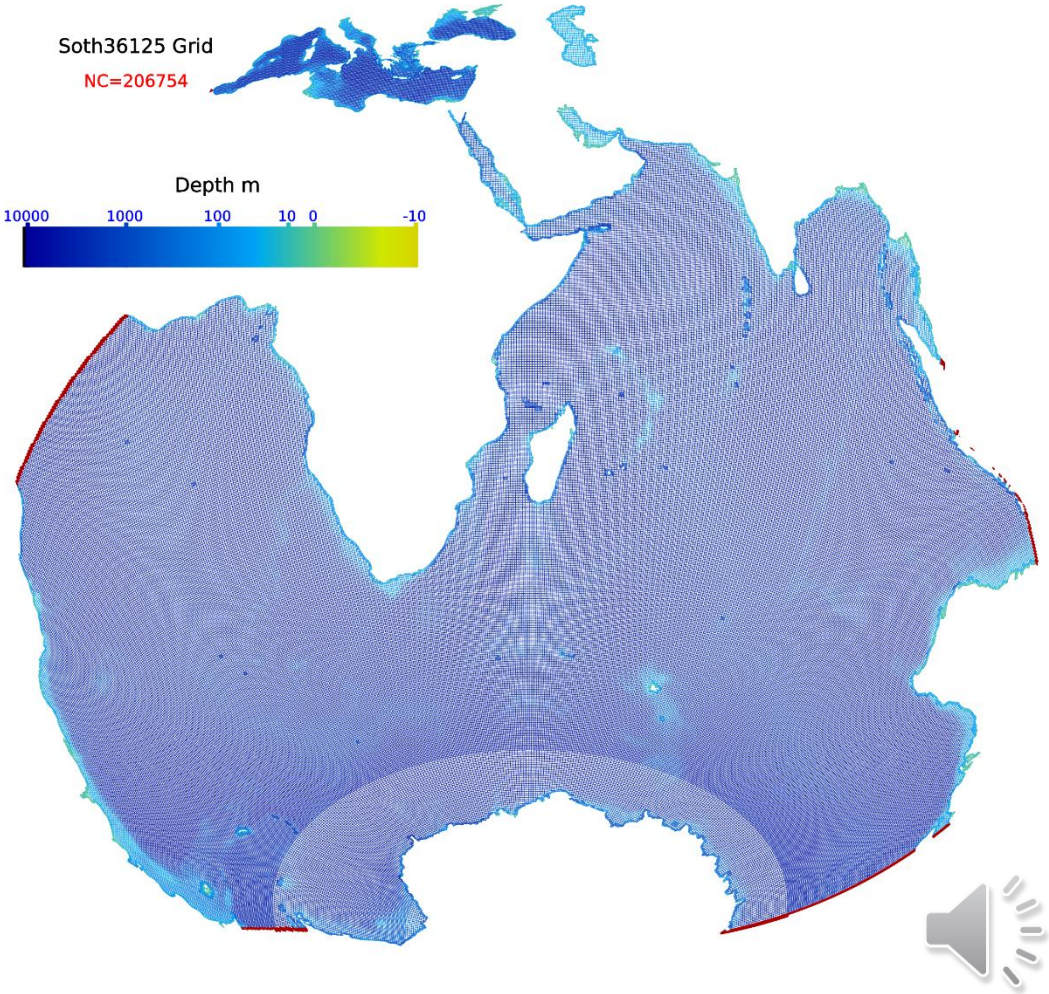
NB=256


Soth36125 Grid
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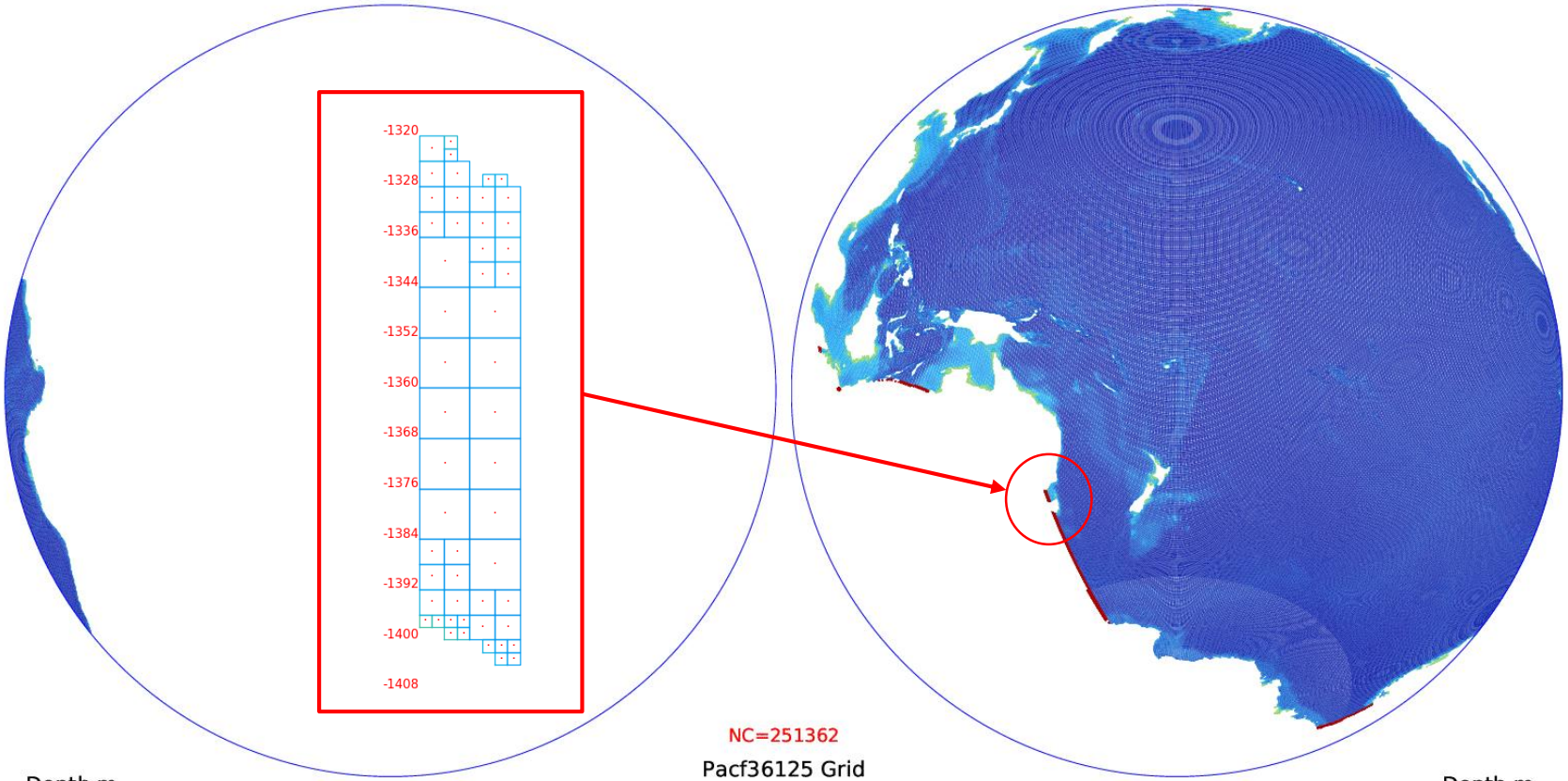
Depth m
10000
1000
100
10
0
-10


-1320
-1328
-1336
-1344
-1352
-1360
-1368
-1376
-1384
-1392
-1400
-1408
NC=251362
Pacf36125 Grid
Depth m
10000
1000
100
10
0
-10
Depth m
10000
1000
100
10
0
-10

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Cells in the 3 sub-grids and their computing load

	NSEA	N1	N2	N4	N8	NEqu^	NBdy	T/20N*
Soth	206754	18990	19810	24665	143289	423779	953	50 s
Pacf	251404	566	23083	26000	201755	350615	653	55 s
Atln	137818	17155	25868	34422	60373	369929	308	48 s
Global	594063	36617	68305	84652	404489	1139949	0	132 s

^ Equivalent number of cells = N8 + 2xN4 + 4xN2 + 8xN1

* Elapsed time for one model day on 20 nodes (360 ranks, 2 threads per rank)

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Balance of computing load among sub-grids

