The development and design of the multi-grid model

Or, what changed from WAVEWATCH III ® model version 2.22 to 3.14.

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Background

- Virtually all present wave models consider one-way nesting only, with low resolution providing boundary data for high resolution models. (exceptions: Spanish WAM, unstructured grids).
- Hurricanes require high resolution in generation area, but their swells are covering full basins. Hurricanes therefore require two-way nesting.
- Coupling with hurricane models for the atmosphere benefit from identical grids.

Background

- NWS Forecast Offices (WFO) are required to produce gridded forecast products for the National Digital Forecast Database (NDFD), but lack consistent guidance across deep ocean, offshore and coastal domains. Consistency between such grids also requires two-way interactions between grids.
- NCEP: We need to build upon the present operations.

  Structured grids for now.

  Mosaic or multi-grid approach.

Regional models have a spatial resolution of 25km. With multi-grid technology selective resolutions of 5-10km are feasible.

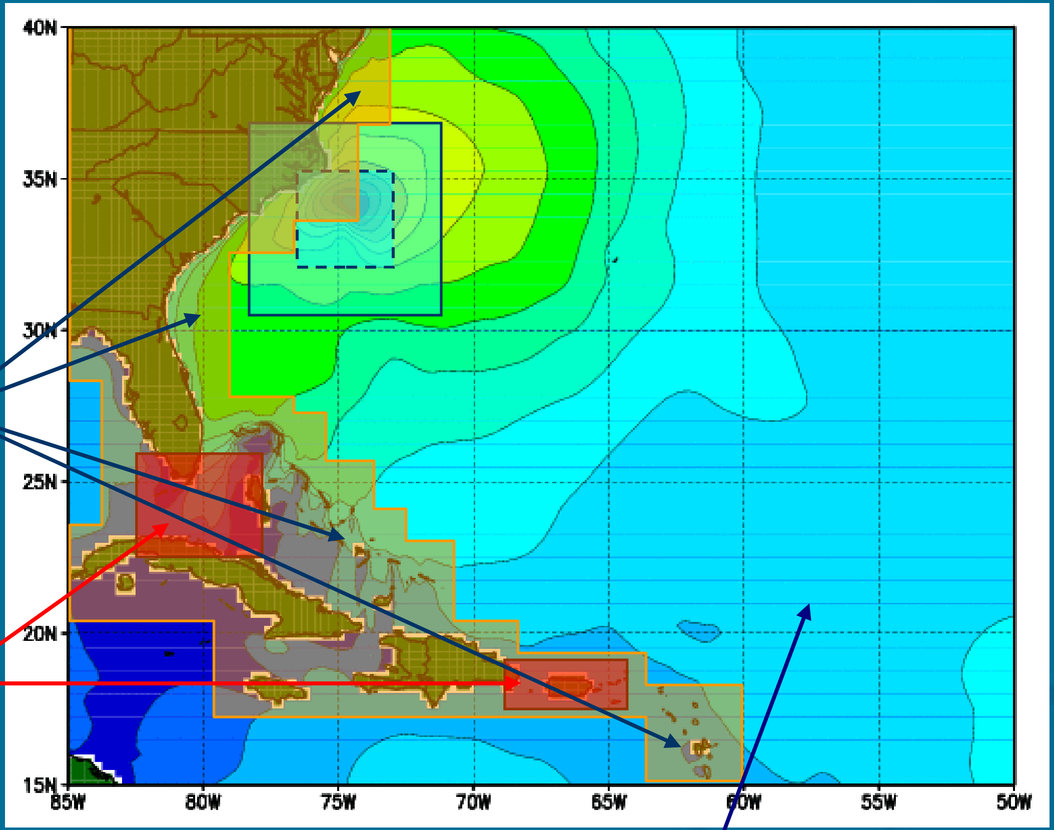
- Two-way nesting of models with different scales that run simultaneously.
- Moving nests follow features of interest (hurricanes, to be developed later).
- Nests remove the need for running separate large regional models.
- Selective application of highest resolution nests makes ensemble wave forecasting more feasible.

The NCEP philosophy

Deep ocean model resolution dictated by GFS model

Higher coastal model resolution dictated by model economy

Highest model resolution in areas of special interest



Hurricane nests moving with storm(s) like GFDL and WRF

Major software development effort done in steps:

- Develop capability to run multiple models in single executable.
  - Design and test the basic dynamic data structure.
  - Convert the model accordingly.
- Develop the basic logical algorithm to deal with all nests.
- Prepare model details (MPI, I/O, status maps, …., coupling).

Development steps, continued:

- Develop basic nesting techniques with using a set of nests.
- Develop techniques for overlapping grids.
- Develop techniques for moving nests.
- Model implementation replacing present wave models, and incorporation in HWRF.
- It is also desirable to develop methods for automatic grid generation (particularly, sub-grid obstacles).

The Earth Systems Modeling Framework is Intended to become the standard approach for coupled modeling.

- In WAVEWATCH IIII it is intended to be dealt with by a simple wrapper around the three basic code parts (initialization, time stepping, finalization).
- Used as a coupling tool only, not as the basis of the underlying model.
- Tentatively joint development with NRL (Tim Campbell),

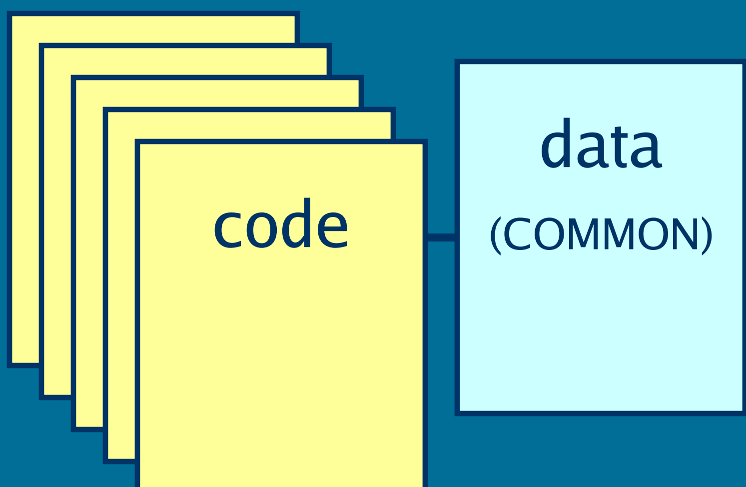
Data structure

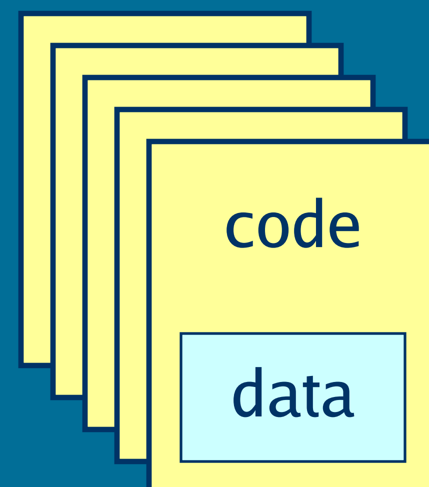
Model version 1.18 (1999)

- FORTRAN 77
- COMMON data structure
- Single static data structure.

Model version 2.22 (2002)

- FORTRAN 90
- Modular
- Object oriented, static data structure bundled with code

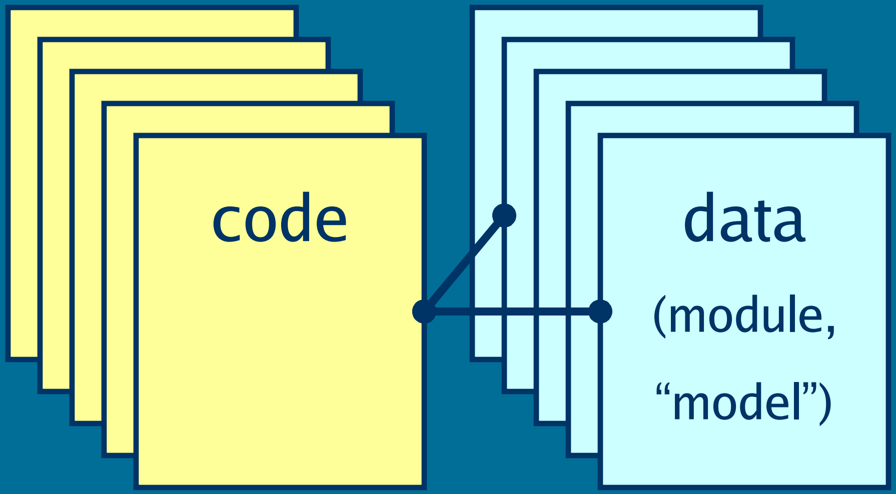




Data structure

Model version 3.06 (2005)

- Modular FORTRAN 90
- Dynamic / multiple data structure (modular)
- Small overhead (7% on Linux, 2% on IBM SP)



Data structure utilizes pointers to alias previous static data structure.

```
!/
!/ data structure
!/
      TYPE GRID
        INTEGER       :: NX, NY
        REAL, POINTER :: ZB(:,:)
      END TYPE GRID
!/
!/ Data storage
!/
      TYPE(GRID), TARGET,                &
                 ALLOCATABLE :: GRIDS(:)
!/
!/ Pointers
!/
      INTEGER, POINTER :: NX, NY
      REAL, POINTER    :: ZB(:,:)

!/ ***********************************

      NX => GRIDS(I)%NX
      NY => GRIDS(I)%NY
      ZB => GRIDS(I)%ZB
```

Due to choice of working with individual grids, the computation for individual grids needs to be ordered in time. To organize this introduce:

- Grid rank: grids are ordered in terms of resolution. Lowest rank corresponds to lowest resolution.
- Several grids can share the same rank.
- Within a given rank, groups can be identified for processing in parallel of the corresponding grids.

General algorithm

With this in mind, 8 sequential actions can be identified for the completion of a time step for each grid.

These steps fully define the logical management algorithm for all grids.

1	Update external input.
2	Update input form lower ranked grids.
3	Update overall model time step (multiple grids).
4	Run wave model (except for output)
5	Reconcile grids within rank, stage data.
6	Reconcile with higher ranked grids, stage data.
7	Data assimilation
8	Generate output.

To simplify time step management, a global synchronization time step is adopted, based on the largest possible time step within the group of grids with the lowest rank.

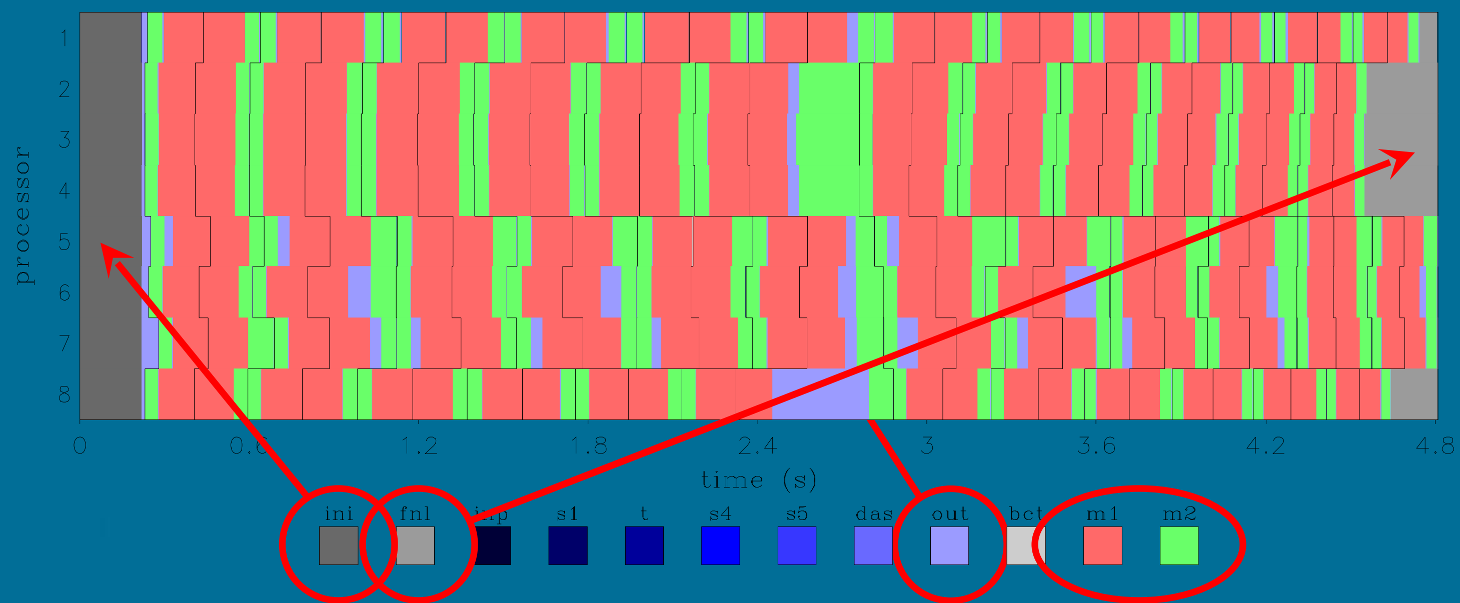
Another simplification used is to force synchronization at input data time stamps (not strictly necessary for logical control structure).

Added to the basic model is a consistent way to deal with time steps that are fractions of seconds (keeping track of residuals).

For individual grids, WAVEWATCH III already is highly optimized and parallelized (Tolman, *Par. Comp.*, 2002).

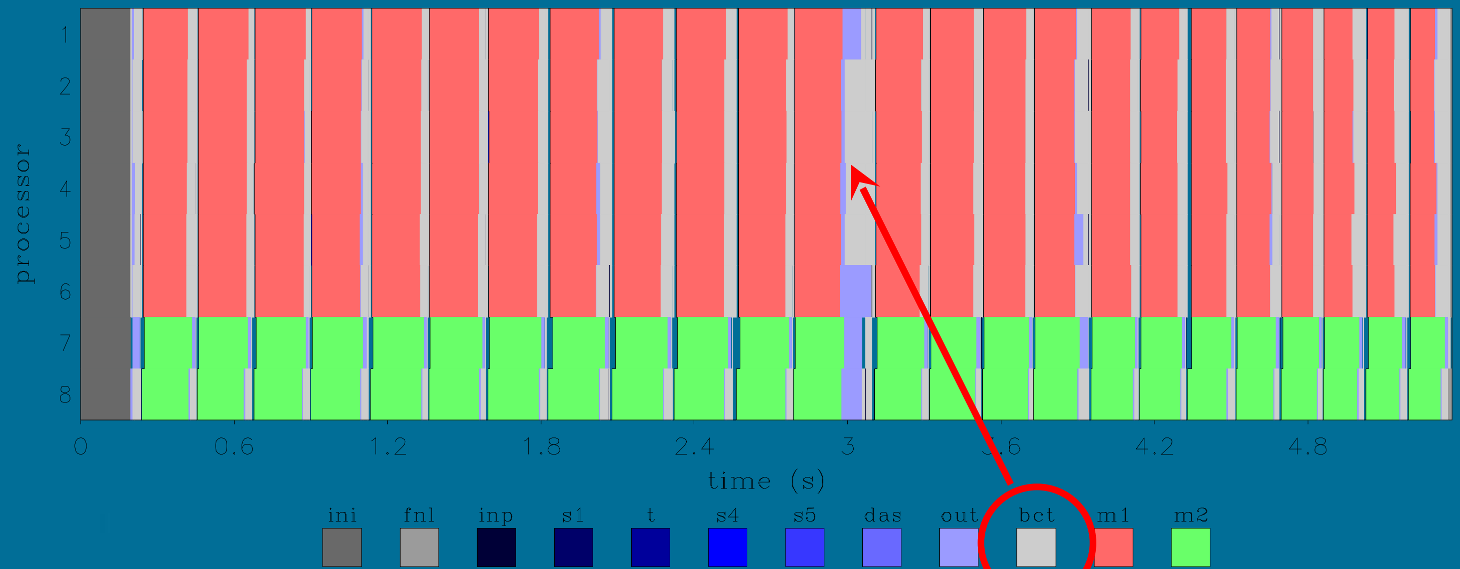
- Defining an explicit MPI communicator for the wave model allows us to run on a pre-defined set of processors.
  - Needed for coupled applications.
  - Allows for side-by-side running of grids in the multi-grid model.
- Refine control structure with proper synchronization of (control) data.

