WW3 Tutorial 4.2: Time stepping

Purpose

In this tutorial exercise we will go through the selection of time steps in WAVEWATCH III®. The exercise consists of three parts. First time stepping for a single grid will be considered. Effects of taking too large a propagation time step will be experienced (case 1), as well as impacts of time steps on source term integration (case 2). After that, time stepping for the multi-grid model will be considered, particularly the interplay between grids and effects of output requests (case 3).

Input files

The test cases used here are versions of standard WW3 test cases. File needed to be able to run these tests are found in the directory `day_4/tutorial_timestepping`.

```
case1                 (directory, including files below)
    switch            (switch file)
    clean.sh          (auxiliary scripts)
    run_it.sh
    ww3_grid.inp      (input files)
    ww3_strt.inp
    ww3_shel.inp
    ww3_outf.inp
    gx_outf.inp
    cbarn.gs          (GrADS scripts)
    colorset.gs
    map2_1.gs
    figs              (directory with example graphics)

case2                 (directory, including files below)
    switch            (switch file)
    clean.sh          (auxiliary scripts)
    run_it.sh
    ww3_grid.inp      (input files)
    ww3_strt.inp
    ww3_shel.inp
    ww3_outp.inp
    gx_outp.inp
    spec.gs           (GrADS scripts)
    source.gs
    colorset.gs
    results           (directory with example results)

case3                 (directory, including files below)
    switch            (switch file)
    clean.sh          (auxiliary scripts)
    run_it.sh
    ww3_grid.low      (input files)
    ww3_grid.hgh
    ww3_grid.point
    ww3_strt.inp
```

```
ww3_multi.inp
ww3_outp.inp
gx_outf.inp
map.gs          (GrADS scripts)
colorset.gs
results         (directory with example results)
```

Case 1: instability in propagation

The case we will use here is the old test `ww3_tp2.1`, representing deep-water propagation in a simple two-dimensional grid without any source terms. Material for this test case is gathered in the directory `day_4/tutorial_timestepping/case1`. This case considers deep water propagation in a simple two-dimensional grid. For this test, the model is compiled without source terms, and with a propagation scheme of choice. The corresponding `switch` file is in the data directory, and needs to be copied to the WW3 bin directory, after which the model needs to be re-compiled.

```
cd ~/day_4/tutorial_timestepping/case1
cp switch ~/wwatch3/bin
w3_make
```

We will start of with the first order propagation scheme, identified in the switch file with the PR1 switch

```
F90 NOGRB LRB4 SHRD NOPA PR1 FLX0 LN0 ST0 NL0 BT0 DB0 TR0 BS0 XX0
WNX1 WNT1 CRX1 CRT1 O0 O1 O2 O3 O4 O5 O6 O7 O11 O14
```

Time steps in the wave model are set in `ww3_grid.inp`. The corresponding part of the input file is presented below

```
$ WAVEWATCH III Grid preprocessor input file
$ ------------------------------------------
  '2-D PROPAGATION TEST #1        '
$
   1.1 0.03679  3  24  0.
$
   F  T  T  F  F  F
  360.  360.  360.  360.
$ 450.  450.  450.  450.
$ 600.  600.  600.  600.
$ 900.  900.  900.  900.
$
. . .
```

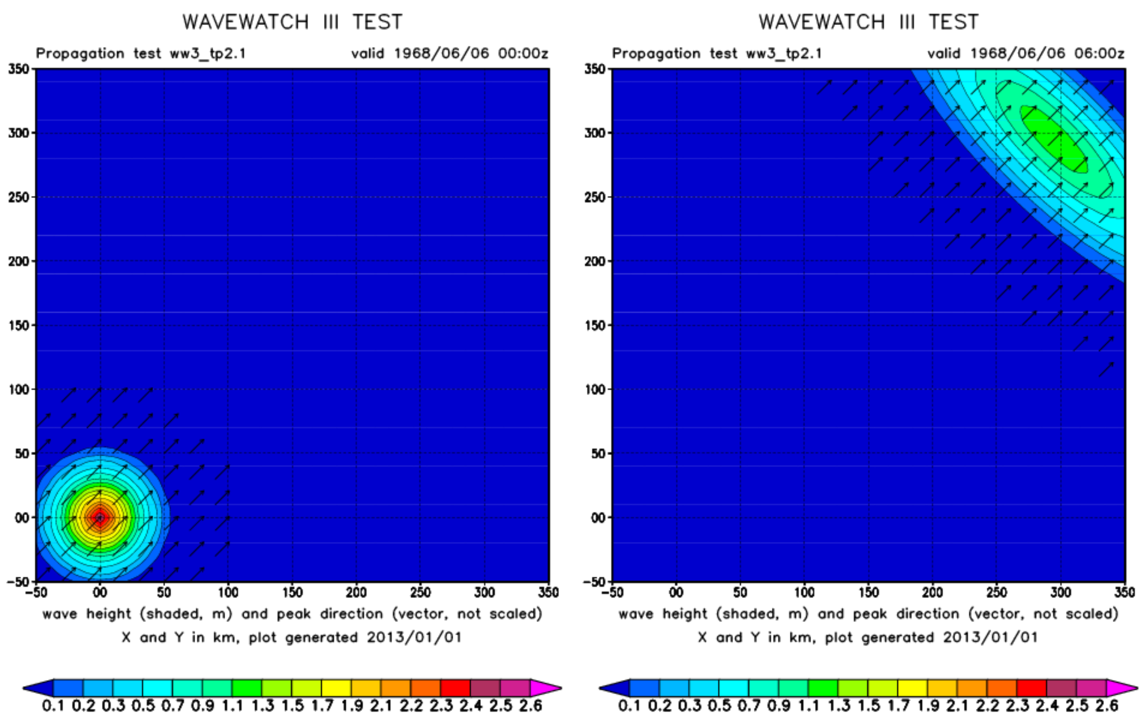
This input file has four settings for the time steps, three of which are commented out with the '$' at the start of the line. Note that spatial propagation is on, but spectral propagation and source terms are off, as set in the flags above the line with time step data. We will start with the smallest time step of 360s, which will result in stable propagation for the first order scheme. Note that the first order scheme is implemented as a full 2D scheme, meaning that the propagation distance $(\Delta x^2 + \Delta y^2)^{1/2}$ is the relevant distance to compute the CFL criterion. Running this test case requires the subsequent execution of the following commands

```
ww3_grid
ww3_strt
ww3_shel
```

after which output can be generated by running

```
ww3_outf
gx_outf
grads -pc "run map2_1"
```

The initial conditions and the results after 5 hours of model integration are shown in the plots below, obtained with the GrADS run indicated above.



