Hindcasting of Waves and Wave Loads on Dutch Wadden Sea Defenses

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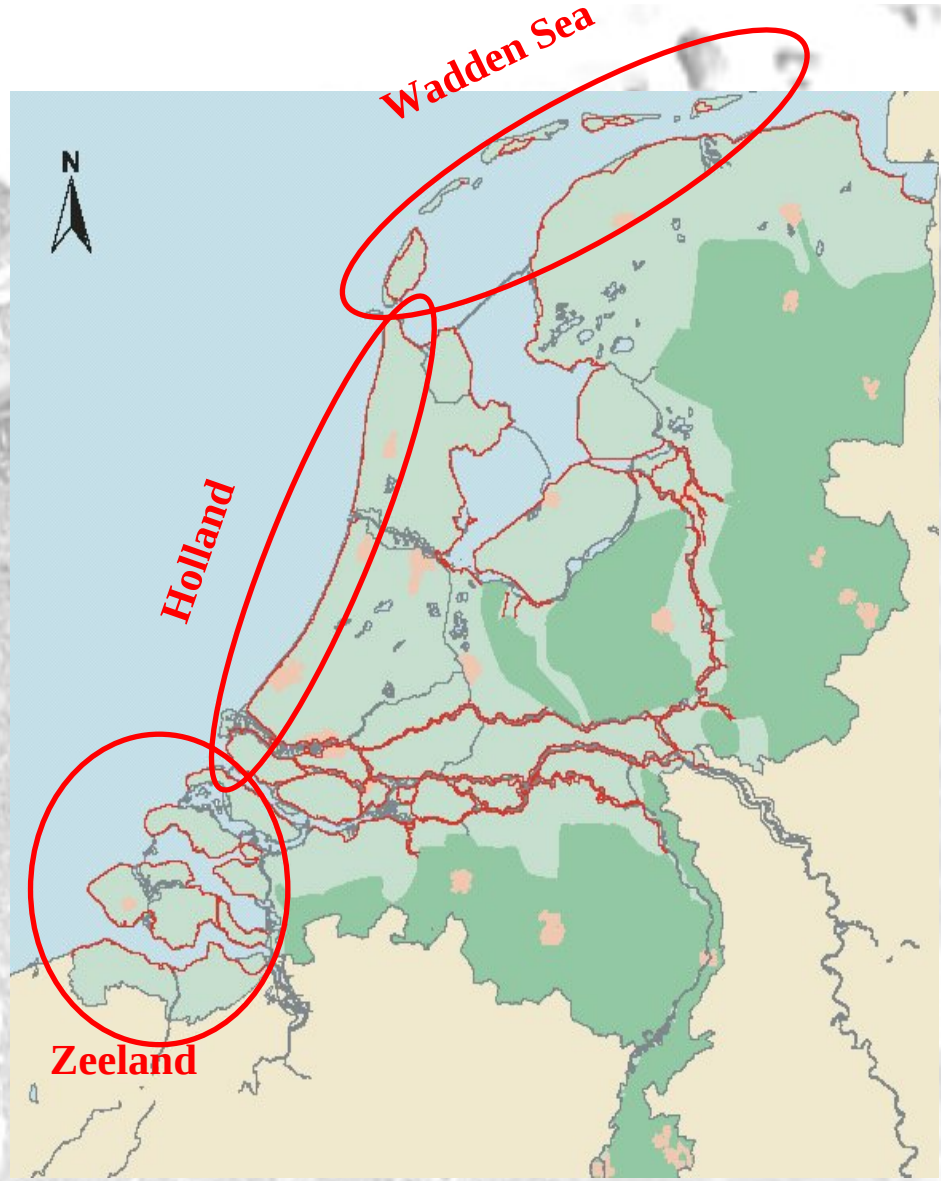
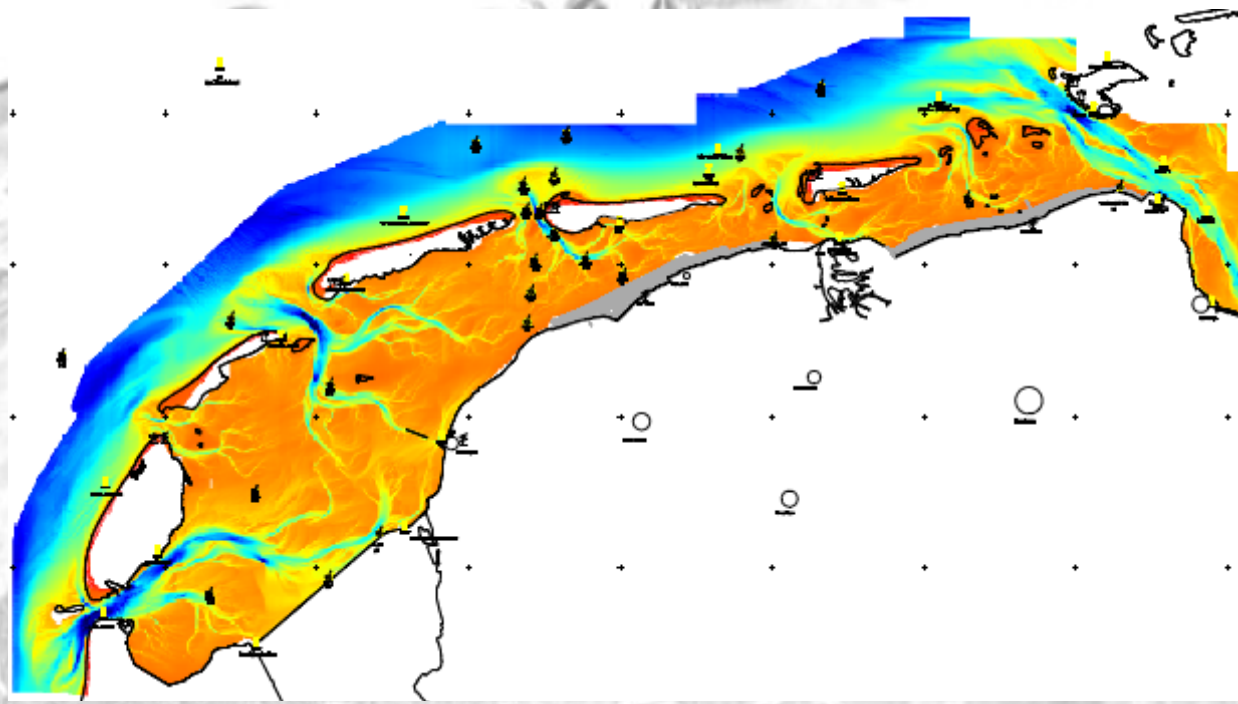
Motivation

- **Safety** level of Dutch Sea defenses checked every five years
- Need **Hydraulic Boundary Conditions** (HBCs) at toe of dike
- For Holland and Zeeland coasts **SWAN** is used for wave transformation offshore/nearshore
- In **Wadden Sea** historic/design data are used instead.



The problem with SWAN in the Waddensea

- **SWAN** results lack **confidence** a.o. due to unsatisfactory performance in cases of North Sea waves penetrating into German Norderney Inlet (version 40.01).



- **No relevant data** available in Wadden Sea for testing and improving SWAN.

Performance testing of SWAN in the Wadden Sea part of the larger SBW (Strengths and Loads on Sea Defenses) Research Program

Approach

- Investigate the performance of the SWAN model in the Norderneyer Seegat and Amelander Zeegat for storm conditions by comparing to buoy measurements
- Investigate wave and flow modelling under (hypothetical) extreme conditions
- Investigate the sensitivity of wave parameters near coastal defenses to input parameters

Conclusions

Storm conditions

- good agreement at buoy locations but deviations due to current effects (wave age), wave tunneling and triads
- Improvement by using non-uniform water level and currents
- Ebb tidal inlet refracts and dissipates most North Sea waves at Amelander Inlet
- Wave conditions in the Ameland inlet sea dominated by local wind growth, current effects and depth-limitation

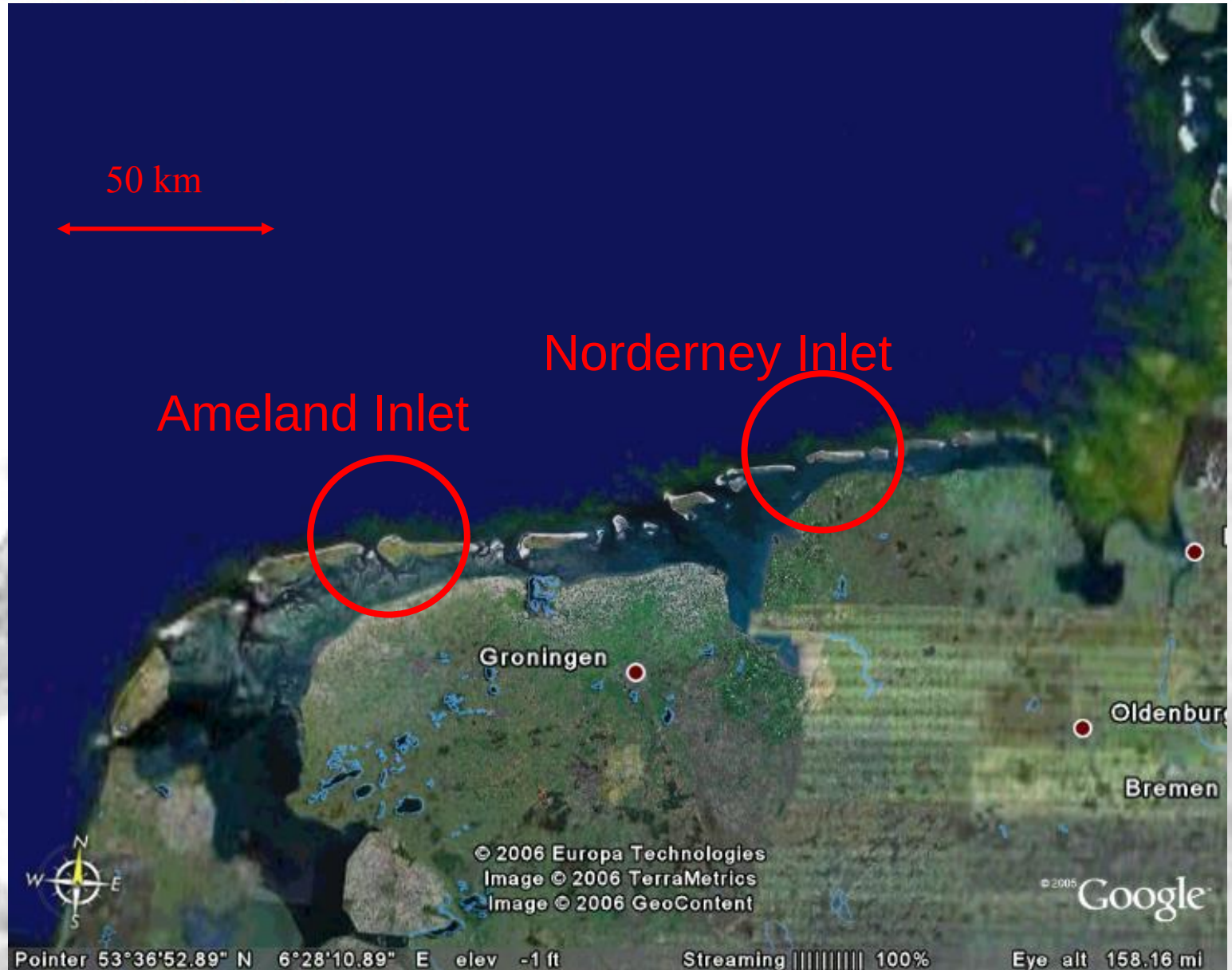
Extreme conditions

- Wind-driven circulations dominate astronomical tidal currents, causing large scale flow across the divides and "valve" effects through the inlet
- Strong West-East flow reduces spectral $T_{m-1,0}$ wave periods (following current, larger wave age may have effect on dikes.
- At coast lines, wave heights are still depth-limited, even in extreme cases