Parallel architecture



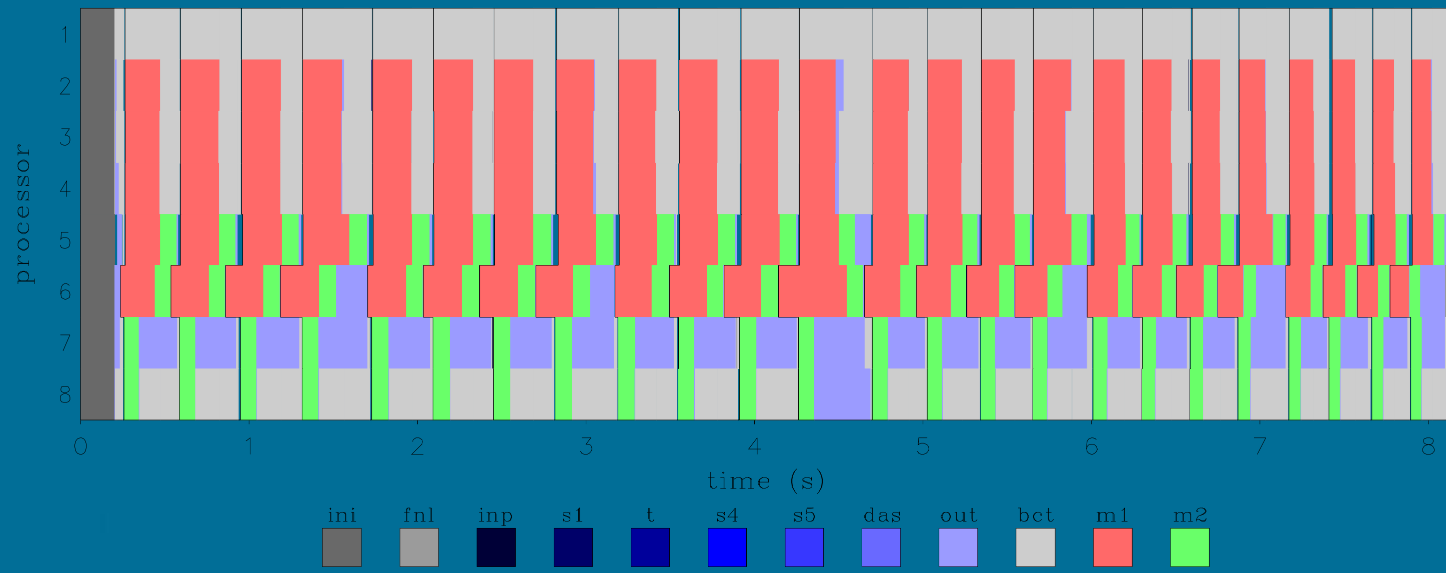
modSmall finalizatiouse logical synchronizactual modelsOutput results
in local wait times forced by necessary synchronization.

Presented here is some profiling information for the multi-grid model with two small independent grids. The profiling information shows time spent per processor for various activities.



The same two models, but now each is run on a dedicated set of processors. Now status information is broadcasted to processors that are not used. Presently, this is implemented as a hard synchronization barrier. For large models, parallel implementation of grids is expected to benefit from Amdahl's law.

Parallel architecture



The same two models, but now loaded in a highly unbalanced way. Processor 1 does no work at all! This is not the way to do real work, just an illustration of the flexibility built into the multi-grid management algorithm.

Initially, each grid had its own input and output, as if it was a separate model.

- Internal data flow for nesting is kept separate from file-based nesting.
- Grid synchronization required before output.

Refinements :

- Input data can be defined on separate input grids, and processed internally in the driver. For example, use a single global 0.5° GFS wind field to drive a set of grids.

Refinements cont'd

- Output of internally used boundary data to be able to run nests separately with the full multi-grid model input as wanted.
- Master point output. Define a single list of output points after which the driver selects from which model the output data is obtained and produces a single consistent point output data file.
- Dynamic unit number assignment.

Grid status map

Grid status map is used to identify the status of grid points in the full spatial grid. In model version 2.22, the status map identifies :

0	Land points	
- 1	Regular sea points	(ice covered)
- 2	Sea points with active boundary points	(ice covered)

Modifications will make multi-grid model more versatile:

- Exclude points form grid without labeling as land.
- Temporary mark point as land in relocatable grid.
- Drying out of points with shallow water.

Redefine meaning of grid map slightly, and define secondary grid map.

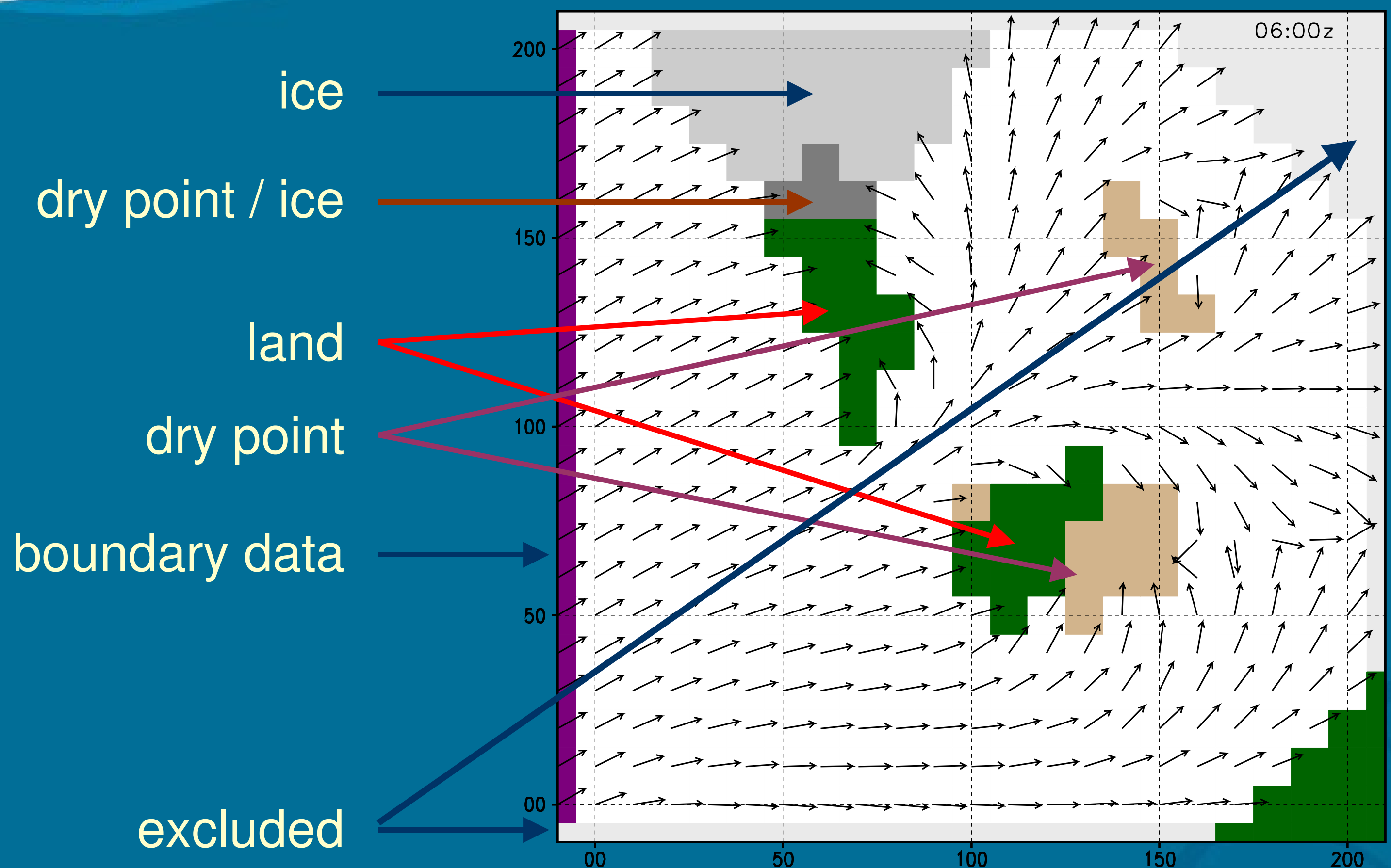
0	Point excluded from grid	
- 1	Regular sea points	(disabled)
- 2	Sea points with active boundary data	(disabled)

0	Land
1	"undefined"

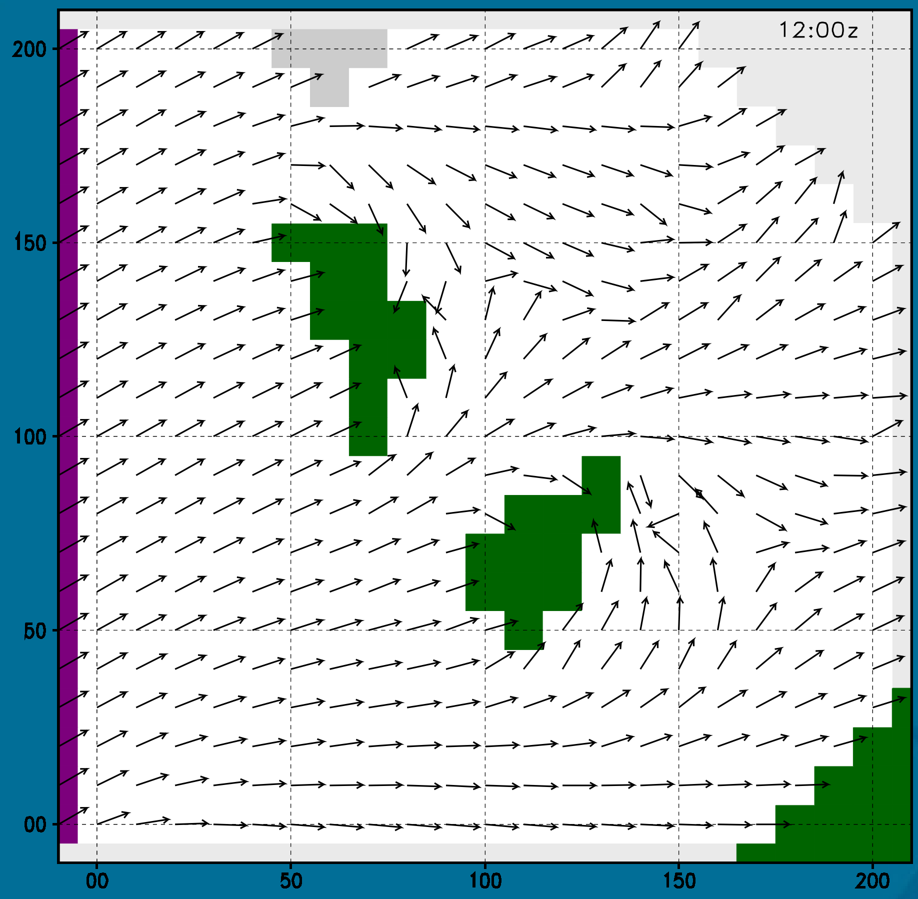
separate map for graphics

bit	Flag for
1	Ice
2	Dried out point
3	Land in moving grid / nesting
4	Masked in nesting

Grid status map



Grid status map



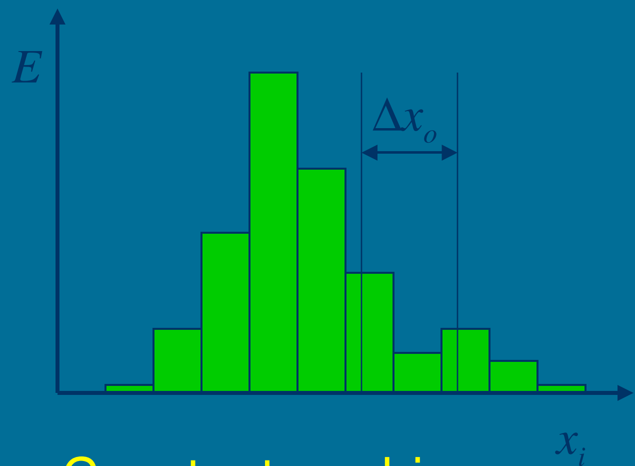
Traditionally, spectral resolutions of a model, initial conditions and boundary data for a given WAVEWATCH III model are all required to be identical. Particularly boundary data at different resolutions is useful, for instance for

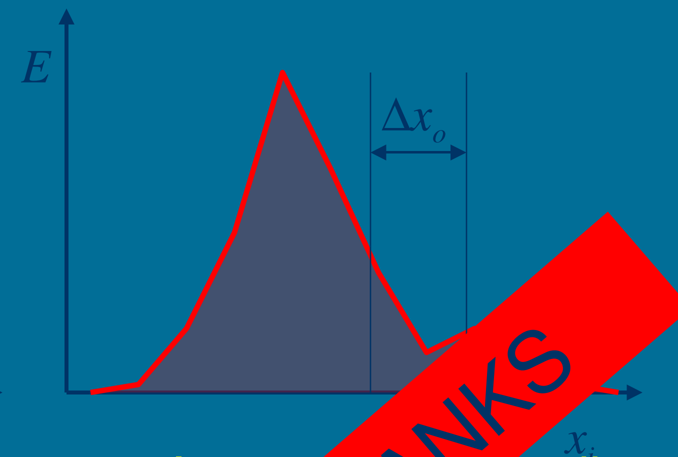
- Focus on / neglecting of swell in selected areas (grids), to improve CFL conditions.
- Increasing directional resolution in areas with important shadowing or refraction.

Requirements for a conversion algorithm:

- Conservative in energy.
- No change in spectra if discrete frequency range is expanded (contracted).
- Minimal diffusion.

Algorithm is generally determined by how the discrete spectral densities are converted to a continuous presentation.





NO THANKS

Constant per bin:

- Looks primitive.
- Satisfies requirements.
- Reversible.

Interp … om discrete … data.

- … advanced.
- … rge diffusion.
- Not reversible.

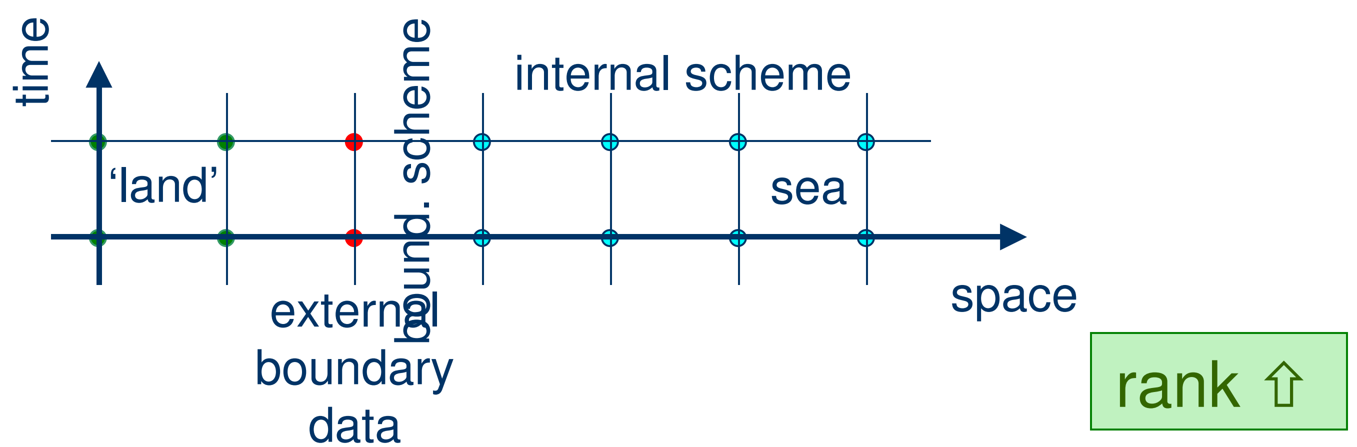
Two types of data flow needed:

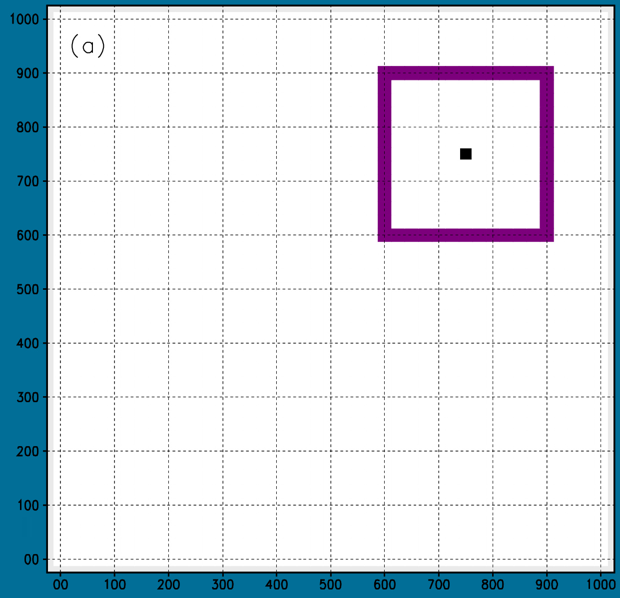
- From low rank to high rank.
- From high to low rank.

