



Wind Wave Modeling

An intro to WAVEWATCH III[®]

*Hendrik L. Tolman
Chief, Marine Modeling and Analysis Branch
NOAA / NWS / NCEP / EMC*

Hendrik.Tolman@NOAA.gov





Contents of presentation

- Wind wave basics
 - Wind waves
 - Wave spectra.
 - Wave modeling basics.
 - Third generation models.
- WAVEWATCH III basics.
 - Running the model.
 - Model output.
 - Model input.
- Setting up a wave model for Lake Victoria.



Wave modeling basics.



- Wind waves are the waves at sea that are generated by local or distant winds. Waves generated locally are usually referred to as wind sea. Waves generated at distant locations in the past are referred to as swell.
- Wind waves range in wave height from negligible to 30m (100ft) and more, and in length (distance between consecutive waves) from centimeters to 1 km.
- Corresponding wave periods (i.e., the time it takes for two consecutive waves to pass a given location) range from less than 1 second to about 25s.



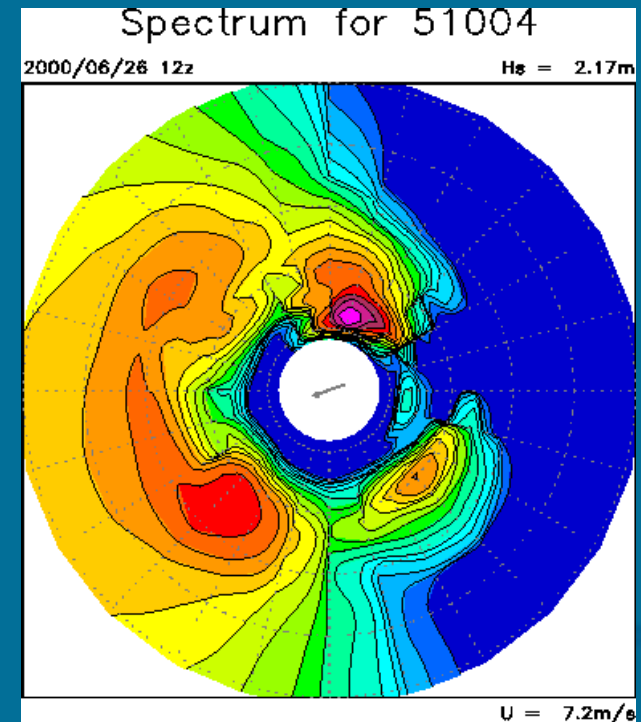
- Although wind wave conditions generally change slowly, no two consecutive waves are identical. Furthermore, individual waves are so small that it would be practically impossible to predict every individual wave. Instead the wave field is described with average measures for wave heights.
- The commonly used wave height to describe the wave field is the significant wave height H_s , which is usually defined as the average wave height of the highest 33% of all individual waves. Because smaller waves are generally not seen against the background of the larger ones, this corresponds closely to the visually observed mean wave height.



- Generally, it is assumed that individual wave heights can be described using a Rayleigh distribution. This implies that for a significant wave height $H_s = 10\text{m}$ (33ft), one can expect :
 - 1 in 10 waves to be larger than 10.7m (36ft).
 - 1 in 100 waves to be larger than 15.1m (51ft).
 - 1 in 1000 waves to be larger than 18.6m (62ft).
- This implies that the largest individual wave that one might encounter in a storm is roughly twice as high as the significant wave height !
- In rapidly changing conditions the disparity between the significant wave height and the largest individual waves might even be larger.

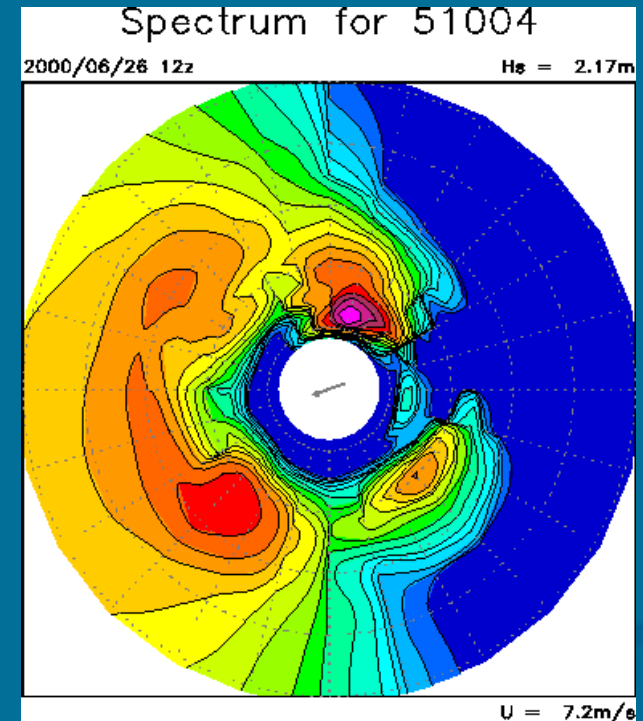


- In advanced wave observations and inside wave models, the wave field is not described with a single wave height, but with a so-called wave spectrum, which describes the distribution of wave energy over wave directions and frequencies at a fixed location.
- A graphical representation of such a spectrum as can be found on the web page is shown here (buoy location 51004, SE of Hawaii).



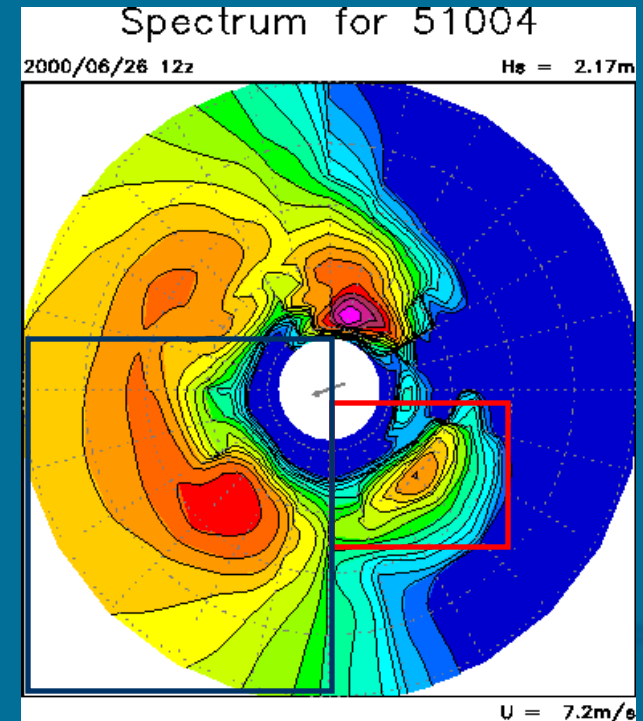


- Dark blue indicates absence of wave energy, light purple the local maximum. Each new contour level corresponds to a factor of two increase of wave energy.
- The direction relative to the center of the plot indicates the direction in which the waves travel. The frequency increases from about 0.04Hz (25s wave period) at the center of the plot to 0.25Hz (4s wave period) at the outside of the plot.





- The energy in the red box thus represents an individual wave field traveling in SE direction with a peak period of about 10s. Because wave energy is concentrated in frequency and direction, this corresponds to a fairly regular, well organized wave field.
- The energy in the blue box travels in SW direction at lower periods, and is more chaotic as energy is distributed over a wider range in directions and frequencies.





- The spectral plots from the wave model mostly give qualitative information. The corresponding quantitative information can be found in the bulletins.
- A piece of such a bulletin is presented below. The first column gives date and hour, the second the overall wave height and number of identified individual wave fields. The next six columns (only two shown here) identify wave fields by height, period and direction.

Location : 51004 (17.40N 152.50W)
 Model : NWW3 global 1x1.25 degr.
 Cycle : 20000626 t00z

day & hour	Hst n x (m) - -	Hs Tp dir (m) (s) (d)	Hs Tp dir (m) (s) (d)
25 12	1.9 7	1.0 17.5 19	1.0 7.0 292
25 13	1.9 7	1.0 17.6 19	1.0 7.0 292
25 14	1.9 6	1.1 17.6 19	0.9 7.1 292



The basis of all spectral random-phase models is the spectra action balance equation

$$\frac{\partial N(\mathbf{i})}{\partial t} + \nabla_{\mathbf{x}} \cdot (\mathbf{c}_g + \mathbf{U})N(\mathbf{i}) + \nabla_{\mathbf{i}} \cdot \mathbf{c}_i N(\mathbf{i}) = \sum S(\mathbf{i})$$

$$N(\mathbf{i}) = \frac{F(\mathbf{i})}{\sigma}$$

\mathbf{i}

Action density spectrum in term of the energy spectrum and intrinsic frequency.

Spectral phase space (wavenumber, frequency, direction, 2D).

$$\nabla_{\mathbf{x}}, \nabla_{\mathbf{i}}$$

Divergence operators.

$$\mathbf{c}_g, \mathbf{c}_i, \mathbf{U}$$

Characteristic and current velocities.