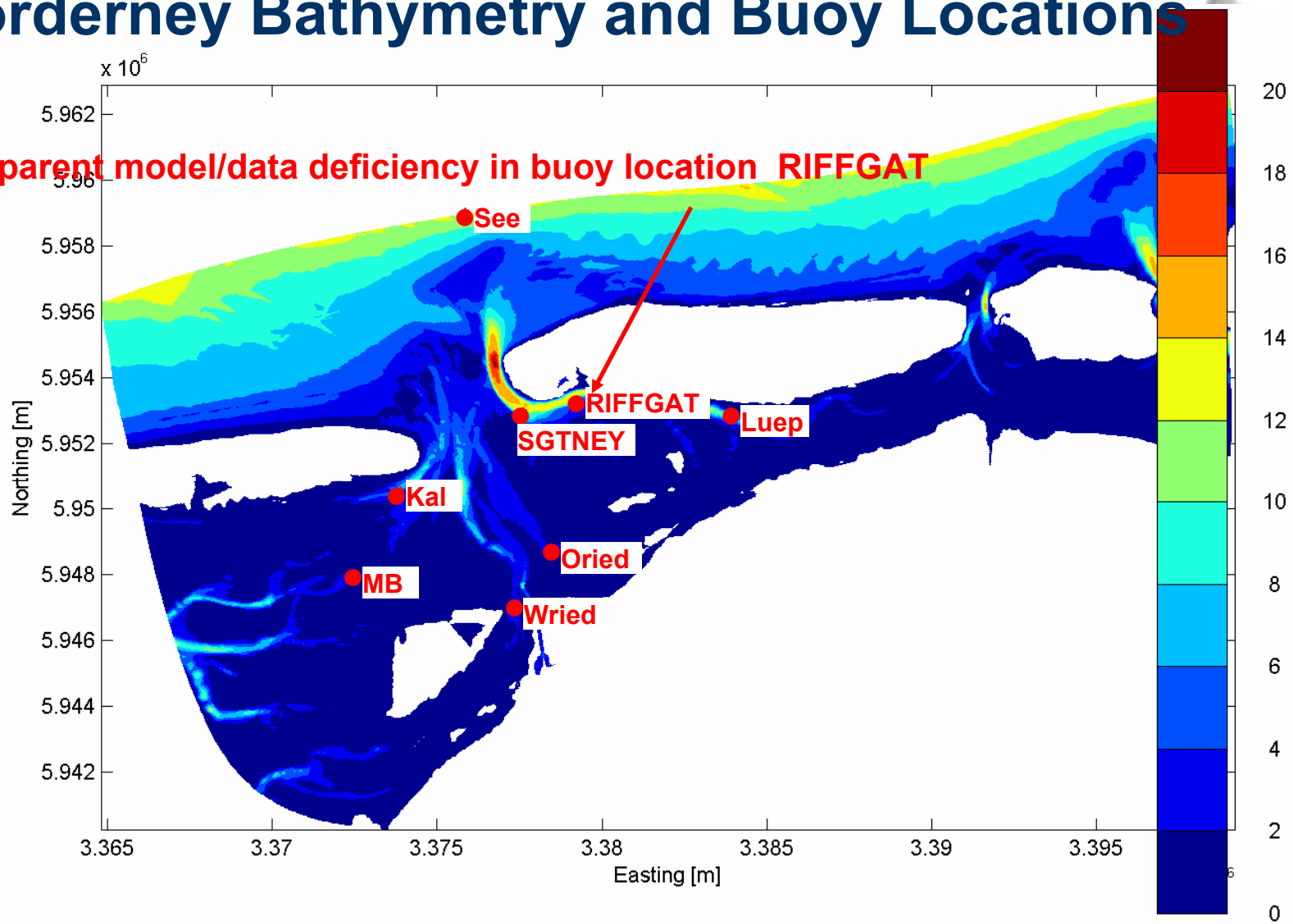
Alkyon

WL | delft hydraulics

Dutch and German Waddenzee



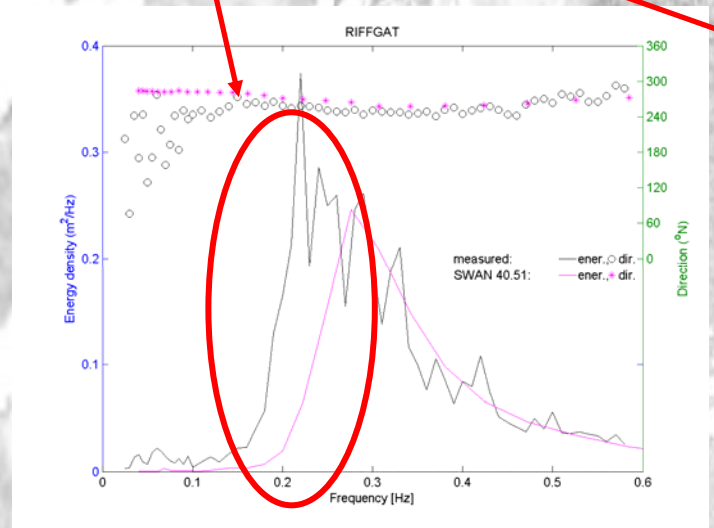
Norderney Bathymetry and Buoy Locations

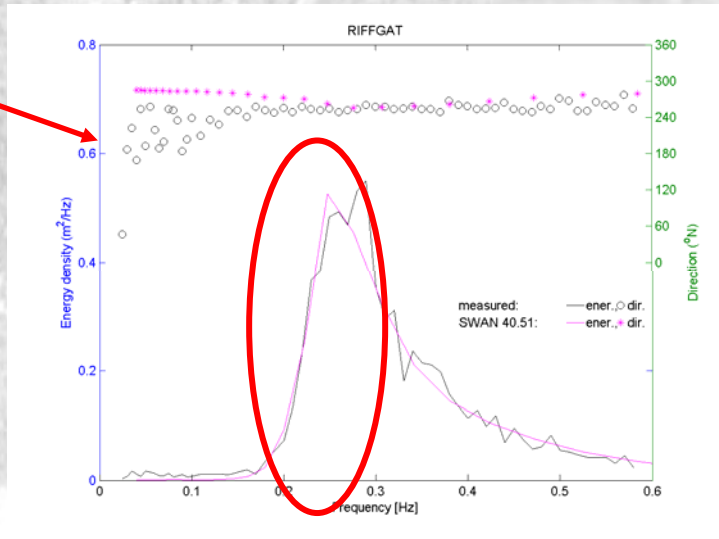


* Waverider buoy locations

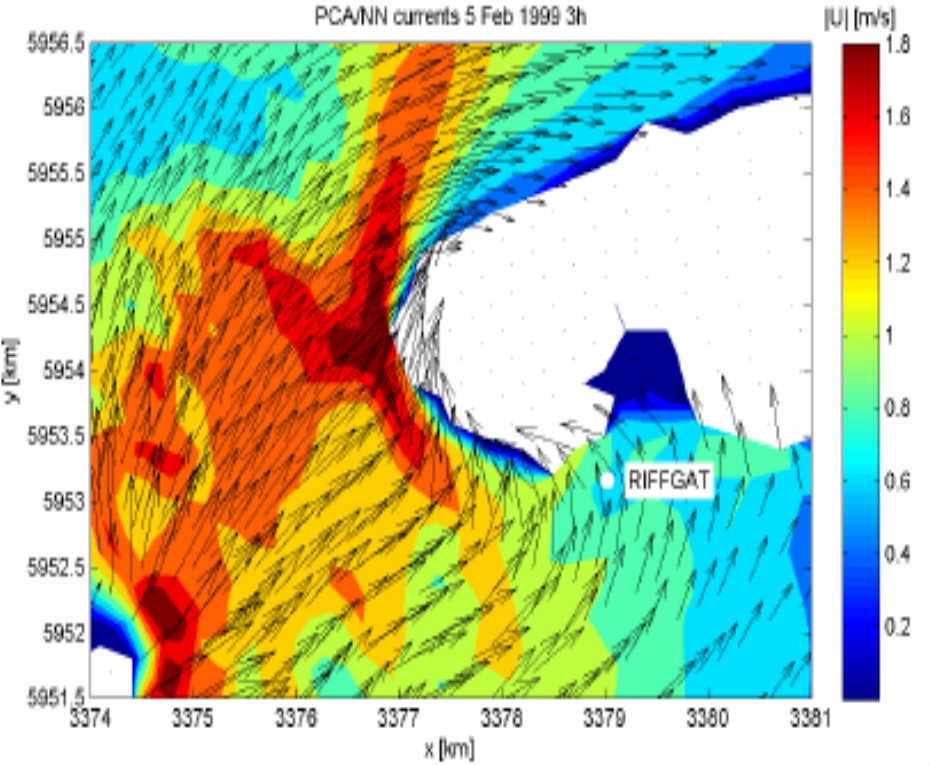
"Puzzling" Spectra at RIFFGAT

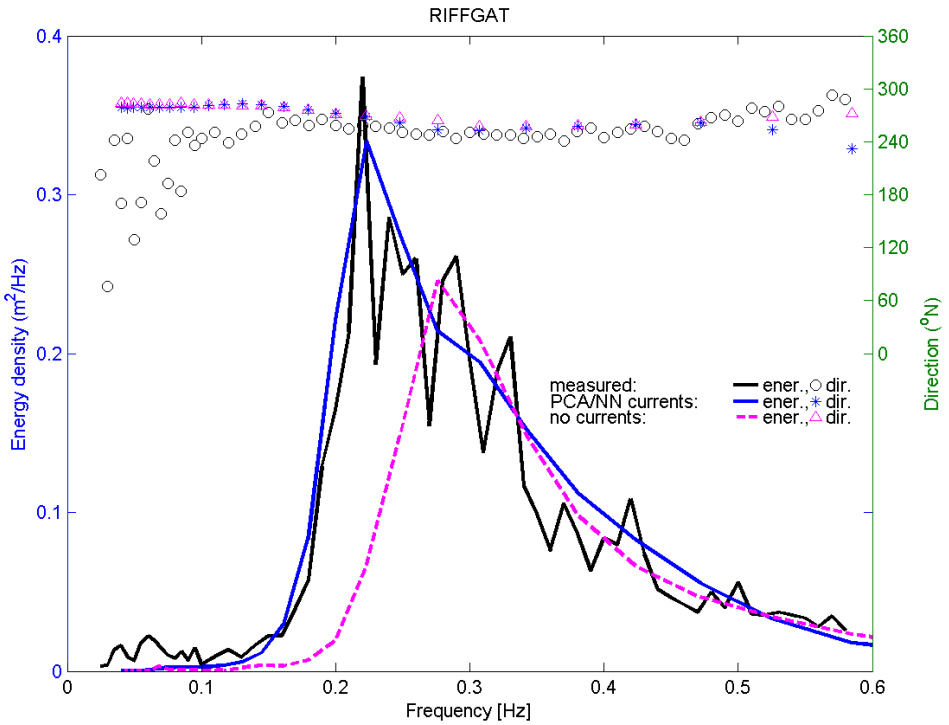
date	time	WL [m MSL]	θ_w [°N]	U_{10} [m/s]	H_{m0} [m]	T_p [s]	θ_{peak} [°N]
5/02/99	03:40h	3.4	290	19.0	6.0	14.3	330
3/12/99	18:30h	3.2	290	25.7	5.9	13.3	300





