INWAVE: THE INFRAGRAVITY WAVE DRIVER OF COAWST

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COAWST WORKSHOP

Woods Hole, 15th -19th August, 2016

OUTLINE

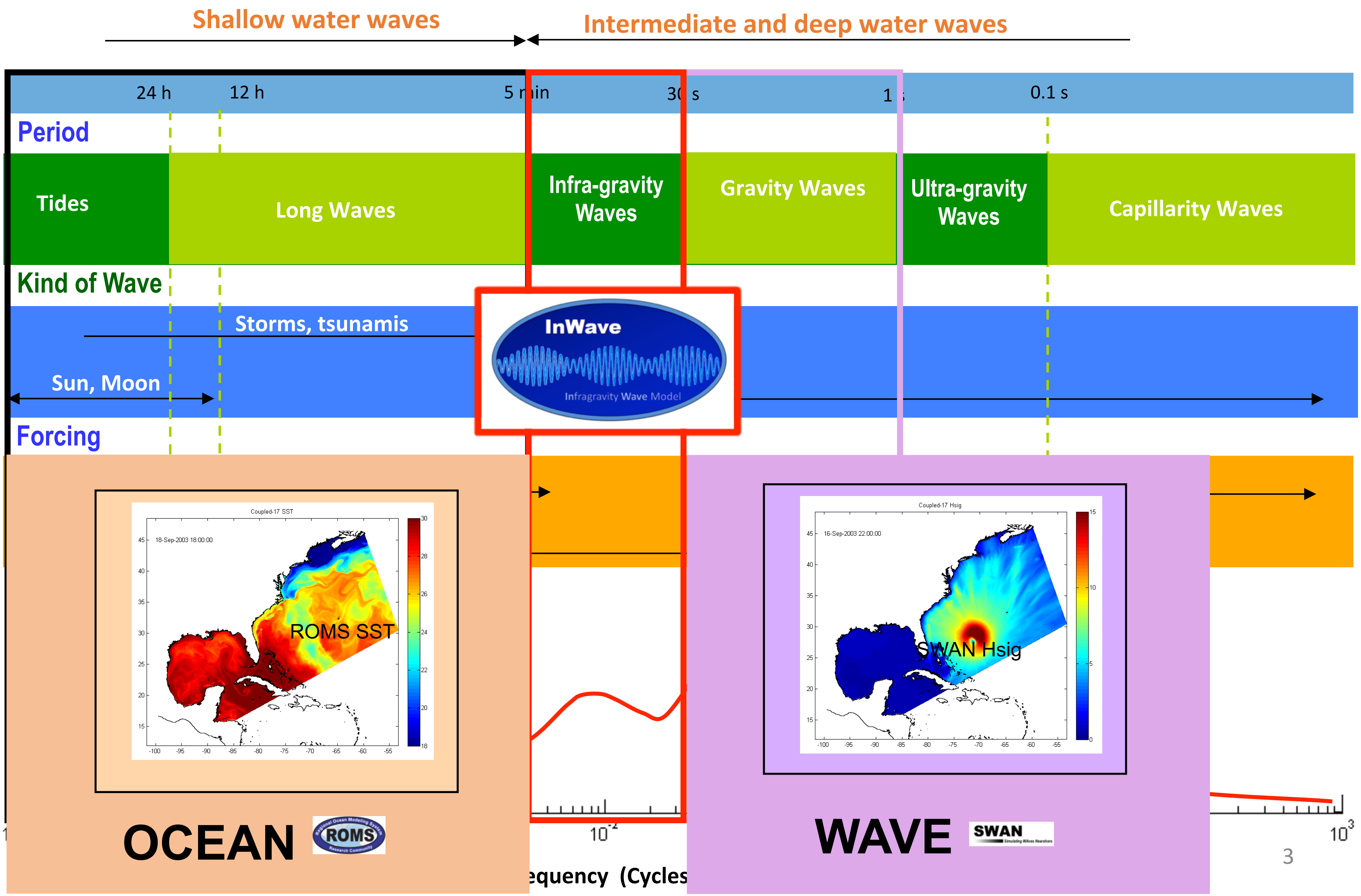
1. INTRODUCTION AND MOTIVATION
2. IG WAVE GENERATION AND DISSIPATION MECHANISMS
3. IG WAVE MODELLING TECHNIQUES
4. INWAVE

   a. EQUATIONS AND NUMERICAL SCHEME

   b. HOW IS IT LINKED TO THE VORTEX FORCE?

   c. APPLICATIONS

   d. FUTURE PLANS



Shallow water waves
Intermediate and deep water waves
24 h
12 h
5 min
30 s
1 s
0.1 s
Period
Tides
Long Waves
Infra-gravity Waves
Gravity Waves
Ultra-gravity Waves
Capillarity Waves
Kind of Wave
Storms, tsunamis
Sun, Moon
Forcing
InWave
Infragravity Wave Model
Coupled-17 SST
18-Sep-2003 18:00:00
ROMS SST
Coupled-17 Hsig
16-Sep-2003 22:00:00
SWAN Hsig
OCEAN
ROMS
WAVE
SWAN
equency (Cycles

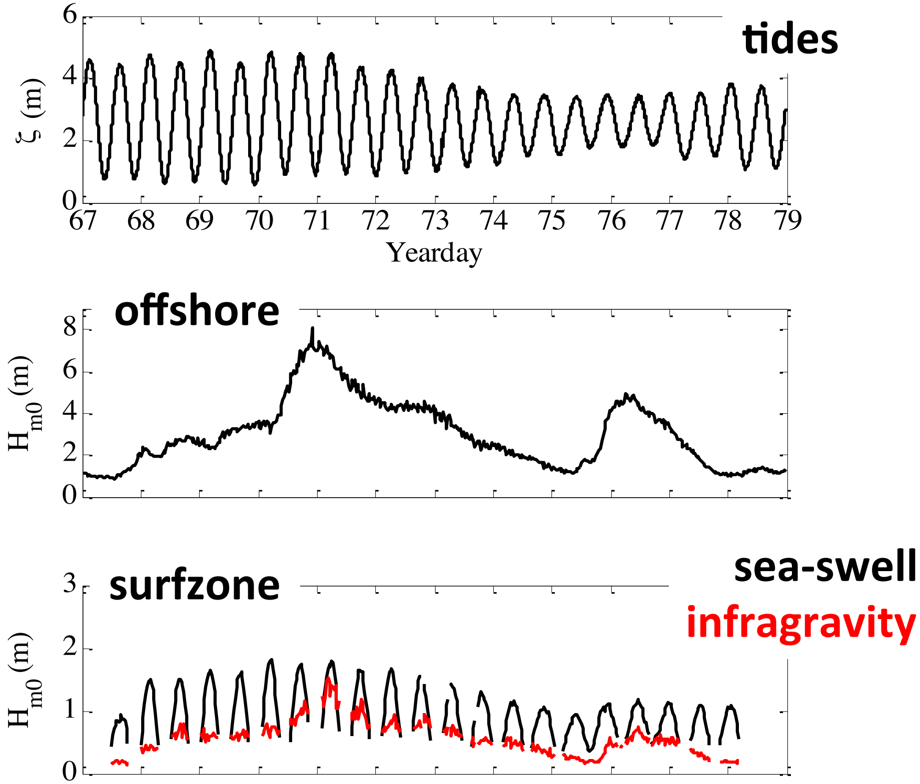
- InfraGravity (IG) waves are defined as waves with **periods between 30 and 300 seconds** generated by the **non-linear interactions of gravity waves**.

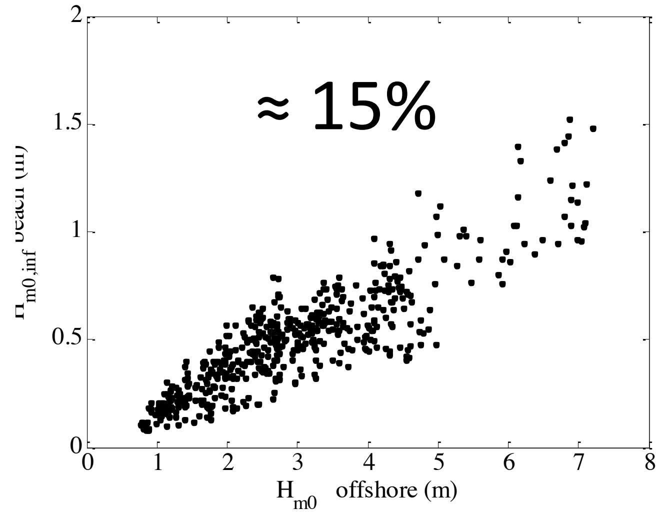
- In deep water the energy transfer to IG waves is non-resonant and the height of the IG waves is few millimeters. In **shallow water** the **energy transfer becomes near-resonant** and IG wave height can increase to over 1 m.

- IG waves are highly correlated with the modulation of wind or swell waves.