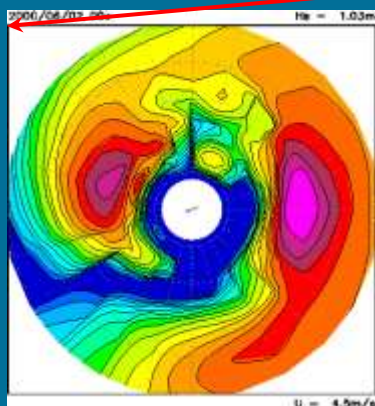
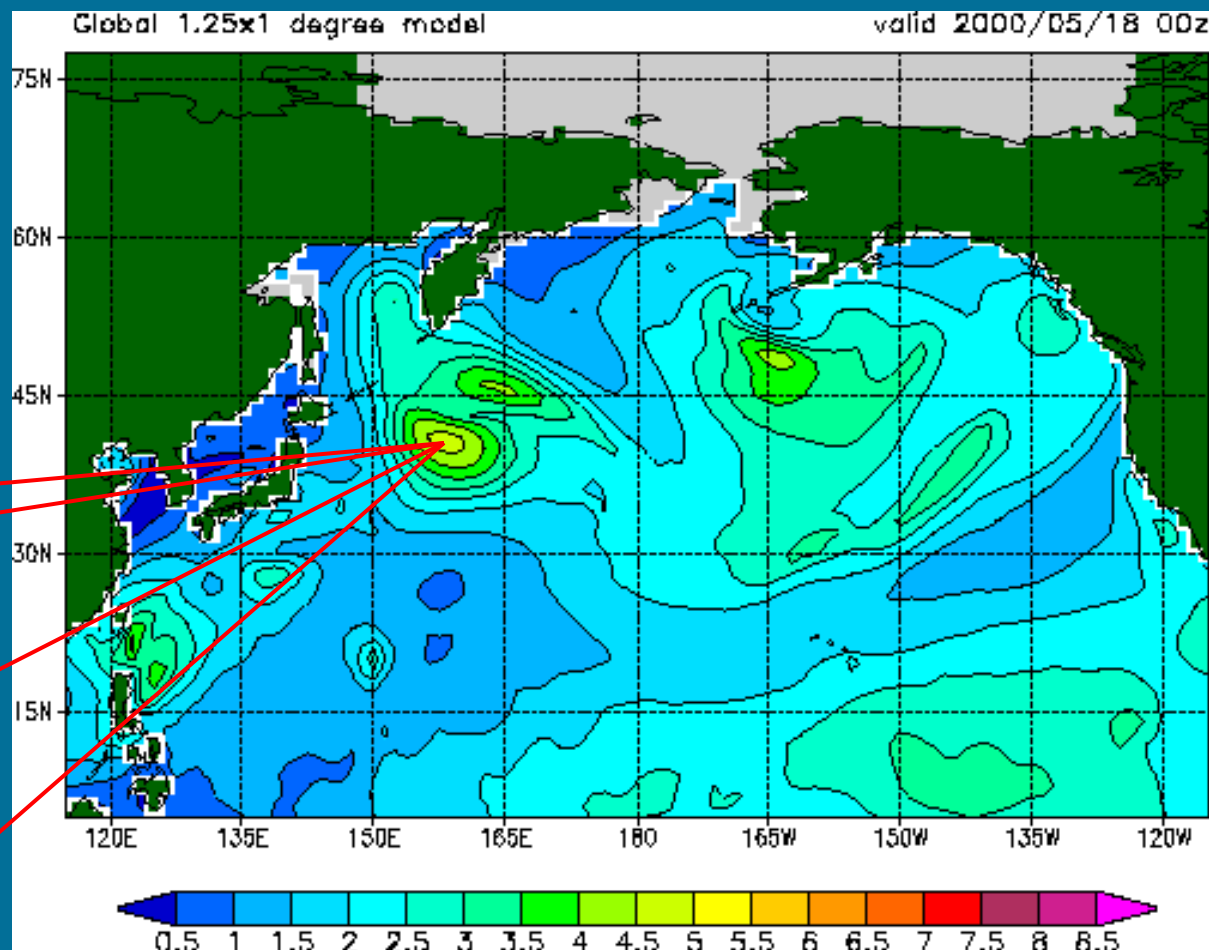
$$\sum S(\mathbf{i})$$

Sources and sinks of energy / action.



significant wave height (m)

Spectral description
of wave field at
each grid point





Ocean wind wave models are classified by their treatment of the source terms.

$$\frac{\partial N(\mathbf{i})}{\partial t} + \nabla_{\mathbf{x}} \bullet (\mathbf{c}_g + \mathbf{U})N(\mathbf{i}) + \nabla_{\mathbf{i}} \bullet \mathbf{c}_i N(\mathbf{i}) = \sum S(\mathbf{i})$$

- First and second generation models use observed spectral shapes and sustained spectral energy levels to infer effects of physical processes.
- Third generation (3G) model parameterize all physical processes explicitly (degrees of freedom = spectral bins), without imposing spectral shapes or energy levels.
 - Exception is unresolved high-frequency part of wave spectrum (shape defined, level is not).



3G models have become the standard for ocean wave modeling.

- Much more expensive than 1G and 2G models.
- Much more versatile than 1G and 2G models.
 - Less need for site-specific tuning.
 - New science directly applicable.
- Still too expensive for some applications ?
 - Coupled modeling.
 - Commercial applications.



There are many 3G models available.

- The most widely used models are WAM, SWAN and WAVEWATCH III.
 - WAM is the original.
 - ➔ No strong central support system since the mid 1990' s.
 - ➔ Now semi-proprietary versions.
 - SWAN and WAVEWATCH III actively supported and freely available.
- Several commercial models:
 - OceanWeather, DHI,
- Several research models
 - Exact-NL,



$$\frac{\partial N(\mathbf{i})}{\partial t} + \nabla_{\mathbf{x}} \bullet (\mathbf{c}_g + \mathbf{U})N(\mathbf{i}) + \nabla_{\mathbf{i}} \bullet \mathbf{c}_i N(\mathbf{i}) = \sum S(\mathbf{i})$$

- The traditional way to solve this equation is to consider it as a hyperbolic equation and march the solution forward in time. This technique is used by most models.
- The exception is the SWAN model, which traditionally considered the quasi-stationary version of the Eqs.

$$\nabla_{\mathbf{x}} \bullet (\mathbf{c}_g + \mathbf{U})N(\mathbf{i}) + \nabla_{\mathbf{i}} \bullet \mathbf{c}_i N(\mathbf{i}) = \sum S(\mathbf{i})$$

- This becomes an elliptical Eq., that is solved by an iterative sweeping procedure.
- Later, SWAN reintroduces instationarity ...



- Features of hyperbolic approach:
 - Simple/cheap solvers for each time step (typical explicit FD formulations).
 - Explicit FD formulations result in small time steps for high-resolution models, making models expensive for typical coastal applications.

focus here

- Features of elliptical approach:
 - In stationary mode, solutions only when needed; cheap modeling for high resolution coastal applications.
 - Iterative solver for implicit problem more complicated.
 - Large time steps possible for coastal models.
 - Stability versus accuracy with large time steps.



Economical solution:

- Five dimensional problem. To save memory and to keep numerical schemes simple, use a fractional step method.

$$\frac{\partial N(\mathbf{i})}{\partial t} + \nabla_{\mathbf{x}} \cdot (\mathbf{c}_g + \mathbf{U})N(\mathbf{i}) + \nabla_{\mathbf{i}} \cdot \mathbf{c}_i N(\mathbf{i}) = \sum S(\mathbf{i})$$

- Subsequent equations solved in WAVEWATCH III
 - Spatial propagation.
 - Intra-spectral propagation.
 - Source terms
 - Water level changes (remapping only).



Sources and sinks

$$\sum S(\mathbf{i}) = S_{in}(\mathbf{i}) + S_{nl}(\mathbf{i}) + S_{ds}(\mathbf{i}) + \dots$$

- Wind input (linear and exponential).
- Nonlinear interactions (4-wave, resonant)
 - Not important for propagation, critical for wave growth,
- Dissipation (whitecapping) + swell dissipation.
- Many additional processes in shallow water.
 - Bottom friction.
 - Shallow water wave breaking.
 - Triad interactions.
 - ...



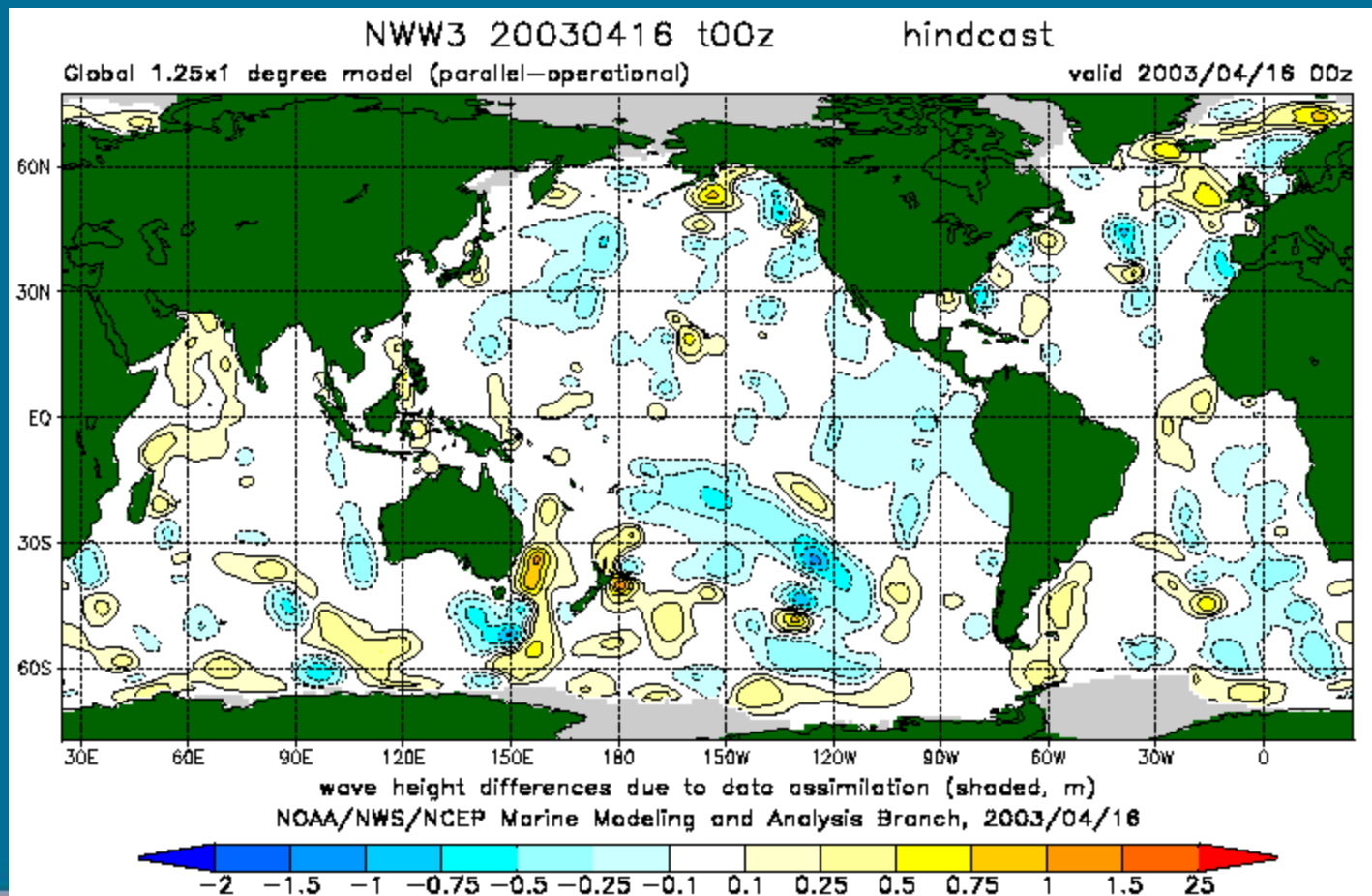
This is not a weather model !!!!