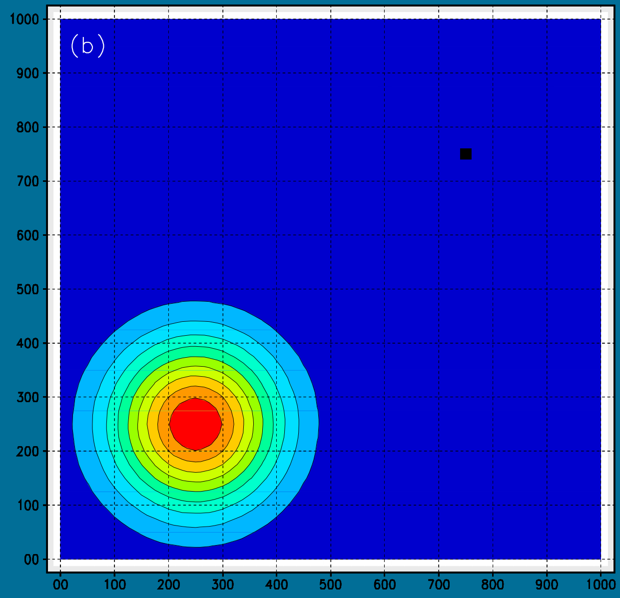
- The choice of working with individual grids limits the choice of applicable methods, as grids need to be processed in some order.
- Starting the computations with the lowest rank, the data flow to higher ranked grids is most naturally dealt with by means of providing lateral boundary conditions, as in previous version of WAVEWATCH III.

Provide data from lower ranked grid(s) at the edge of the computational domain, and apply a first order scheme locally.

- Internal boundary conditions with lower order accuracy.
- No loss of accuracy in first order scheme.

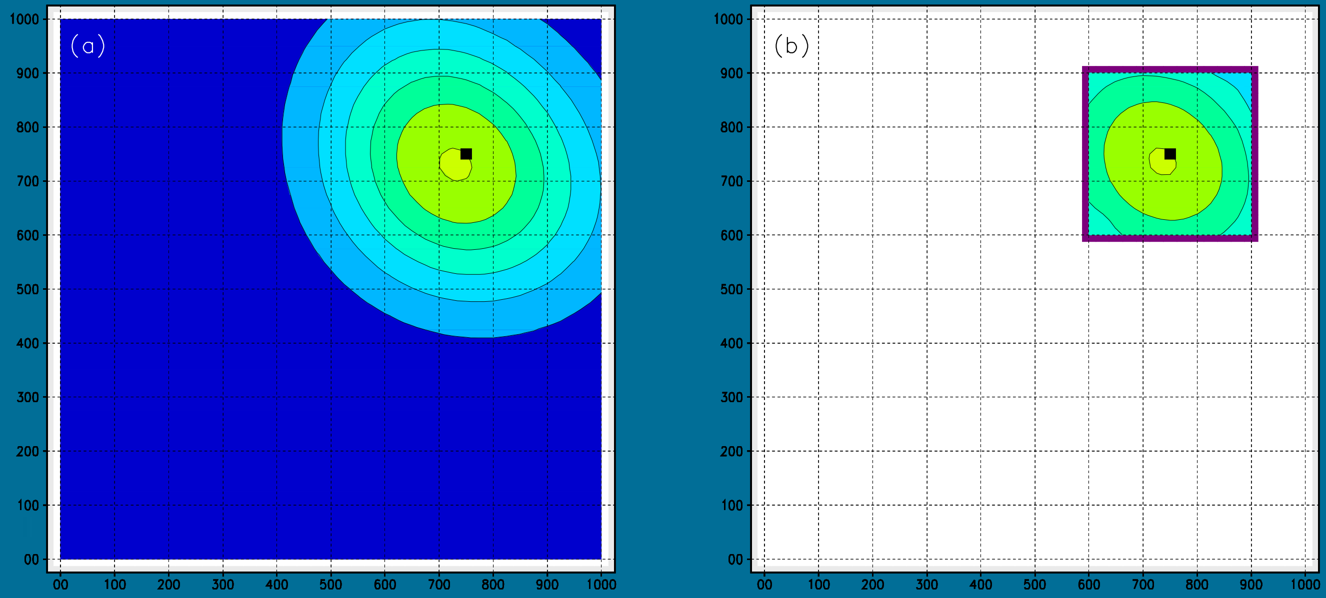






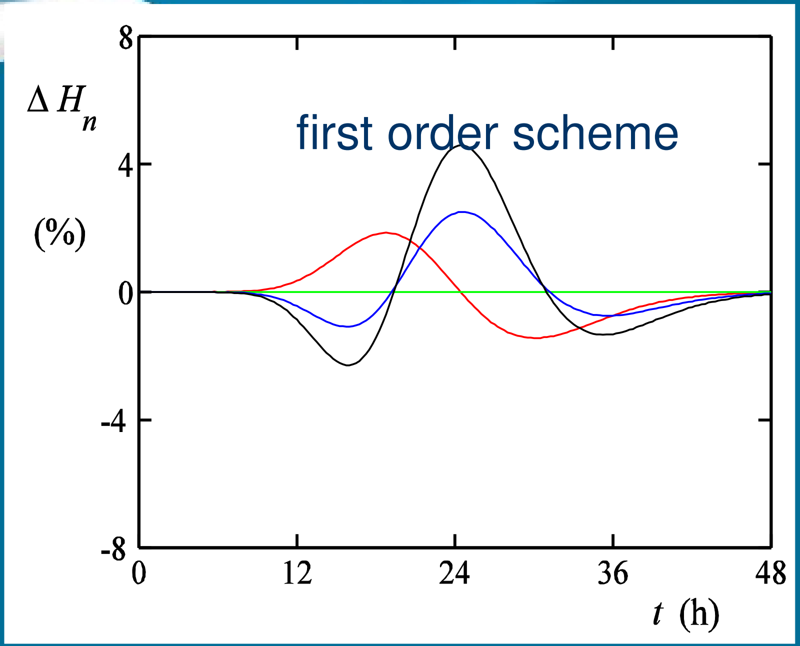
Simple test with grid resolution of 25km in inner and outer grid, first order scheme, and data transferred every time step. Initial wave heights travel from lower left to upper right corner of outer grid (monochromatic, unidirectional).

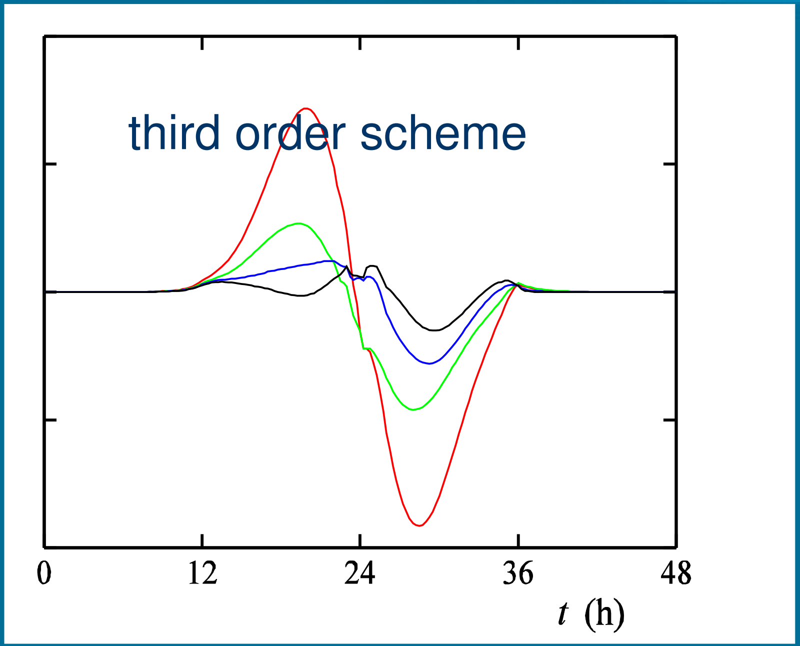
rank ⇧



Results in outer (left) and inner (right) grids with old WAVEWATCH III model should be identical but are not, due to non-optimal (erroneous) updating of boundary data. Can be fixed easily.

rank ⇧





should be zero, but is not. The third order scheme has bigger differences due to larger gradients in solution.

Black lines: inner grid at 1/5 resolution.

In the multi-grid model the flow of boundary data should be internal, not using files.

- Updating the appropriate boundary data inside the wave model before the wave model routine is called.
- This leaves the original model unchanged, and allows for mixing of internal data flow and reading from file (choose one).
- Capability to write internal boundary data to file is useful for testing / development.

rank ⇧

Cont'ed.

- Additional features:
  - User provides location of input boundary points in each grid. After this all data transfer is automated.
  - Each grid can receive data from each lower ranked grid simultaneously.
  - Each grid can have its own spectral resolution (within reason).

Works just like old model, but much more flexibility!

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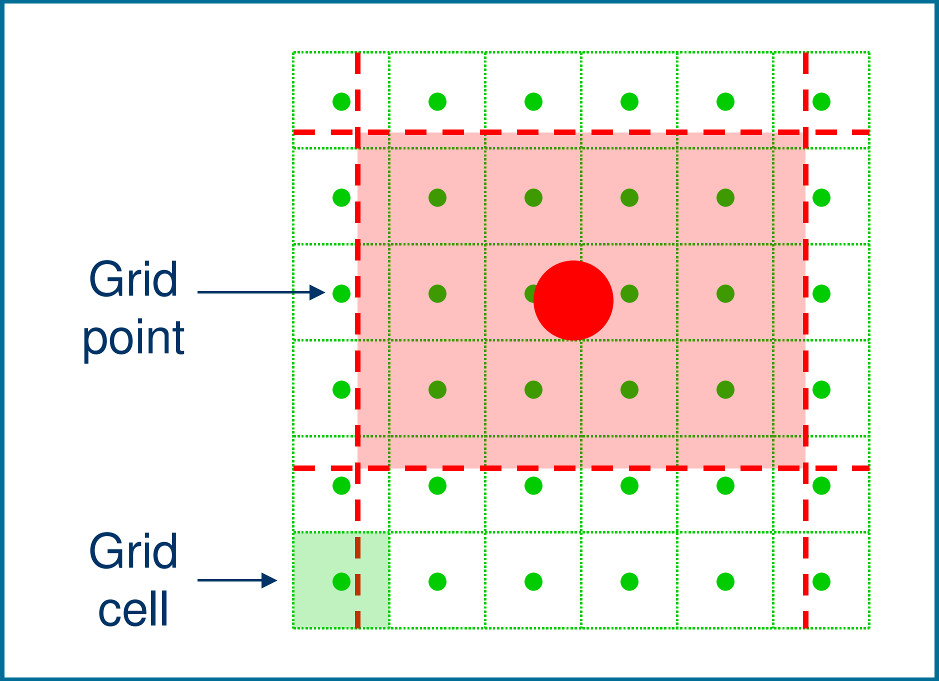
The data flow from higher ranked grids to lower ranked grid is not commonly considered in wave models.

Simple technique used here:



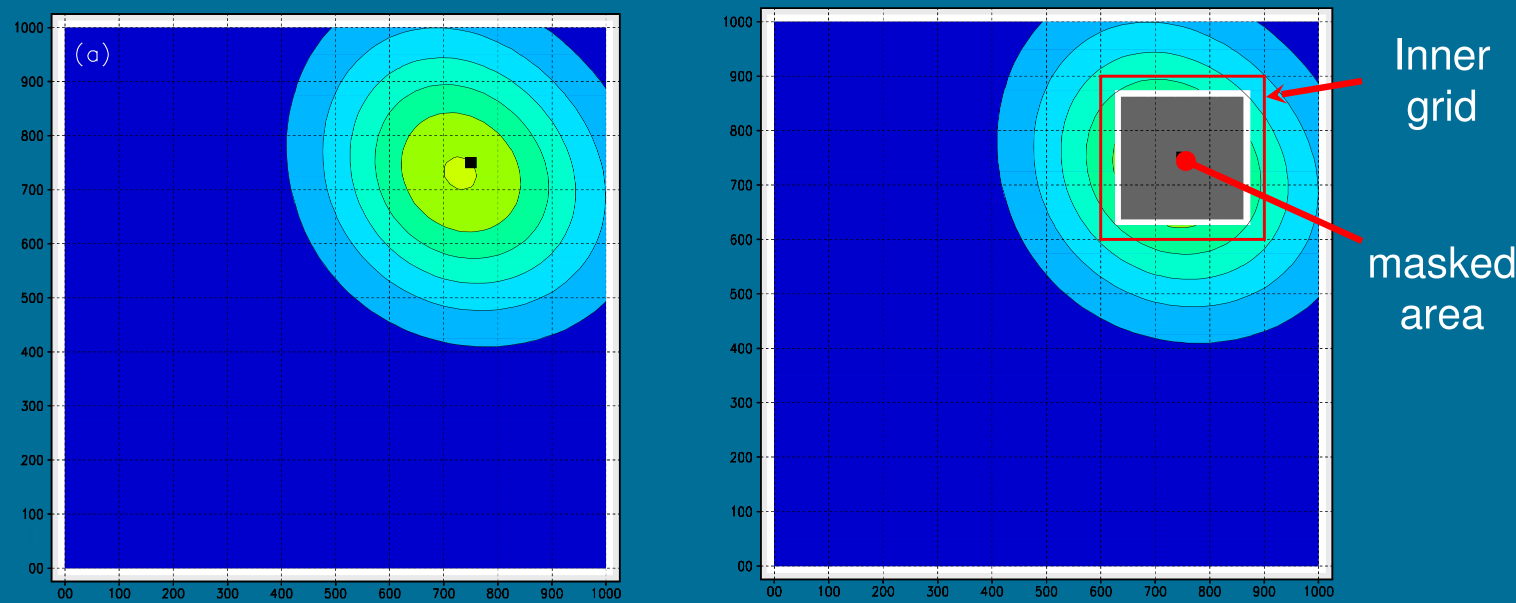
- Averaging with weight based on of high-res cell surface covering low-res cell.
- Obstructions not specially treated.

Additional considerations:

- Data from high resolution grid updated each time step of low resolution grid. This implies that only data near the boundary of the high resolution grid is ever used in the computations for the low resolution grid, depending on the stencil width of numerical scheme.
  - Option included to mask out computations in lower ranked grid.
  - Option included to mask out output similarly.

rank ⇩

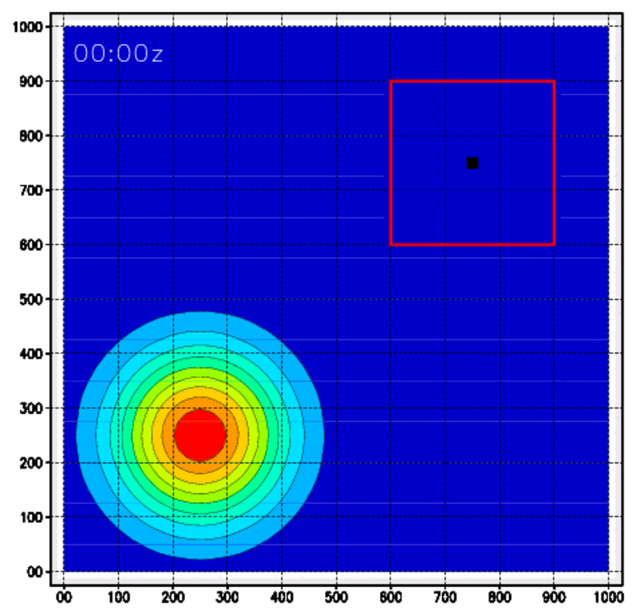
Static nests

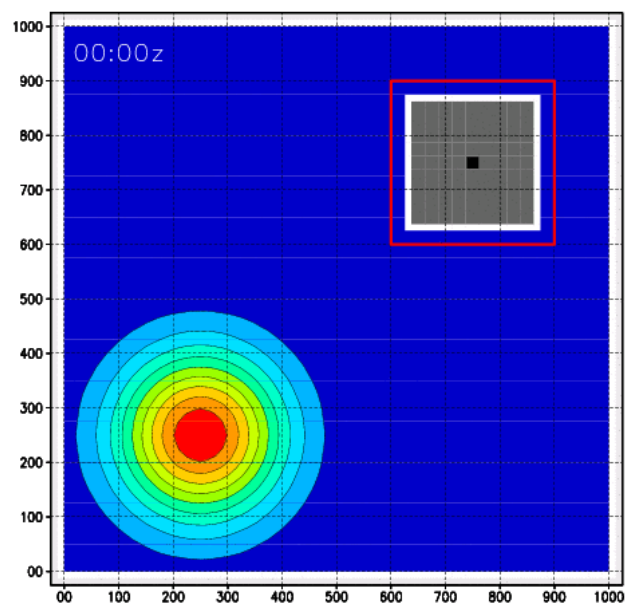


Propagation test with the first order propagation scheme and an inner grid with identical resolution. Left, full solution, or solution for single grid. Right `outer' grid with two-way nesting and masked area.

rank ⇩

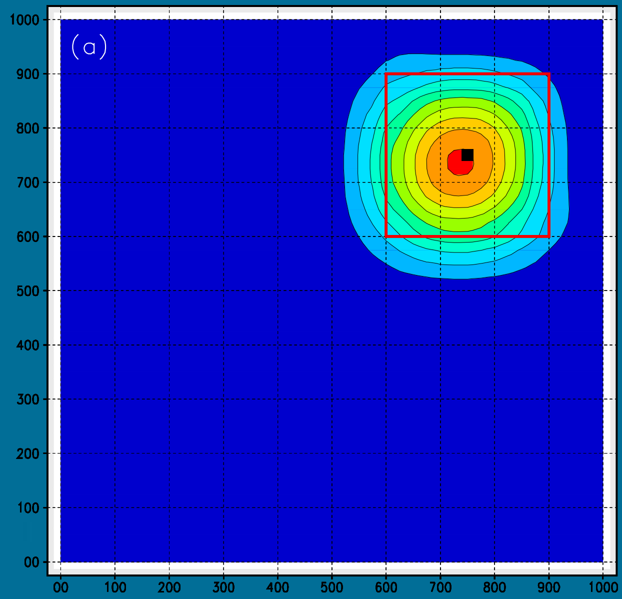
Static nests

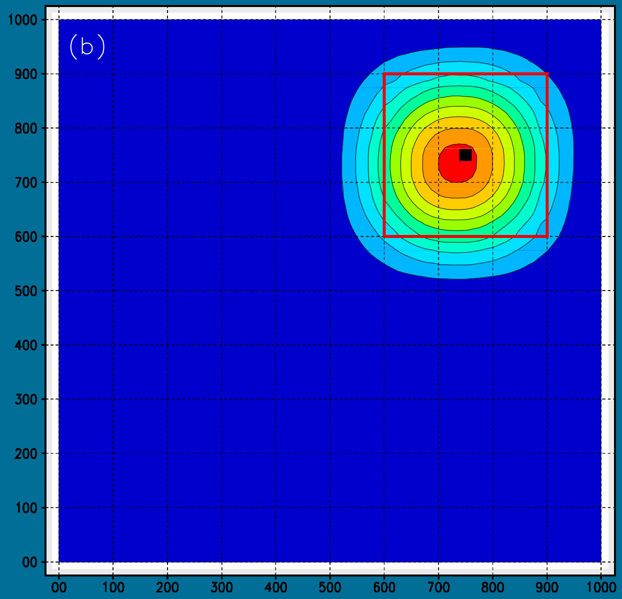




Corresponding movie loops of full solution (identical to single-grid solution) on the left, and masked inner grid on the right.

rank ⇩





With the higher order propagation scheme and identical resolutions some impact of degenerated boundary scheme can be seem (left), but this disappears with higher resolution inner grid (right).