RUNUP AND BEACH-DUNE EROSION

HARBOR RESONANCE





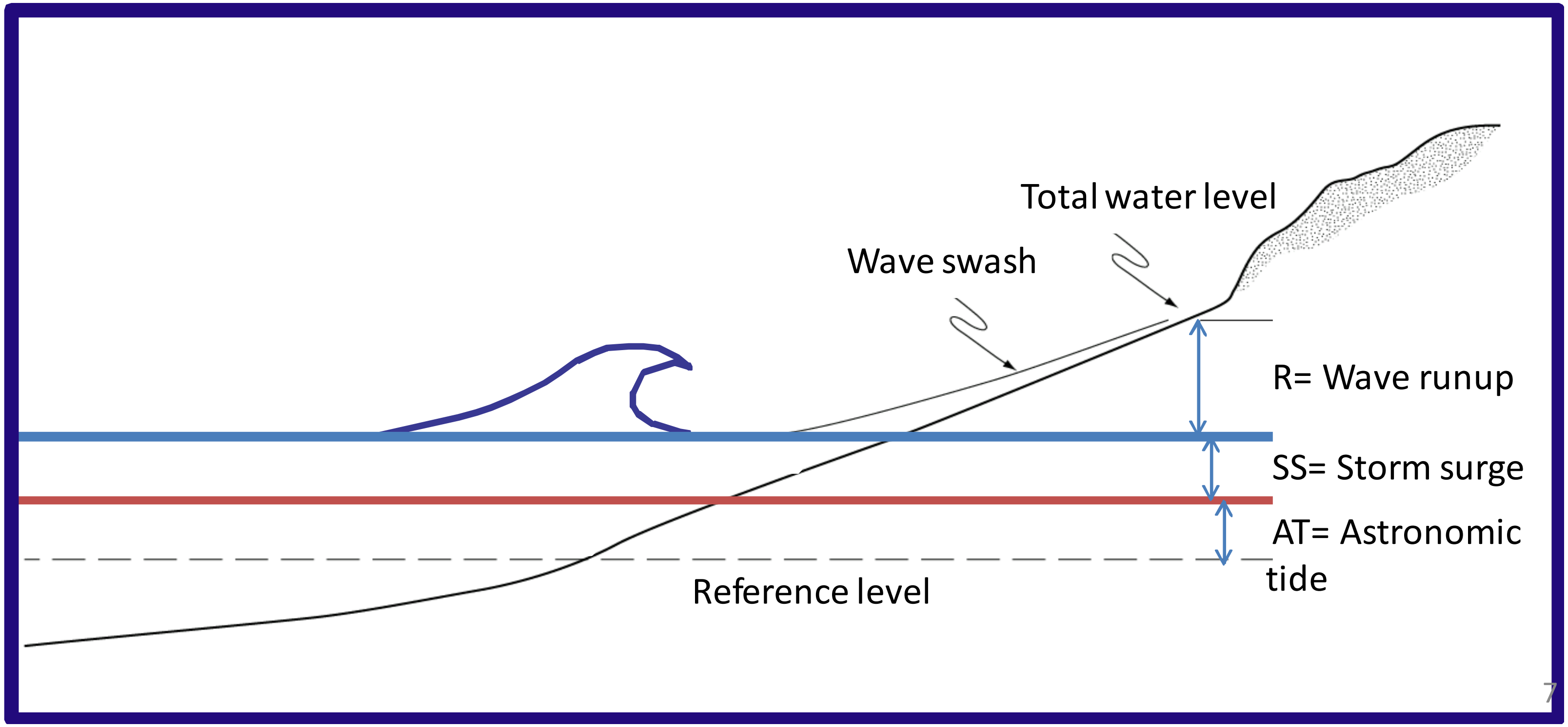
Ruessink, B.G. (2010). Observations of turbulence within a natural surf zone. *Journal of physical oceanography*, 40 (12).

TOTAL WATER LEVEL=

ASTRONOMIC TIDE (AT) + STORM SURGE (SS) + WAVE RUNUP

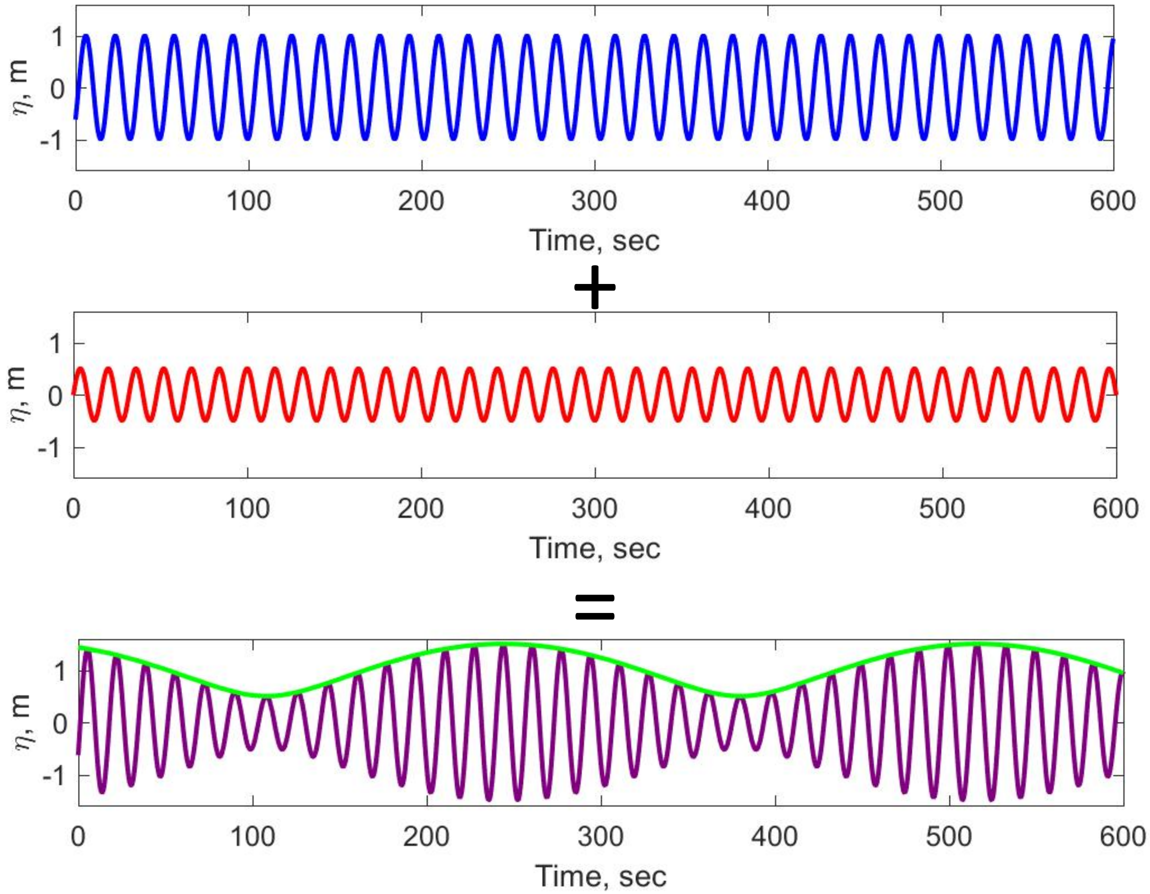
STORM SURGE (SS):
atmospheric pressure +
wind stress +
shelf oscillations or seiche

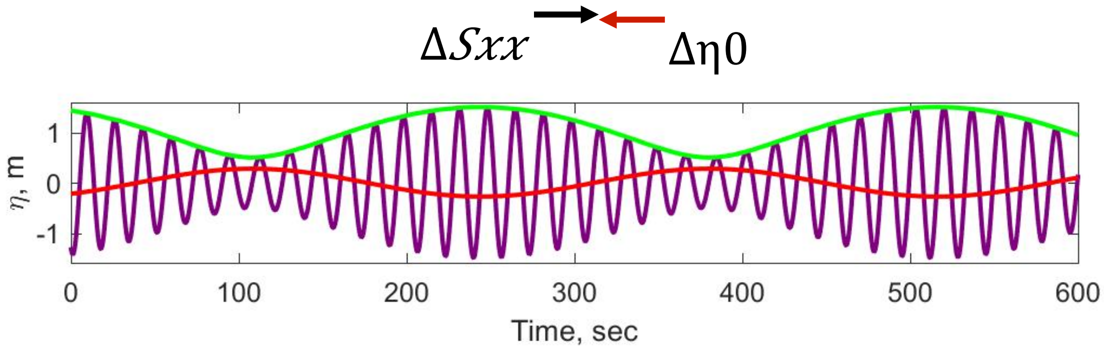
WAVE RUNUP:
wave setup +
incident wave runup +
IG wave runup



GENERATION MECHANISMS

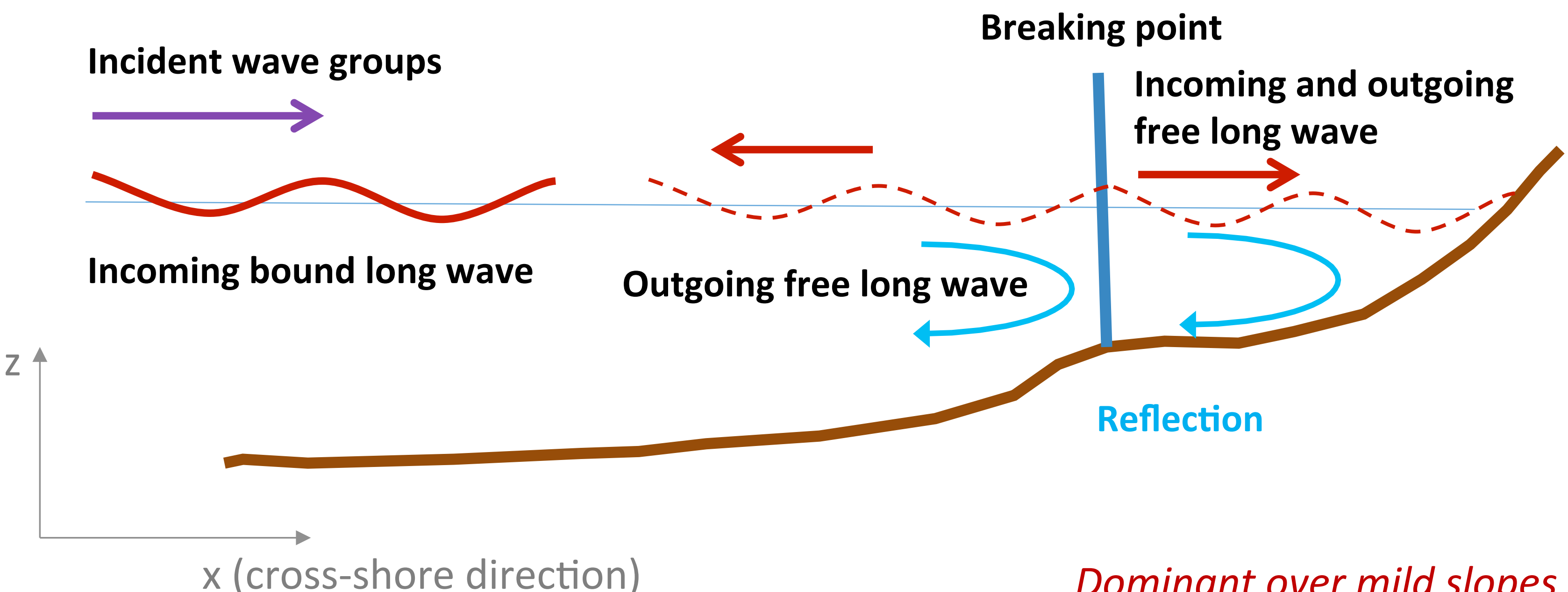
1. **GROUP-BOUND WAVE GENERATION AND SHOALING:** Quadratic difference interaction among pairs of primary waves, resulting in group-bound second-order waves (Biesel, 1952; Longuet-Higgins and Stewart, 1962).