- Wind waves represent a forced and damped problem.
 - This is not an initial value problem like a weather or ocean model.
- Therefore, a very good wave model can be build without any data assimilation.
 - Weather and ocean models are critically dependent upon initial conditions and therefore on data assimilation.
- Due to the forced and damped nature, retention time of data into a wave model is limited by definition:
 - Typically 12-36 hours in terms of impact on wave height in typical operational models.
 - May be much smaller if a coastal model uses coastal buoy data.
 - Up to weeks for Pacific swell.



There is not enough data.

- There is no data-dominated analysis.
- Quality of analysis is by definition misleading.





WAVEWATCH III basics.



Model version 3.14 will be the considered here.

The model consists of a set of programs :

- Grid preprocessor (*ww3_grid*).
- Initial conditions program (*ww3_strt*).
- Model input preprocessor (*ww3_prep*).
- The actual wave model (*ww3_shel*, *ww3_multi*).
- Output post-processors:
 - Numerical (*ww3_outp*, *ww3_outf*, *ww3_trck*, *ww3_grib*).
 - GrADS (*gx_outf*, *gx_outp*).

Introduced in version 3.14

Introduced in version 2.22



Basics :

- All programs read their instructions from a file with the extension *.inp*, for instance *ww3_grid* reads from *ww3_grid.inp*.
- The first character of the first line of the *.inp* file identifies the comment character.
 - Lines starting with this character are skipped while reading.
 - In all examples used by us the comment character is '\$'.
- All programs write output to standard output.
- All raw output files of the wave model are identified by the extension *.ww3*. (exception: running *ww3_multi*).
- The presentation will first focus on running the conventional single-grid wave model *ww3_shel*.



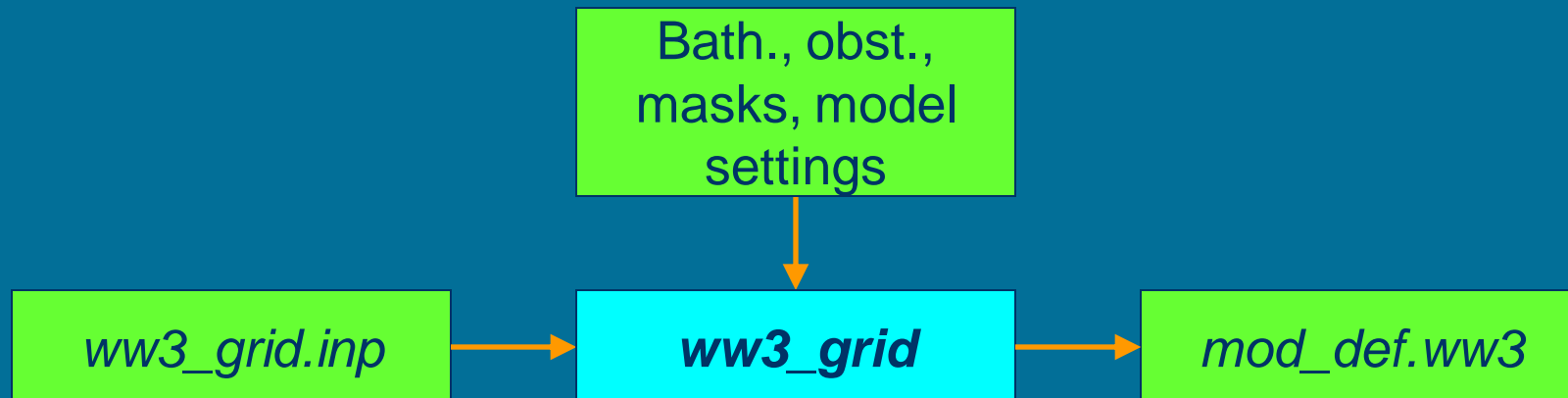
Cont' ed :

- Before anything else can be done, a model or grid is defined using ***ww3_grid***, resulting in a model definition file ***mod_def.ww3***. This file contains:
 - Bathymetry, obstruction grids, masks. select at compile
 - Parameter settings for all physics and numerical approaches (including flags and dry-run option).
 - Data fields for above approaches as needed.
 - Time steps for grid.
 - Input boundary points for grids.
 - Output boundary points for nested grids if off-line nesting is performed (***ww3_multi*** does in-line nesting).
 - ➔ Points are defined, but output is controlled by ***ww3_shel***.



Running *ww3_grid* :

- *ww3_grid* is typically run once, and *mod_def.ww3* is then stored for use with all other programs.



file, data

program

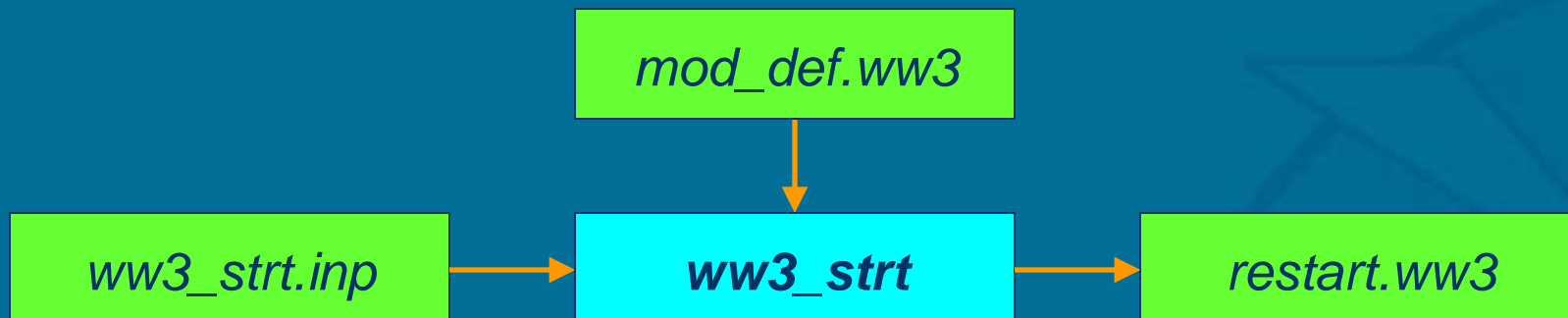


data flow



Creating initial conditions :

- Initial conditions are generated using ***ww3_strt***. Options:
 - Gauss / cosine (idealized swell).
 - JONSWAP, Gauss in space.
 - JONSWAP, fetch limited based on local wind and grid spacing.
 - Single user-defined spectrum.
 - All at rest (**new in 3.14**).





With the *mod_def.wv3* and *restart.wv3* files we have enough to run a basic wave model.

The input file for the basic wave model (*ww3_shel.inp*) contains :