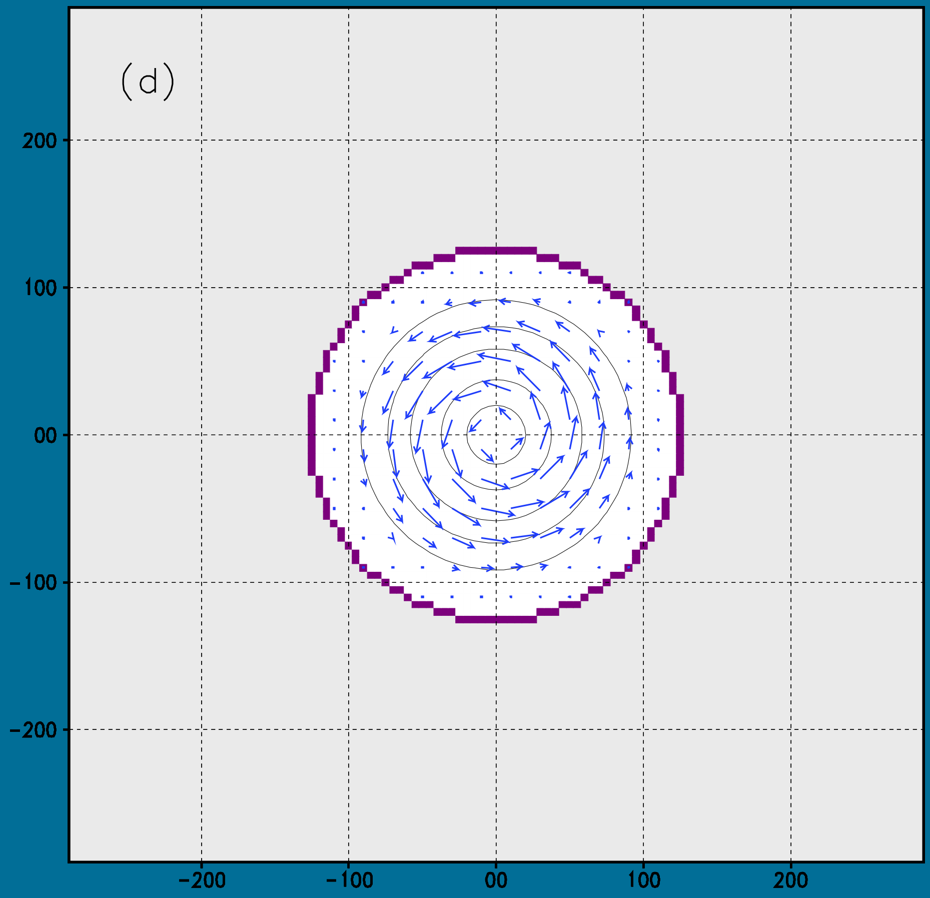
rank ⇩

Additional test:

- Swell propagating through an outer region with constant depth and no currents, and through an inner region with a parabolic sea mount and/or an annular current.
- A telescoping nest on a synthetic hurricane with or without motion.

rank ⇳

Static nests



Boundary data grid with 1-D propagation.

Outer grid with full propagation but constant depth and no currents.

Inner grid with output locations.

Alternative inner grid with depth and current.

rank ⇳

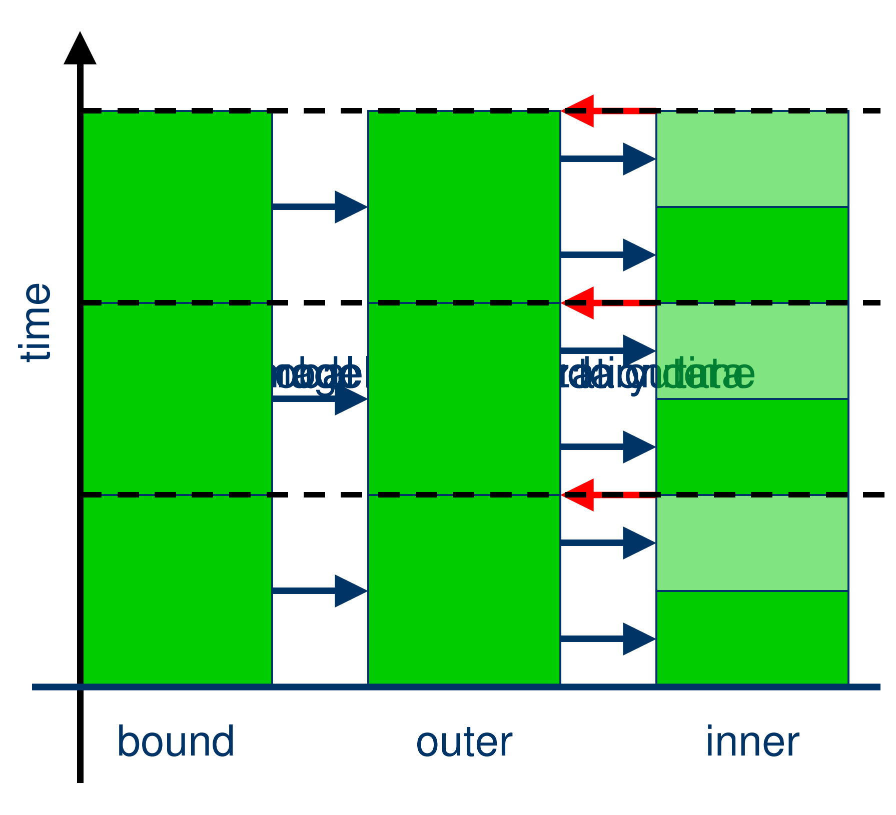
Static nests

Boundary and outer grid share time step.

Boundary grid does not receive data back from outer grid.

Inner grid at half the time step of the outer grid.

Fully automated data flow / time stepping..



run model

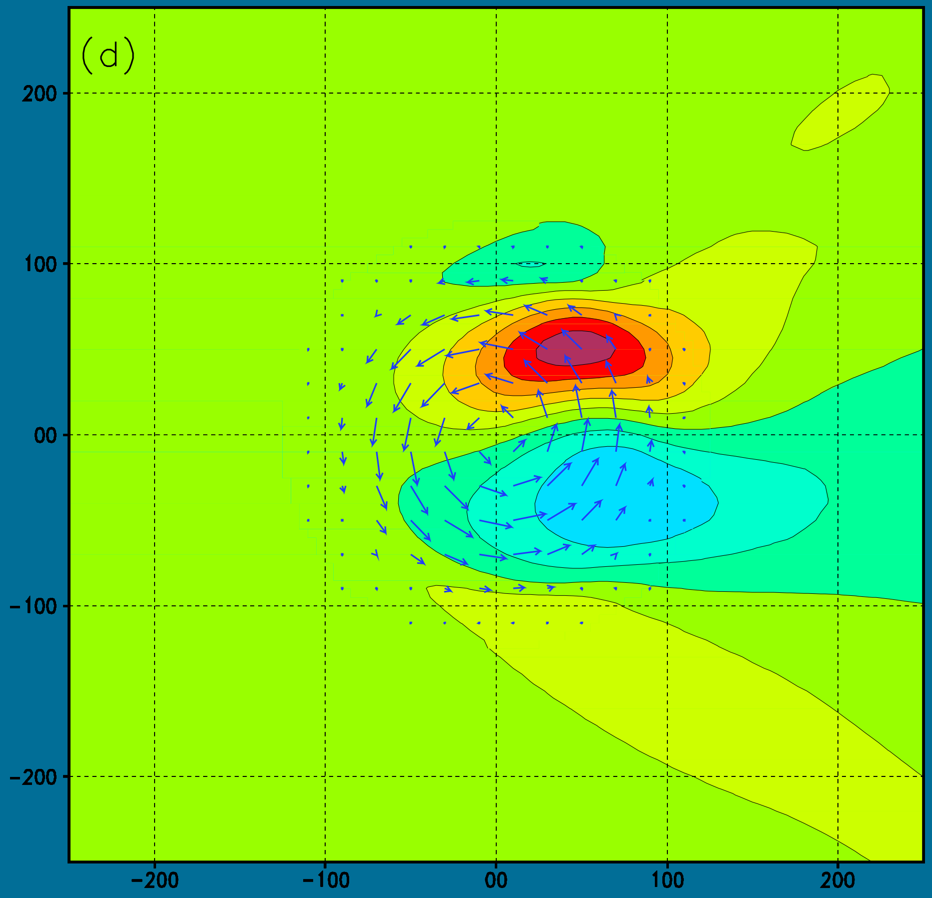
bound. data

global sync.

averaging

rank ⇳

Static nests



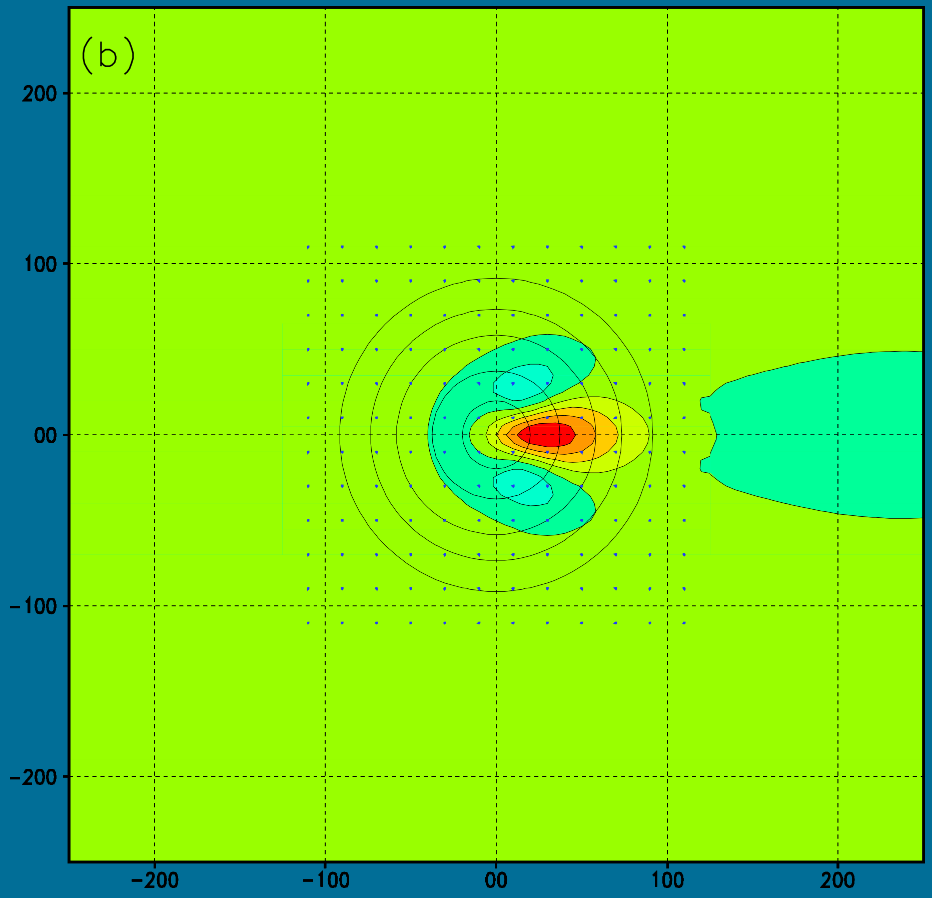
Current ring with circular inner domain. Input wave height is 2.50m, contours at 0.20m, including 2.40 and 2.60. Third order UQ scheme.

One-way nesting

Two-way nesting

Movie loop.

rank ⇳



Parabolic sea mount ring with square inner domain. Minimum depth 15m, incoming waves with period of 10s.

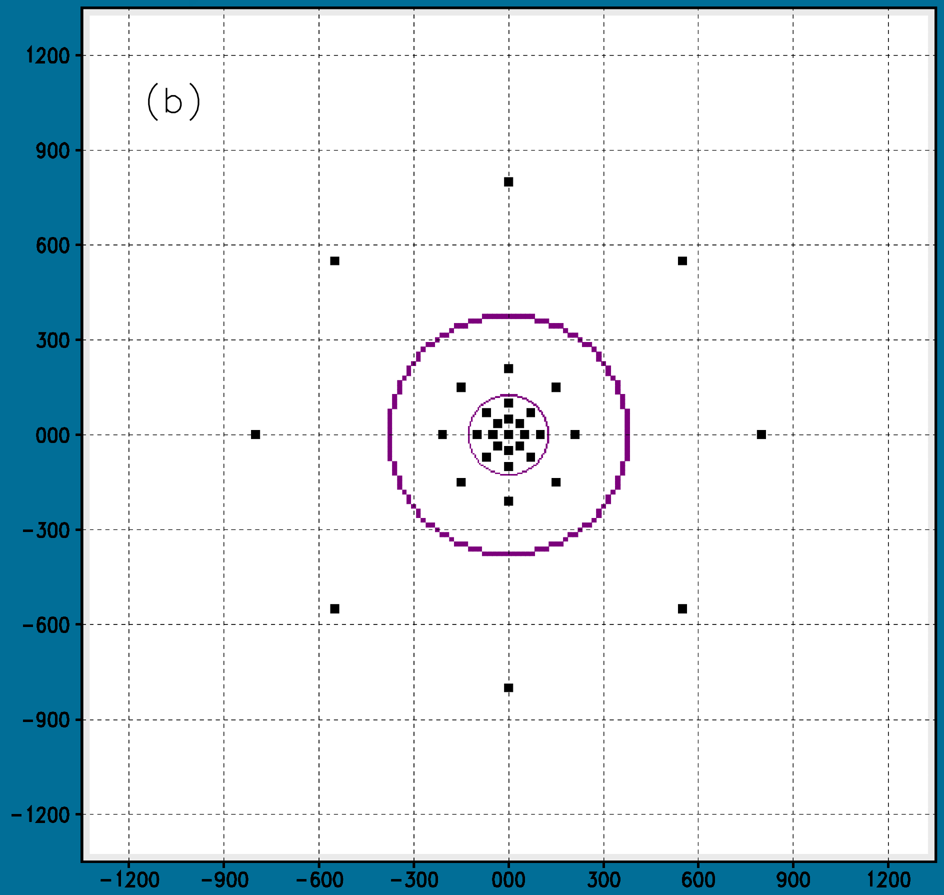
One-way nesting

Two-way nesting

Movie loop.

rank ⇳

Static nests



Hurricane described with Rankin vortex with maximum wind of 45 m/s at radius of 50km. Stationary hurricane or continuously moving grids.