The initial distribution is propagated from the lower left corner of the grid to the upper right corner with the diffusion intrinsic to the first order scheme as expected. To simplify running ts test case a script is provided to execute all above commands in the proper order. To run the entire test case at once, execute

```
run_it.sh
```

Note that this script generates output files like `ww3_grid.out` for later inspection of the results of executing elements of the wave model. Whereas the raw WW3 files (`*.ww3`) are cleaned up in this script, the GrADS data files are not, so that the GrADS script can be run again as often as desired. The script

```
clean.sh
```

removes all files generated by the interactive run or by `run_it.sh`.

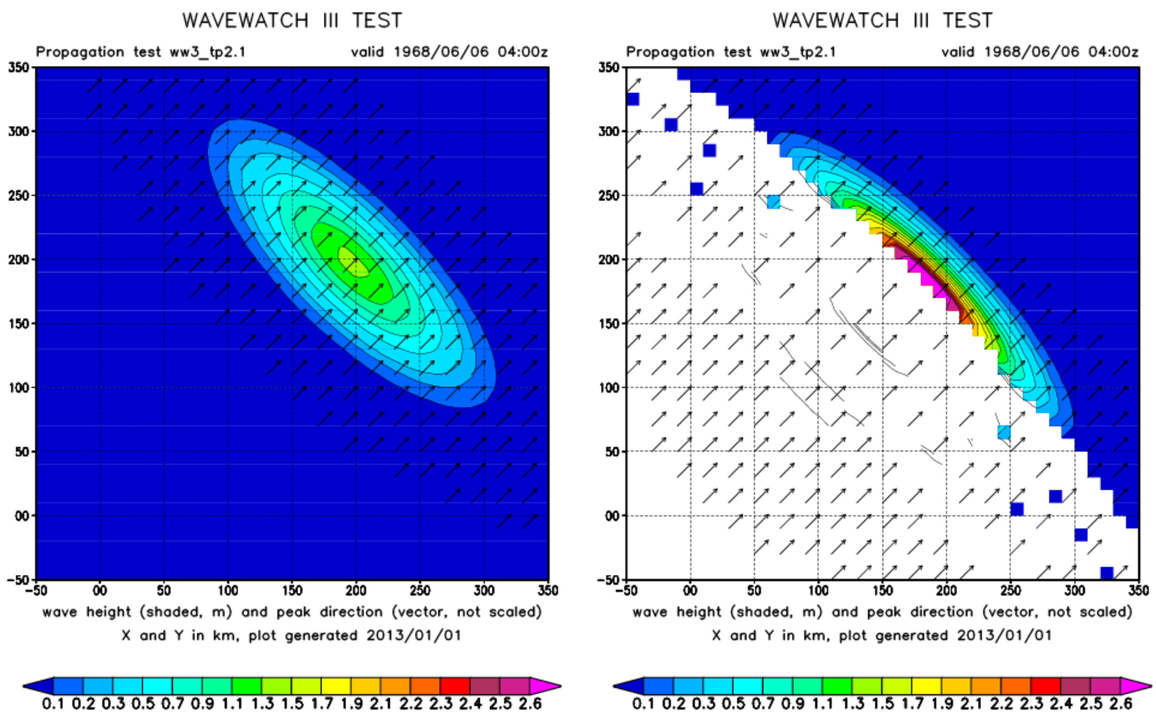
The next step in the test is to increase the model time step to result in unstable propagation. This is done by editing `ww3_grid.inp` to activate the second optional line of time step definitions, resulting in a time step of 450s.

```
$
   F T T F F F
$ 360.  360.  360.  360.
  450.  450.  450.  450.
$ 600.  600.  600.  600.
$ 900.  900.  900.  900.
$
```

With these model setting, the test case s rerun by executing

```
clean.sh
run_it.sh
```

Not that the first command is not strictly necessary. Below, results after 4h of model integration for a time step of 360s (stable) are shown left, and for a time step of 450s (unstable) are shown right.



The effects of the instability are obvious in the plot, and even more so in the output of `ww3_outf` (not reproduced here).

The next step it to run this test for the third order propagation scheme. Here we will use the PR2 setting with the Booij and Holthuijsen (1987) GSE alleviation (alleviation switched off by setting swell age to 0. for now). To activate this scheme, we need to go to the WW3 directories

```
cd ~/wwatch3/work
```

and modify the `switch` file to read

```
F90 NOGRB LRB4 SHRD NOPA PR2 FLX0 LN0 ST0 NL0 BT0 DB0 TR0 BS0 XX0
WNX1 WNT1 CRX1 CRT1 O0 O1 O2 O3 O4 O5 O6 O7 O11 O14
```

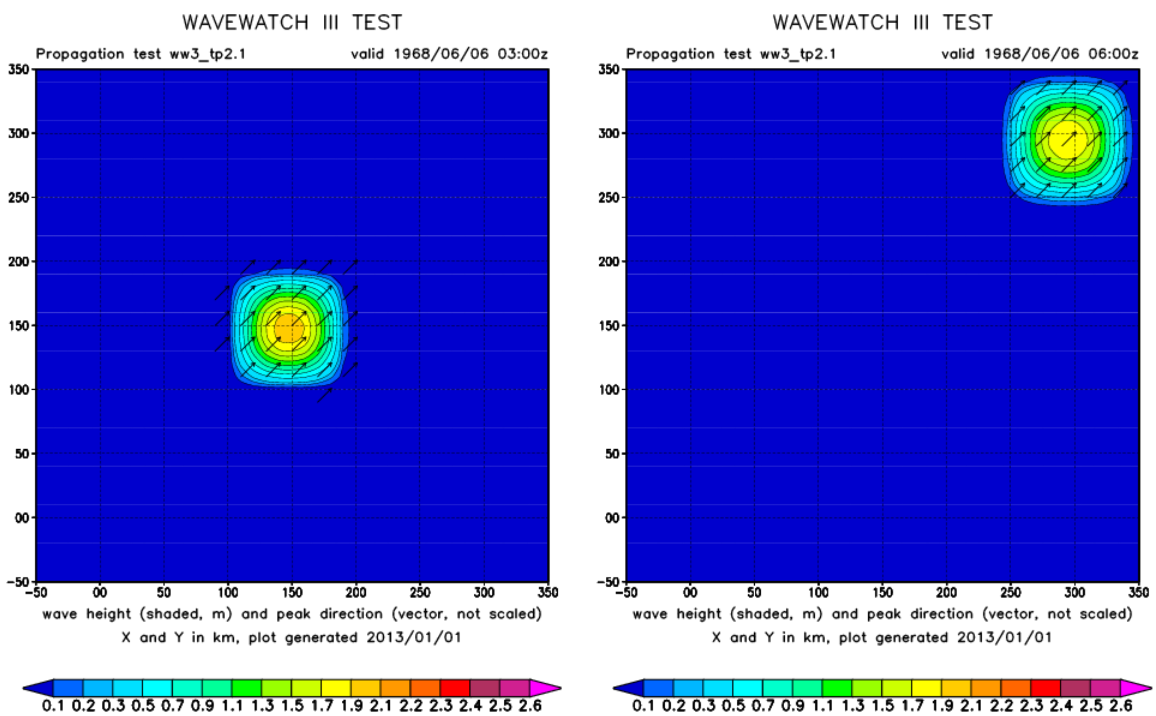
Subsequently, the model needs to be re-compiled, and we need to go back to the work directory of this test:

```
cd ~/day_4/tutorial_timestepping/case1
w3_make
```