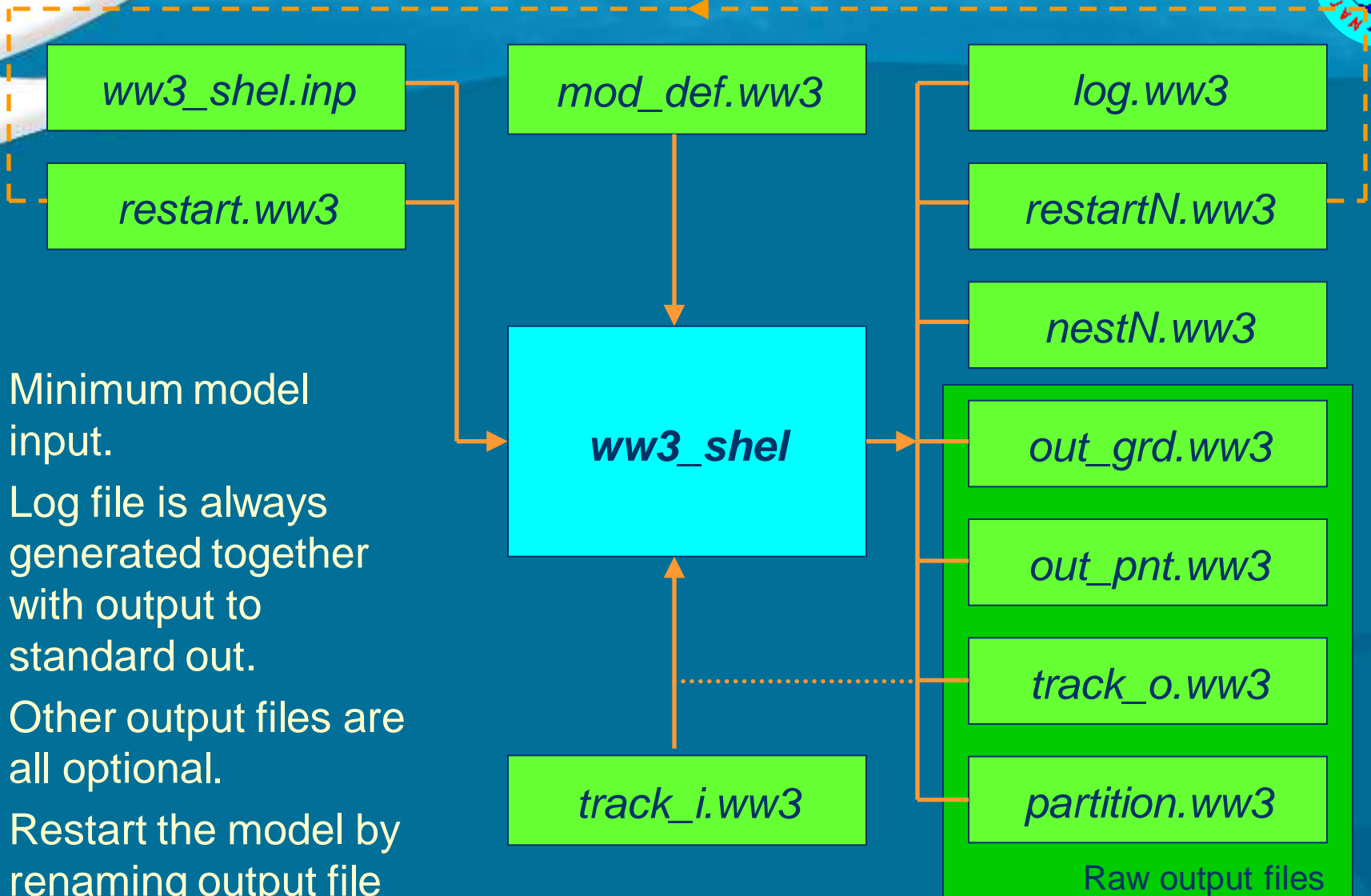
- Definition of inputs to use (level, current, wind, ice; homogeneous or variable).
 - Homogeneous input data makes it possible to run model without separate input data files.
- Start and end time.
- Output requests for six types of standard output.
- Homogeneous input field data if requested.



ww3_shel.inp cont' ed:

- Output needs to be selected in *ww3_shel.inp*.
 - Gridded output fields.
 - Point output containing full spectral data.
 - Nesting data for higher resolution grids.
 - ➔ Only output times set in *ww3_shel.inp*.
 - ➔ Up to nine different files.
 - Restart files.
 - ➔ Up to nine different files.
 - Output of spectra along pre-defined tracks.
 - Partitioned spectral data (new in 3.14).

Running the model



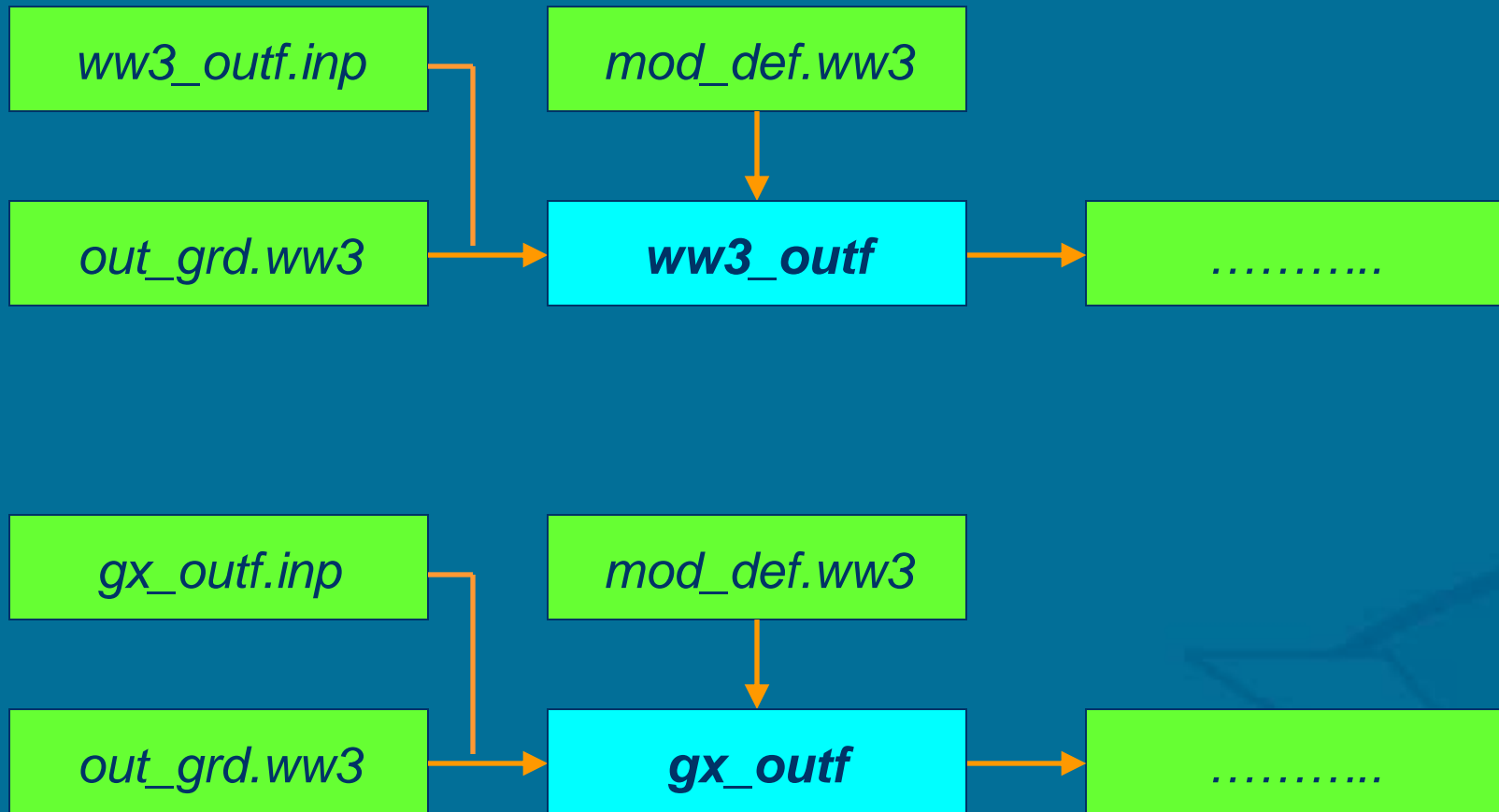
- Minimum model input.
- Log file is always generated together with output to standard out.
- Other output files are all optional.
- Restart the model by renaming output file to input file.

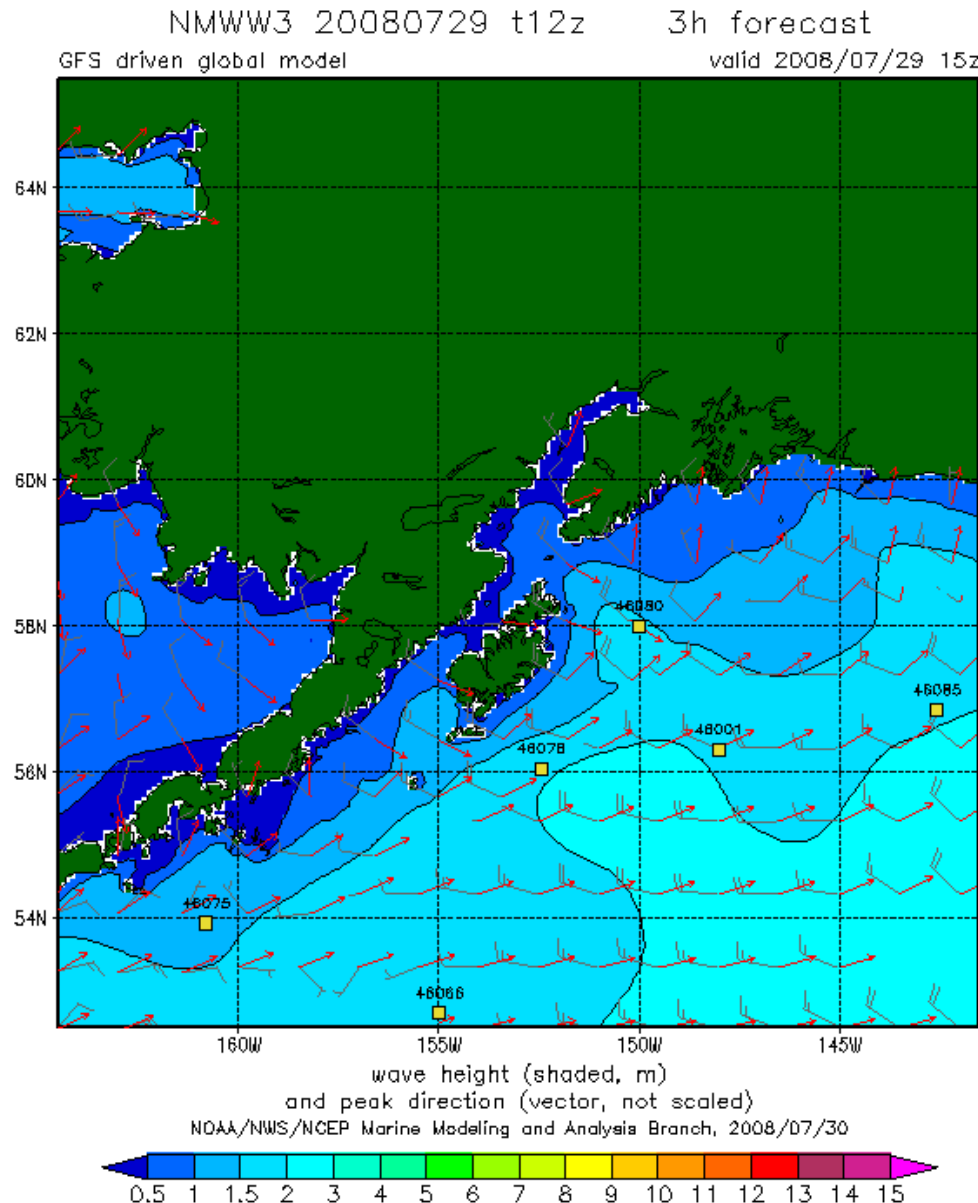


- The ***ww3_shel*** model generates two formatted output files.
 - std out output tracks progress “on screen”.
 - ***log.ww3*** is generated by the actual wave model routines. This file is provided to assure consistent info on the model when the routine is included in an integrated model.
- The raw data files and the output restart file are only generated upon request (***track_i.ww3*** only needed for request). They are unformatted and partially packed.
 - ***restartN.ww3*** and ***nestN.ww3*** are used by subsequent model runs as is (after renaming).
 - All other raw output files require postprocessing.