Telescoping grids with 50, 15 and 5 km resolution.

Alternative circular domains.

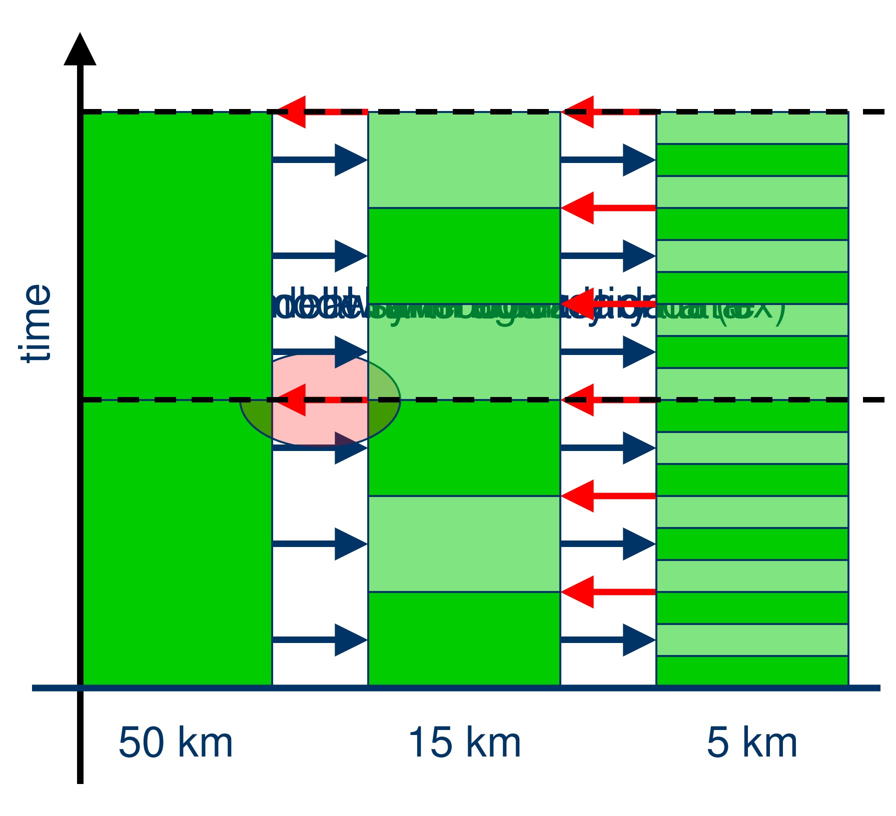
rank ⇳

Static nests

Factor 3 in time steps between grids.

Full communication between grids

Fully automated data flow / time stepping.



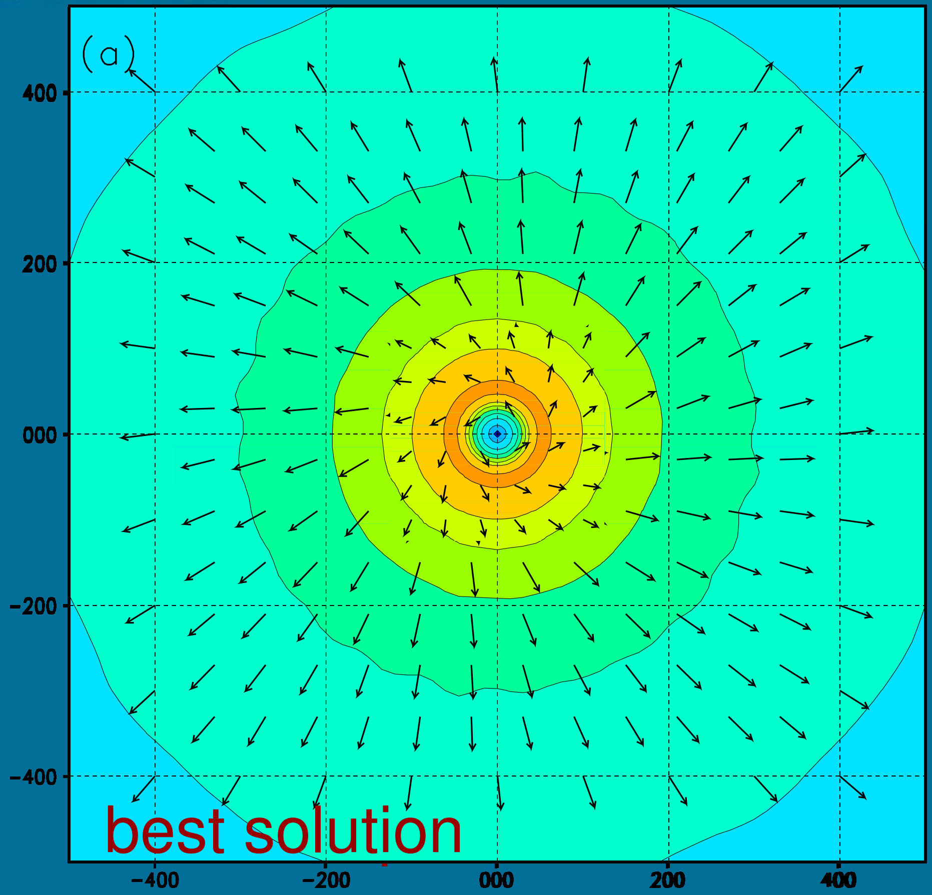
run model

global sync.

bound. data

averaging

rank ⇳



Stationary hurricane with default settings in WAVEWATCH III.

50km grid

15km grid

5km grid

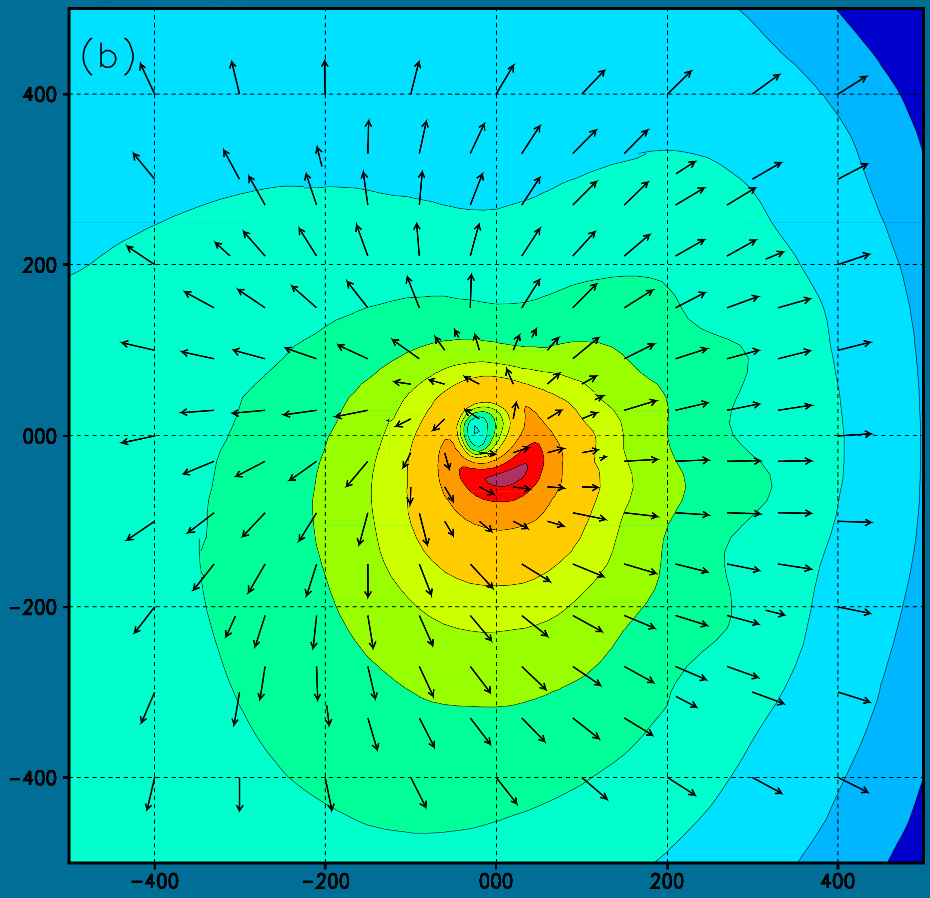
composite of grids

large 5km grid

multi-grid model

rank ⇳

Static nests



Hurricane moving to the right at 5m/s with circular domains and Tolman and Alves (2005) moving grid approach.

composite of grids

multi-grid model

rank ⇳

Multi-grid approach gives consistent results between grids.

- Avoids some of the GSE due to natural scale enlargement in hurricane modeling.
- Adds approximately 15% to run time compared to sum of constituent grids, with good scaling behavior for large number of processors on a Linux cluster.
- Up to orders of magnitude faster than large grid with high resolution, *and* more physical results.
- Minor inconsistencies at boundaries possible, particularly at the corners.

rank ⇳

Overlapping grids

- For overlapping grids with similar or identical resolutions it is not possible to define an order of computation, in which boundary and averaging techniques can be used.
- Instead, computation is performed for all individual grids, after which the grids are 'reconciled' in the areas where they overlap.
- Another alternative would be to consider the solutions simultaneously, but this in effect results in the generation of a single grid.

rank ⇔

Requirements for a reconciliation technique:

- If grids are of identical resolution and grid points coincide, results should be identical to those for the corresponding single grid.
  - Internal boundary degeneration not accepted (explicit FD schemes).
  - More stringent requirement than for nests.

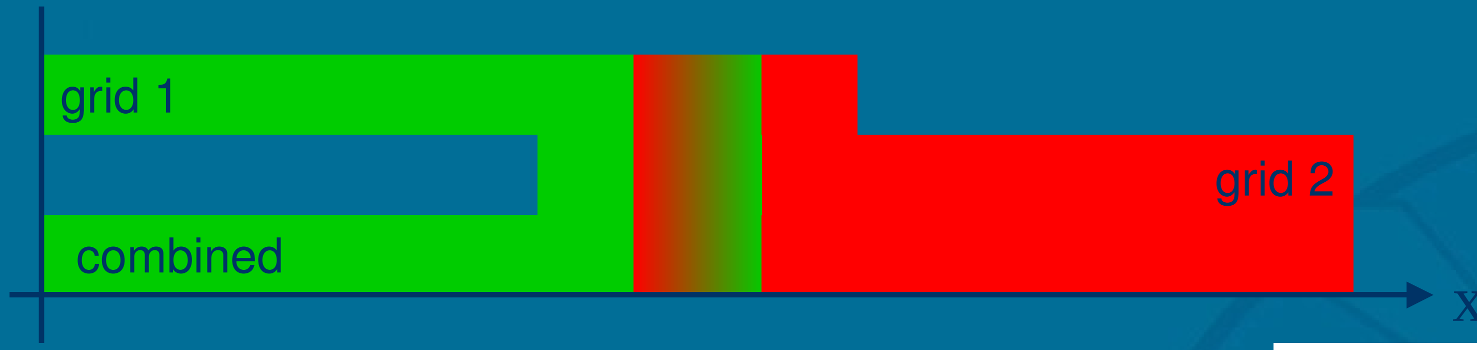
- The system should be sufficiently flexible to allow for (minor) differences in resolution, and / or non-coinciding grid points.

rank ⇔

Requirement are satisfied by:

- Updates per time step taking into account depth of penetration of data at boundaries.
- Update boundary as needed.
- Spatial interpolation as needed.

Example with 1-D propagation only.



rank ⇔

Test case:

- Swell propagation in constant water depth with single grid or three partial grids.
- Optionally coastal shallow area nested with higher resolution and concentric depth contours.
    - Offshore boundary points always needed.
    - Lateral boundary points optional.

Results for composite grids plotted consecutively in graphics.

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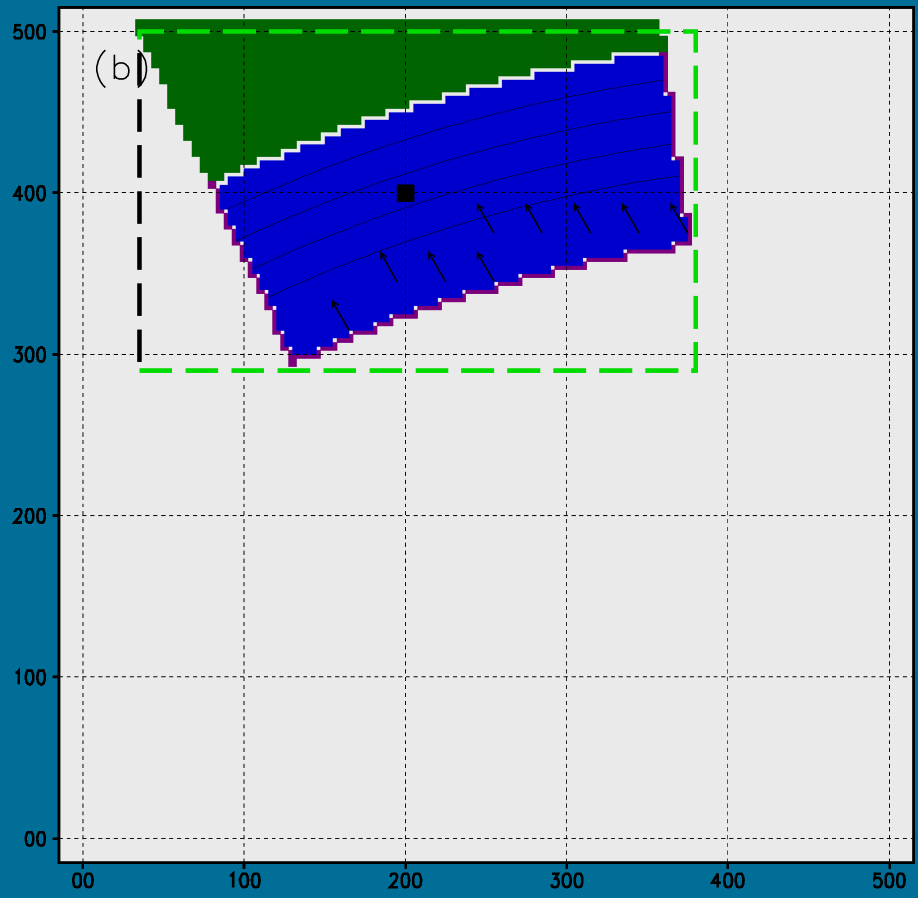


Layout of grids

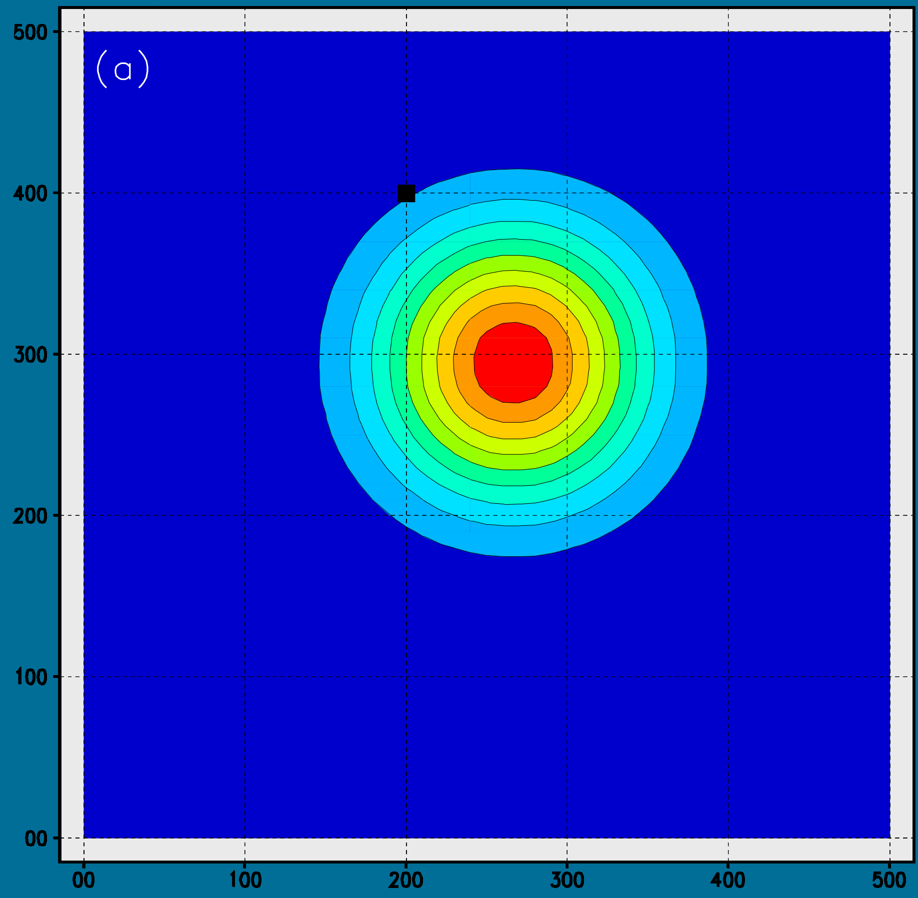
Total low resolution grid with partial grids as red outlines.