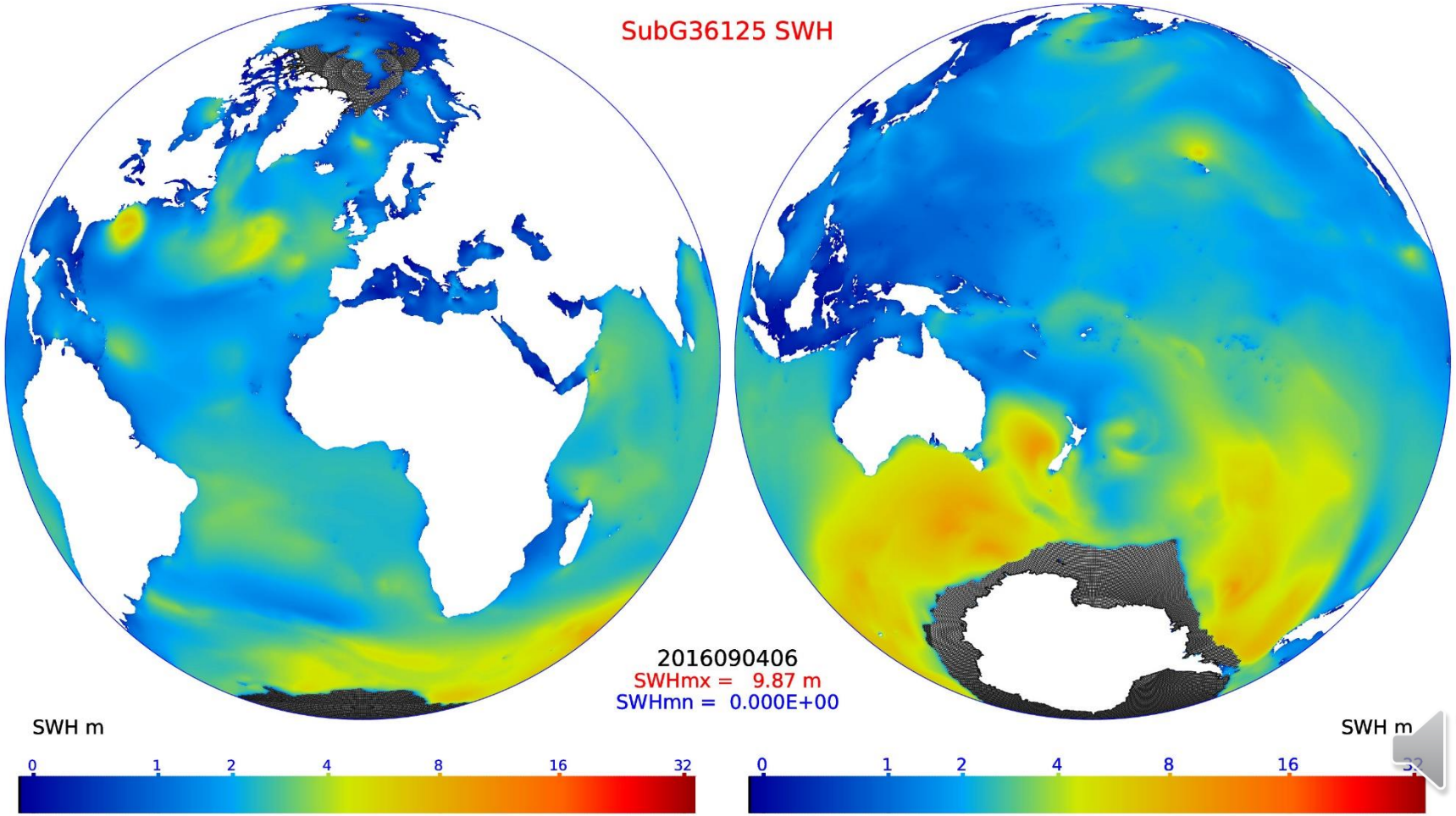
- WW3 multi-grid option allows distribution of computing resource among sub-grids by given ratios.