- The file `out_grd.ww3` contains fields of mean wave parameters such as the significant wave height, and is processed using `ww3_outf`. `ww3_outf` produces :
 - File inventories of `out_grd.ww3`.
 - Print plots of fields.
 - Statistics for given ranges of the grid
 - Data transfer files.
- The file `out_grd.ww3` can be converted into GrADS data files using `gx_outf`, which operates similar to `ww3_outf`.

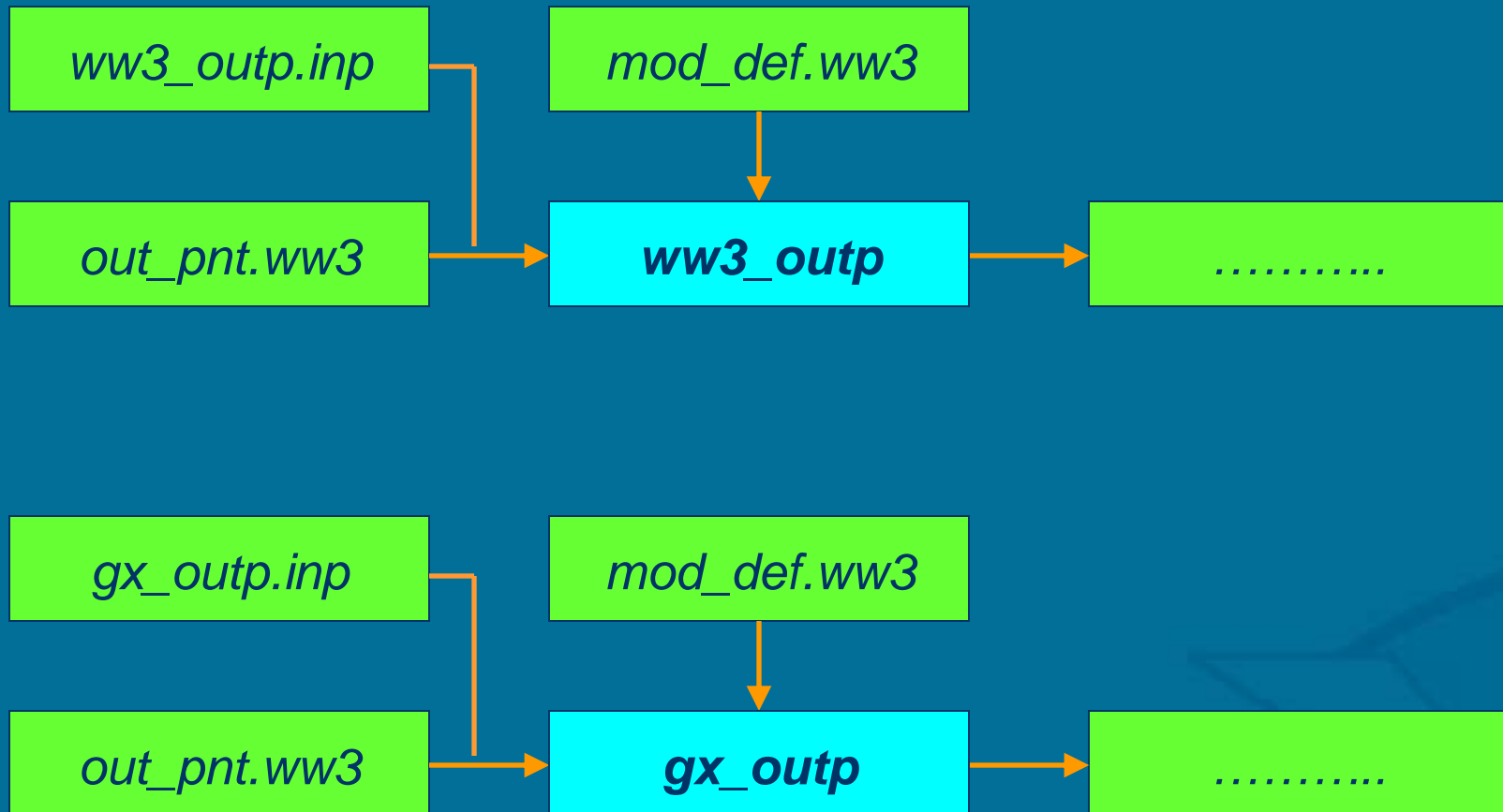




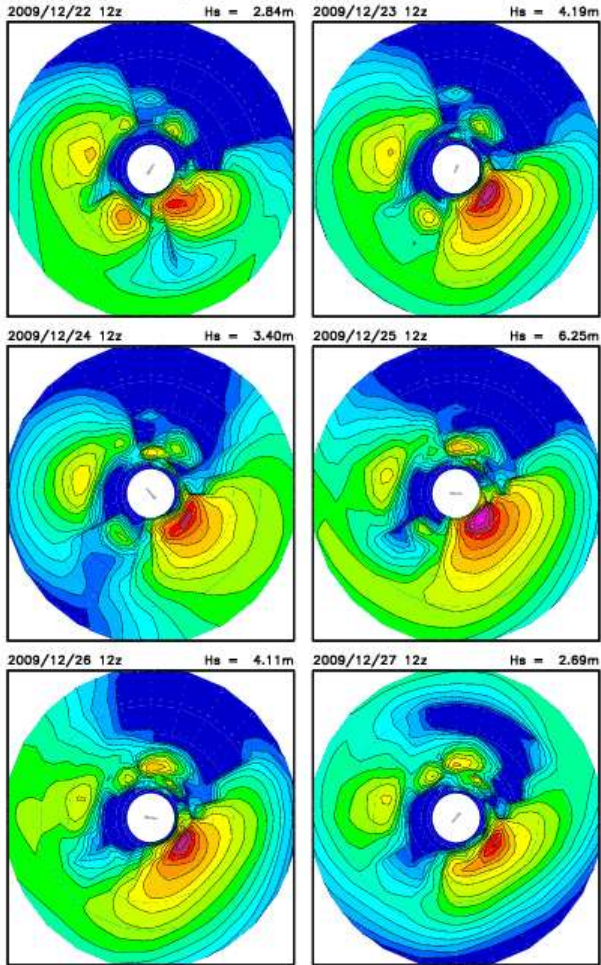
Example of GrADS
output for present
operational
resolution for Cook
Inlet in Alaska,
generated after post-
processing
out_grd.ww3 with
gx_outf.



- The file `out_pnt.ww3` contains full spectral data for selected output points, and is processed using `ww3_outp`. `ww3_outp` produces :
 - File inventories of `out_pnt.ww3`.
 - Spectral data as print-plots, tables of 1-D spectra and data transfer files.
 - Tables of mean environmental and wave parameters.
 - Source term data similar to that of spectra.
- The file `out_pnt.ww3` can be converted into GrADS data files using `gx_outp`



Spectra for 51001

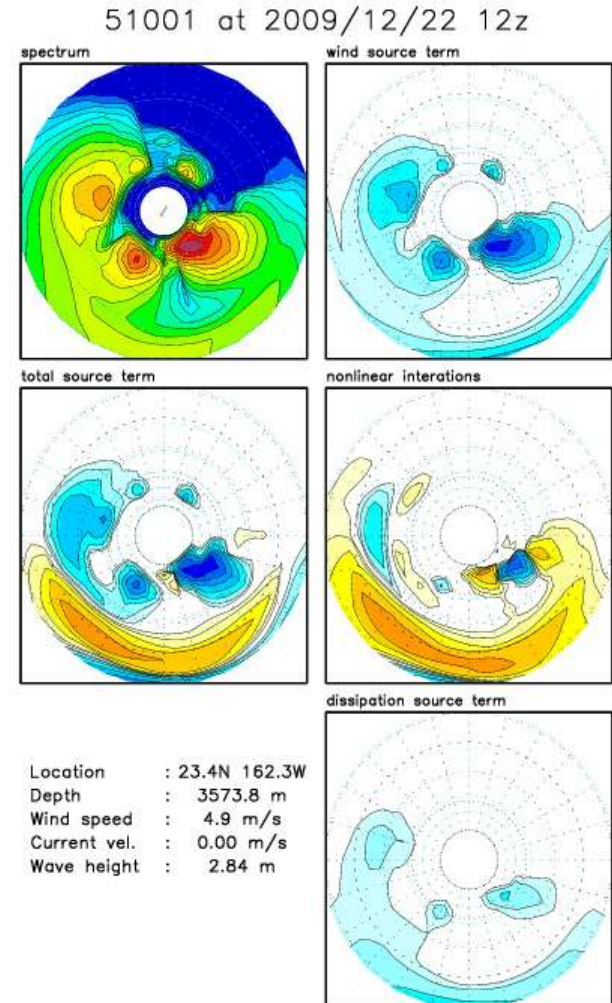


NOAA/NWS/NCEP Marine Modeling and Analysis Branch, 2009/12/22
Global 1.25x1 degree (NWW3)