We will leave the time steps at 450s. The third order UQ scheme (Leonard, 1979, 1991) is applied to each direction individually, as this is more accurate than trying to apply a 2D version of this scheme (e.g., Fletcher, 1988). Rerunning the test case with the newly compiled code

```
run_it.sh
```

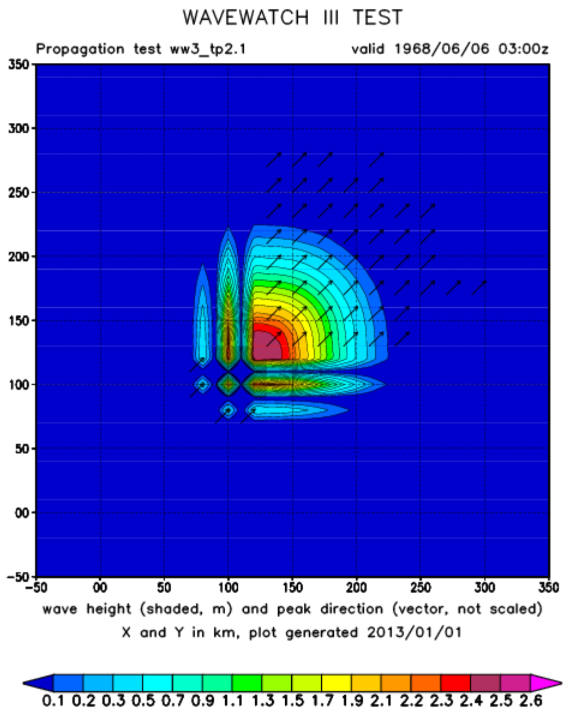
gives the stable results after 3h or 6h as shown below. Note that initial conditions are the same as displayed above for the first order scheme.

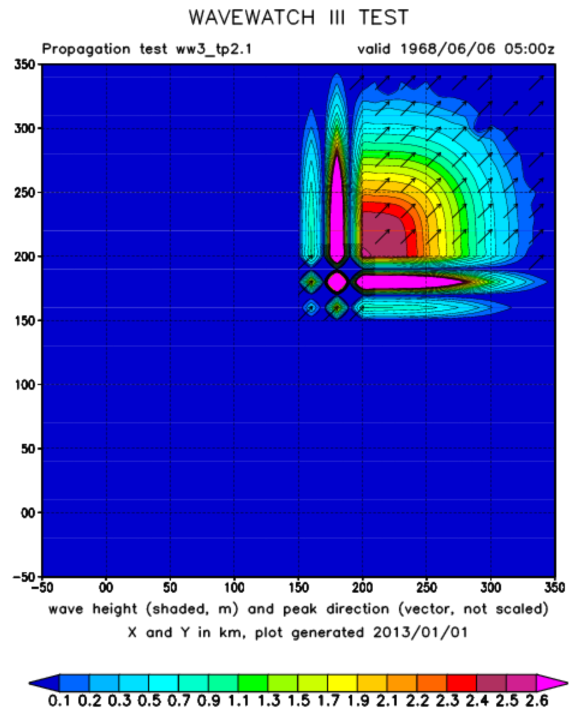


We will now increase the time step to 900s, by editing `ww3_grid.inp` as shown below

```
$ 360.  360.  360.  360.
$ 450.  450.  450.  450.
$ 600.  600.  600.  600.
  900.  900.  900.  900.
$
```

Running the test again by executing `run_it.sh`, now results in unstable model integration, as is illustrated below with plots after 3h and 5h of model integration.





Whereas the impact of the instability is very different than for the first order scheme, it is nevertheless clear that propagation does not work as planned.