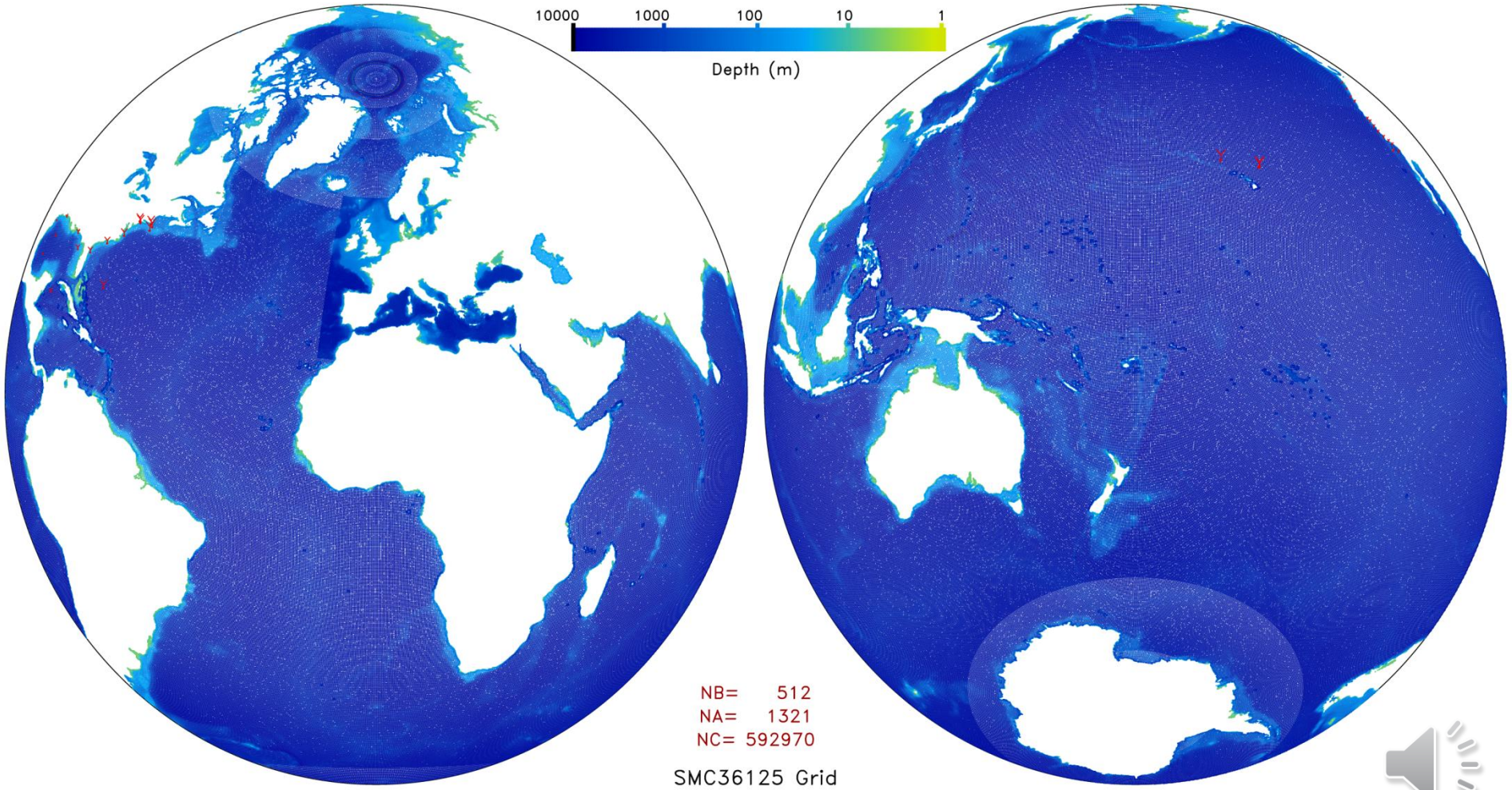
- For example, the 3 sub-grids are assigned the same ratio of 0.3333 and they can ran on 30, 60, 90, 180, … nodes with 360 MPI ranks each and 1, 2, 3, 6, … OpenMP threads per rank, respectively.

- If computing loads are not balanced among the sub-grids, different ratios may be used for different sub-grids to re-balance the run time, for instance a 4 sub-grids run with the resource ratios: 0.2 : 0.25 : 0.25 : 0.3