One of the partial grids

Outer high resolution grids with green outlines

Inner high resolution grid.

rank ⇔



Swell propagation in low resolution grids. Results after 6h propagation.

First order scheme

Third order scheme

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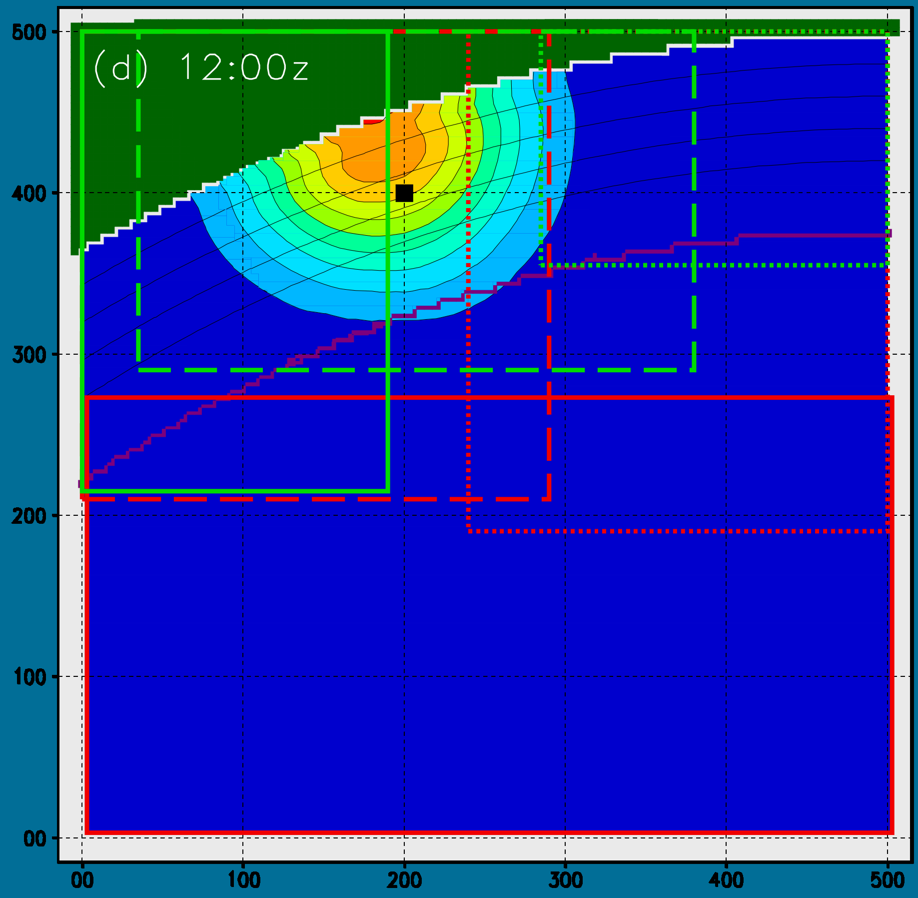
Overlapping grids



Swell propagation in low and high resolution grids.

Consistent grids

Inconsistent grids

rank ⇔

Reconciliation gives consistent results between grids.

- Identical if grids coincide in overlap.

  Not possible for all numerical approaches,
- Small grid inconsistencies acceptable.

No special considerations for obstruction grid.

- Automated consistent obstruction generation advisable.

rank ⇔

Three test cases from the real world will be used for illustration purposes:

- From Atlantic scales into a Norwegian Fjord.
- Modeling Alaskan coastal waters.
- Setting up a new NCEP operational model.

All test cases use the same wind and ice data for January 2006

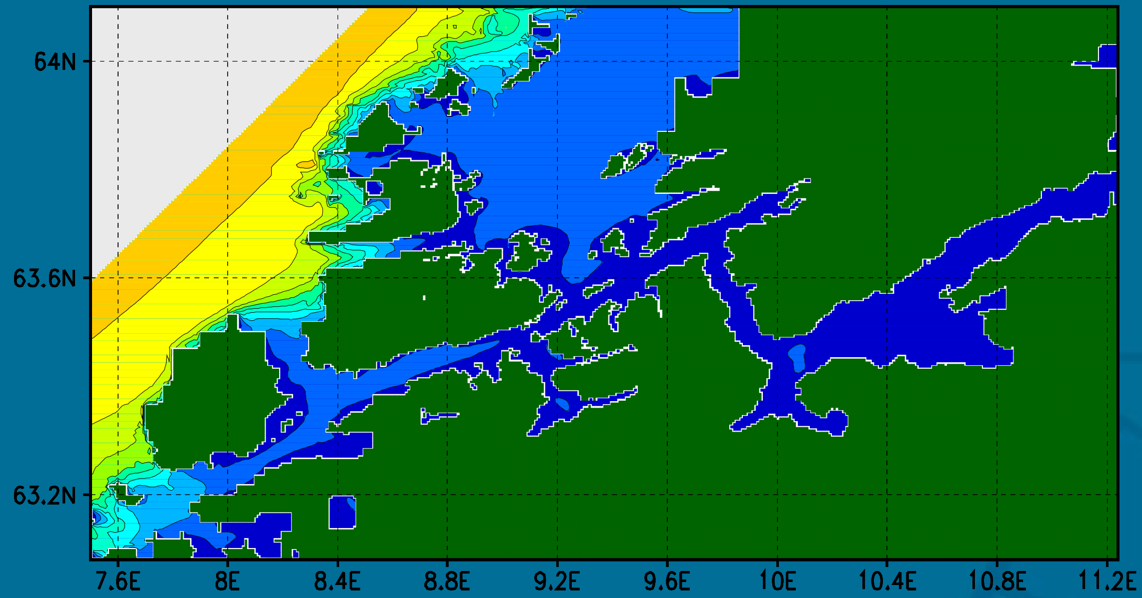
- GFS three hourly winds at $1° \times 1°$ resolution.
- Ice analyses at $5' \times 5'$ every three days.

Most grids generated by Chawla and Tolman (2007) utilities.

Case I

A wave prediction problem for the entrance to the natural harbor of Trondheim, Norway, presented by Birgitte Furevik at WISE 2006.

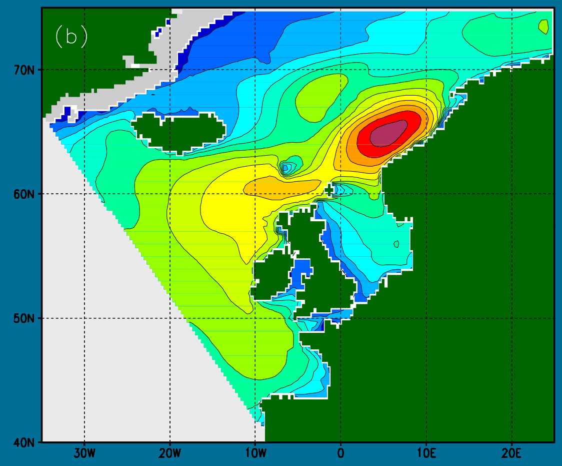
- 500m resolution grid with boundary data from a regional wave model.



Case I

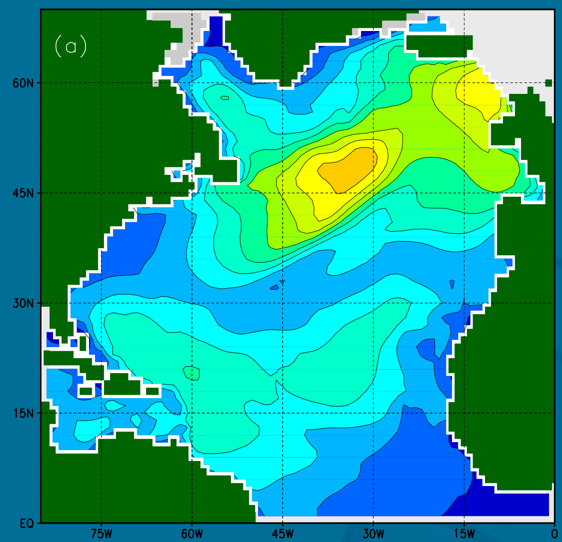
Set up a set of four grids to feed information into the 500m grid.

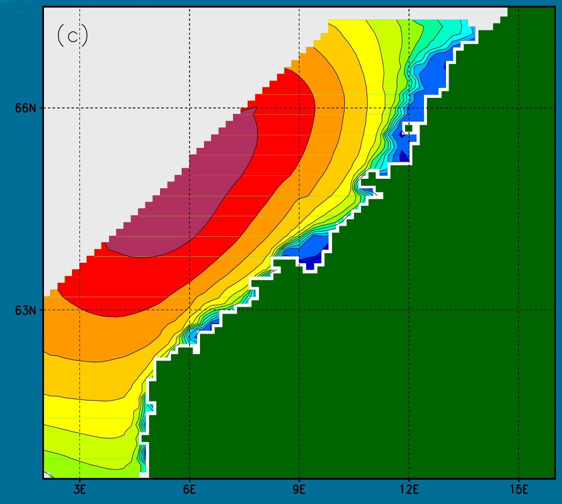
- Atlantic basin (1°)
- Northern seas (20')
- Two Norwegian grids (6'×12' and 2'×4')

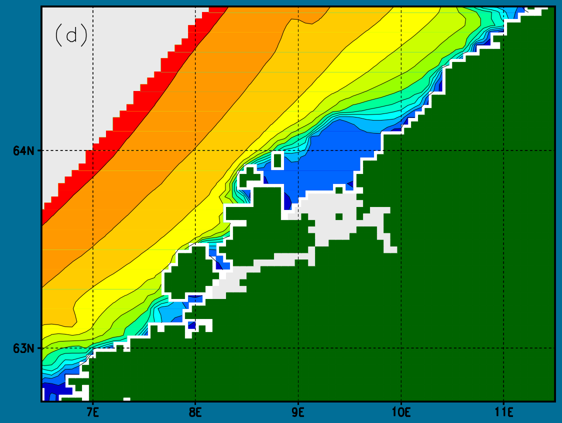


Only partial grid overlap needed.

Note disposed parts of grids (economy).

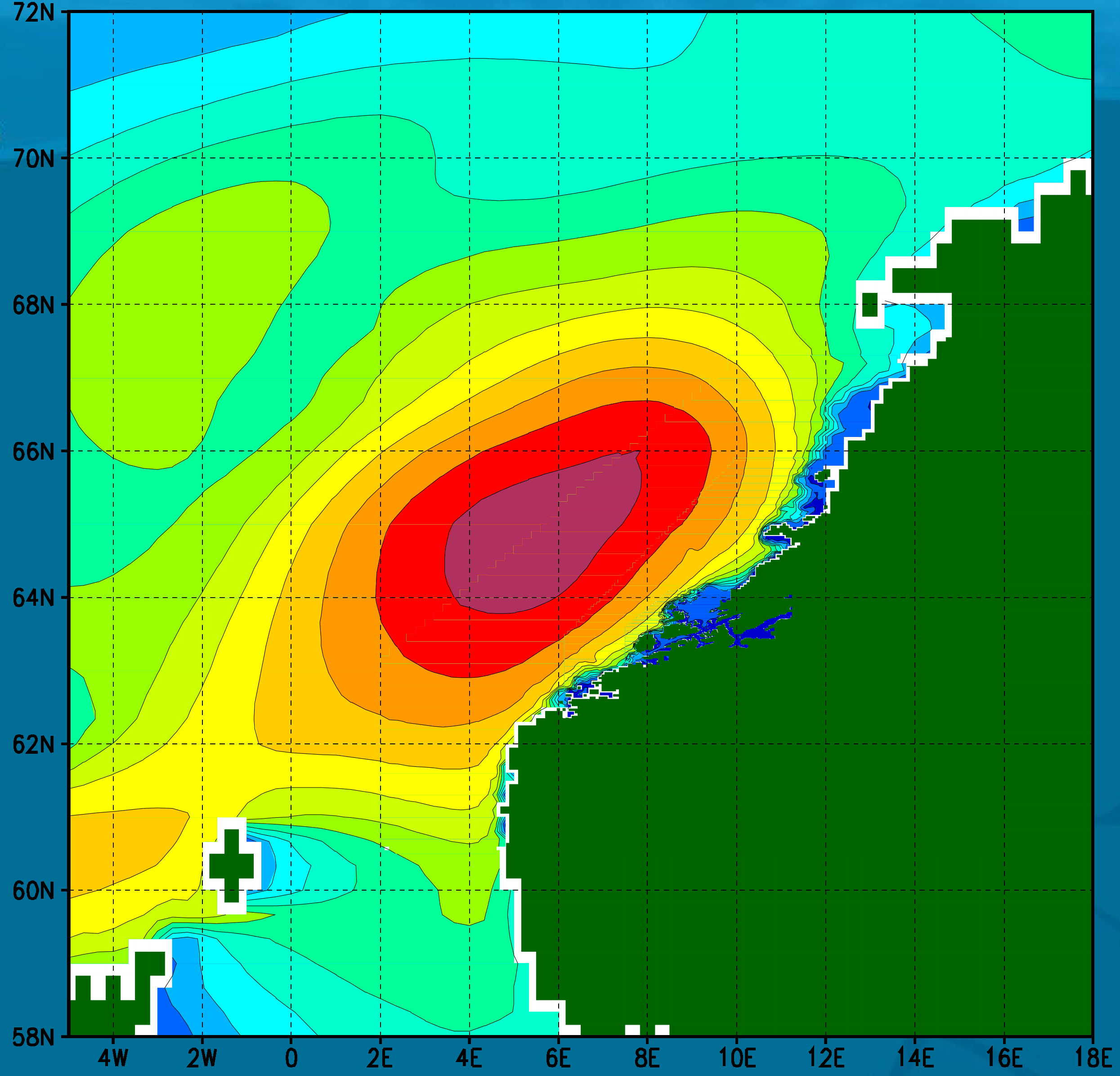






Inner fjords masked out in fourth grid.

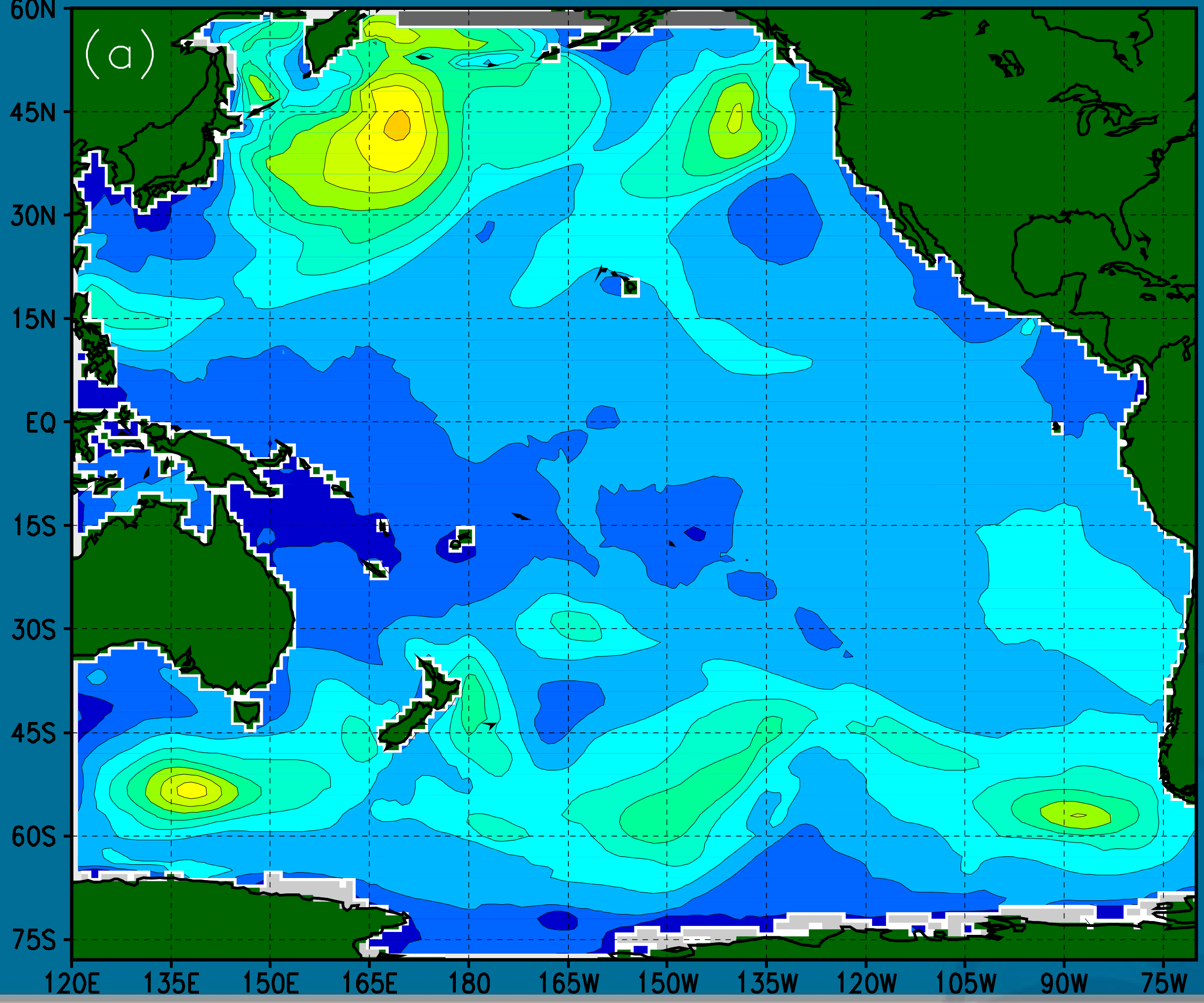
Putting it al together for a severe storm on Jan 11, 2006 …