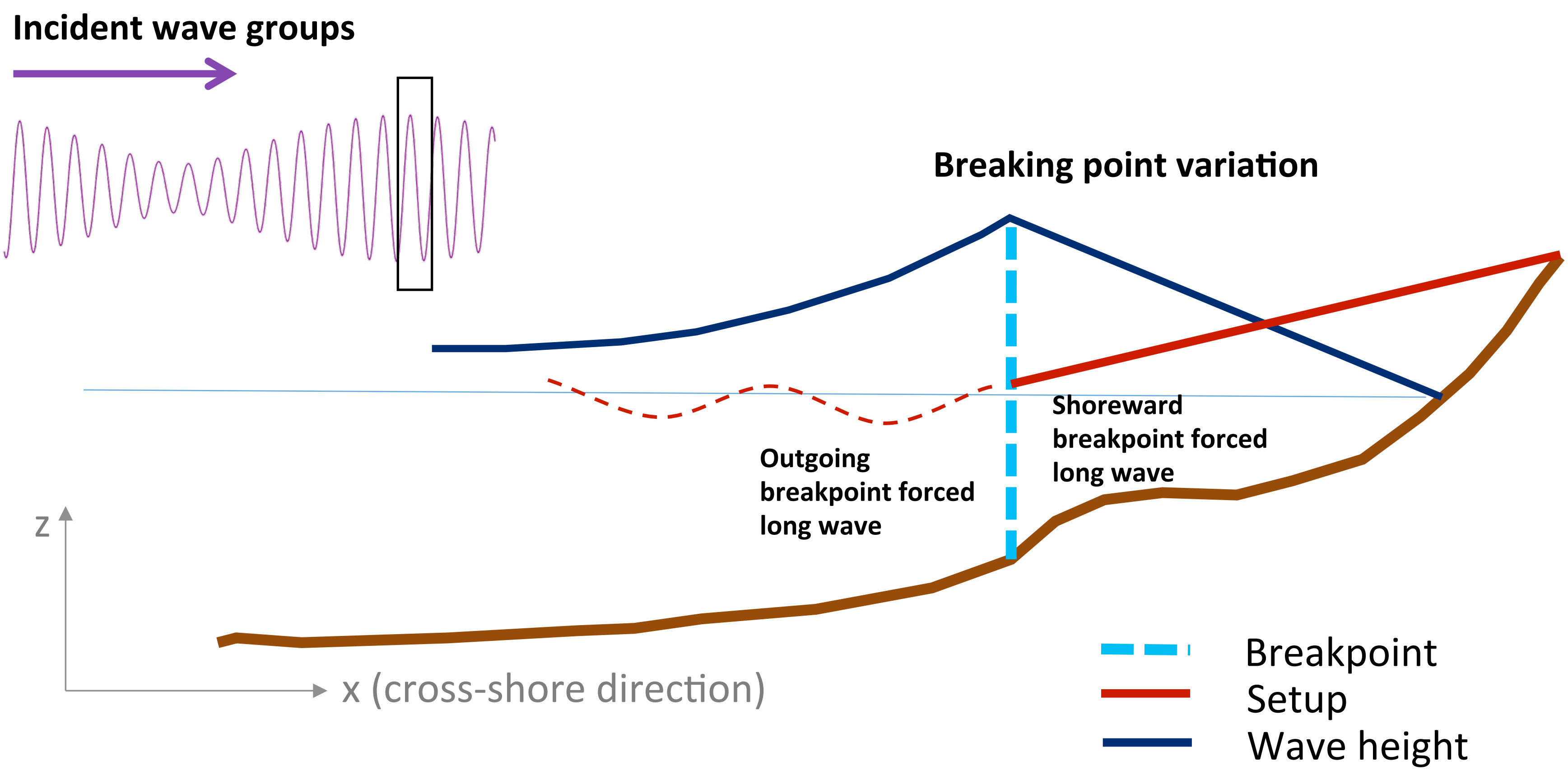
$\eta 0$= wind-wave averaged water level

Sxx=radiation stress



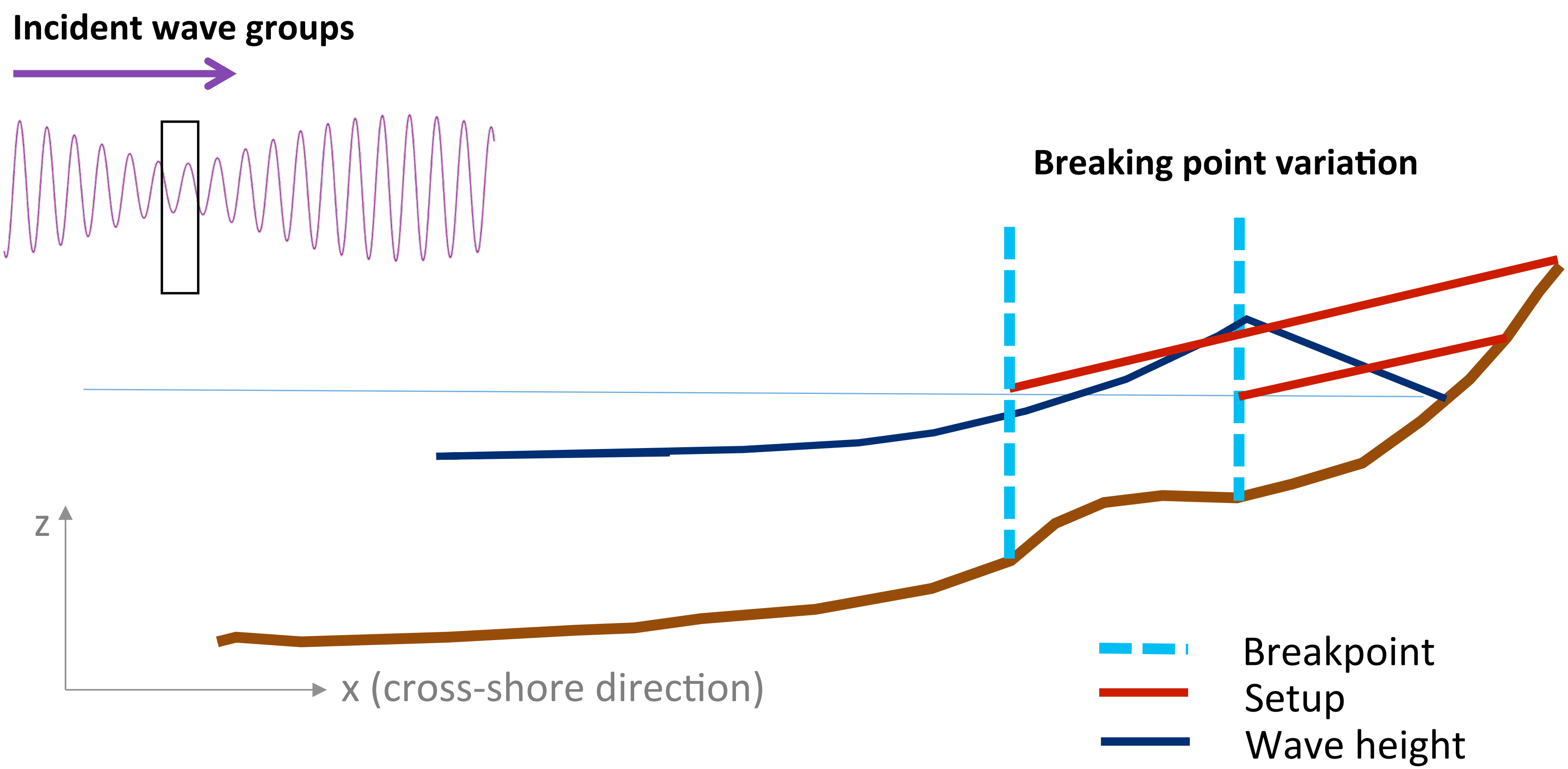
Dominant over mild slopes

2. BREAK-POINT MOVEMENT: Symonds et al., 1982; Symonds and Bowen, 1984, Schaffer and Jonsson, 1990 and Schaffer, 1990.



Dominant over steep slopes

The highest waves in the wave group produce a higher setup than the smallest waves: wave group modulation of the wave setup



GENERATION MECHANISMS

Battjes, J. A., H. J. Bakkenes, T. T. Janssen, and A. R. van Dongeren (2004), Shoaling of subharmonic gravity waves, J. Geophys. Res., 109, C02009.

$$\beta = \frac{h_x \sqrt{gh}}{w}$$

$\beta =$ Normalized bed slope

$h_x =$ bed-slope

$w =$ long-wave frequency (rad s^{-1})

$h =$ water depth (m)

Breakpoint mechanism is dominant over steep slopes $\beta > 1$

Bound-wave shoaling is dominant over mild-slopes $\beta \leq 0.3$

DISSIPATION MECHANISMS

- Bottom friction (Henderson and Bowen, 2002; de Bakker et al., 2014).
- Non-linear energy transfer back to sea-swell frequencies through triad interaction (Henderson et al., 2006; Thomson et al., 2006; Guedes et al., 2013).
- IG wave breaking (Battjes et al., 2004; Van Dongeren et al., 2007; Lin and Hwung, 2012; Nazaka and Hino, 1991).
- Energy transfer thru non-linear interactions to lower periods.

It is not clear which is the main dissipation mechanism and it might depend on the beach slope and on the frequency of the IG components.