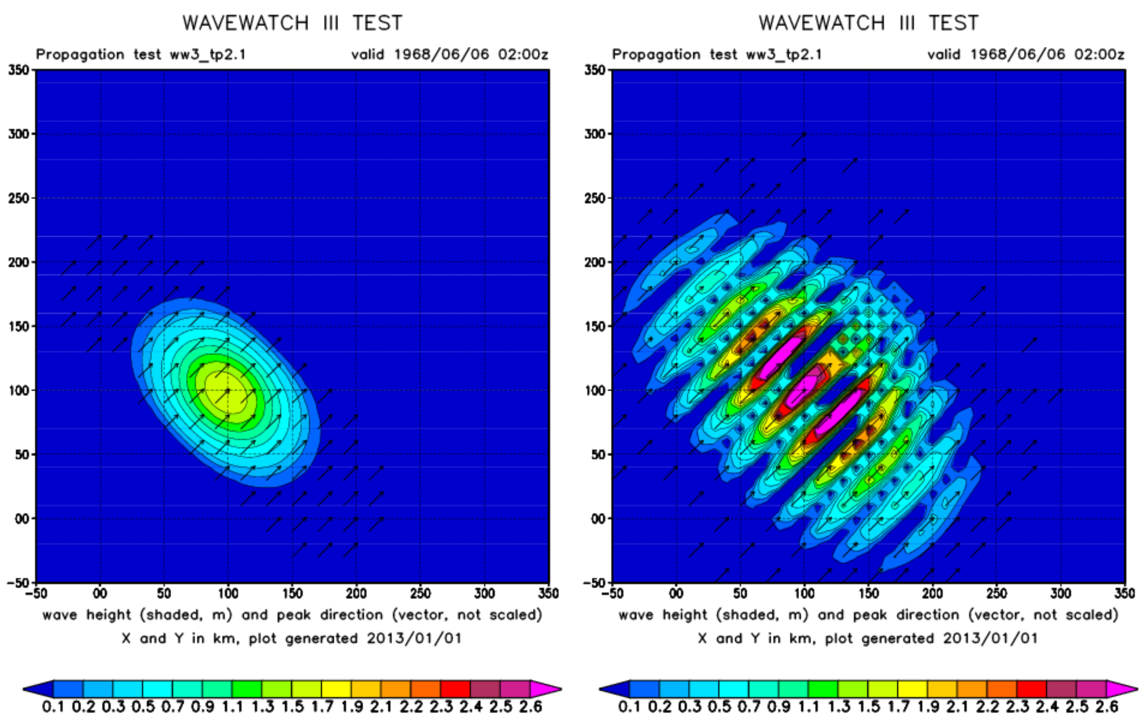
Whereas CFL instability is the main reason for issues with stability in propagation, one other source of instabilities exists when the Booij and Holthuijsen (1987, PR@ switch as used here) GSE alleviation method is used. This adds a finite difference approximation for a diffusion equation, with its own stability criteria (see manual). Particularly, a representative swell age *T* needs to be set. If this age *T* is set too large, then the diffusion operator will become unstable. To illustrate and experience this, set the model time step to 600s, and set *T* = 4h (14400s) by editing the file `ww3_grid.inp` as follows.

```
$
   F  T  T  F  F  F
$ 360.  360.  360.  360.
$ 450.  450.  450.  450.
  600.  600.  600.  600.
$ 900.  900.  900.  900.
$
$ &PRO2 DTIME = 0. /
  &PRO2 DTIME = 14400. /
$ &PRO2 DTIME = 86400. /
  &PRO3 WDTHCG = 0., WDTHTH = 0. /
END OF NAMELISTS
```

and run the test by executing `run_it.sh` again. This results in stable results, but with a clear diffusion of the wave field (illustrated below with the results of the unstable run). If the swell age is increased to 1d,

```
$ &PRO2 DTIME = 0. /
$ &PRO2 DTIME = 14400. /
  &PRO2 DTIME = 86400. /
  &PRO3 WDTHCG = 0., WDTHTH = 0. /
END OF NAMELISTS
```

Running the test by executing run_it.sh now gives unstable results. Below, stable results after 3h of model integration for T = 4h (left) and the corresponding unstable results for T = 24h (right) are presented.



This concludes case 1for spatial propagation. Some additional notes on this follow before we go to case 2:

1) For the UQ scheme with the averaging technique of Tolman (2002), no additional stability concerns exist other than the CFL criteria for the UQ scheme.
2) Whereas for simplicity all time steps have been changed here at once, we in fact only deal with the second (spatial CFL) time step. It is essential that the first time step (the overall time step) is at least as large as the CFL time step, otherwise, the model propagation time step simply becomes the overall time step.

Case 2: source term integration

The case we will use here is the old test `ww3_ts1`, representing wave growth in a one-point model (no propagation, quasi-homogeneous solution, or time-limited growth). Material for this test case is gathered in the directory `~/day_4/tutorial_timestepping/case2`. For this test, the model is compiled with default source terms, and with no propagation scheme. The corresponding `switch` file is in the data directory, and needs to be copied to the WW3 work directory, after which the model needs to be re-compiled.

```
cd ~/day_4/tutorial_timestepping/case2
cp switch ~/wwatch3/bin
w3_make
```

In this test, we will consider a variety of overall time steps, and minimum source term time steps. Moving between cases will require activating the appropriate line in the `ww3_grid.inp` file. The relevant part of the file is reproduced below

```
$ WAVEWATCH III Grid preprocessor input file
$ ------------------------------------------
  'HOMOGENEOUS SOURCE TERM TEST  '
$
   1.10  0.042  25  24  0.
$
   F F F F F T
$ 3600.  3600. 3600. 3600.
$ 1800.  1800. 1800. 1800.
$ 1200.  1200. 1200. 1200.
  1200.  1200. 1200.   30.
$ 1200.  1200. 1200.   15.
$ 1200.  1200. 1200.    5.
$ 1200.  1200. 1200.    1.
$  600.   600.  600.  600.
$  300.   300.  300.  300.
$  150.   150.  150.  150.
$   75.    75.   75.   75.
$   30.    30.   30.   30.
$   15.    15.   15.   15.
$    5.     5.    5.    5.
$
  &FLX3  CDMAX = 2.5E-3, CTYPE = 1 /
END OF NAMELISTS
$
. . .
```

Note that in this test the second (spatial CFL) and third (spectral propagation) time step are not used as all propagation is switched off. For simplicity, these time steps are kept identical to the overall time step (the first). The initial setting of time steps is close to default for large scale models. The overall time step is set to 20min (1200s), and the minimum source term time step is set to 5s, allowing for an aggressive use of the dynamic time stepping algorithm of Tolman (1992), modified as documented in the manual. The test case is run by consecutive execution of

```
ww3_grid
ww3_strt
ww3_shel
ww3_outp
gx_outp
```

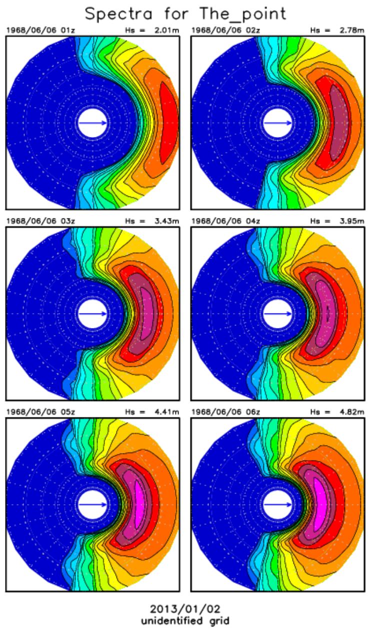
The first three code perform the actual model run. `ww3_outf` produces a `table tab50`.ww3 with mean wave parameters, and `gx_outp` and `grads` produce spectra for the first hours of model integration. Note that for all model set ups, point output is requested every hour, and that the selection of time steps as preset in `ww3_grid.inp` does not interact with this. As in the previous case, the entire test can be executed in an automated fashion by running

```
run_it.sh
```

and all can be cleaned up by running

```
clean.sh
```

With the initial setting for the time steps, graphics results and the table are reproduced below.