Inclusion of (wind-driven) current at slack



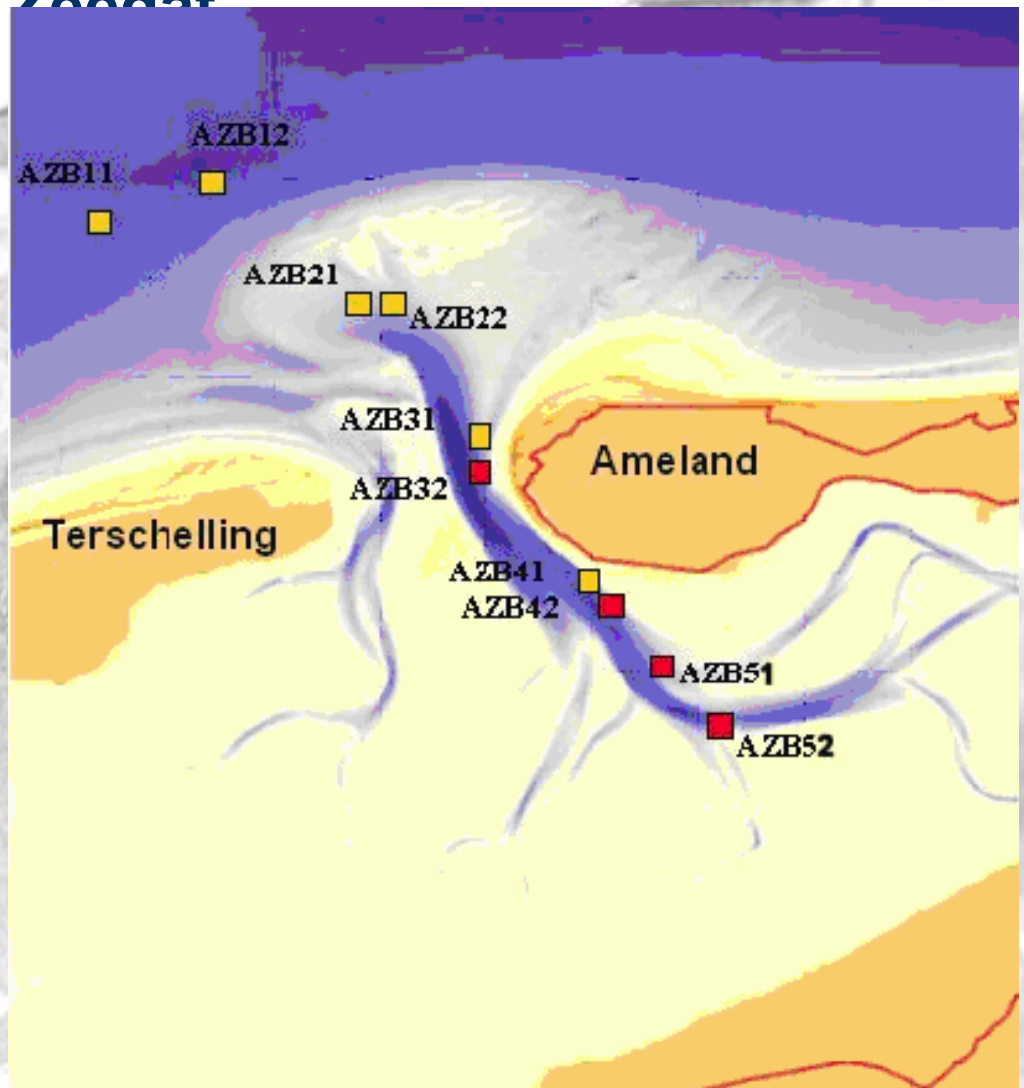


opposing current, smaller wave age, more growth

Bathymetry and buoy locations (2004/5) Amelander Zeegat

Wave riders:

- directional
- non-directional

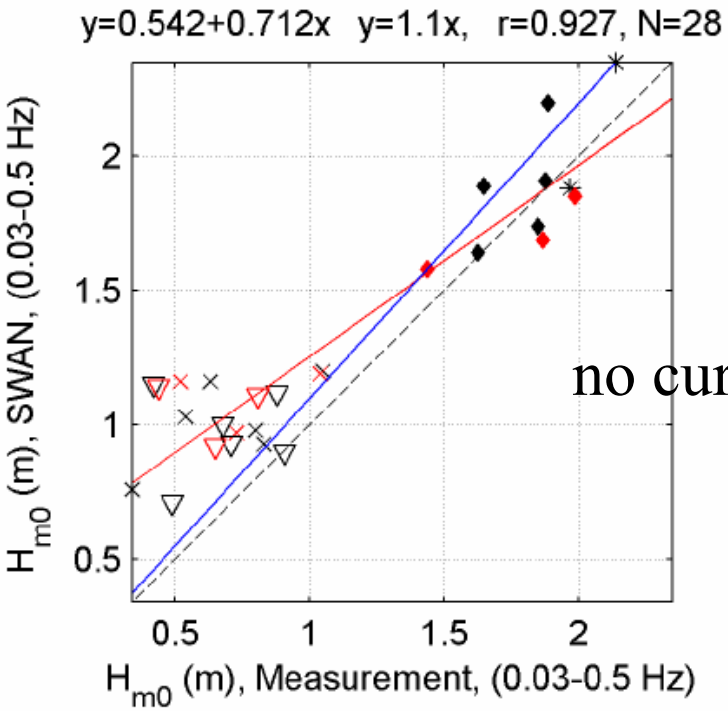


2 storms,

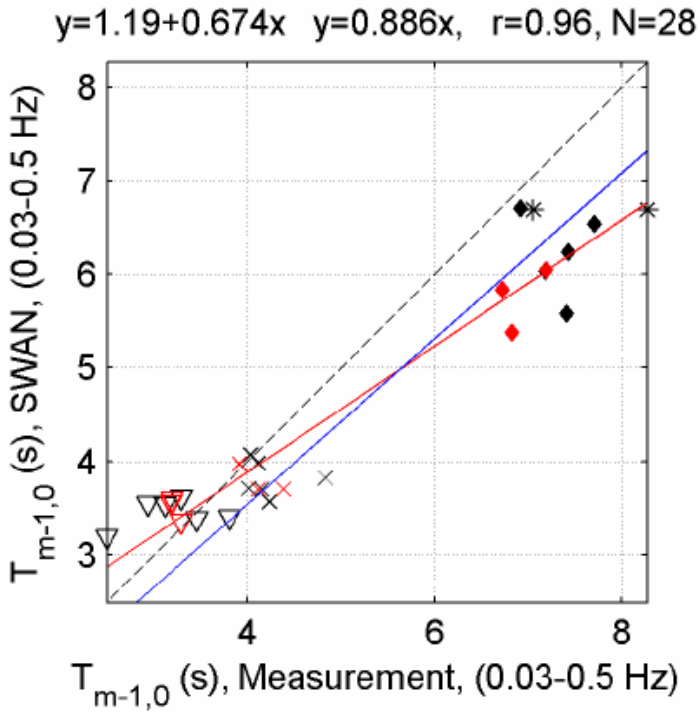
3 tidal stages each

(max flood, max ebb, "slack")

Integral wave heights and periods (all cases)



no currents



overestimation Hm0 inner buoys,
but much scatter
and much better
than w/o currents

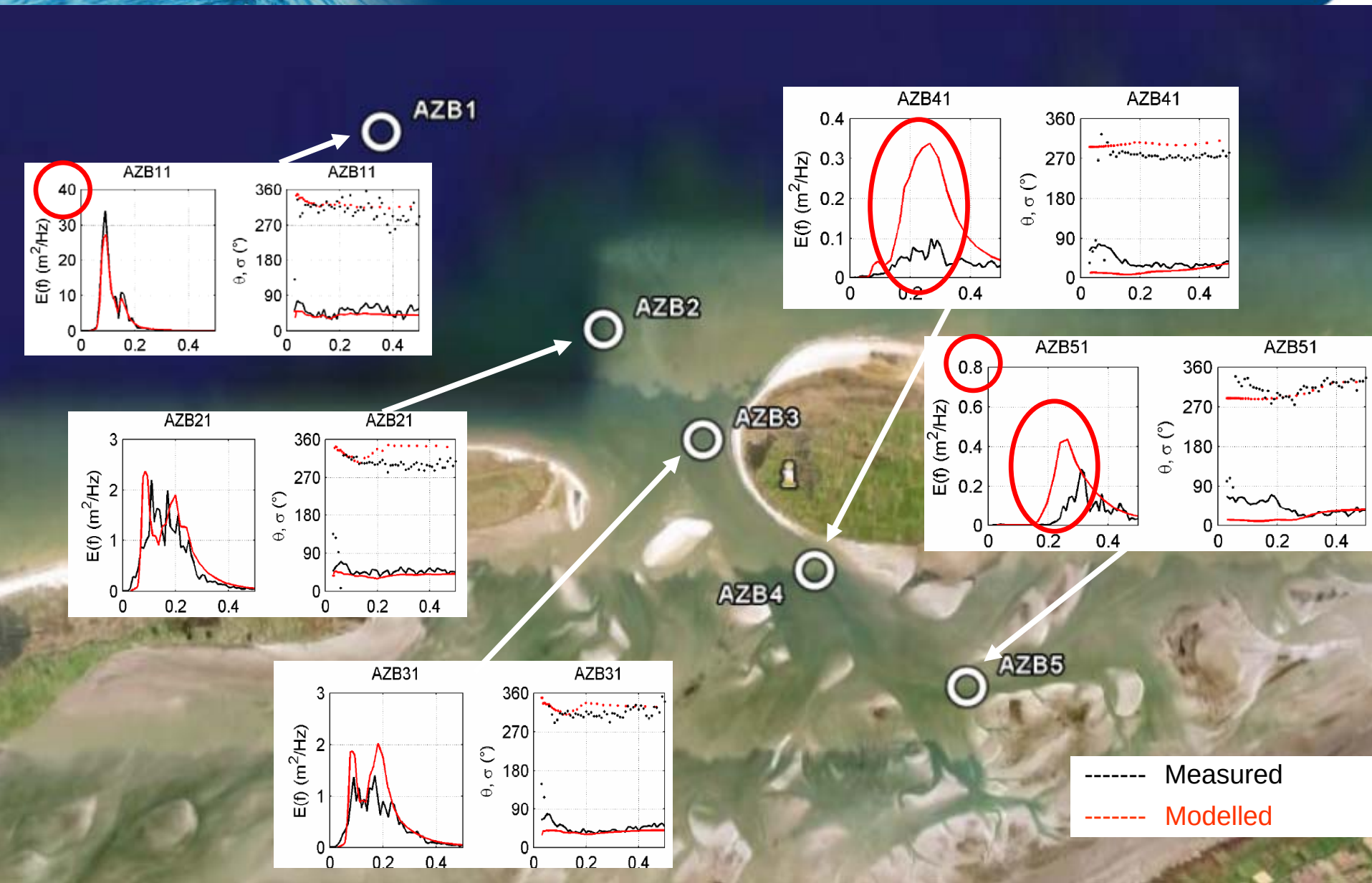
underestimation T_{m-10} buoys in gorge,
due to triads