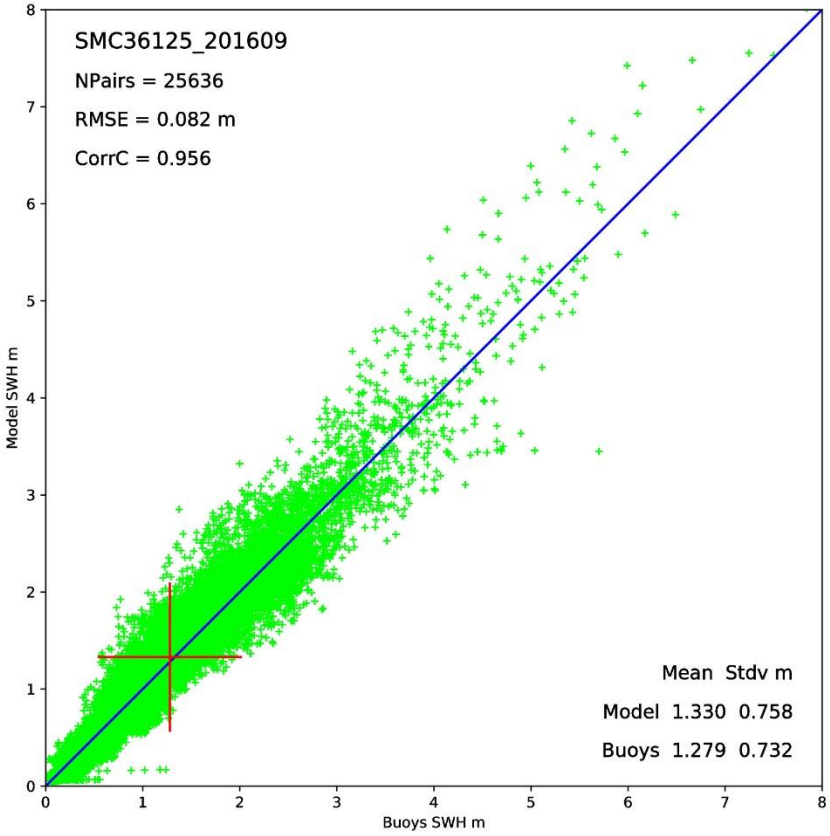
Sea point wind via regular wind in WW3

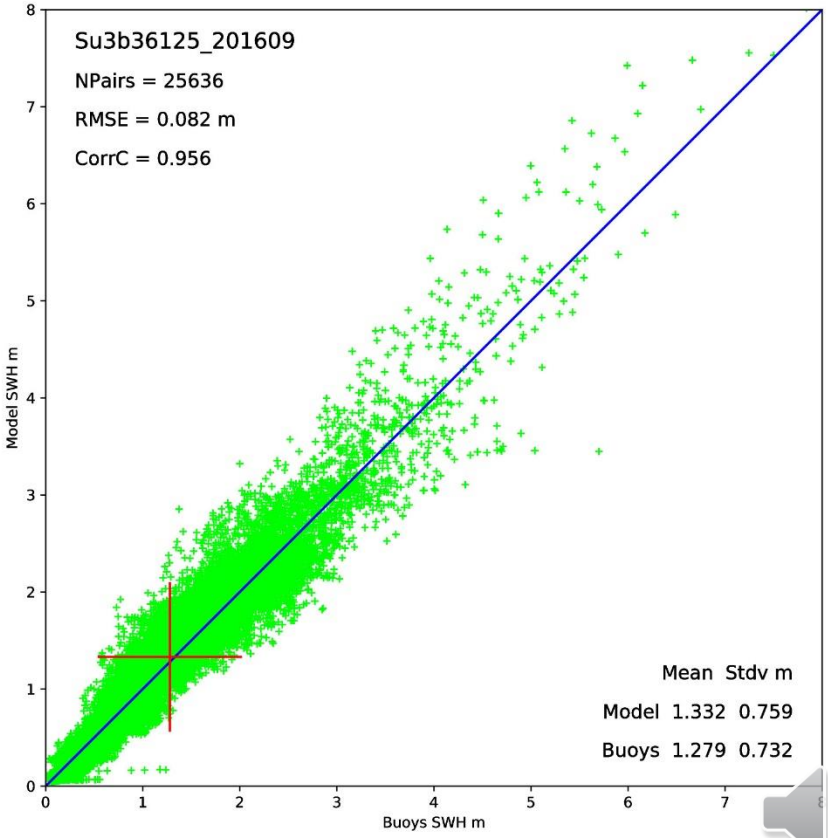
- Wind forcing is on a rectangular grid for lat-lon grid in WW3 though its wave spectra are stored for sea points only.
- SMC grid has introduced an option to use sea-point only wind forcing.
- MO global wave model is forced by 17 km regular wind from our atmospheric model.
- Regular wind input for the 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.