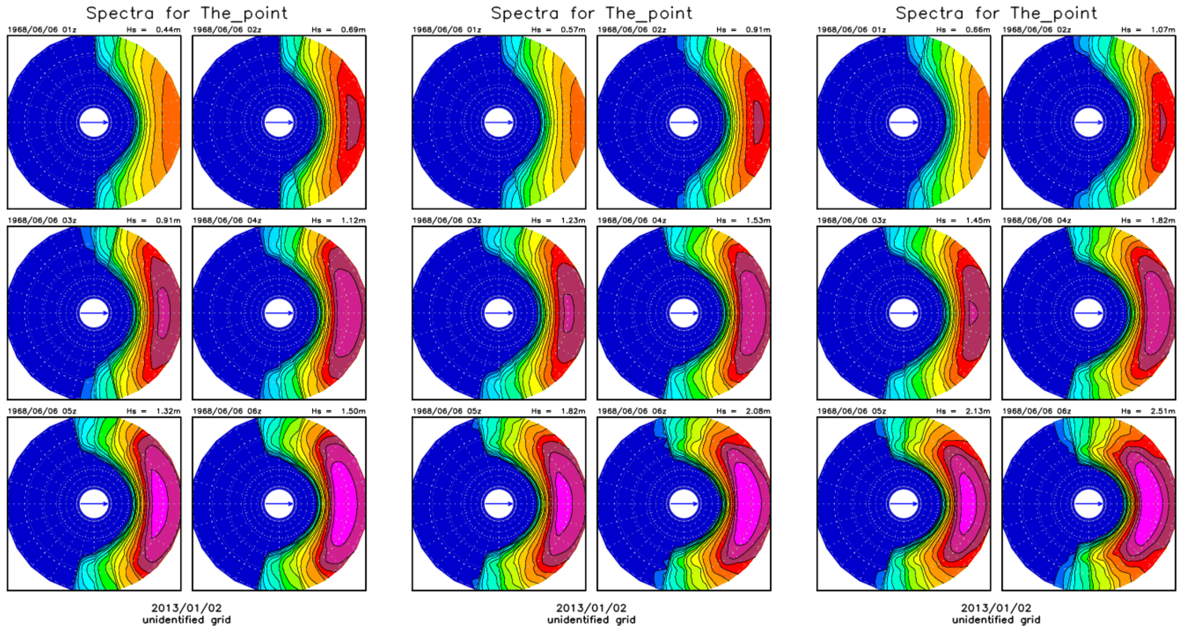


Date	Time h	m	s	Hs (m)	L (m)	Tr (s)	Dir. (d.N)	Spr. (deg)	fp (Hz)	p_dir (d.N)	p_spr (deg)
19680606	0	00	00	0.000	0.0	0.00	0.0	0.00	0.0000	0.0	0.00
19680606	1	00	00	2.009	28.0	4.13	270.0	28.49	0.2282	270.0	24.68
19680606	2	00	00	2.776	41.9	5.06	270.0	29.31	0.1877	270.0	25.36
19680606	3	00	00	3.425	54.3	5.76	270.0	30.11	0.1607	270.0	27.01
19680606	4	00	00	3.953	65.3	6.31	270.0	30.35	0.1466	270.0	27.37
19680606	5	00	00	4.410	75.3	6.78	270.0	30.39	0.1398	270.0	26.84
19680606	6	00	00	4.816	84.9	7.20	270.0	30.57	0.1298	270.0	26.60
19680606	7	00	00	5.186	93.8	7.57	270.0	30.56	0.1225	270.0	27.45
19680606	8	00	00	5.525	102.5	7.91	270.0	30.61	0.1181	270.0	26.53
19680606	9	00	00	5.862	110.4	8.21	270.0	30.51	0.1149	270.0	27.04
19680606	10	00	00	6.178	118.4	8.50	270.0	30.62	0.1087	270.0	26.70
19680606	11	00	00	6.477	126.1	8.77	270.0	30.51	0.1070	270.0	26.32
19680606	12	00	00	6.781	133.3	9.02	270.0	30.42	0.1046	270.0	26.86
19680606	13	00	00	7.072	140.6	9.26	270.0	30.50	0.0995	270.0	26.58
19680606	14	00	00	7.344	148.0	9.50	270.0	30.47	0.0979	270.0	26.13
19680606	15	00	00	7.616	154.9	9.72	270.0	30.33	0.0969	270.0	26.12
19680606	16	00	00	7.893	161.5	9.93	270.0	30.28	0.0950	270.0	26.65
19680606	17	00	00	8.161	168.2	10.13	270.0	30.34	0.0910	270.0	26.21
19680606	18	00	00	8.416	175.0	10.33	270.0	30.35	0.0895	270.0	25.79
19680606	19	00	00	8.664	181.7	10.53	270.0	30.27	0.0887	270.0	25.58
19680606	20	00	00	8.914	188.0	10.71	270.0	30.17	0.0879	270.0	25.67
19680606	21	00	00	9.166	194.2	10.89	270.0	30.12	0.0865	270.0	26.08
19680606	22	00	00	9.415	200.4	11.06	270.0	30.16	0.0835	270.0	25.83
19680606	23	00	00	9.658	206.7	11.22	270.0	30.20	0.0820	270.0	25.46
19680607	0	00	00	9.893	212.9	11.39	270.0	30.19	0.0812	270.0	25.18

The next step of the testing will be to show the robustness fo the time integration routine, and the limiters that are still used when the dynamic time stepping is not allowed, that is, if the minimum time step is set to be equal to the overall time step. We will first be going to an extreme model setup with an overall time step of 1h and a source term time step of 1h, achieved by editing `ww3_grid.inp` as follows

```
$
   F  F  F  F  F  T
  3600.  3600. 3600. 3600.
$ 1800.  1800. 1800. 1800.
$ 1200.  1200. 1200. 1200.
$ 1200.  1200. 1200.   30.
$ 1200.  1200. 1200.   15.
$ 1200.  1200. 1200.    5.
```