AZB11 AZB12 AZB21 AZB31 AZB32 AZB41 AZB42 AZB51 AZB52

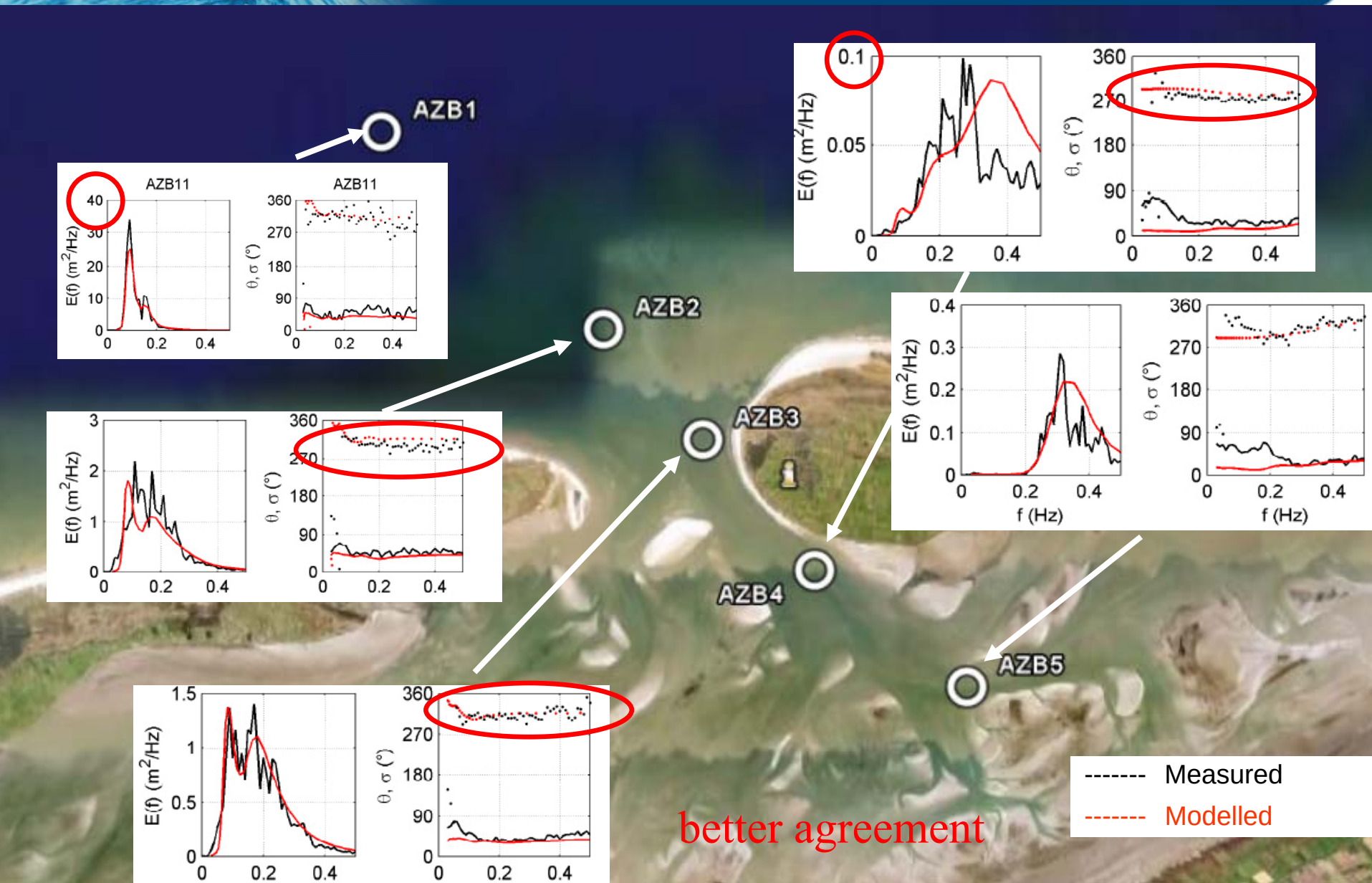
Alkyon

WL | delft hydraulics

Spectra at 8 Feb 2004 (no slack currents)

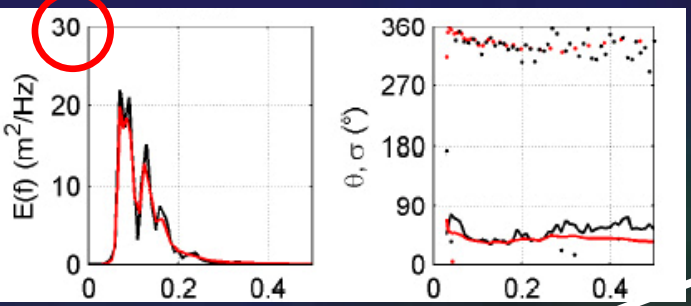


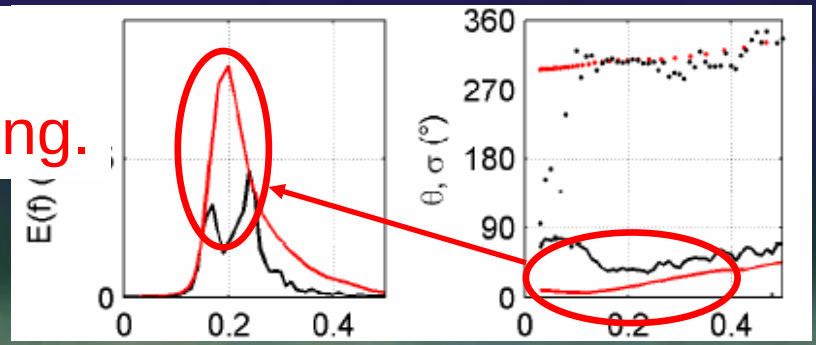
Spectra at 8 Feb 2004 (with slack currents)

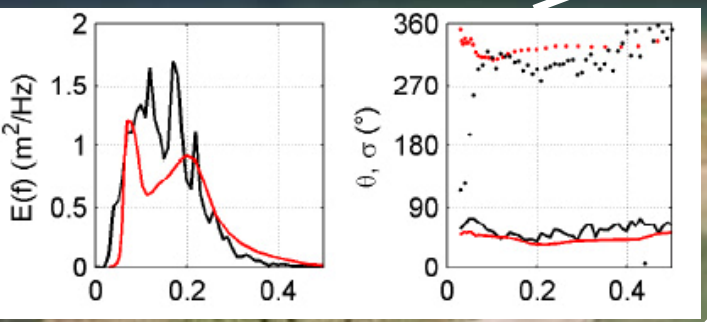


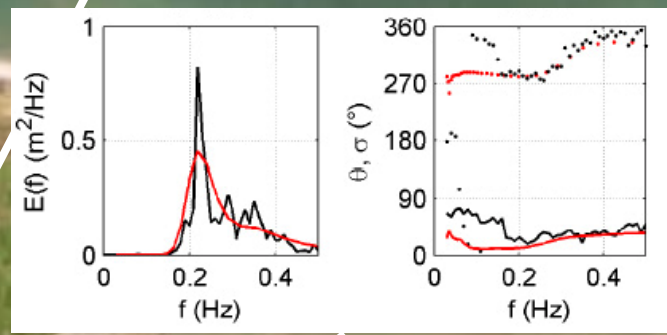
Spectra at 8 Feb 2004 (ebb)

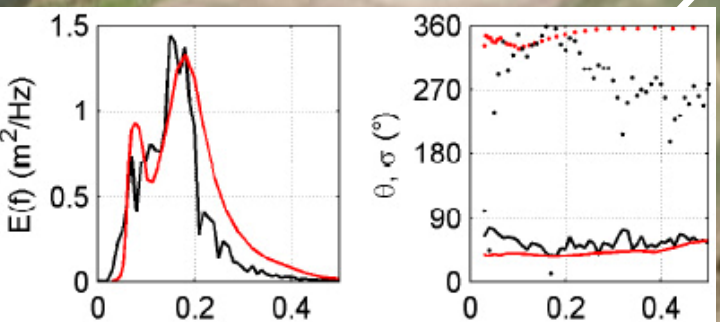
overestimation of Hm0 at ebb,
due to smaller modelled spreading.