SubG36125 SWH
2016090406
SWHmx = 9.87 m
SWHmn = 0.000E+00
SWH m
0
1
2
4
8
16
32
SWH m
0
1
2
4
8
16

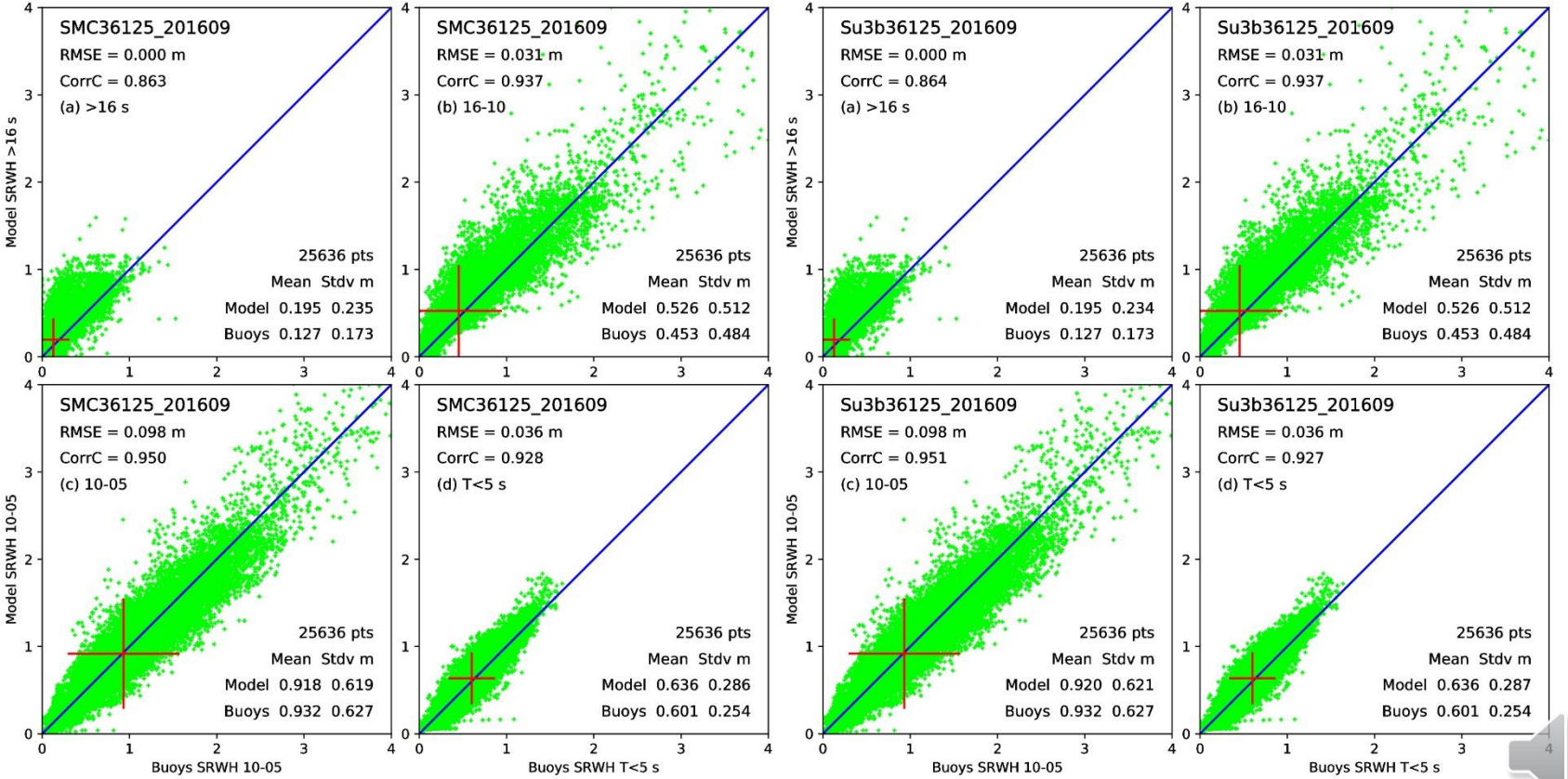

10000
1000
100
10
1
Depth (m)
NB= 512
NA= 1321
NC= 592970
SMC36125 Grid

Comparisons with spectral buoys SMC via 3-Sub-Grids



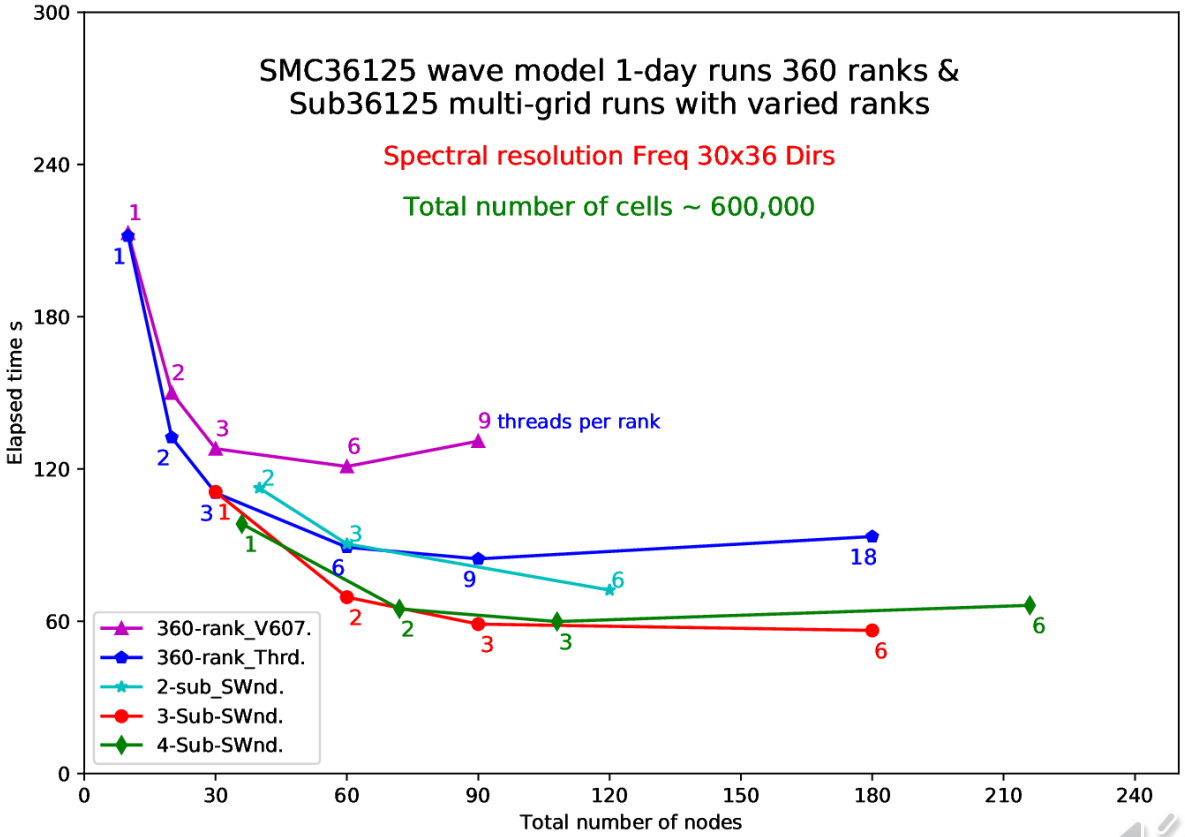


Spectral buoy 4-bin SRWH comparison SMC via 3 Sub-Grids



Timing results

- 2 sub-grids in multi-grid run are close to single grid hybrid run.
- 3 sub-grids are the most efficient configuration with minimal boundary exchanges.
- 4 sub-grids may be slightly quicker at same threads but slower on same nodes than 3 sub.
- Sea-point wind has noticeable contribution to reduce run time.



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Summary and conclusions

- The SMC grid module in WAVEWATCH III® has been updated with improved hybrid parallelization and multi-grid option.
- Improve hybrid parallelisation leads to better scaling with higher OpenMP threads and may reduces the elapsed time by 50% in comparison with MPI run.
- Multi-grid option is added for same ranked SMC sub-grids and allows expanded use of computing resources and reduction of run time by about 30%.
- Different sub-grids configurations of a global SMC36125 grid have been tested and the best is the 3-sub one with minimised boundary exchanges. The 3-sub run on 90/180 nodes (3/6 threads) takes <1 min for one model day. The quickest MPI run on 12 nodes is over 3 min.
- Hybrid multi-grid option creates room for higher resolution models.