MODELLING APPROACHES OR TECHNIQUES

WAVE RESOLVING TECHNIQUES:
BOUSSINESQ , PARTICLE METHODS, NON-HYDROSTATIC MODELS OR RANS MODELS

WAVE AVERAGED OR PHASE AVERAGED TECHNIQUES:
WAVE ACTION BALANCE EQUATION + NLSW

Modeling approaches: from Reniers, 2012 (Long Wave and Runup Workshop)

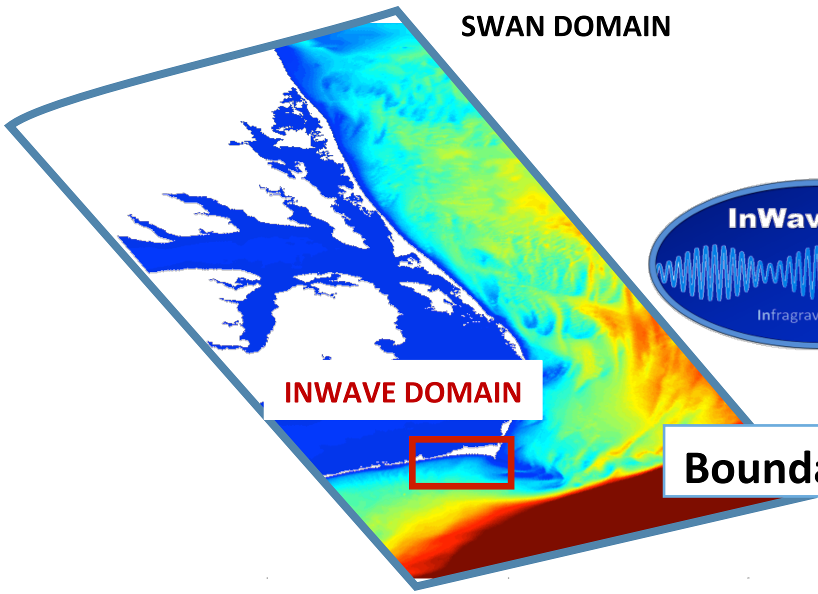
Dimension	Short wave resolving	Short wave averaged	LSWE	NSWE	RANS	NH	BSNQ	WKB
1D	2,7,8	1,30,3,5,9	1,5,9	2,30,3			7,8	
1D+		10,11,25, 26	10,11,26					25
2DH	18,17, 32	15,14,23		15,14,23			18,17,3 2	
2DV	33				33			
Q3D		30		30				
3D	22	19		19		22		

[1] List [1992], [2] Watson and Peregrine [1992], [3] Roelvink [1993], [4] Karunarathna and Tanimoto [1995], [5] Symonds et al. [1982], [6] Van Leeuwen [1992], [7] Bosboom et al. [ ], [8] Rhaka et al. [1997], [9,10] Shaffer [1993,1994], [11] Reniers et al. [2002], [12] MacMahan et al., [2010], [13] Herbers and Burton [1997], [14] Van Dongeren et al. [2003], [15] Long and Ozkan-Haller [2009], [16] Chen and Guza [1993], [17] Chen et al., [2003], [18] Spydell and Feddersen [2009]. [19], Reniers et al., [2009], [20] Uchiyama et al. [2010], [21] Janssen et al. [2009], [22] Stelling and Zijlema [2010], [23] Roelvink et al. [2009], [24] Foda, M. A., and C. C. Mei,[1981], [25] Herbers et al. [1995], [26] Howd et al. [1992], [27] Lippmann et al. [1997], [28] Madsen et al., [1997], [29] Henderson et al. [2006], [30] Van Dongeren and Svendsen [2000], [31] Haller et al. [1999], [32] Johnson and Pattiaratchi [2006], [33] Bakhtyar et al. [2009], [34] Thompson et al. [2007], etc.

INWAVE IS BASED ON THE **WAVE AVERAGED OR PHASE AVERAGED TECHNIQUE**

INWAVE IS SIMILAR TO XBEACH MODEL (Roelvink et al., 2009) BUT WITH THE DIFFERENCE THAT INWAVE+ROMS IS ABLE TO SIMULATE **3D CIRCULATION** WHILE XBEACH IS 2D

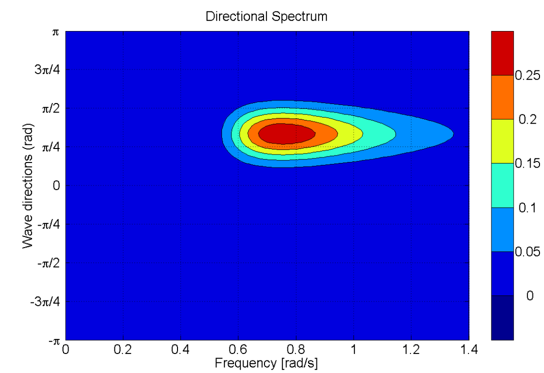
SWAN DOMAIN

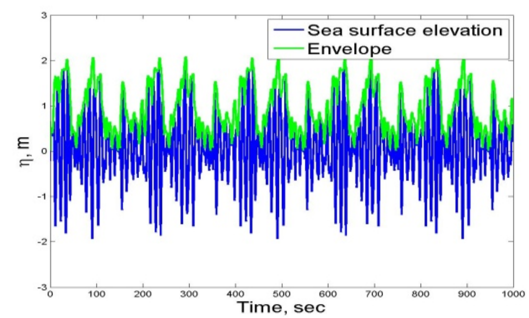


Boundary region

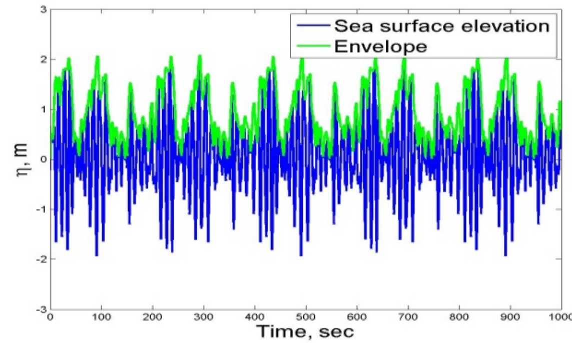
SWAN domain: Wave **spectral** time scale

DIRECTIONAL WAVE SPECTRUM





Wave group time scale



FREE SURFACE ELEVATION AND WAVE ENERGY ENVELOPE TIME VARIATION

Boundary condition for the wave action conservation equation

$$\frac{\partial A}{\partial t}+\frac{\partial c_{g,x} A}{\partial x}+\frac{\partial c_{g,y} A}{\partial y}+\frac{\partial c_{g,\theta} A}{\partial \theta}=-\frac{D}{\sigma} \quad \text{where} \quad A(x,y,\theta,t)=\frac{E(x,y,\theta,t)\ \text{wave energy}}{\sigma(x,y,t)\ \text{intrinsic frequency}}$$

Vortex Force terms varying in wave group scale

Wave group scale varying Wave forcing ⟹ ROMS (Regional Ocean Modeling System, Research Community) = **Infragravity wave generation + 3D hydrodynamics**

MAIN MODULES OF INWAVE

READ SWAN DIRECTIONAL SPECTRAL OUTPUTS AT THE CHILD GRID BOUNDARIES

RECONSTRUCT THE GROUP SCALE VARYING WAVE ACTION TIME SERIES AT THE CHILD GRID BOUNDARY

RECONSTRUCT THE INCOMING BOUND INFRAGRAVITY WAVES (e.g. Herbers et al. 1994)

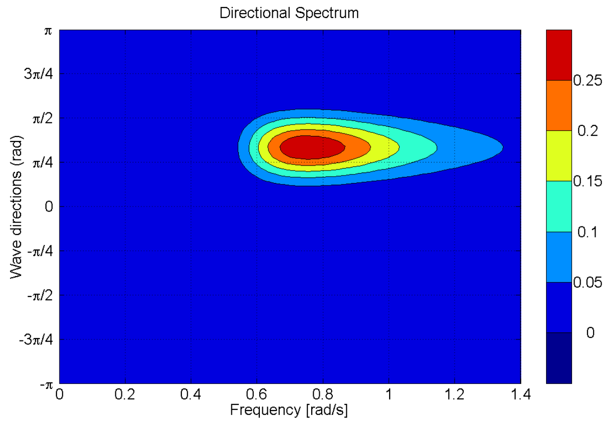
PROPAGATE IN TIME AND SPACE THE GROUP VARYING WAVE ENERGY AT THE CHILD GRID

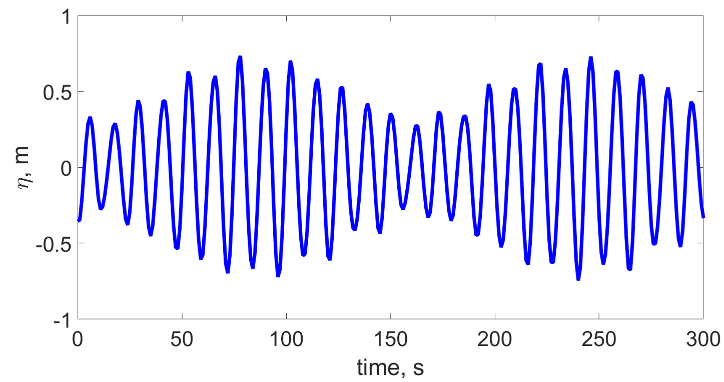
USE THE GROUP VARYING WAVE ENERGY FORCING AS INPUTS FOR THE VORTEX-FORCE (VF) IN ROMS

Infragravity wave generation thru VF and propagation of the bound IG wave **ROMS**