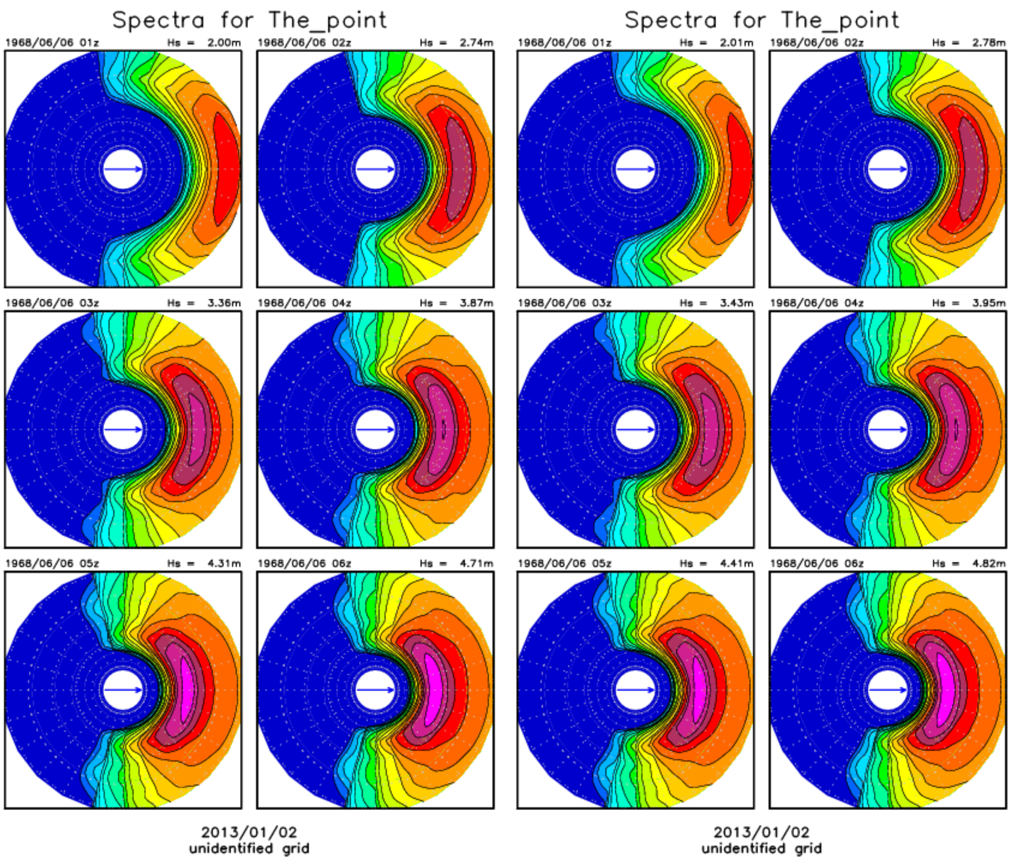
and by running the test by executing `run_it.sh`. Even for these very large time steps the limiters keep the model stable, but do suppress the initial wave growth as has been shown graphicaly in the presentation earlier this morning. Running the model similarly with time steps of 30m and 20m (1800s and 1200s, respectively) but without dynamic time stepping (source term time step equal to overall time step), similar results are obtained, but with more rapid initial growth. Graphical results for 3600s, 1800s and 1200s can be obtained similarly by editing the file `ww3_grid.inp` and running `run_it.sh`, and are presented (from left to right) below.



As shown in the presentation, the impact of the time step through the limiters is massive. However, the limiter in WW3 is convergent, meaning that the error disappears with the time step approaching 0. Thus, editing the input file to give

```
     F  F  F  F  F  T
  $ 3600.   3600. 3600. 3600.
  $ 1800.   1800. 1800. 1800.
  $ 1200.   1200. 1200. 1200.
  $ 1200.   1200. 1200.   30.      +
  $ 1200.   1200. 1200.   15.      | dynamic time stepping
  $ 1200.   1200. 1200.    5.      |
  $ 1200.   1200. 1200.    1.      +
  $  600.    600.  600.  600.
  $  300.    300.  300.  300.
  $  150.    150.  150.  150.
  $   75.     75.   75.   75.
  $   30.     30.   30.   30.
  $   15.     15.   15.   15.
       5.      5.    5.    5.
  $
```

Will give the numerically converged solution (exact with respect to numerical integration errors). Results of this model run with a very small fixed source term time step, and with the “default” model with an overall time step of 20min, but a minimum dynamical time step of 5s (red option above) are presented left and right, respectively, below.



The two solutions are very similar, showing the power of the dynamical source term integration. Additional suggested exercises with his material include:

1) Use other static source term integration options in the file, and by inspecting tables assess convergence of results with reduction of time step.
2) Ditto with changing minimum source term time step for dynamic integration with overall time step of 1200s.
3) Compare run time of various options. Run times are printed at the end of the output of `ww3_shel`, or in the log file `log.ww3`.

Additional considerations for this test case:

1) The dynamic integration of source terms has many parameter settings in the `&MISC` namelist, as documented in the manual. It may be interesting to play with these settings, but generally, the default settings have served us very well. Add the namelist to `ww3_grid.inp` here to play with these settings. Copy initial settings from the namelist as output by `ww3_grid`.
2) When the spectral grid is extended to high frequencies, the dynamic integration may become more expensive as spectral time scales at higher frequencies are smaller and need to be resolved. In such cases, setting a slightly high minimum source term time step may have a big impact on model run times.
3) The same occurs if strong shallow water physics are considered.

Case 3: grid interaction and output

The case we will use here is a reduced version of the old test mww3_tets_03, representing a low and high resolution grid with a coast in the latter grid (propagation only). Material for this test case is gathered in the directory day_4/tutorial_timestepping/case3. For this test, the model is compiled without source terms, and with the default propagation scheme. The corresponding switch file is in the data directory, and needs to be copied to the WW3 work (or bin) directory, after which the model needs to be re-compiled.

```
cd ~/day_4/tutorial_timestepping/case3
cp switch ~/wwatch3/bin
w3_make
```

In this test, we will consider ww3_multi. First, all grids need to be prepared, with their initial conditions as needed. This is achieved by executing

```
ln -sf ww3_grid.low ww3_grid.inp
ww3_grid
ww3_strt
mv mod_def.ww3 mod_def.low
mv restart.ww3 restart.low

ln -sf ww3_grid.hgh ww3_grid.inp
ww3_grid
ww3_strt
mv mod_def.ww3 mod_def.hgh
mv restart.ww3 restart.hgh

ln -sf ww3_grid.point ww3_grid.inp
ww3_grid
mv mod_def.ww3 mod_def.point

rm -f ww3_grid.inp
```