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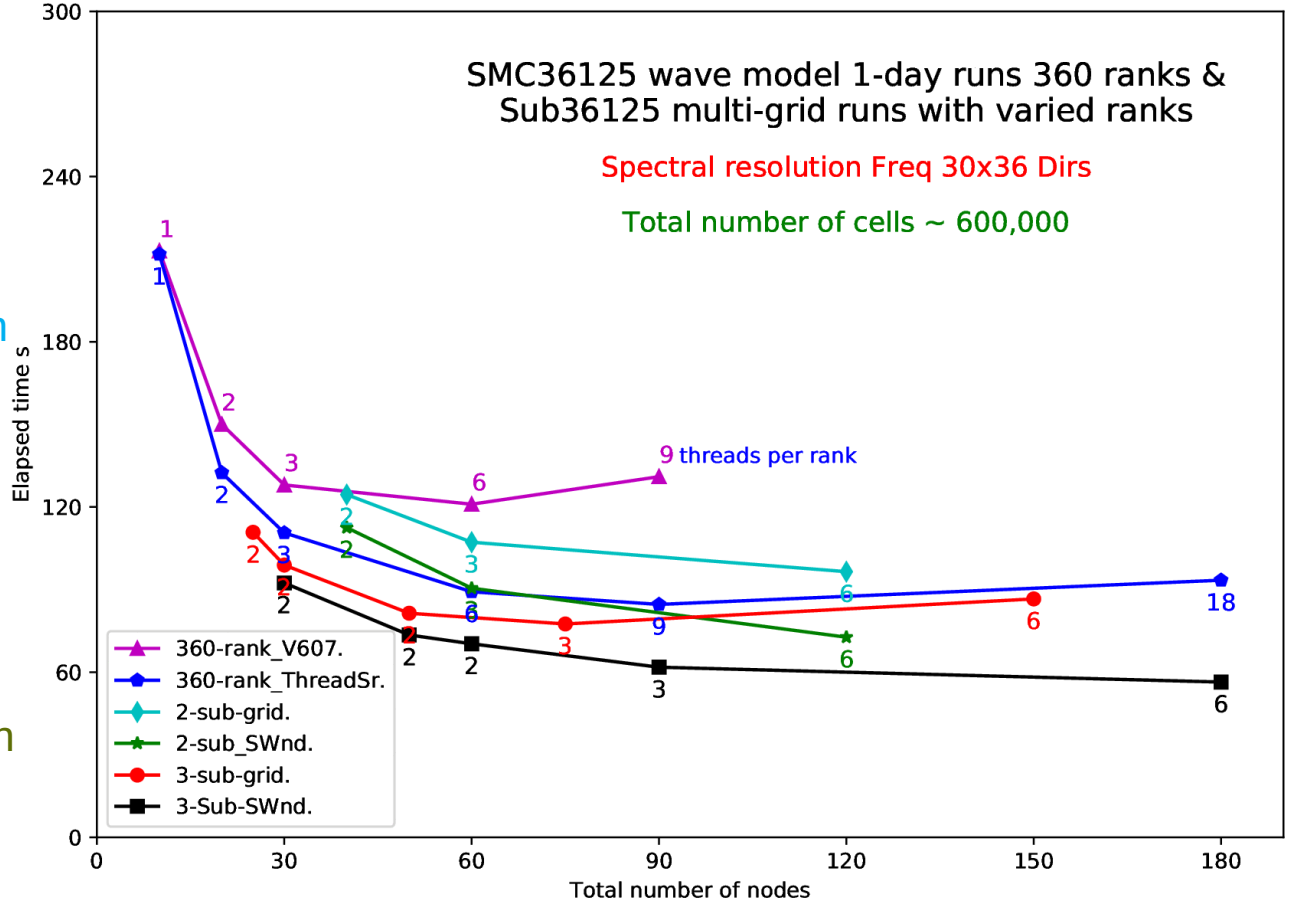
Thanks! Questions?

Timing results

- 2 sub-grids in multi-grid run are slower than single grid hybrid run on same number of nodes.
- 3 sub-grids are quicker than single grid model.
- Sea-point wind and boundary optimisation could reduce elapsed time further, the quickest run is < 60 s on 180 nodes (6 OpenMP threads).



Applications of SMC grids so far

- Implemented in WAVEWATCH III® ocean surface wave model and applied in Met Office global (SMC3-6-12-25km) and regional (UK1.5-3km) wave forecasting models and coupled climate models (wave model only SMC50km).
- Environment Canada and Ocean University of China used for Arctic wave climate studies (Global SMC100km + Arctic SMC12-25 km).
- Regional wave forecasting system on a 6-level SMC grid in NMEFC of China.
- Global wave forecasting model on 2-levels (6-12 km) in BoM, Australia.
- Collaboration with other international partners in USA (NOAA-NCEP), Canada (Uni McGill), Australia (Univ. Melbourne), New Zealand (Ocean Num.), Japan(JMA), China (OUC, CMA, Ship Res. Ctr.), and Russia (Hydrometeorological Institute, Vladivostok).
- Shallow water equations on SMC grid for possible surge and tsunami simulations. Li, J.G. 2018: *Q.J.Royal Meteoro. Soc.,* **144***,* 1-12. Li, J.G. 2021: *Ocean Model.,* **157,** 101729.