Model output

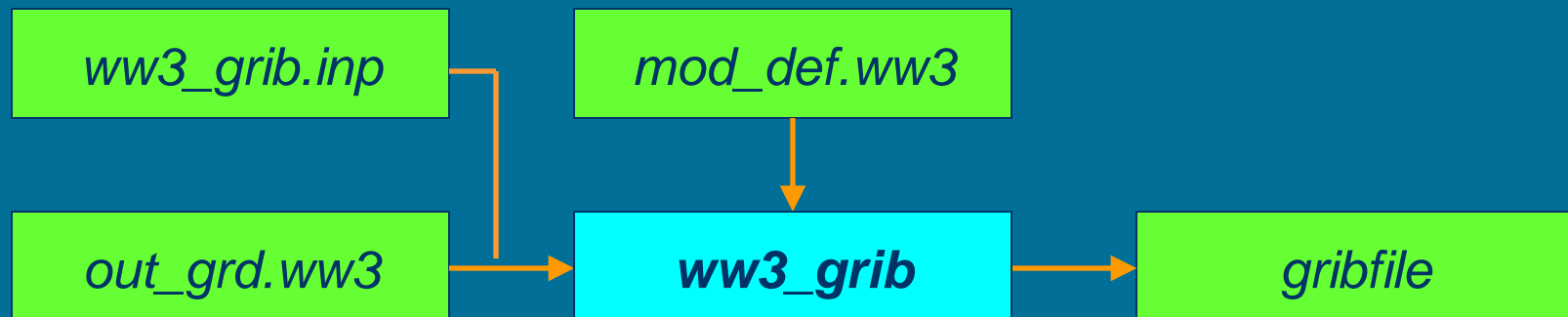


Example of GrADS spectral and source term output made by processing *out_pnt.ww3* with *gx_outp*, and using GrADS script provided with the wave model distribution.





- ***ww3_grib*** takes the raw data file ***out_grd.ww3*** and converts it to a GRIB or GRIB2 file.
- GRIB and GRIB2 packing routines are not provided with WAVEWATCH III yet.





So far, we have been running the model with homogeneous input fields for

- water levels
- currents,
- winds,
- and ice.

None of these input fields are mandatory, and a mixture of homogeneous on non-homogeneous fields can be used.



All input fields are pre-processed and written to files with a standard WAVEWATCH III format.

- This separates processing input from the wave model.

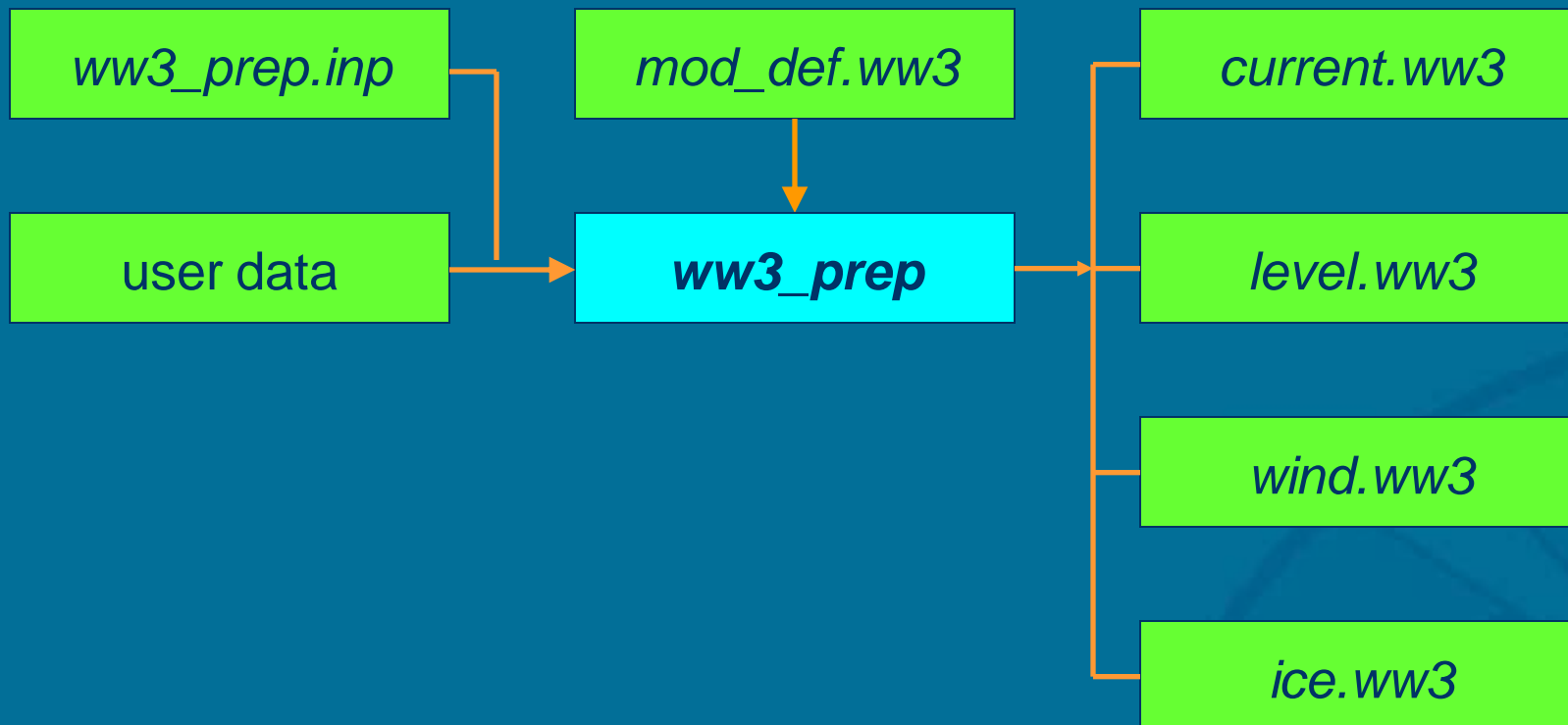
In the standard WAVEWATCH III data files, each data field has its own time stamp. *ww3_shel* deals with these time stamps on a field by field basis. This implies that :

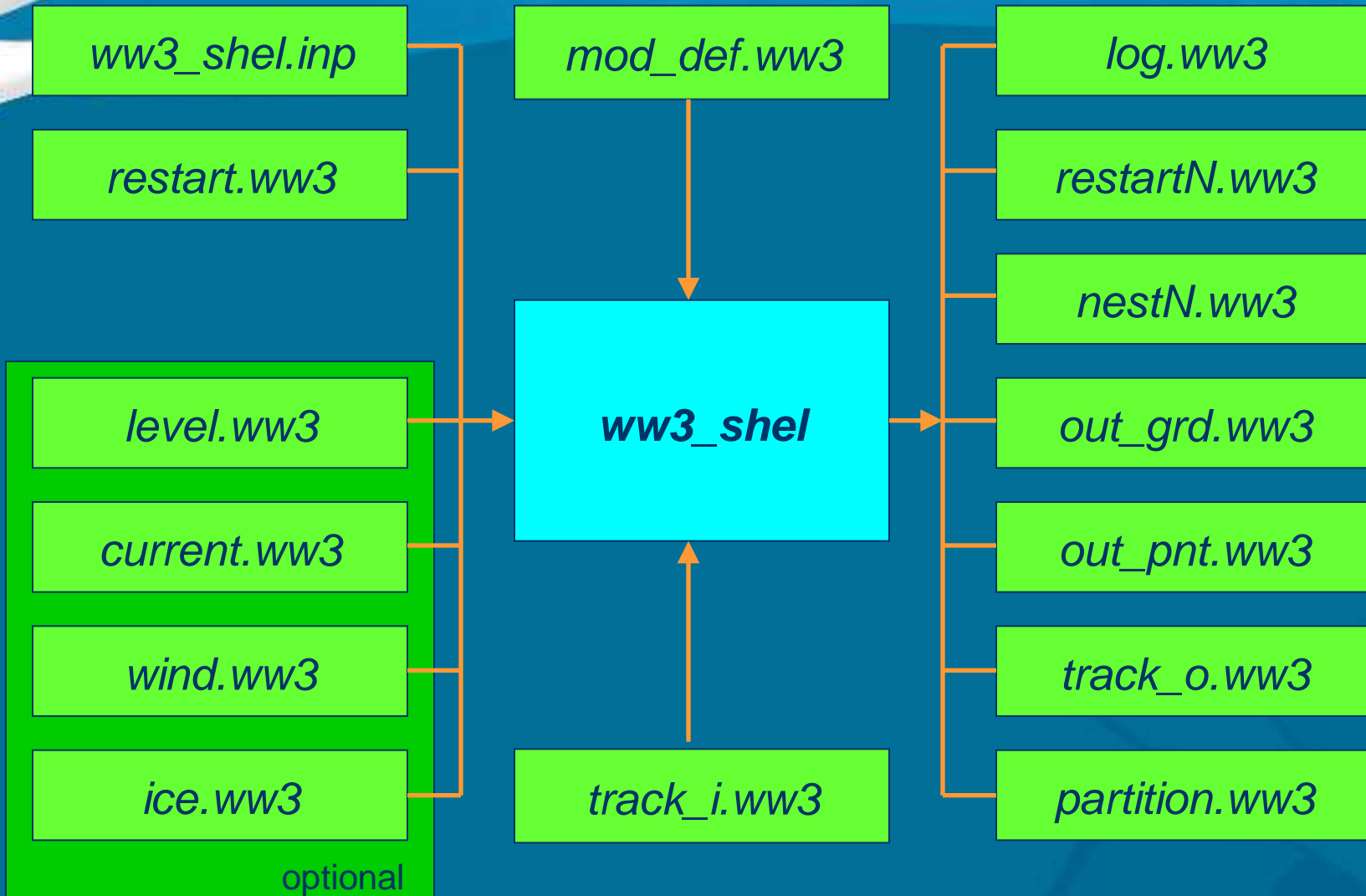
- The model does not require input fields at constant intervals.
- The user need not supply field interval time steps in any of the programs as they are meaningless.