AZB2

AZB3

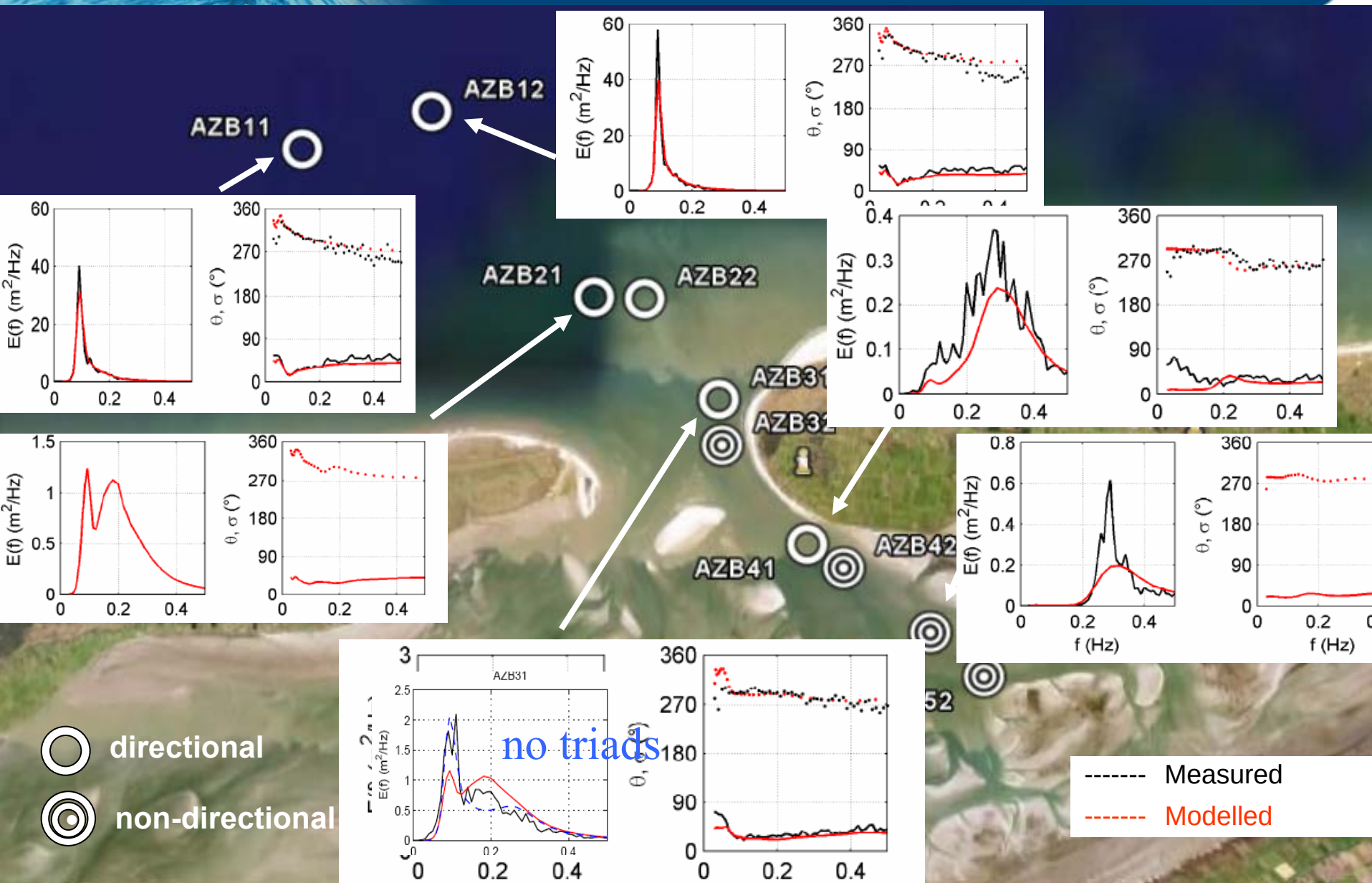
AZB4

AZB5

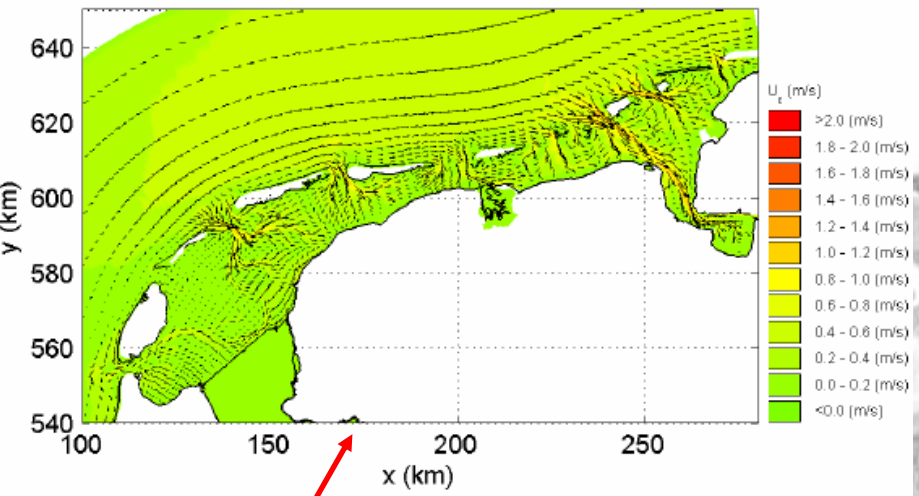
------- Measured

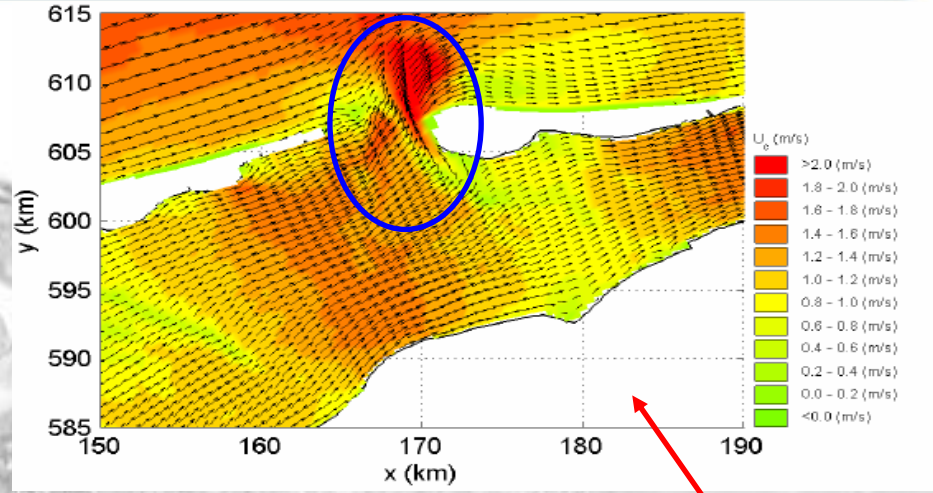
------- Modelled

Spectra at 2 Jan 2005 slack



Storm vs. Extreme storm – currents at Jan 18, 2007 - 2000 hrs



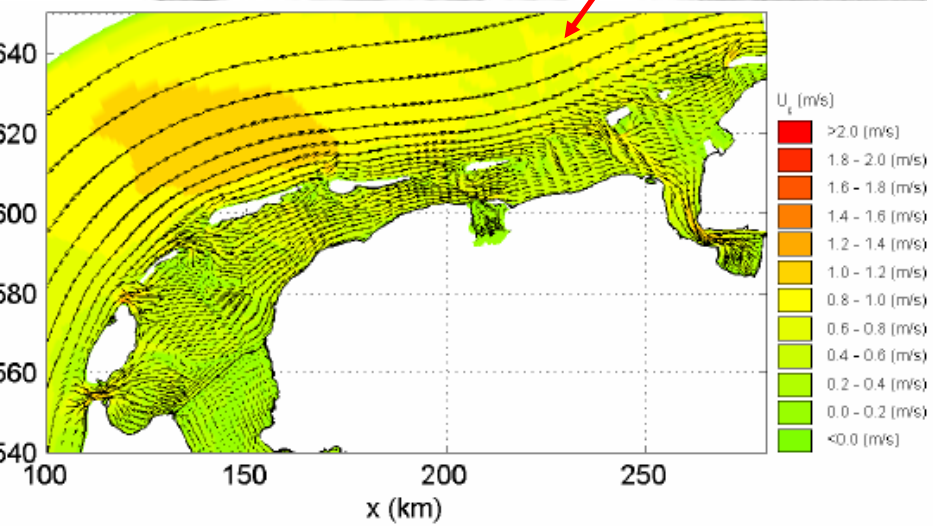


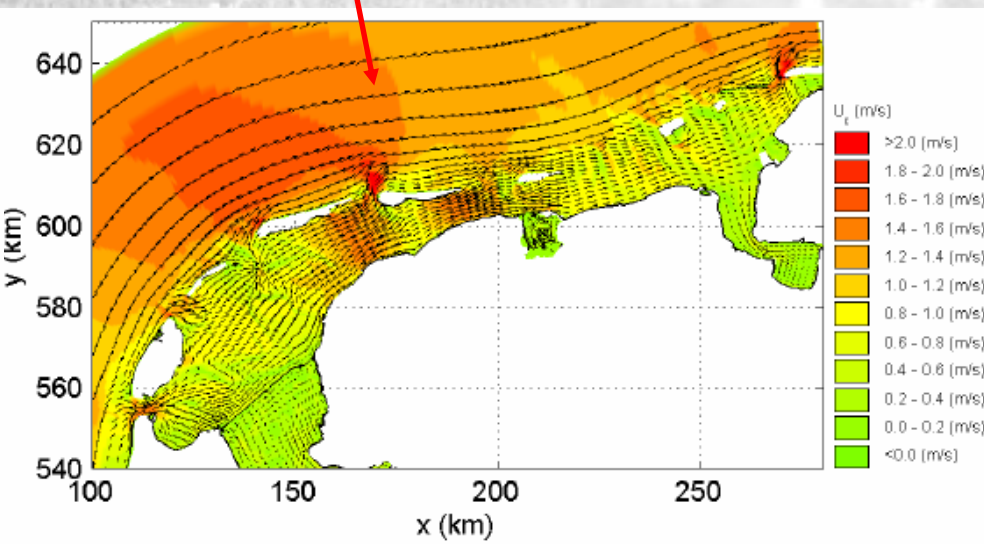
Astronomical

forced by measured Wind

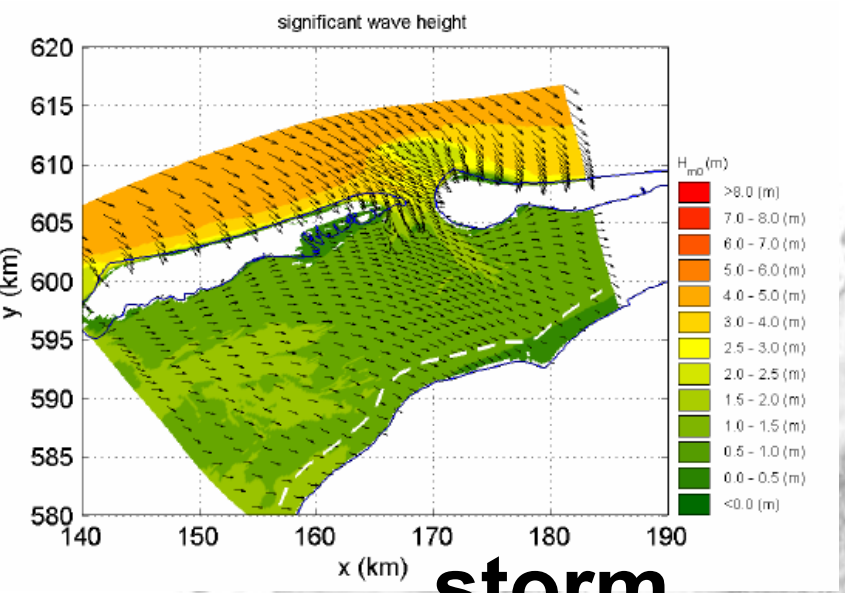
Extreme Wind

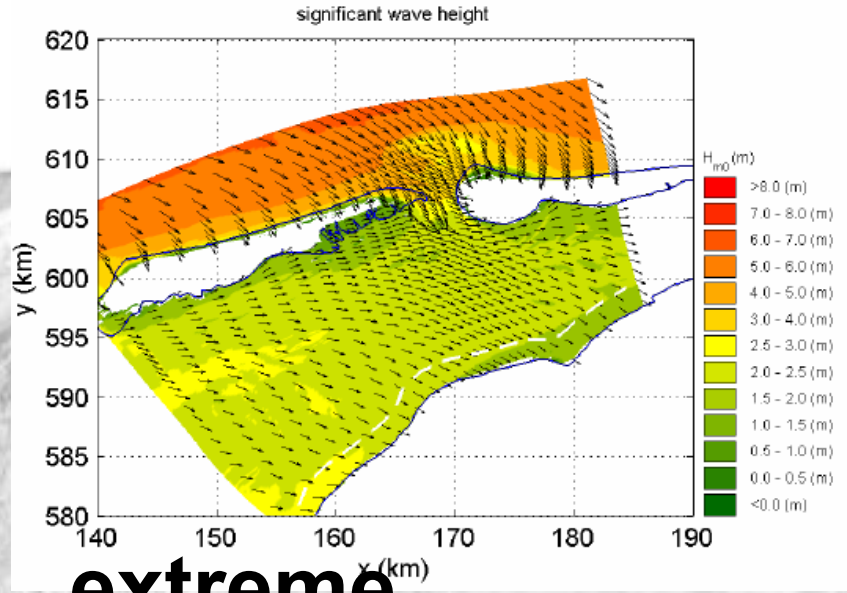
Detail





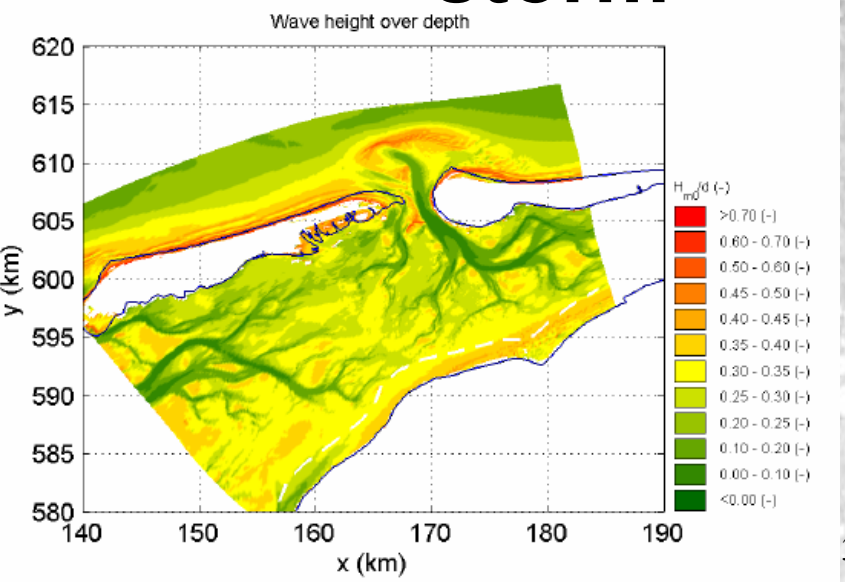
Storm vs. Extreme storm - waves

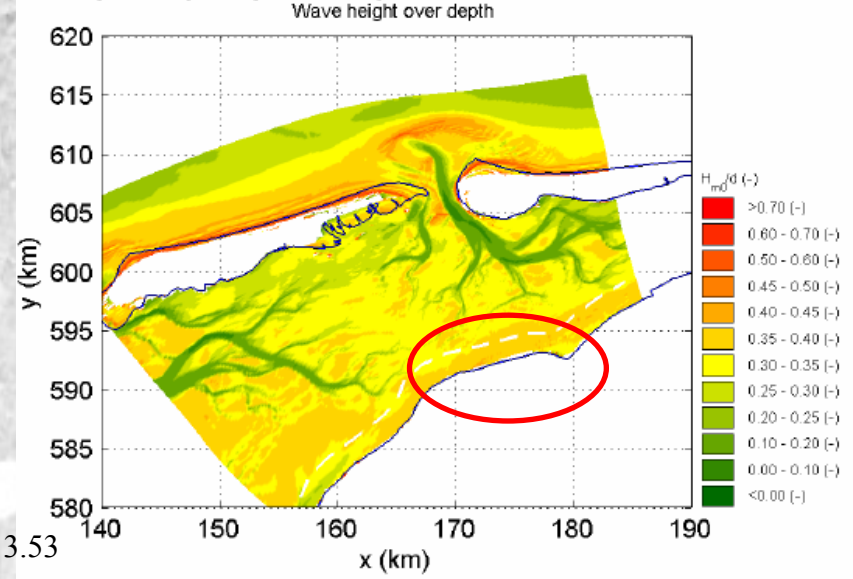




storm **extreme**

H_{m0}

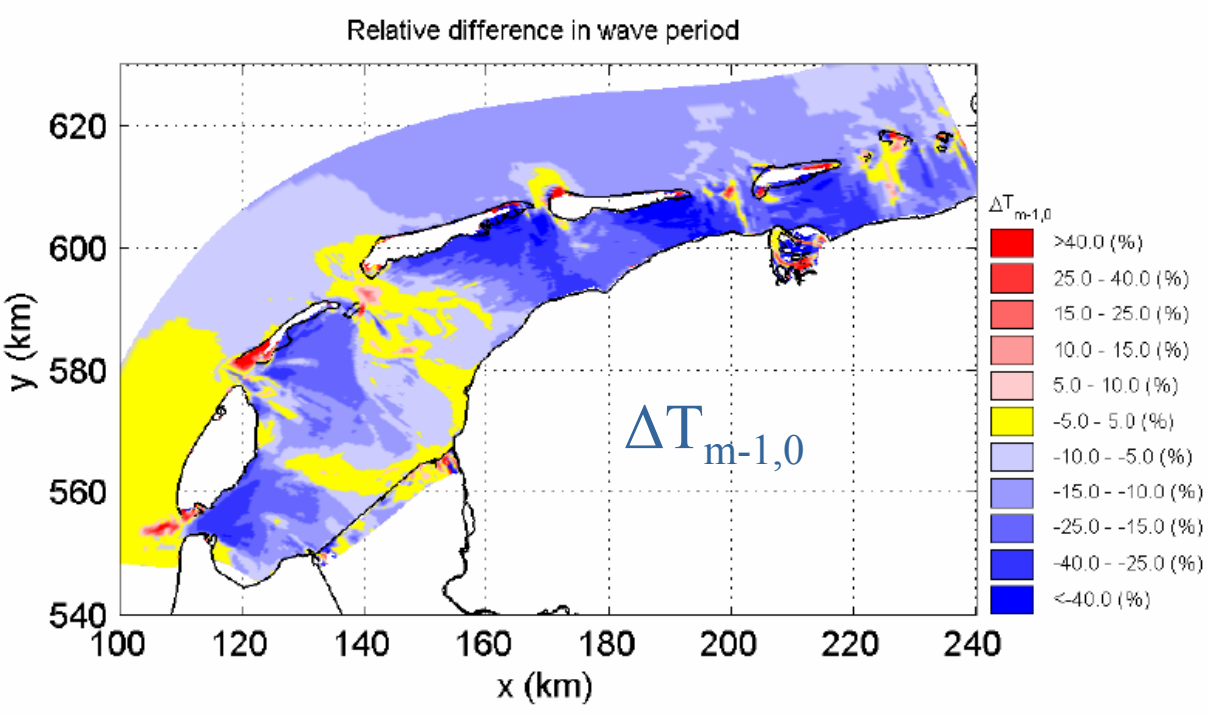




H_{m0}/d

3.44 3.52 3.45 3.53

Difference between current vs. no current



Wave period is reduced due to following currents
Reason: not “shoaling””, but increasing wave age
(c_rel+Ucur)/U*

Conclusions