Leaky, bound and trapped infragravity waves

RANDOM PHASES +
INVERSE FFT

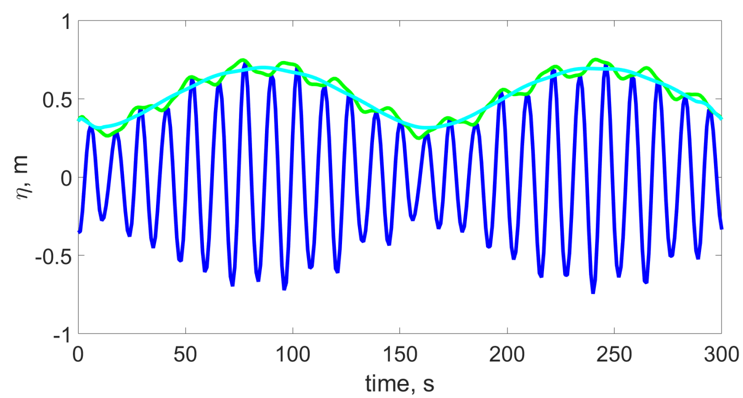




HILBERT TRANSFORM +
LOW-PASS FILTER

$$A(x,y,\theta,t) = \frac{E(x,y,\theta,t)}{\sigma(x,y,t)} = \frac{1}{2}\rho g \,|\, A_{low}(x,y,\theta,t) \,|^2$$

at INWAVE boundaries



For each realization A(x,y,θ,t) is going to be different

RECONSTRUCT THE INCOMING BOUND INFRAGRAVITY WAVES

Van Dongeren et al. (2003) -> Hasselman (1963) & **Herbers et al. (1994)**

1. The energy of the secondary forced elevation E_3 (Δf) for one particular pair of interacting primary waves can be computed following Herbers et al. (1994)

$$E_3(\Delta f) = 2\int_{\Delta f}^{\infty}\int_0^{2\pi}\int_0^{2\pi} D^2(f+\Delta f, -f, \Delta\theta+\pi) \cdot E(f+\Delta f, \theta_1)E(f, \theta_2)d\theta_2\, d\theta_1\, df,$$

$$f_2 = f_1 + \Delta f.$$

$$\begin{aligned} D(-f_1, f_2, \Delta\theta+\pi) &= \frac{g\, k_1 k_2 \cos(\Delta\theta+\pi)}{8\pi^2 f_1 f_2}\frac{\cosh(k_3 h)}{\cosh(k_1 h)\cosh(k_2 h)} \\ &- \frac{g(-f_1+f_2)}{\left[g\, k_3 \tanh(k_3 h) - (2\pi)^2(-f_1+f_2)^2\right] f_1 f_2} \\ &\times \left\{ (-f_1+f_2)\left[\frac{(2\pi)^4 (f_1 f_2)^2}{g^2} - k_1 k_2 \cos(\Delta\theta+\pi)\right] \right. \\ &\left. - \frac{1}{2}\left[\frac{-f_1 k_2^2}{\cosh^2(k_2 h)} + \frac{f_2 k_1^2}{\cosh^2(k_1 h)}\right]\right\}, \end{aligned}$$

$$k_3 \equiv \left|\vec{k_1} - \vec{k_2}\right| = \sqrt{k_1^2 + k_2^2 - 2 k_1 k_2 \cos(\Delta\theta)}.$$

$$A_3 = \sqrt{2E_3\, df},$$

2. Bound wave out of phase with the envelope formed by each interacting pair

$$\psi_3 = \psi_2 - \psi_1 + \pi.$$

3. The direction of the bound wave is give by

$$\theta_3 = \arctan\left(\frac{k_2 \sin\theta_2 - k_1 \sin\theta_1}{k_2 \cos\theta_2 - k_1 \cos\theta_1}\right).$$

4. The time series of the surface elevation of the bound wave is

$$\zeta_3(0, y, t) = A_3 \cos(k_3 \sin\theta_3\, y - 2\pi\Delta f t + \psi_3).$$

5. This process is repeated for every pair of short-wave components. The summation of all components gives the total bound wave.

Wave action balance equation in Cartesian coordinate system

$$\frac{\partial (A)}{\partial t} + \frac{\partial (C_{g,x} A)}{\partial x} + \frac{\partial (C_{g,y} A)}{\partial y} + \frac{\partial (C_{g,\theta} A)}{\partial \theta} = -\frac{D_w}{\sigma}$$

$$C_{g,x} = C_g \cos\theta + U$$

$$C_{g,y} = C_g \sin\theta + V$$

Wave dispersion relation + Doppler relation

$$\sigma = \sqrt{gk \tanh(kh)}$$

$$C_g = 0.5 C \left(1 + \frac{2kh}{\sinh(2kh)}\right)$$

$$C = gk \tanh(kh)/\sinh(2kh)$$

$$w = \sigma + k \cdot u$$

Eikonal equation

$$\frac{\partial k_x}{\partial t} = -\frac{\partial (w)}{\partial x}$$

$$\frac{\partial k_y}{\partial t} = -\frac{\partial (w)}{\partial y}$$

$$|k| = k_x^2 + k_y^2$$

Wave breaking

$$D_w = D_b \cdot Q_b$$

D_w = Total energy dissipation

D_b = Energy dissipation in a breaking wave

Q_b = Fraction of breaking waves

Roelvink (1993)

$$Q_b = \min(1, 1 - \exp(-(H/\gamma h)^n))$$

H= γh

γ = Breaking parameter

h = water depth

H = wave height

Battjes and Janssen (1978)

$$D_b = 2 \alpha f_{rep} E_w$$

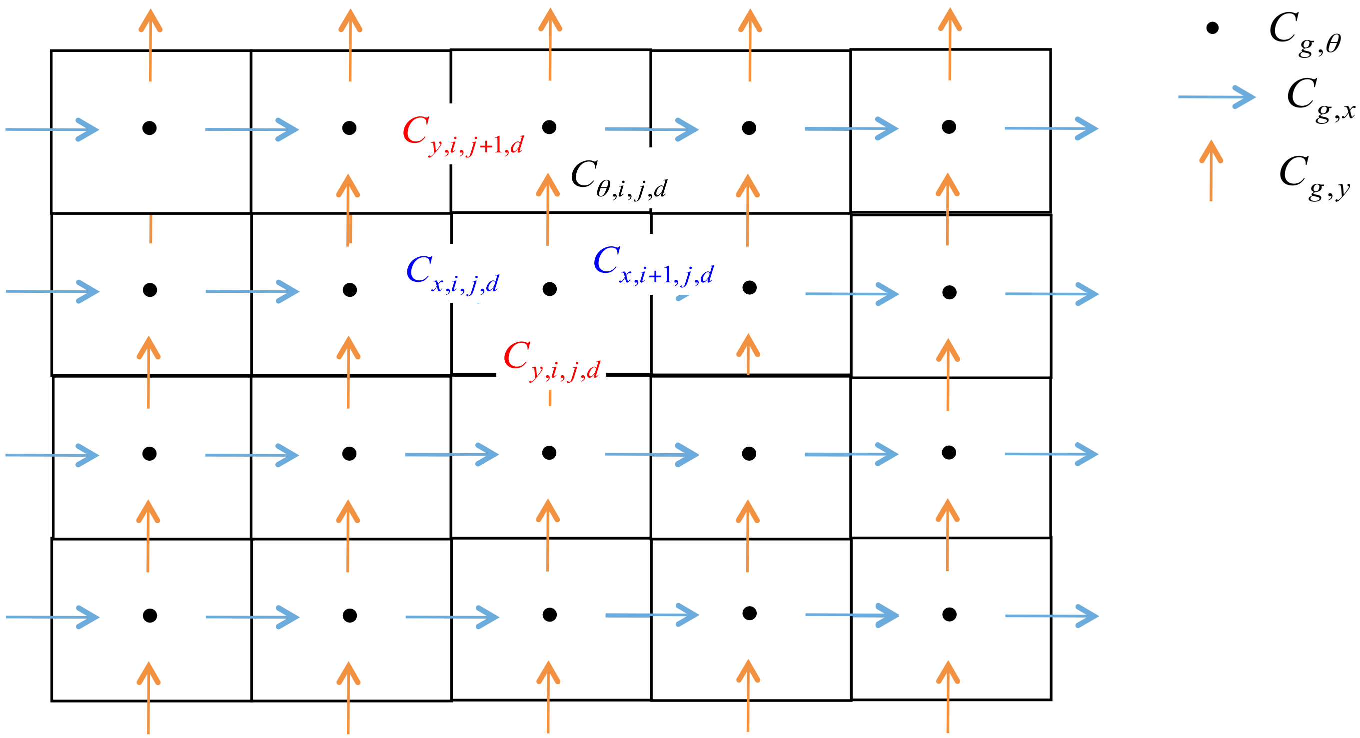
α = Coefficient O(1)

f_{rep} = Representative frequency

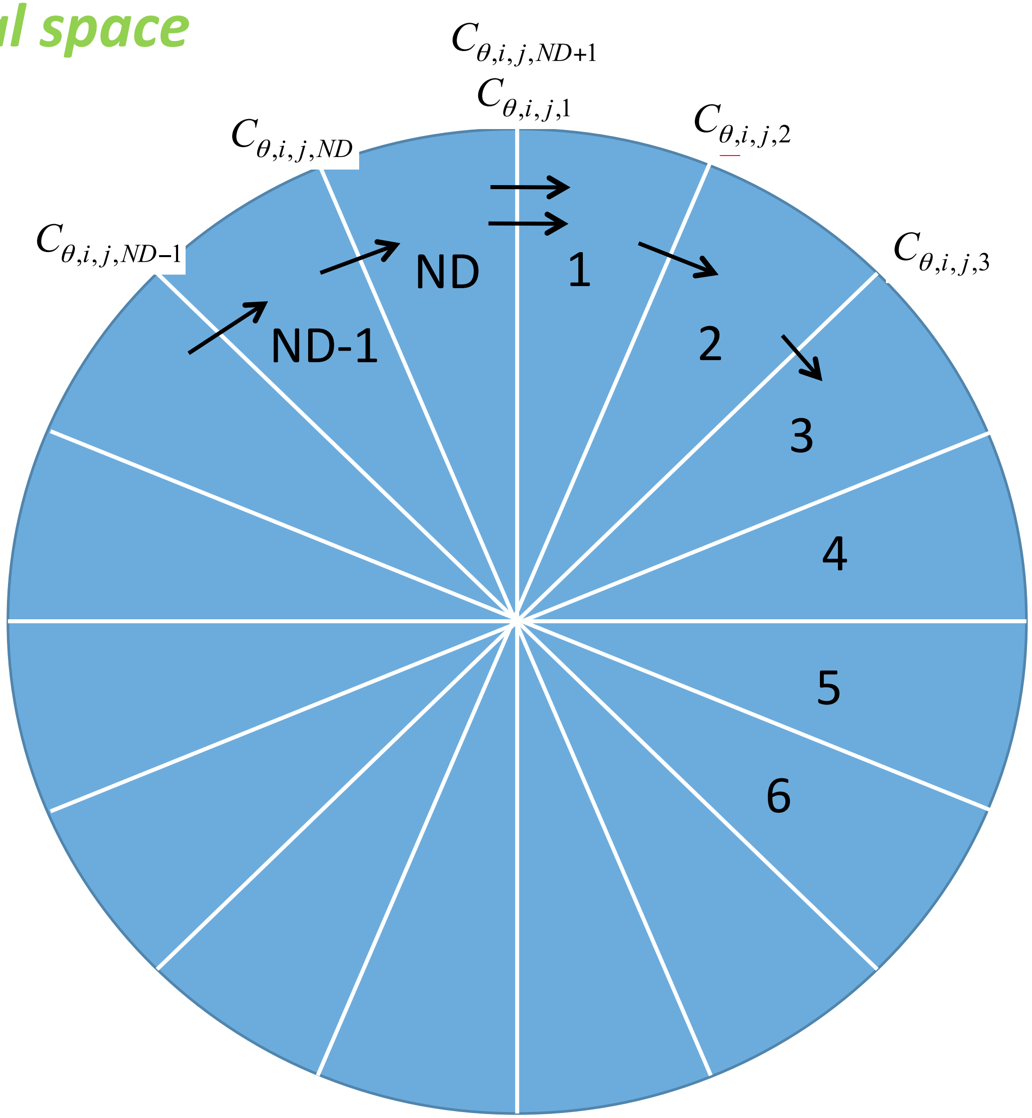
E_w = Wave energy integrated over directions