Input data are kept constant before the first and after the last time stamp in the file.



- Preprocessing of input fields is performed by *ww3_prep*. This program deals with all four types of input fields (**one at a time**) and can deal with user-supplied fields of several formats.







Lake Victoria



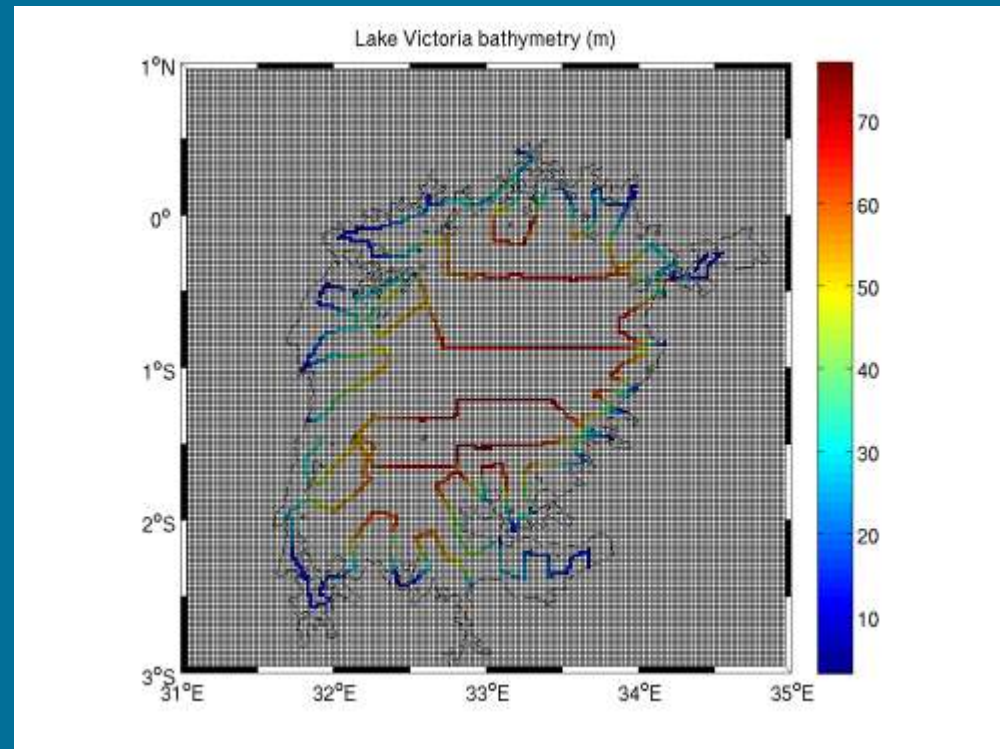
What do we need to set up a model, for instance for Lake Victoria?

- A bathymetry.
- Spectral discretization.
- Time stepping.
- Winds:
 - Can play with constant winds first ...
 - but need real winds eventually.



Bathymetry:

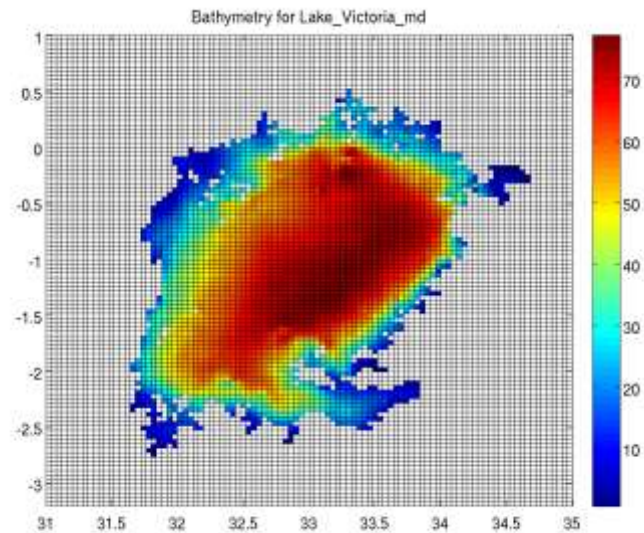
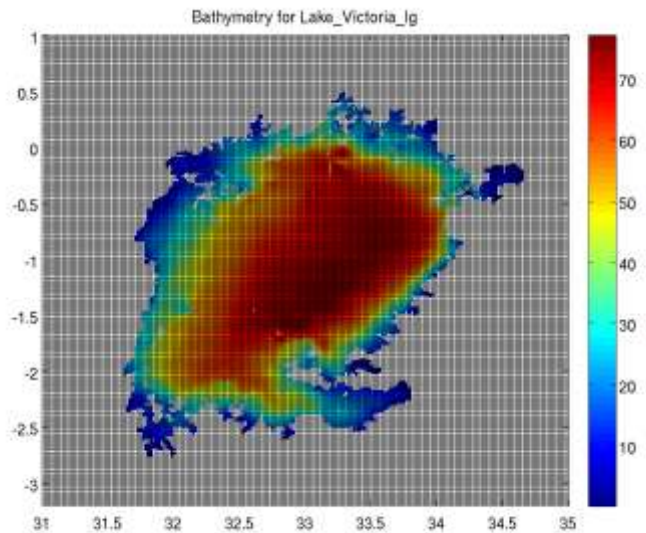
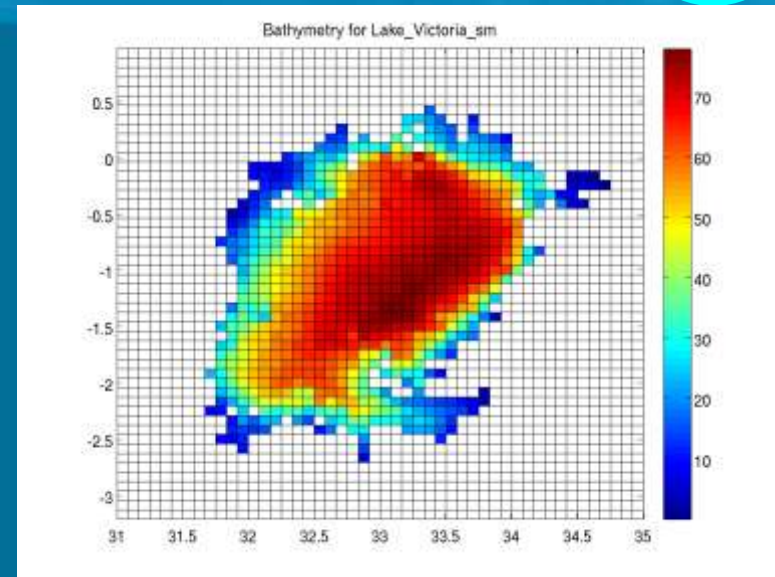
- At the very least, you need to know where the coast is.
 - Land sea mask for grid, can assume deep water anywhere.
- Better is to know water depths too.
 - From Ali Mafimbo:
 - ➔ Soundings.





Tools used :

- Matlab grid interpolation.
- Coastline polygon data set.
- WW3 gridgen software.
- Three grids:
 - 5', 2.4', 1.2'
 - (10km, 4km, 2km)





Spectral discretization:

- “Default” WW3 for large basins:
 - 24 directions with 15° resolution.
 - 25 frequencies with factor 1.1 increment, starting at 0.042Hz (up to 0.42Hz) . Max period 25s.
- Lake Victoria is small basin with depth less than 80m.
 - Waves longer than 160m ($T = 10$ s) feel bottom.
 - Could start at 0.Hz instead of 0.042hz.
 - For safety, start at 15s.
- Lake Victoria has weak winds:
 - Higher frequencies worth while.
- Use 29 frequencies (0.066 – 0.96Hz).



Time step considerations:

- CFL criterion for spatial propagation: Discrete propagation in single time step should be less than smallest spatial grid increment.
 - Small shallow-water grid tend to have limited sensitivity to propagation stability.
- Overall time step can be little bigger, but not too much.
- Refraction time step half overall time step.
- Minimum source term time step small.
- Run time on 4 Nehalem processors for 2 day run.