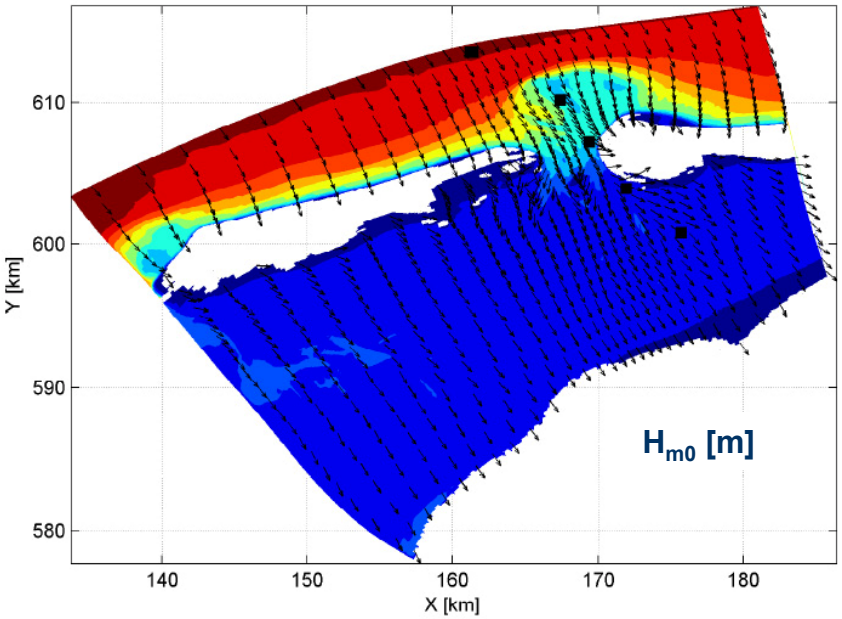
Storms

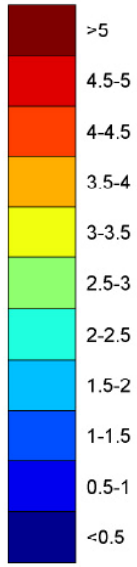
- good agreement at buoy locations but deviations due to current effects (wave age), wave tunneling and triads
- Improvement by using non-uniform water level and currents
- Ebb tidal inlet refracts and dissipates most North Sea waves at Amelander inlet
- Wave conditions in the Ameland inlet sea dominated by local wind growth, current effects and depth-limitation

Extreme events

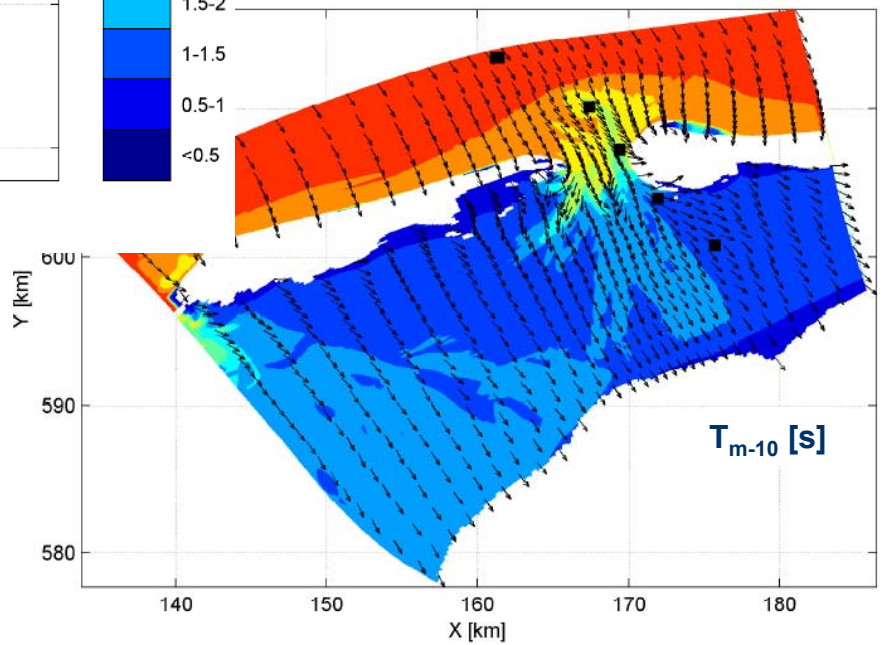
- Wind-driven circulations dominate astronomical tidal currents, causing large scale flow across the divides and “valve” effects through the inlet
- Strong West-East flow reduces spectral $T_{m-1,0}$ wave periods (following current, larger wave age may have effect on dikes.
- At coast lines, wave heights are still depth-limited, even in extreme cases

Integral wave parameters (8 Feb 2004)