n = Coefficient

Horizontal space



Directional space




COAWST
INWAVE
DRIVERS
Driver_inwave.F
MODULES
mod_inwave_bound.F
mod_inwave_swan.F
mod_inwave_params.F
mod_inwave_vars.F
UTILITY
get_inwave_bnd_grid.F
get_inwave_ini.F
set_inwave_data.F
get_inwave_data.F
interp2d.F
set_inwave_swan_data.F
get_inwave_grid.F
math_tools.F
swan_reader.F
INCLUDE
inwave_globaldefs.h
ACTION_ BALANCE
celer_inw.F
dispersion_inw.F
prestep_inw.F
corstep_inw.F
dissip_inw.F
curr_inw.F
frc_inw.F
BOUNDARIES
AC3dbc_im.F
cx3dbc_im.F
ct3dbc_dir_im.F
cy3dbc_im.F
ct3dbc_im.F
Tr3dbc_im.F
TOOLS
mfiles
Inwave_tools
Matlab files for test cases inputs

/* Master list of all InWave cpp options

/**/
/********************************** USER DEFINED OPTIONS *************************************/
/**/

*# define **INWAVE_MODEL** use to turn ON or OFF InWave model
*# define **INWAVE_SWAN_COUPLING** use to turn ON or OFF InWave SWAN coupling
*# define **DOPPLER** use to turn ON or OFF the effect of currents on the dispersion relation
*# define **ACX_ADVECTION** use to turn ON or OFF advection of Ac in the xi direction
*# define **ACY_ADVECTION** use to turn ON or OFF advection of Ac in the etai direction
*# define **ACT_ADVECTION** use to turn ON or OFF advection of Ac in the directional direction
*# define **ENERGY_DISSIPATION** use to turn ON or OFF energy dissipation
*# define **ROELVINK** use to turn ON or OFF Roelvink energy dissipation

/************************* BOUNDARY CONDITION OPTIONS *************************************/

/******* AC IN X-Y SPACE *******/

*# undef **WEST_AC_CLAMPED** Western edge, clamped condition for Ac
*# undef **WEST_AC_GRADIENT** Western edge, gradient condition for Ac
*# undef **WEST_AC_RADIATION** Western edge, radiation condition for Ac
*# undef **WEST_AC_WALL** Western edge, wall condition for Ac

*# undef EAST_AC_CLAMPED Easthern edge, clamped condition for Ac
*# undef EAST_AC_GRADIENT Easthern edge, gradient condition for Ac
*# undef EAST_AC_RADIATION Easthern edge, radiation condition for Ac
*# undef EAST_AC_WALL Easthern edge, wall condition for Ac

*# undef NORTH_AC_CLAMPED Northern edge, clamped condition for Ac
*# undef NORTH_AC_GRADIENT Northern edge, gradient condition for Ac
*# undef NORTH_AC_RADIATION Northern edge, radiation condition for Ac
*# undef NORTH_AC_WALL Northern edge, wall condition for Ac

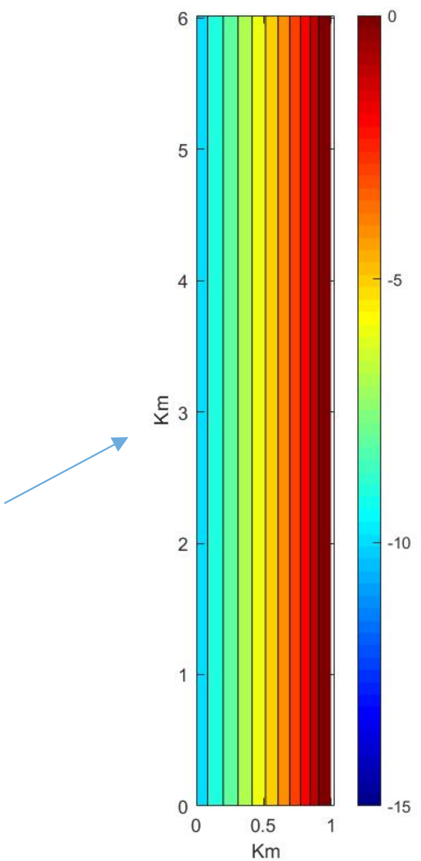
3D CASE IDEALIZED APPLICATION: OBLIQUE INCIDENT BICHROMATIC WAVES

Matlab files for test cases inputs: create_Inwave_files.m

create_Inwave_grd.m

create_Inwave_ini.m

create_Inwave_bnd.m



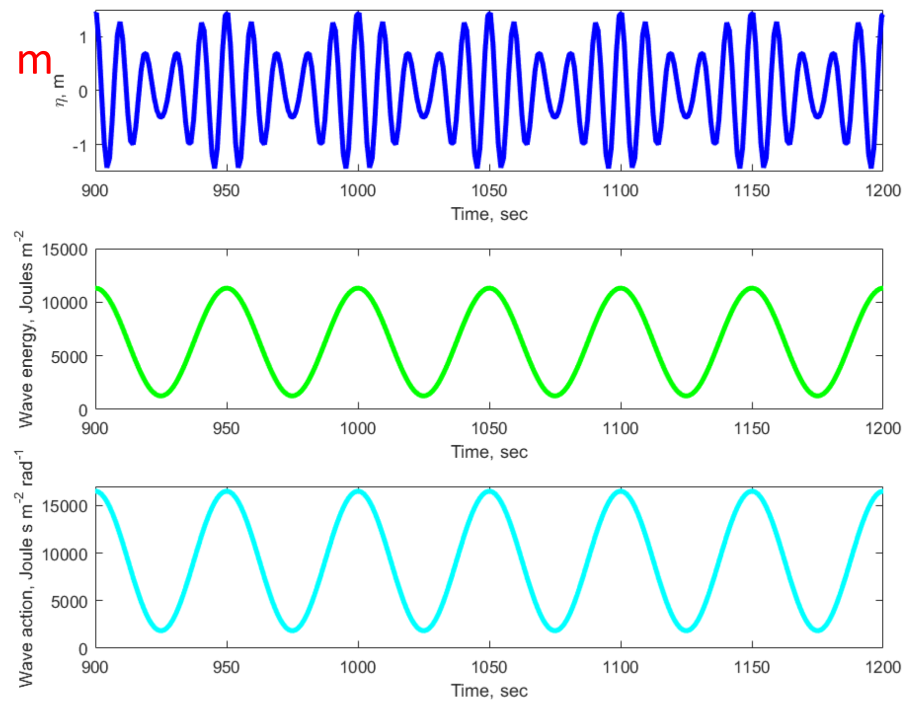
(m)