The first two grids are actual wave model grids, and need to be initialized properly with ww3_strt. The third grid is used only for unified point output (i.e., all point output goes to a single file, with a spectral resolution as defined it the corresponding mod_def file), and requires only the generation of a model definition file. This leaves the following data files for ww3_multi in the directory

```
mod_def.hgh
mod_def.low
mod_def.point
restart.hgh
restart.low
```

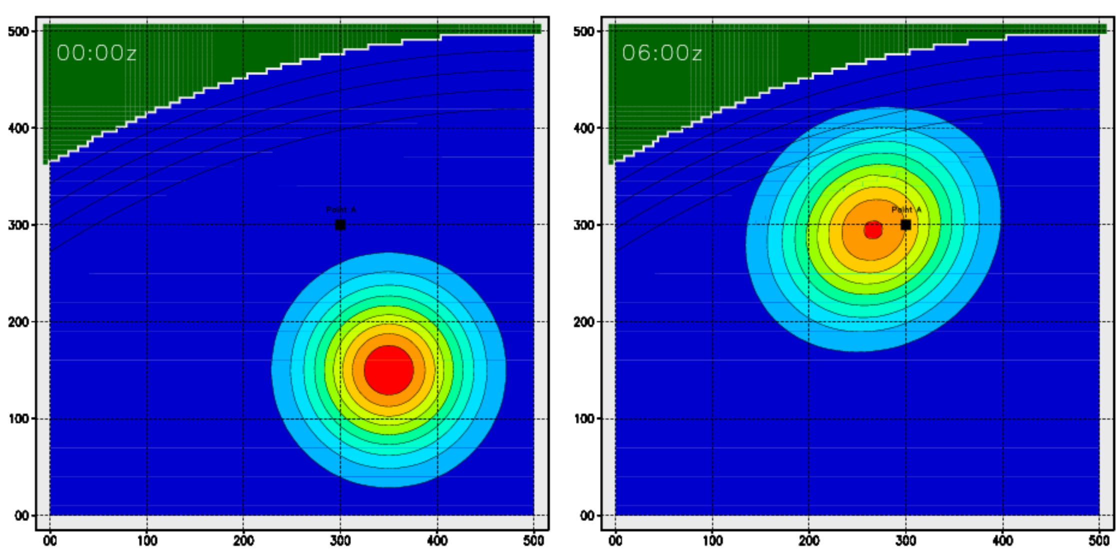
With this, the multi-grid model can be run

```
ww3_multi
```

and various outputs can be generated

```
ln -sf mod_def.low mod_def.ww3
ln -sf out_grd.low out_grd.ww3
gx_outf
sed "s/ww3\.grads/ww3\.low/g" ww3.ctl > low.ctl
rm -f ww3.ctl
mv ww3.grads ww3.low

ln -sf mod_def.hgh mod_def.ww3
ln -sf out_grd.hgh out_grd.ww3
gx_outf
sed "s/ww3\.grads/ww3\.hgh/g" ww3.ctl > hgh.ctl
rm -f ww3.ctl
mv ww3.grads ww3.hgh

grads -pc "run map"

ln -sf mod_def.point mod_def.ww3
ln -sf out_pnt.point out_pnt.ww3
ww3_outp

cat tab50.ww3
```

The first two blocks of commands generate GrADS files for the two grids. These files need some editing and renaming so that `map.gs` can use them simultaneously. As this test propagates very narrow spectrum, spectral graphics are not produced. Instead a table `tab50.ww3` is made. Initial conditions and results after 6h of model integration are shown below (left and right), as is the table output.



```
   Date      Time         Hs      L       Tr     Dir.   Spr.     fp     p_dir  p_spr
           h  m  s        (m)     (m)     (s)    (d.N)  (deg)    (Hz)   (d.N)  (deg)
-----------------------------------------------------------------------------------
 19680606  0 00 00     0.201  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  0 20 00     0.311  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  0 40 00     0.469  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  1 00 00     0.690  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  1 20 00     0.988  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  1 40 00     1.375  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  2 00 00     1.862  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  2 20 00     2.448  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  2 40 00     3.129  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  3 00 00     3.885  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  3 20 00     4.687  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  3 40 00     5.490  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  4 00 00     6.263  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  4 20 00     6.979  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  4 40 00     7.563  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  5 00 00     7.971  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  5 20 00     8.182  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  5 40 00     8.176  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
 19680606  6 00 00     7.925  153.6    9.92  150.0   0.00  0.1008  150.0   0.00
```

As with the other cases, running the test is automated in

```
run_it.sh
```

as is cleaning up the directory

```
clean.sh [all]
```

The all option here deletes all model definition and data files, without this option, only outputs and temporary files are deleted.

The essential part of this test case is not in the model output, but in the time stepping. This can be observed in the log files, and in the screen output of the wave model. In the log file for the low resolution grid, it is seen that the overall model time step is 10min

```
                                         |    input     |     output     |
                                         |--------------|----------------|
    step | pass |     date      time     | b w l c i d  | g p t r b f c  |
 --------|------|----------------------|--------------|----------------|
      1  |   1  | 1968/06/06 00:00:00  |              | X              |
      2  |   2  |            00:10:00  |              |                |
      3  |   3  |            00:20:00  |              |                |
```

Whereas the time overall time step of the high resolution grid is 5min.

```
                                         |    input     |     output     |
                                         |--------------|----------------|
    step | pass |     date      time     | b w l c i d  | g p t r b f c  |
 --------|------|----------------------|--------------|----------------|
      1  |   1  | 1968/06/06 00:00:00  |              | X              |
      2  |   2  |            00:05:00  |              |                |
      3  |   3  |            00:10:00  |              |                |
```

The output of ww3_multi shows that the overall time step of the model equals that of the low resolution grid:

```
MWW3 calculating for 1968/06/06 04:00:00 UTC at 15:23:35  status [ 2- 5]
MWW3 calculating for 1968/06/06 04:10:00 UTC at 15:23:37  status [ 2- 5]
MWW3 calculating for 1968/06/06 04:20:00 UTC at 15:23:38  status [ 2- 5]
MWW3 calculating for 1968/06/06 04:30:00 UTC at 15:23:40  status [ 2- 5]
```

This behavior is as expected, as the overall time steps in the low and high resolution grids are set accordingly, and are in balance (high resolution overall time step is exactly half that of low resoltion grid). So what will happen if the grids are not in balance. To create such a situation, change the high-resolution time step in ww3_grid.hgh as follows

```
$
$    300.0   300.0   300.0     5.0
     360.0   360.0   360.0     5.0
$
```

and rerun the test

```
clean.sh all
run_it.sh
```

This gives very similar numerical results, but a different time stepping of the various grids (see results directory for full logs and outputs). The low resolution grid and overall model stepping are exactly the same as before, but the high-resolution time stepping becomes a little more confused.

```
                                        |    input    |     output    |
                                        |-------------|---------------|
    step | pass |    date       time    | b w l c i d | g p t r b f c |
 --------|------|----------------------|-------------|---------------|
       1 |   1  | 1968/06/06 00:00:00  |             | X             |
       2 |   2  |            00:06:00  |             |               |
       3 |   3  |            00:10:00  |             |               |
       4 |   4  |            00:12:00  |             |               |
       5 |   5  |            00:18:00  |             |               |
       6 |   6  |            00:20:00  |             |               |
```

It still holds on to the synchronization time steps, but behaves less balanced in between[1].