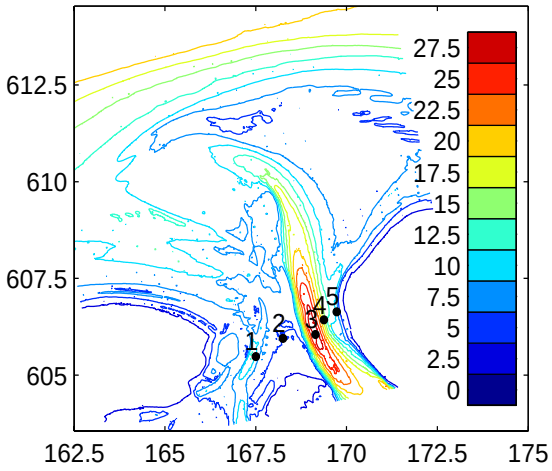


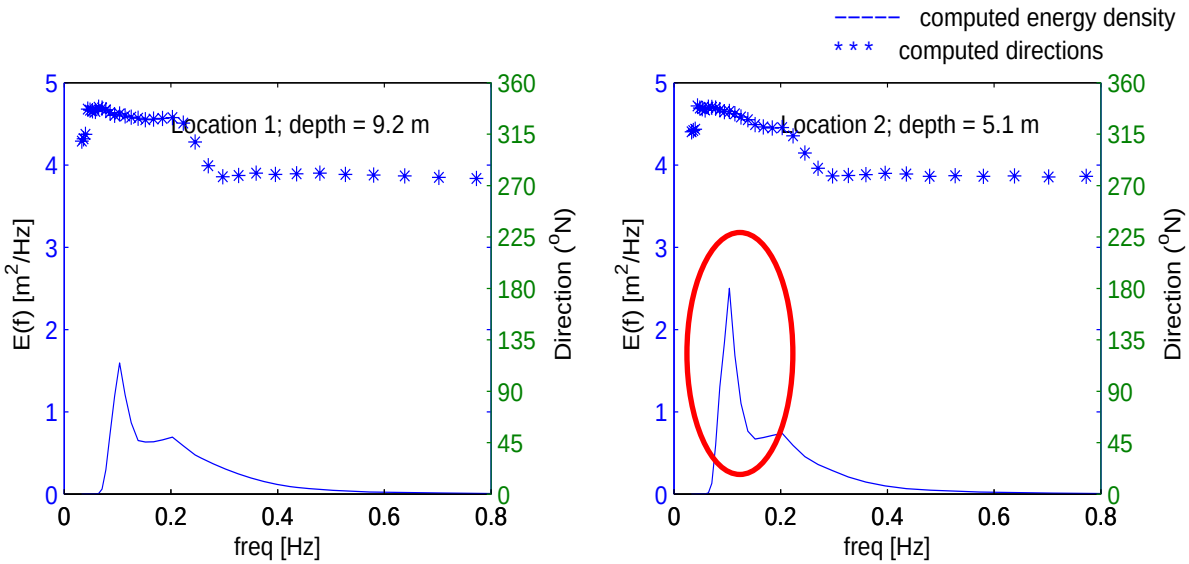


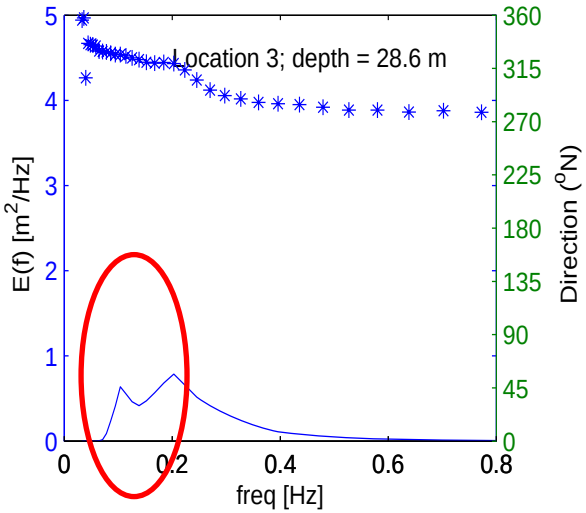
WL = 2.54 m
U_{10} = 15 m/s
θ_w = 325 °N
H_{m0} = 6.3 m
T_{m01} = 7.8 s

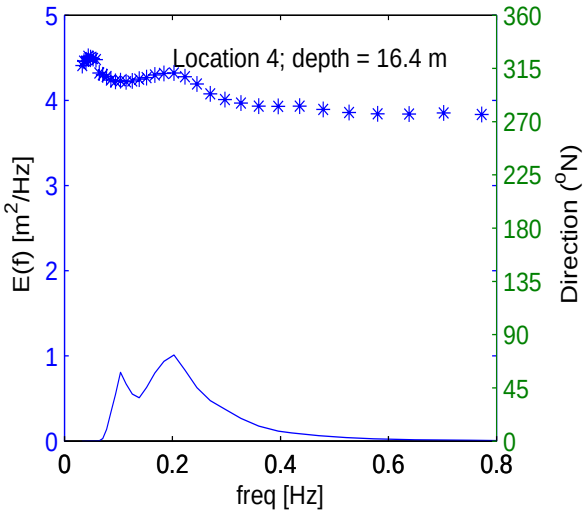


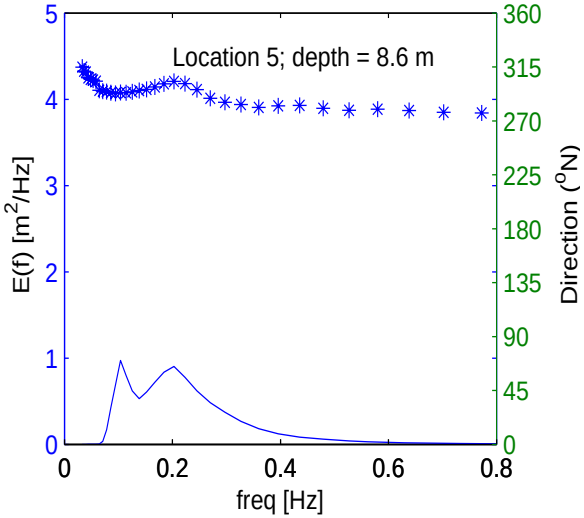
Penetration of swell over shoals



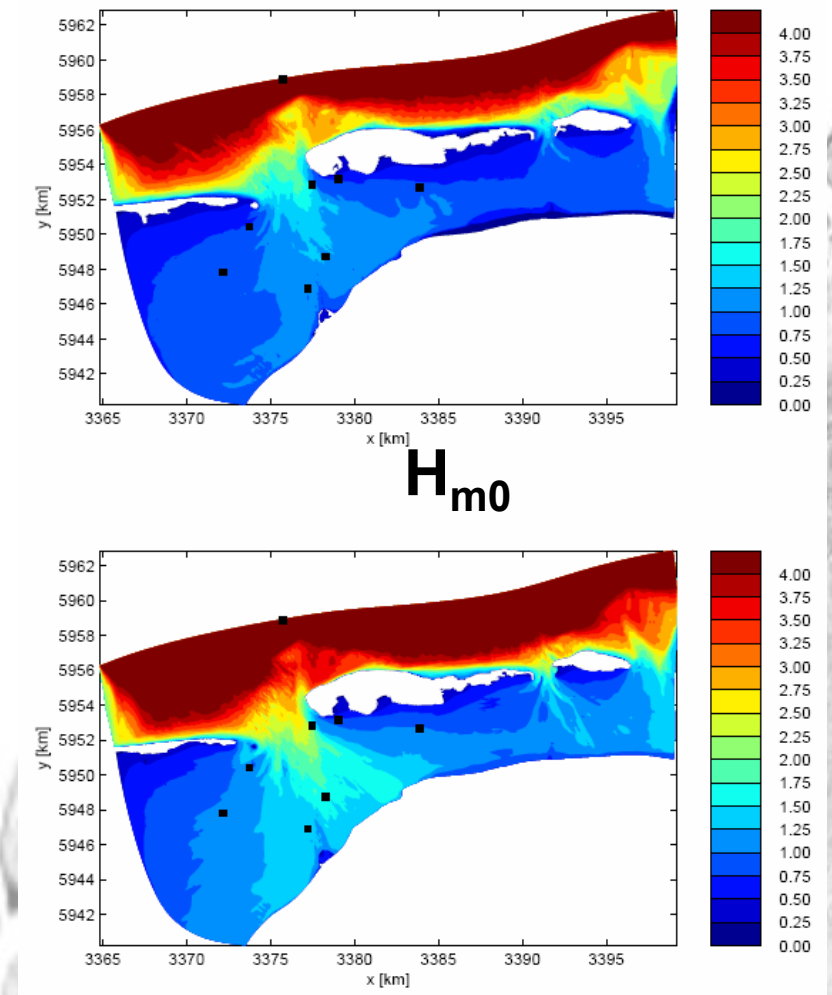








Norderney – hypothetical extreme event



more “open” inlet than Ameland, more penetration of NS waves

Recommendations for modelling

- investigate wind wave growth:
  - in Wadden Sea interior (or similar situations)
  - depth-limited conditions
  - wave growth limit (esp. period) as function of water level and currents (tidal and wind-driven)
- investigate dike locations where H_{m0}/h small (channels) and currents are larger (Lauwersdijk, Eems/Dollard) to generalize results
- improve estimate of total waterdepth (bathy+water level)
- investigate modelling of triads on ebb tidal delta/gorge
- improve shoaling, dissipation and wave focussing on (particularly) ebb currents.

Inputs and boundary conditions

- waterlevels:
  - station NES (uniform)
  - WAQUA model runs (2 January)
- current:
  - WAQUA model runs (2 January)
- wind:
  - windstation VLIELAND (uniform)
  - HIRLAM model (2 January)
- offshore waves:
  - offshore stations ELD and SON (uniform if SON information not available)

Modelled storms at Ameland

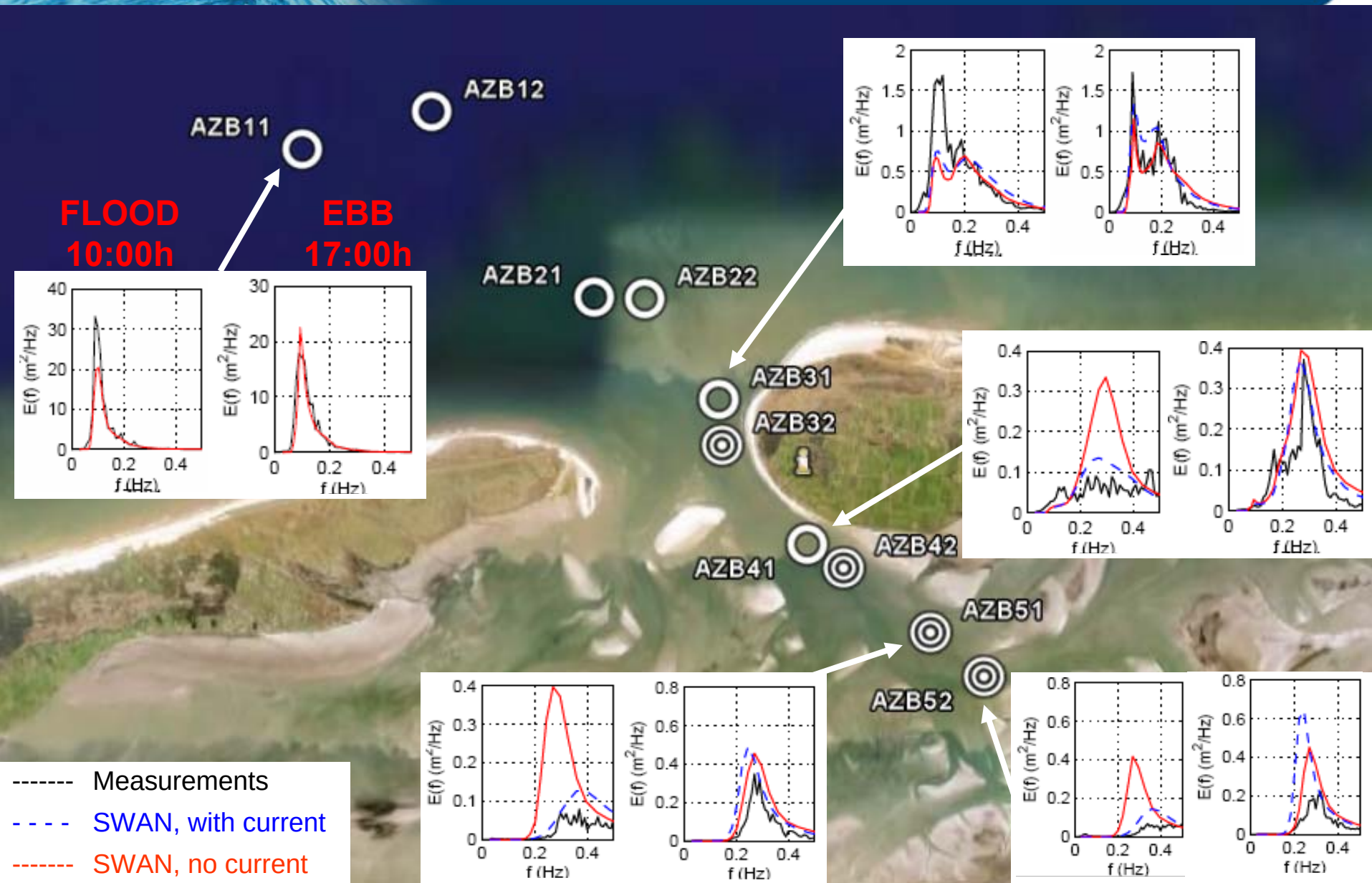
date	time (MET)	tidal stage	Wind speed (m/s)	Winddir. (°N)	Water level (m + NAP)	H_{m0} (m)	$T_{m-1,0}$ (s)	Wave dir (°N)
08-02-2004	20h00	flood	13.5	314	1.00	4.1	7.4	300
08-02-2004	22h30	slack	16.6	325	2.60	5.3	9.5	319
09-02-2004	01h30	ebb	16.3	328	1.75	4.8	9.7	338
02-01-2005	10h00	flood	20.0	277	1.04	5.1	9.0	310
02-01-2005	12h00	slack	17.8	277	2.07	4.9	9.3	317
02-01-2005	17h00	ebb	16.3	275	1.34	4.6	9.0	326