72N
70N
68N
66N
64N
62N
60N
58N
4W
2W
0
2E
4E
6E
8E
10E
12E
14E
16E
18E

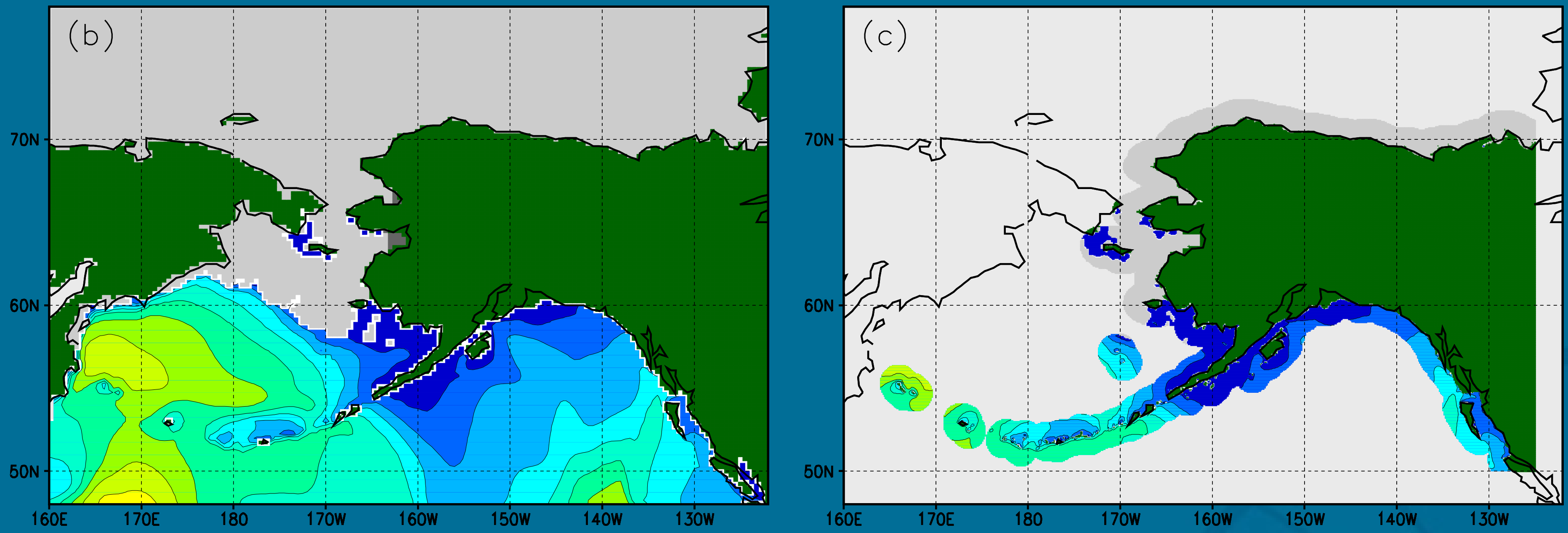
Modeling waves for Alaska with high coastal resolution.

Start with 1° basin grid.



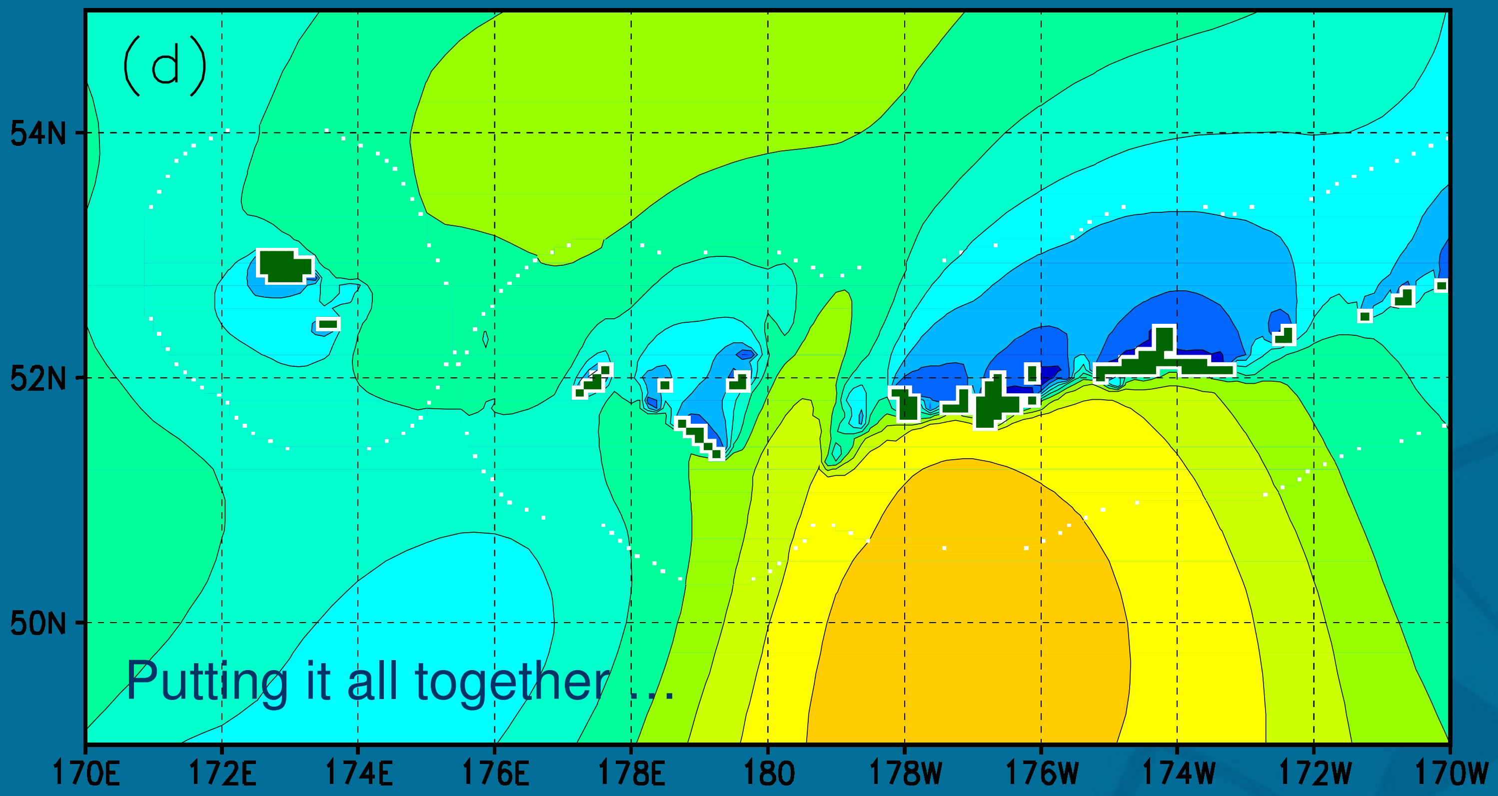
Case 2

Regional and coastal grids with 0.5°×0.25° and 1/8°×1/16° resolution, using extensive masking in the coastal grid to optimize the number of grid points.



Case 2

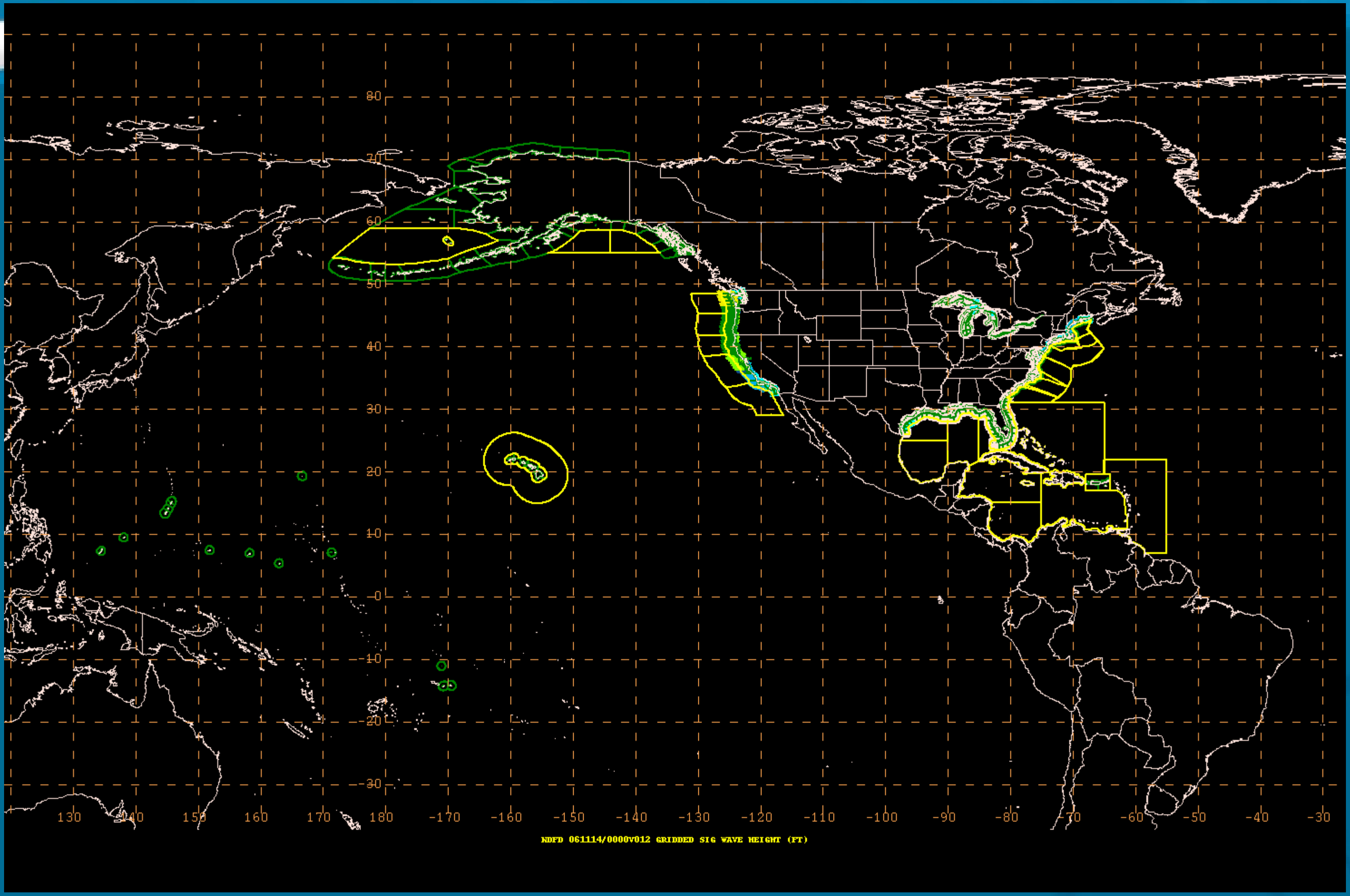
Island blocking is mostly modeled directly in the coastal grid!
Additional strength of two-way nesting.



Implementation in 2007-Q4 of the global model with static grids only.

- Provide model guidance at custom resolution for NWS NDFD responsibilities.
- Replacing AKW, WNA and ENP regional wave models.
- Moving grid versions to follow, replacing NAH and NPH models.

Case 3



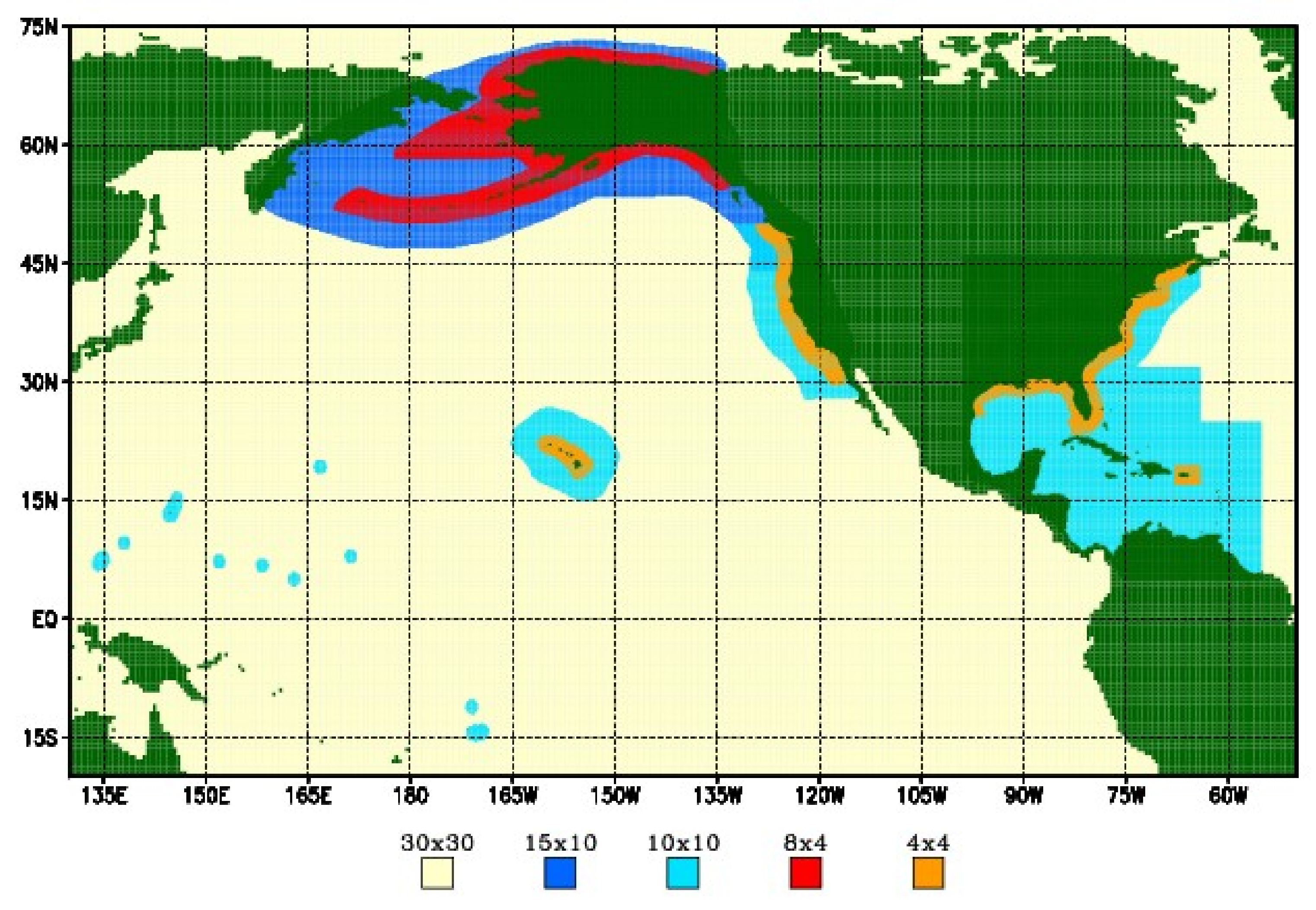
NWS areas of responsibilities and NDFD grids

Courtesy Joe Sienkiewicz

To provide consistent guidance for all these areas, the new operational NCEP model will consist of a mosaic of 8 grids:

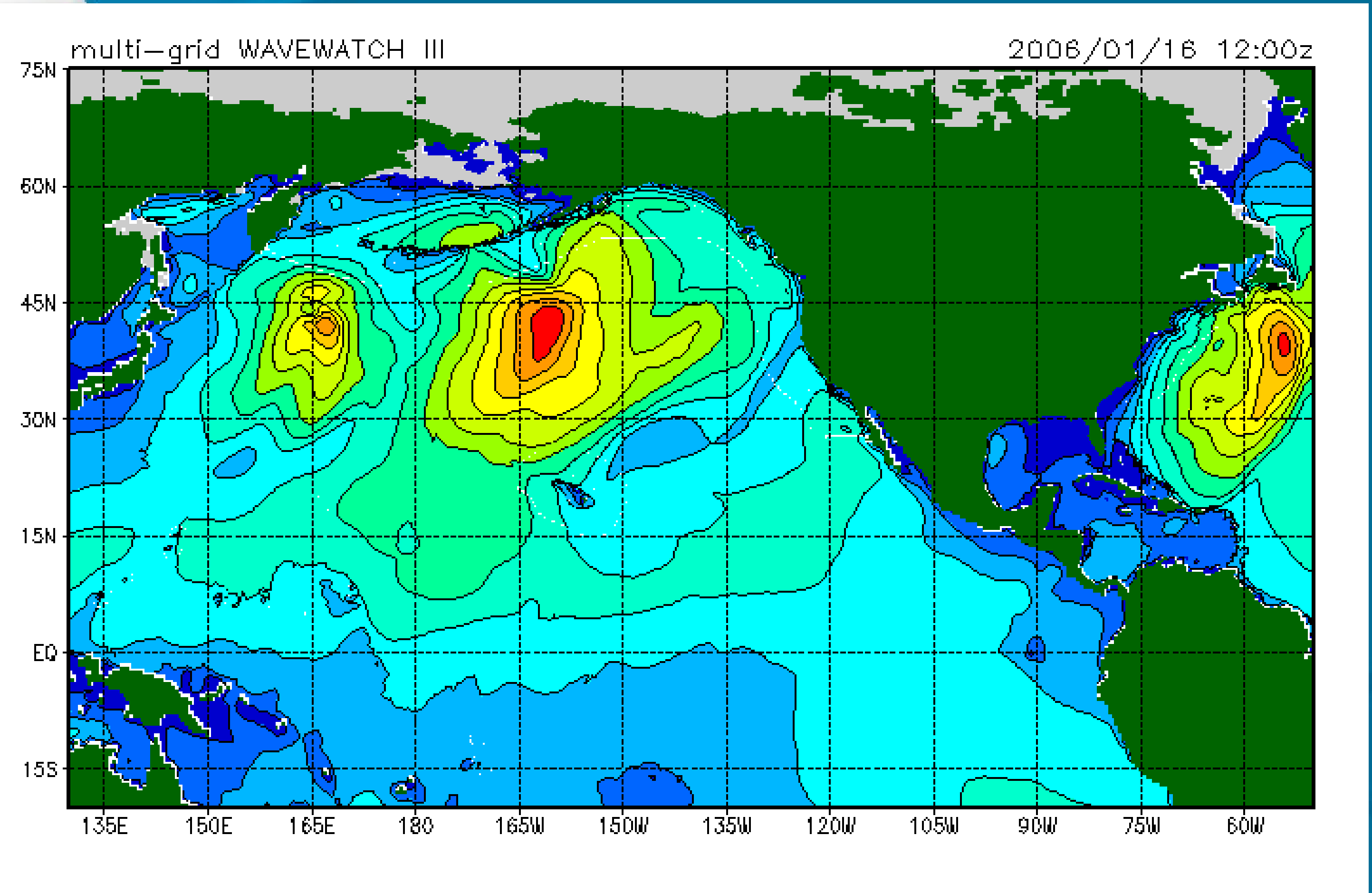
- A global 30’ grid.
- An offshore Atlantic 10’ grid.
- An offshore West Coast 10’ grid.
- A west Pacific 10’ grid.
- An Alaskan 10’x15’ grid.
- A coastal Atlantic 4’ grid.
- A coastal West Coast 4’ grid.
- A coastal Alaskan 4’x8’ grid.

Case 3



Resolution in minutes of the 8 grids making up the multi-grid model

Case 3

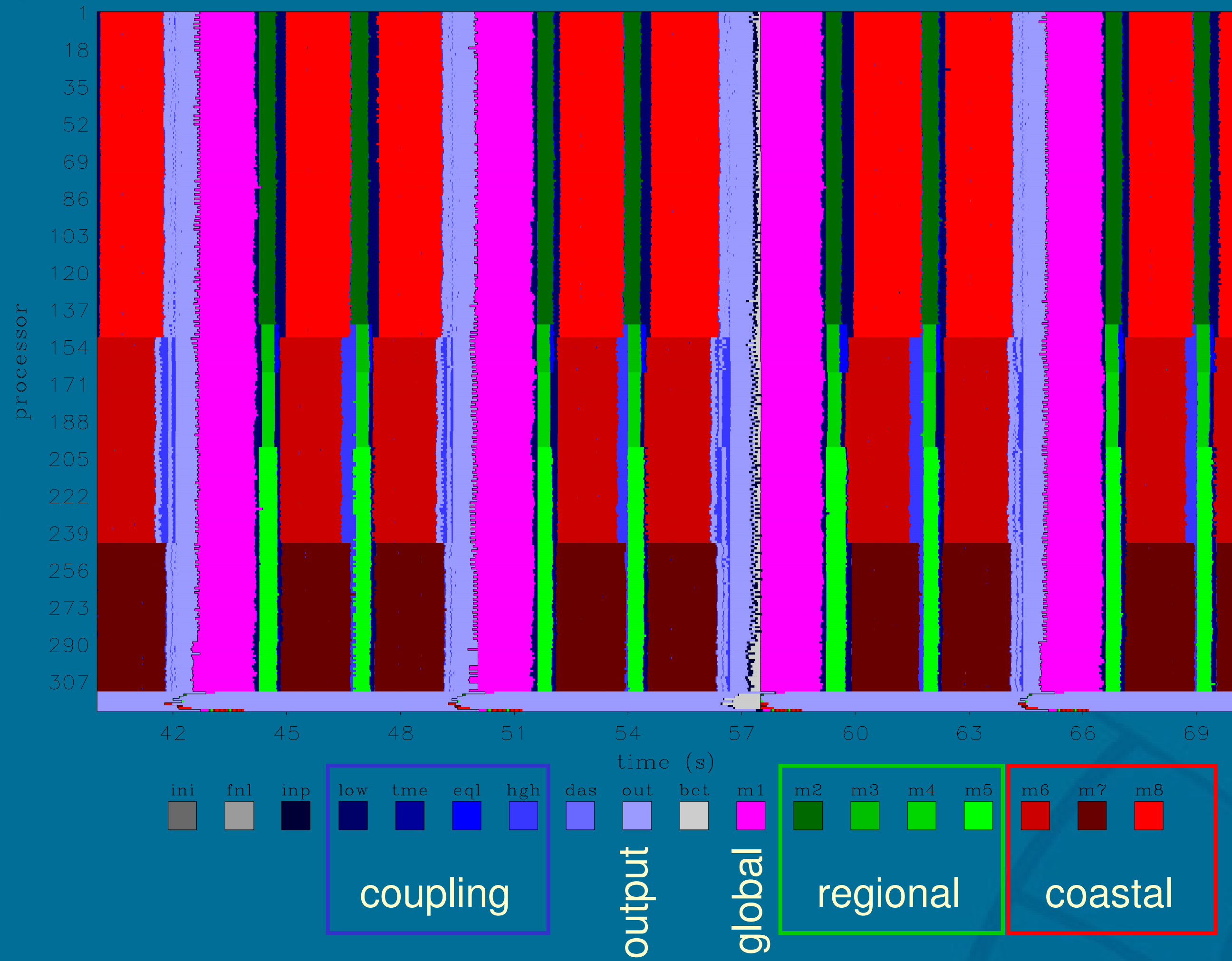


Example of consistency between grids

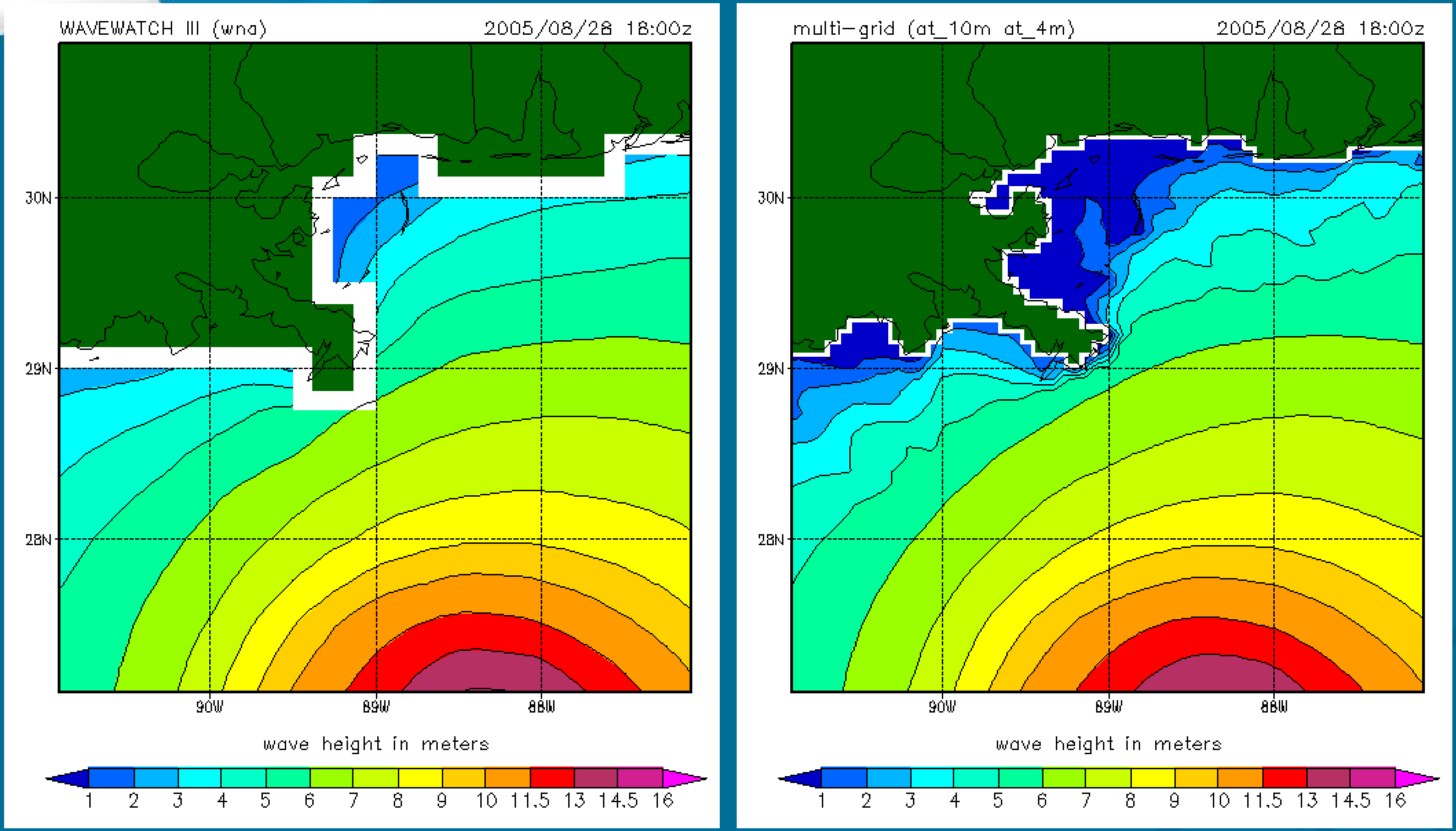
Optimization considerations:

- Running on 10 nodes and 320 processes on IBM mist/dew.
- Individual grids are too small for good scaling: run side-by-side.
- Additional benefit from dedicated nodes for raw output (asynchronous file writing).
- Little overhead for coupling between grids, most occurrences due to waiting for other grids to finish.
- See profiling example in next slide ….

Case 3

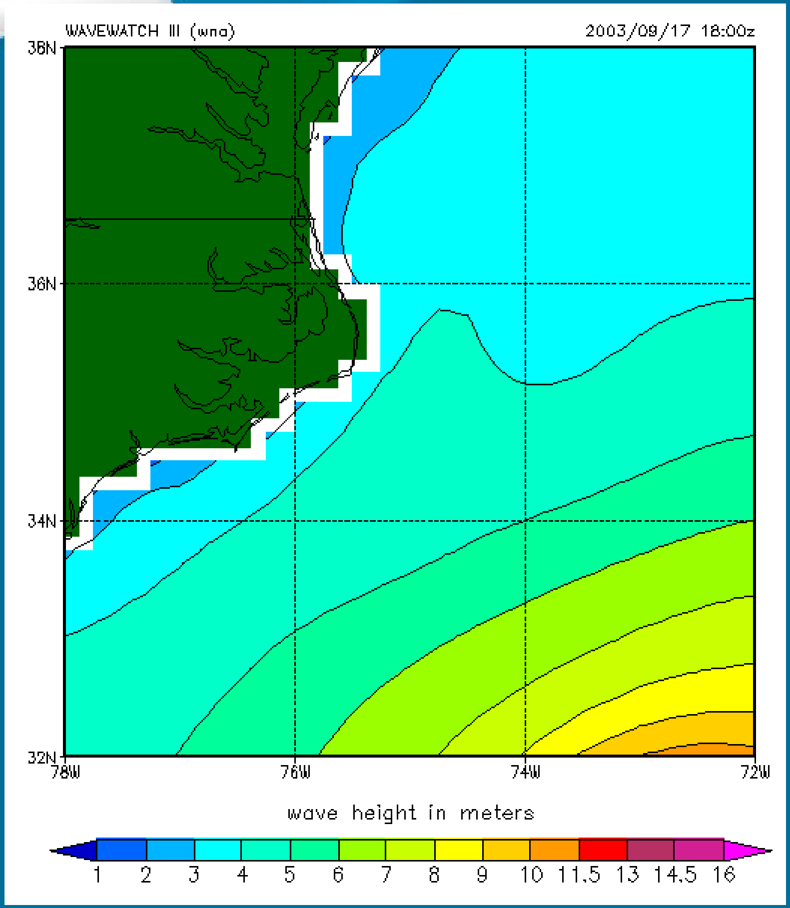

processor
1
18
35
52
69
86
103
120
137
154
171
188
205
222
239
256
273
290
307
42
45
48
51
54
57
60
63
66
69
time (s)
ini
fnl
inp
low
tme
eql
hgh
das
out
bct
m1
m2
m3
m4
m5
m6
m7
m8
coupling
output
global
regional
coastal

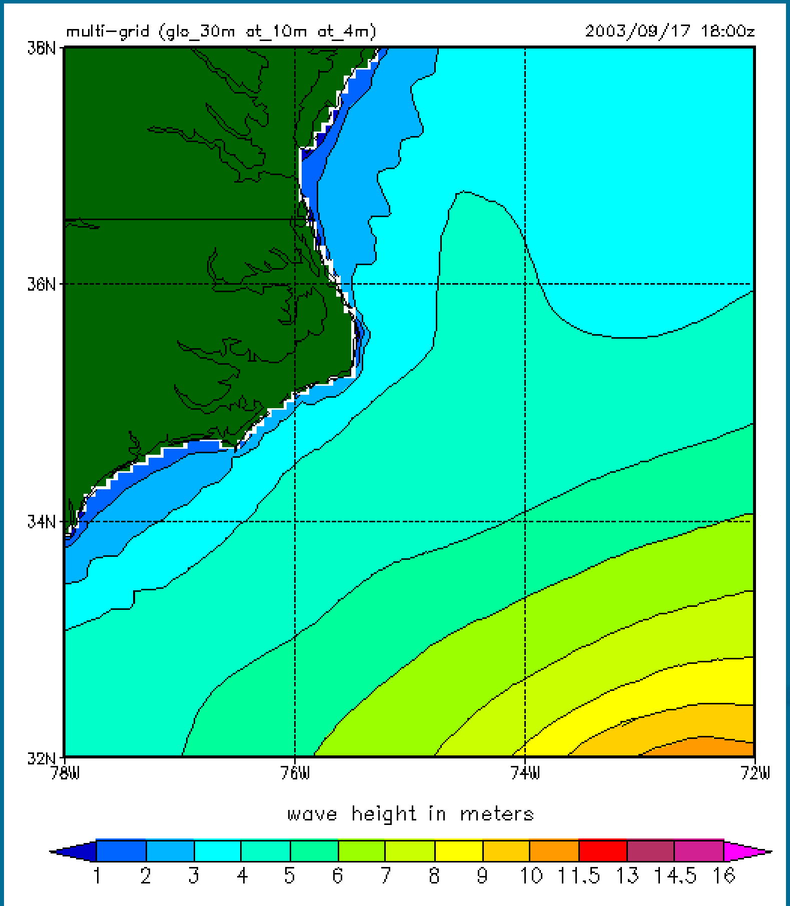
Case 3



Katrina with old and new systems (+ surf breaking)

Case 3





Isabel with old and new systems (+ surf breaking)

Conclusions

This has been a major development effort, but the benefits are enormous.

- Consistent results for all scales of NDFD grids.
- Operational coastal resolution increases from 25km to 7.5 km.

Looking forward to relocatable grid approach and to coupling with HWRF.

The end

End of lecture wwws 3.2