Another model setting that influences time stepping of is the interval of output requests; model output is always produce at output times, and hence output request times override other time stepping settings. To illustrate this, the above edit to `ww3_grid.hgh` needs to be reversed

```
$
     300.0   300.0   300.0     5.0
$    360.0   360.0   360.0     5.0
$
```

[1] In fact, the model behaves differently that I expected, and I will deal with that before the next release. There are, however, no issues with correctness of the solution.

and the output interval for point output in ww3_multi.inp is reduced from 20min to 15min, inconsistent with the 10min overall time step of the low-resolution grid.

```
$ ---------------------------------------------------------------
$  19680606 000000   1200  19680608 000000
   19680606 000000    900  19680608 000000
$  19680606 000000    240  19680608 000000
     300.E3 300.E3  'point_A   '
       0.E3   0.E3  'STOPSTRING'
```

and the test case is rerun

```
clean.sh all
run_it.sh
```

This has no impact on the time stepping of te high-resolution grid, which is 5min and consistent with the output request For the low-resolution grid, however, alternately

```
                                     |    input    |     output     |
                                     |-------------|----------------|
    step | pass |    date      time  | b w l c i d | g p t r b f c |
 --------|------|--------------------|-------------|----------------|
       1  |   1  | 1968/06/06 00:00:00 |             | X              |
       2  |   2  |            00:10:00 |             |                |
       3  |   3  |            00:15:00 |             |                |
       4  |   4  |            00:25:00 |             |                |
       5  |   5  |            00:30:00 |             |                |
```

The overall model shows similar behavior

```
MWW3 calculating for 1968/06/06 03:00:00 UTC at 16:34:20  status [ 2- 5]
MWW3 calculating for 1968/06/06 03:10:00 UTC at 16:34:21  status [ 2- 5]
MWW3 calculating for 1968/06/06 03:15:00 UTC at 16:34:21  status [ 2- 5]
MWW3 calculating for 1968/06/06 03:25:00 UTC at 16:34:22  status [ 2- 5]
MWW3 calculating for 1968/06/06 03:30:00 UTC at 16:34:22  status [ 2- 5]
```

Reducing the time interval of output even more to 4 min

```
$ ---------------------------------------------------------------
$  19680606 000000   1200  19680608 000000
$  19680606 000000    900  19680608 000000
   19680606 000000    240  19680608 000000
     300.E3 300.E3  'point_A   '
       0.E3   0.E3  'STOPSTRING'
```

and rerunning the test case

```
clean.sh all
run_it.sh
```

now impacts the time stepping of all grids, as well as the overall model; all now show an overall time step of 4m. For the low resolution grid

```
                                         |    input     |     output     |
                                         |--------------|----------------|
    step | pass |    date      time      | b w l c i d  | g p t r b f c  |
 --------|------|----------------------|--------------|----------------|
     1   |   1  | 1968/06/06 00:00:00  |              | X              |
     2   |   2  |            00:04:00  |              |                |
     3   |   3  |            00:08:00  |              |                |
     4   |   4  |            00:12:00  |              |                |
```

for the high resolution grid

```
                                         |    input     |     output     |
                                         |--------------|----------------|
    step | pass |    date      time      | b w l c i d  | g p t r b f c  |
 --------|------|----------------------|--------------|----------------|
     1   |   1  | 1968/06/06 00:00:00  |              | X              |
     2   |   2  |            00:04:00  |              |                |
     3   |   3  |            00:08:00  |              |                |
     4   |   4  |            00:12:00  |              |                |
```

and the overall model

```
  MWW3 calculating for 1968/06/06 02:04:00 UTC at 19:18:30  status [ 2- 5]
  MWW3 calculating for 1968/06/06 02:08:00 UTC at 19:18:31  status [ 2- 5]
  MWW3 calculating for 1968/06/06 02:12:00 UTC at 19:18:31  status [ 2- 5]
  MWW3 calculating for 1968/06/06 02:16:00 UTC at 19:18:32  status [ 2- 5]
```

This completes case 3.

Additional considerations on time stepping not considered here:

Refraction:
Refraction uses an internal filter to assure stability, and in the future will allow for separate dynamic integration time step. The refraction time step is therefore not critical for stable model behavior. Several additional considerations are, nevertheless, useful:

- Particularly if you have steep bottom gradients, running with successively reduced refraction time steps can give you an idea of the impact of numerical errors in refraction.
- Current refraction is not filtered, and might give instabilities.
- As refraction is alternately performed before and after spatial propagation, slight wiggles may occur in near-stationary conditions when the overall and refraction time steps are equal. This can be avoided if the refraction time step is half the overall time step (half the refraction donde before spatial propagation, half after it).

Spatial propagation on currents:
If the model is set up stability for spatial propagation without currents, time steps should be automatically adjusted when currents are use, so that the model should remain stable. In other words, there is no need to adjust spatial CFL time steps if currents are added.

Debugging:
If a model appears to be unstable, a following debugging sequence has served me well.

1) Switch off all propagation and rerun, to assure that you do not have weird winds or unstable physics in your run.
2) If this works, switch on spatial propagation only, *switching off GSE alleviation completely*.\
3) If the model works this far, switch on GSE alleviation.
4) Finally, switch on spectral propagation (refraction).

Overall time step versus CFL time step:
The overall time step is used for the entire model, and should/could be a little bigger that the CLF time step. As the CFL time step rapidly increases with decreasing frequency, dominant waves generally have a significantly lower CFL number than the longest waves. I am reluctant to have the overall time step arger than 3-4 times the CFL time step for two reasons:
1) Overlapping grids in ww3_multi become less efficient.
2) Decoupling of propagation and physics will lead to stable bu inaccurate results.

References:

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The manual

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