Wave model settings

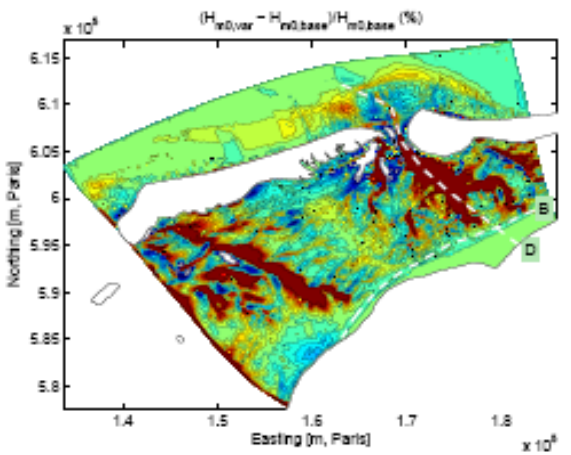
- SWAN version 40.51 (mostly default settings)
- Deep water physics according to Van der Westhuysen et al. (2007):
  - Wind input formulation of Yan (1987)
  - Saturation-based formulation for whitecapping (analogy to Alves and Banner, 2003)
- Triad wave interactions applying LTA (Eldeberky and Battjes, 1996)

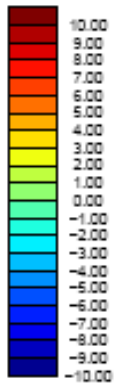
- $\Delta\sigma/\sigma=0.1$; $0.03\ \text{Hz} < \sigma < 0.85\ \text{Hz}$; $\Delta\theta=10^\circ$
- 1% convergence criterion

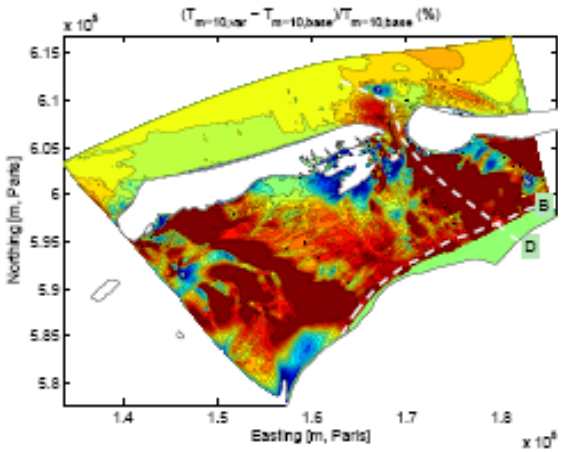
Energy spectra at 2 Jan 2005

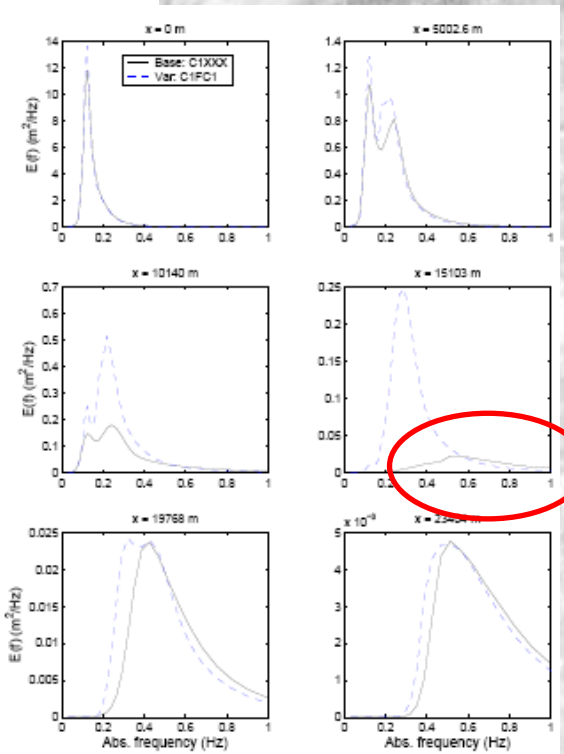


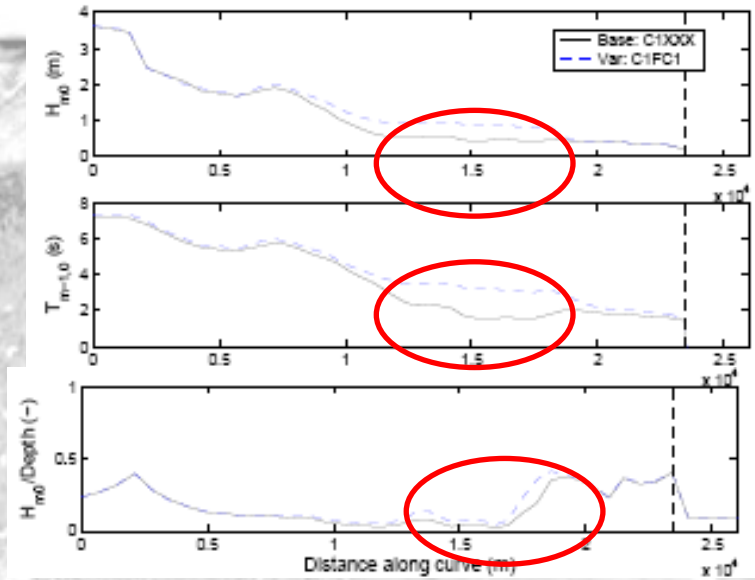
Effects of (normal) tidal currents - following







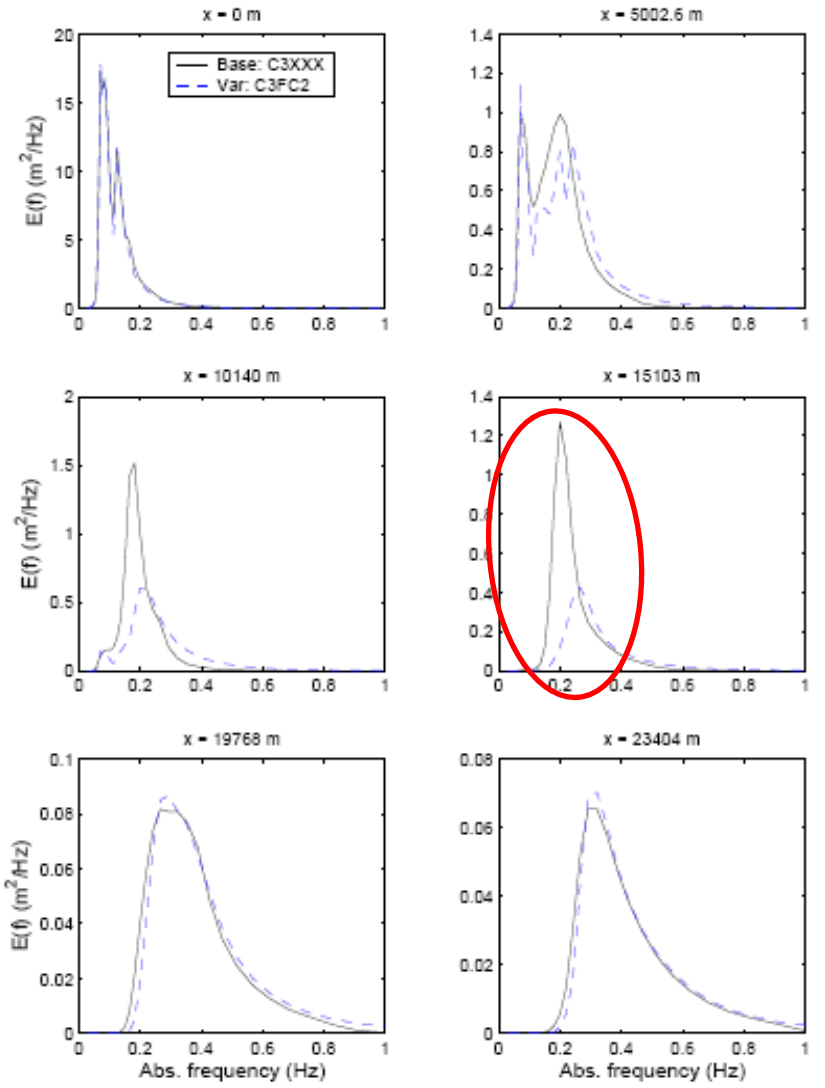


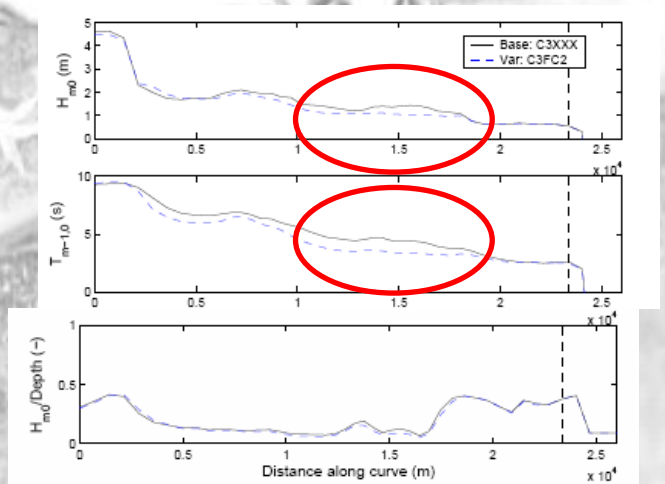


flood current **on (from - - to -)**:

- less shoaling -> H_{m0} smaller
- larger wave age -> less growth in H_{m0} and $T_{m-1,0}$

Effects of (normal) tidal currents - opposing





ebb current **on (from - - to -)**:

- more shoaling -> H_{m0} larger
- smaller wave age -> more growth in H_{m0} and $T_{m-1,0}$

Conclusions (1)

- Validation of storm conditions
  - good agreement w.r.t. integral parameters
  - Fair agreement w.r.t. (details in) spectra.
  - Including non-uniform water level and currents improves results dramatically
  - Ebb tidal inlet dissipates most North Sea waves
  - Wave conditions in the Ameland inlet sea dominated by local wind growth, current effects and depth-limitation.

Conclusions (2)

- Extreme conditions
  - **Wind-driven circulations** dominate astronomical tidal currents, causing large scale flow across the divides
  - In tidal inlet: "Astronomical flood" becomes "**outflow** event" or "valves", which block waves
  - Strong West-East flow **reduces spectral $T_{m-1,0}$** wave periods (following current, larger wave age (**$(c+U_{cur})/U_{wind}$**), may have effect on dikes.

Conclusions (on sensitivity)

- Waves at dikes around Ameland inlet:
  - Wave height depth-limited
  - Wave period determined by Wadden Sea depth-limited growth
  - Results are sensitive to
    - water level, currents, wind field, wind modelling, bottom friction (only when sw growth limit is not reached), depth-limited breaking

    are insensitive to
    - offshore bc's, spatial vs. uniform wind fields, triads (note these ARE important in inlet)