Ta1=10 s, a1= 1 m

Ta2= 8.3 s, a2=0.5 m

Θ= 261 degrees

H_{rms_max}= 3 m

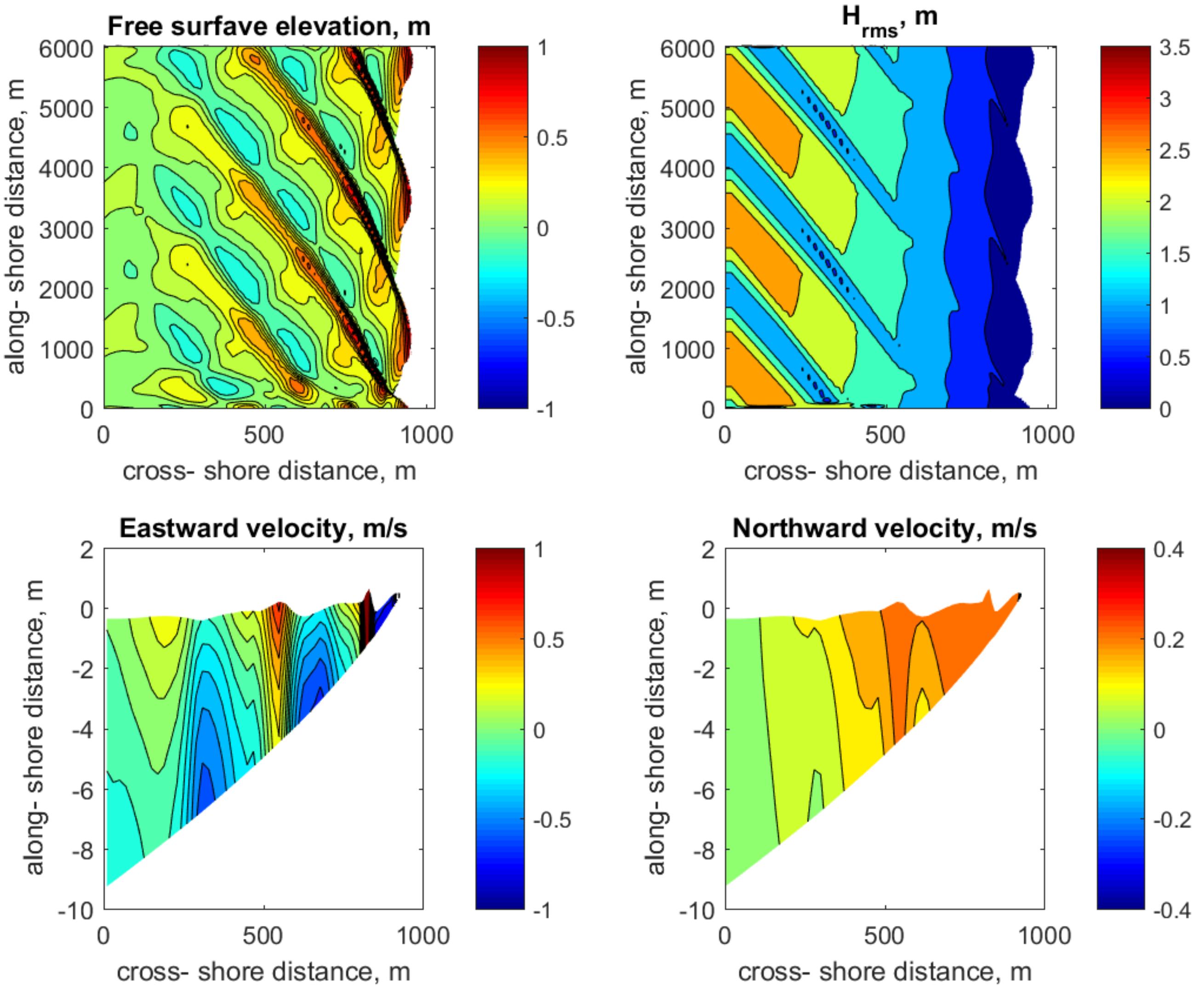


CCP OPTIONS

```
#define ROMS_MODEL
#define INWAVE_MODEL

#define ACX_ADVECTION
#define ACY_ADVECTION
#define ACT_ADVECTION
#undef DOPPLER

#define WEC_VF
#define ENERGY_DISSIPATION
#define WDISS_INWAVE
#undef ROELVINK
```

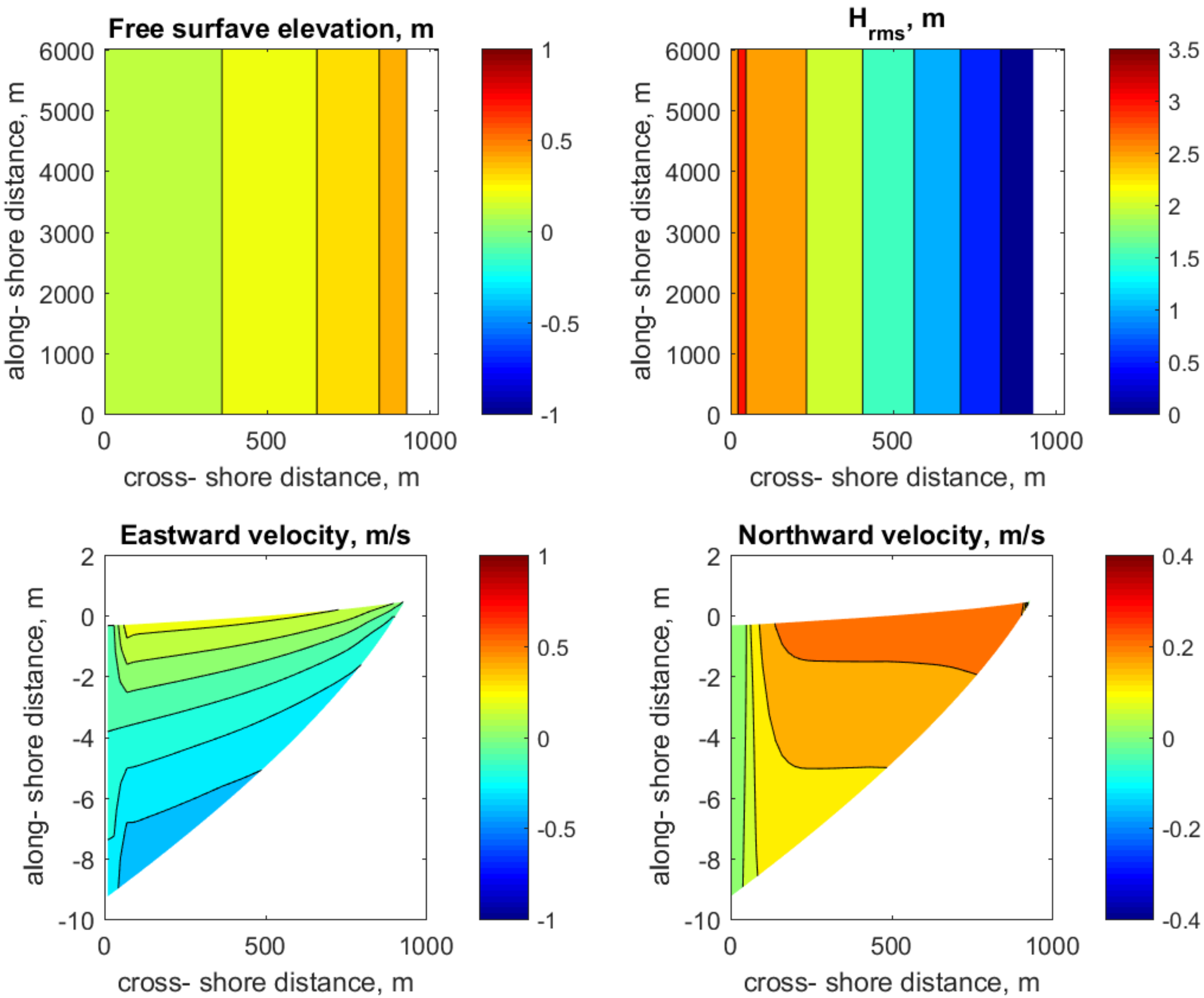
```
! Number of grid nesting layers.  This parameter is used to allow refinemen
! and composite grid combinations.

  NestLayers =  1

! Number of grids in each nesting layer [1:NestLayers].

GridsInLayer =  1

! Grid dimension parameters. See notes below in the Glossary for how to set
! these parameters correctly.

          Lm == 120            ! Number of I-direction INTERIOR RHO-points
          Mm == 300            ! Number of J-direction INTERIOR RHO-points
           N == 11             ! Number of vertical levels
          ND == 11             ! Number of wave directional bins

        Nbed =  1              ! Number of sediment bed layers

         NAT =  2              ! Number of active tracers (usually, 2)
         NPT =  0              ! Number of inactive passive tracers
         NCS =  0              ! Number of cohesive (mud) sediment tracers
         NNS =  1              ! Number of non-cohesive (sand) sediment trac
```

```
Hout(idACen)  == T        ! AC            3D wave action
Hout(idACcx)  == T        ! Cx            2D Group velocity in xi dimension
Hout(idACcy)  == T        ! Cy            2D Group velocity in etai dimension
Hout(idACct)  == T        ! Ct            2D Group velocity in the directional dimension
Hout(idACtp)  == T        ! Tp            2D Group peak period
```