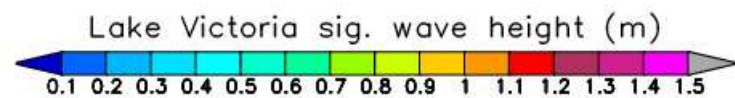
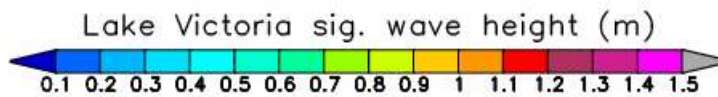
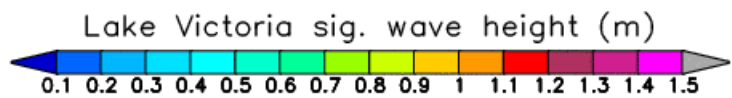
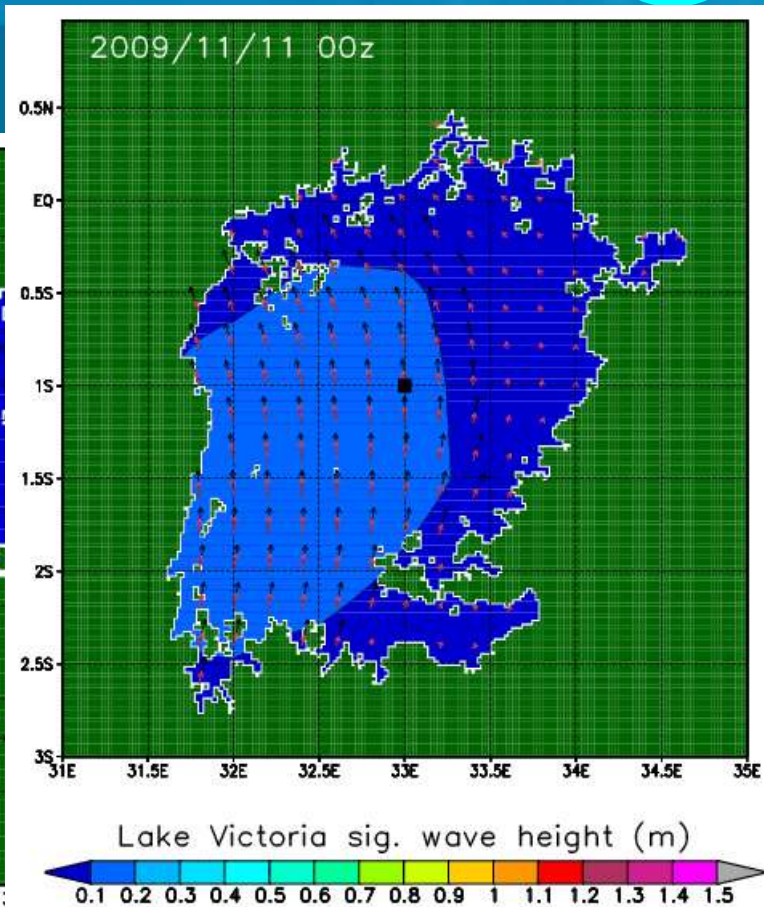
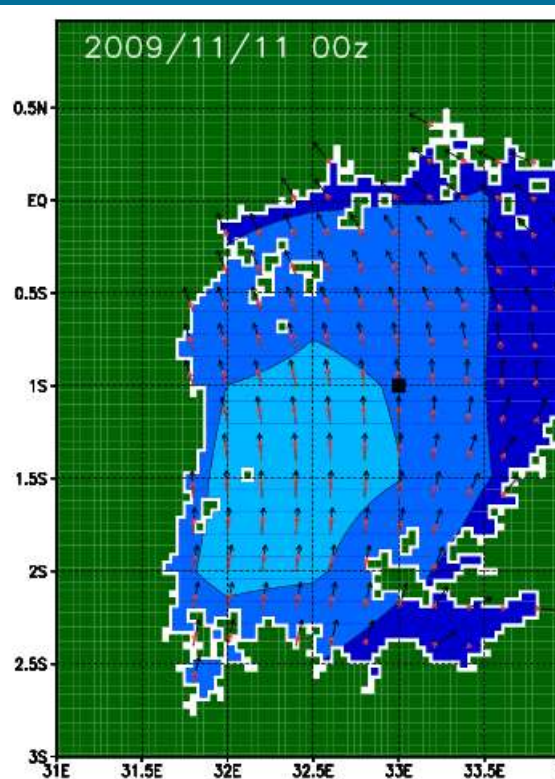
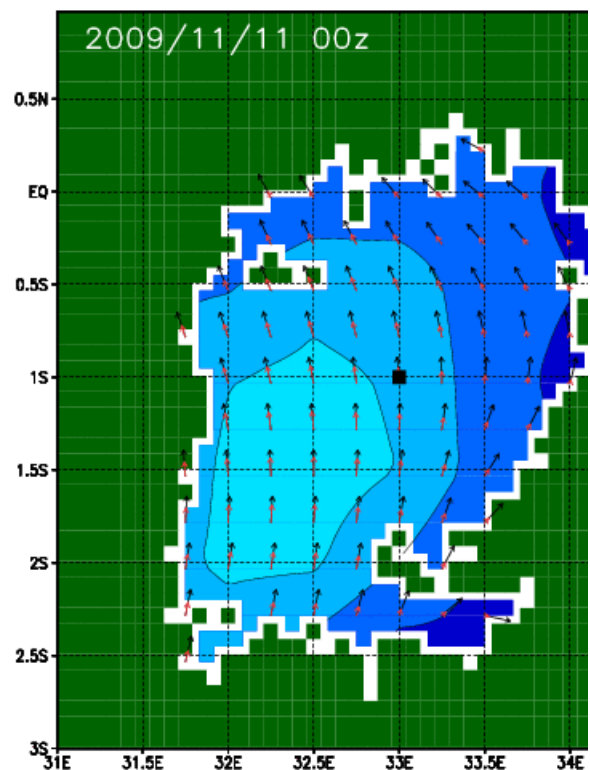
grid	Overall l (s)	CFL (s)	Refract. (s)	Source term (s)	Run time (s)
5' (9.3km)	900	675	450	60	15
2.4' (4.4km)	600	325	300	60	80
1.2' (2.2km)	300	175	150	60	580

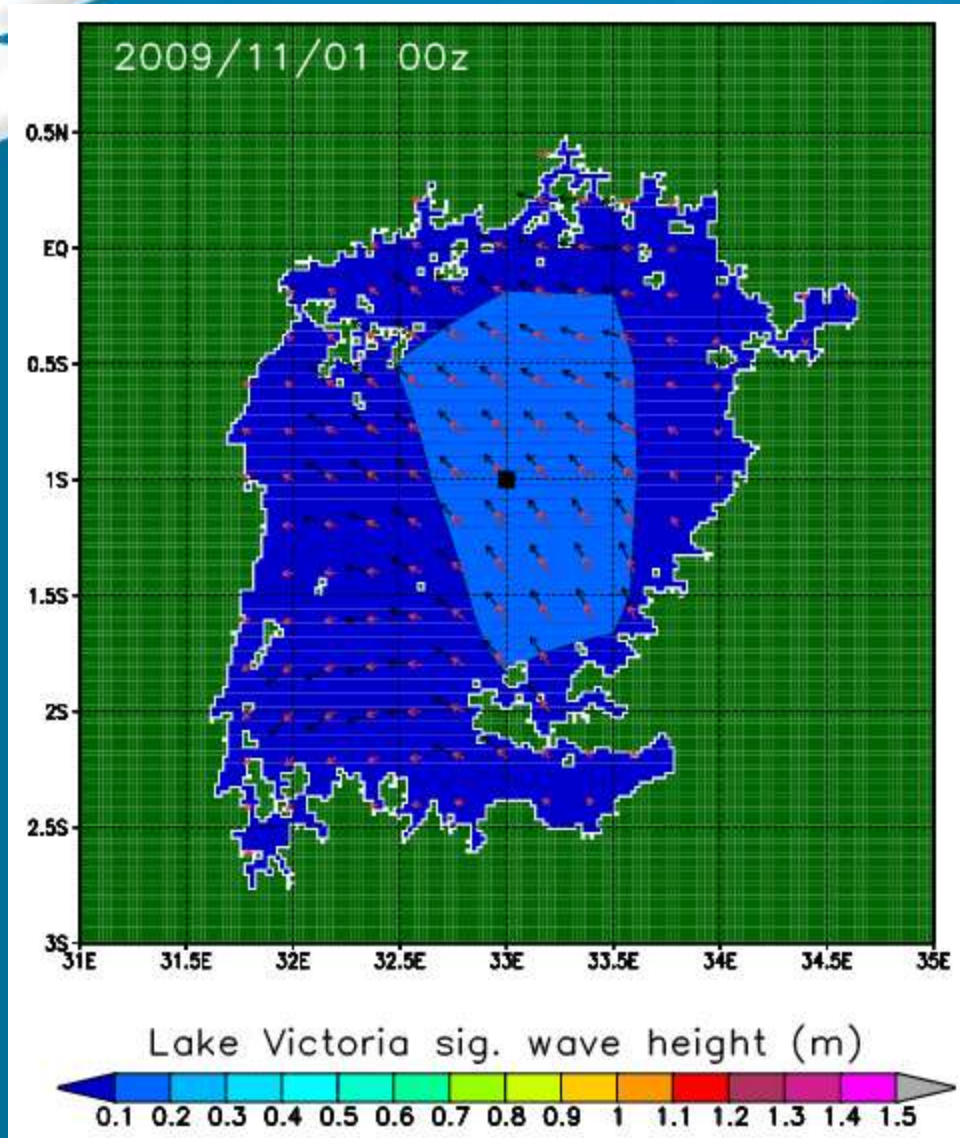


Winds:

- You can test the model with uniform but time varying winds. Note that you can also deal with mean water level variations in this way.
- For testing here we used CFR reanalysis winds at 0.5° and hourly resolution and well-resolved land-sea boundary layer transition.
- Should run this with high-resolution meso-scale winds including diurnal effects.
- Somewhat arbitrary, we ran the model with winds for Nov. 2009.
 - Newspaper article: 26 killed in boating accident 11/13/2009. Boat traveling from Lugala to Hama Island, capsized 24 nmi off Sigulu Island.

Example runs 12-13/11/2009





Simulations for Nov. 2009

- Low resolution CFS, better with meso-scale model with:
 - Land-lake transition.
 - Diurnal signals.
- High-res needed in wave model near coast / islands.
 - Need better bottom near coast.
 - And seasonal water level.



Lake Victoria:

- Several simple model setups are available:
 - Need better coastal info / soundings.
 - Need (seasonal) water level info.
 - All grids feasible on cheap hardware.
- Can be run for now with simple or CFS winds.
- Need high-res meso-scale winds (e.g. WRF).
- Need validation data
 - Better physics in WW3 version 4.xx?
 - Following NCEP Great Lakes implementations.
- Will be the subject of the hands-on training for the rest of the week.



Questions