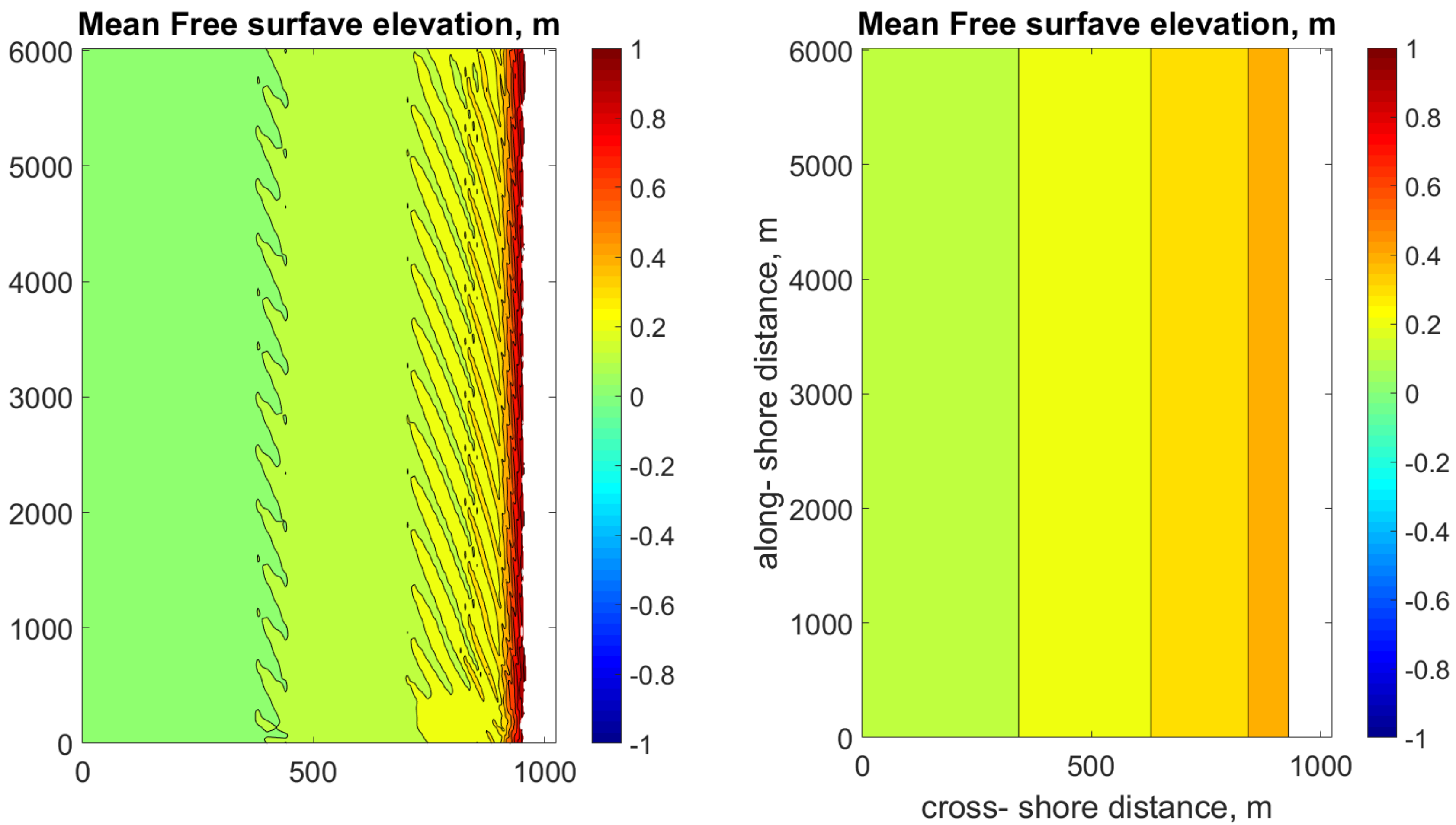


β=1.18 Steep-slope regime: breakpoint generation dominance

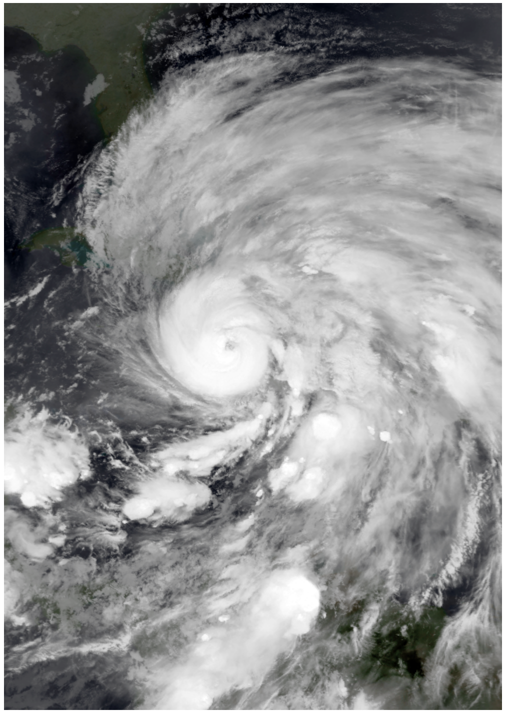
What do we get for the equivalent wave field but without wave-groups?

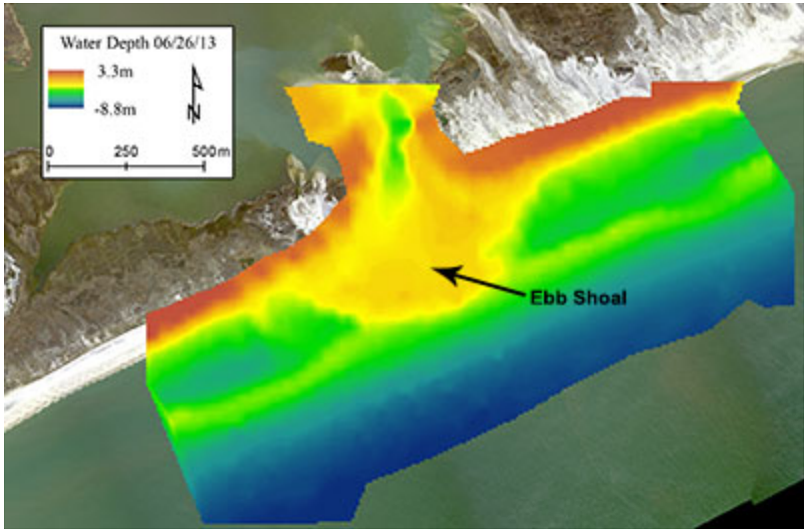


With wave-groups

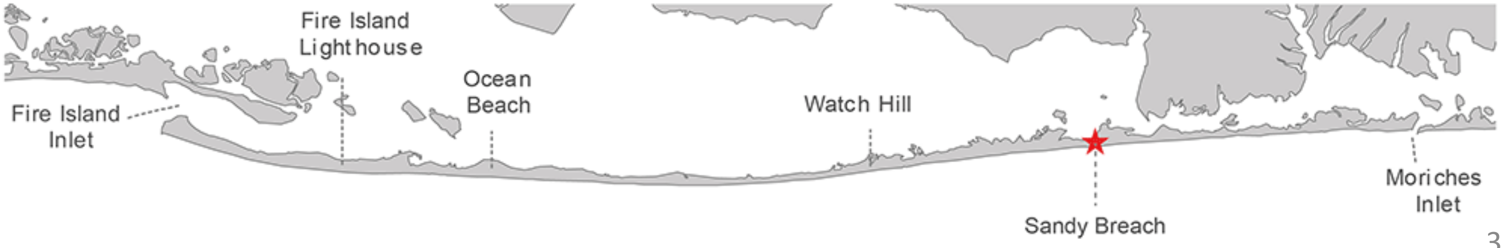


3D CASE REAL APPLICATION: HURRICANE SANDY (2012)

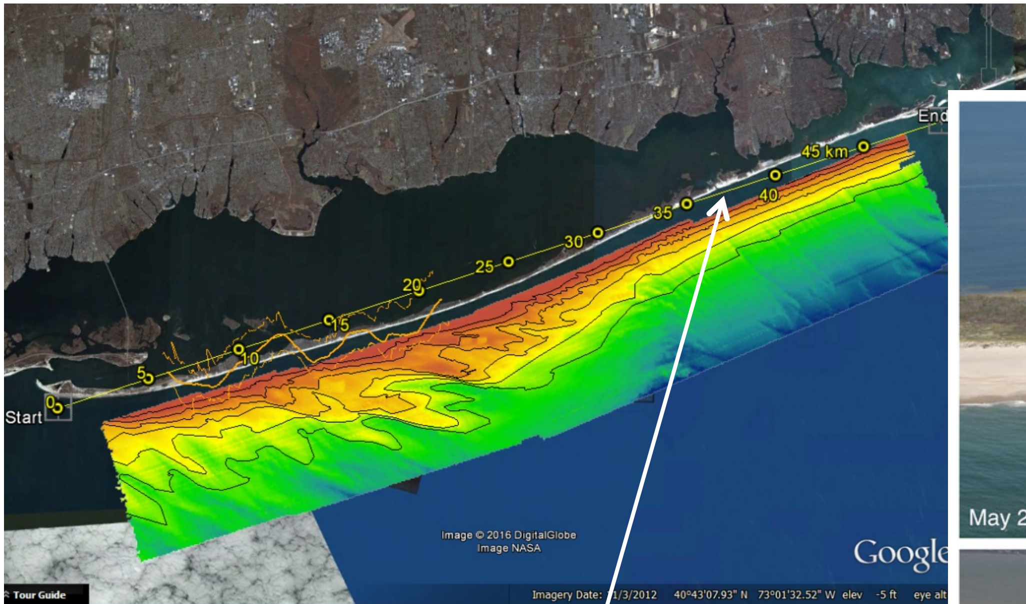




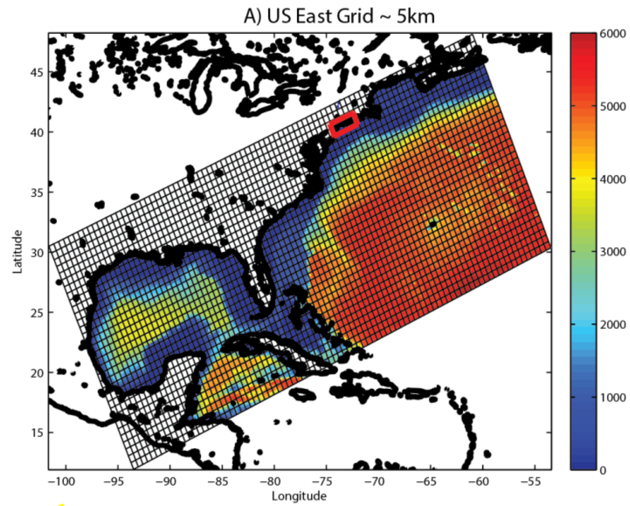
http://storms.ngs.noaa.gov/storms/sandy/



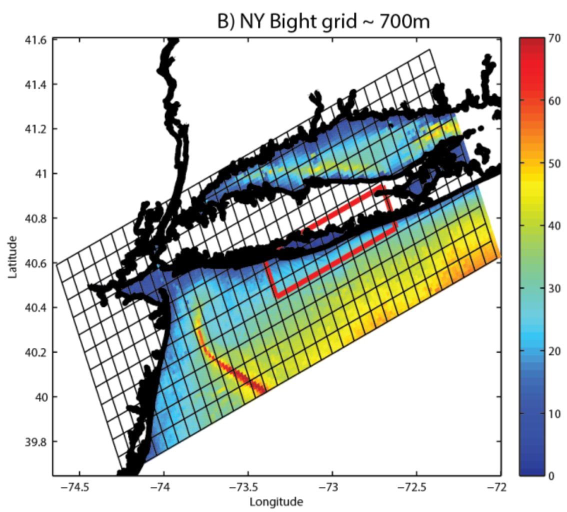
Breach occurred at "Old Inlet“ Was open between 1763 and 1827.
Re-opened during H Sandy. Still open today.



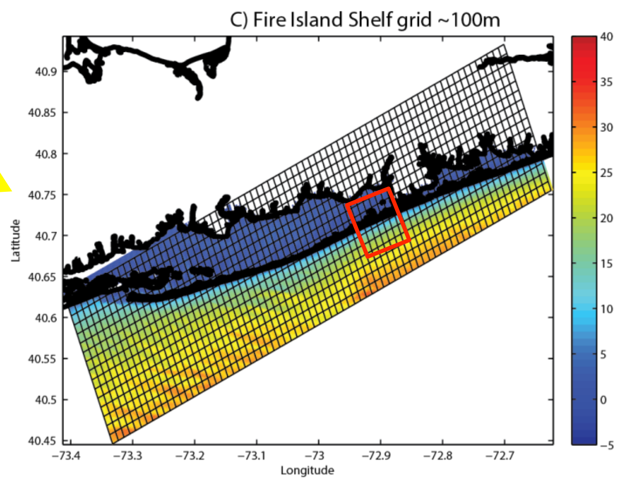
http://coastal.er.usgs.gov/hurricanes/sandy/photo-comparisons/



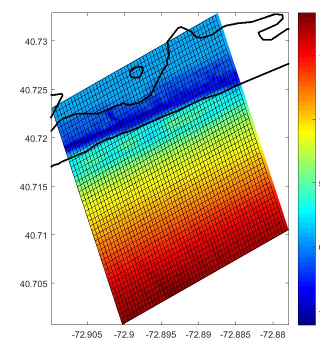
USEast grid
(5-km res.)



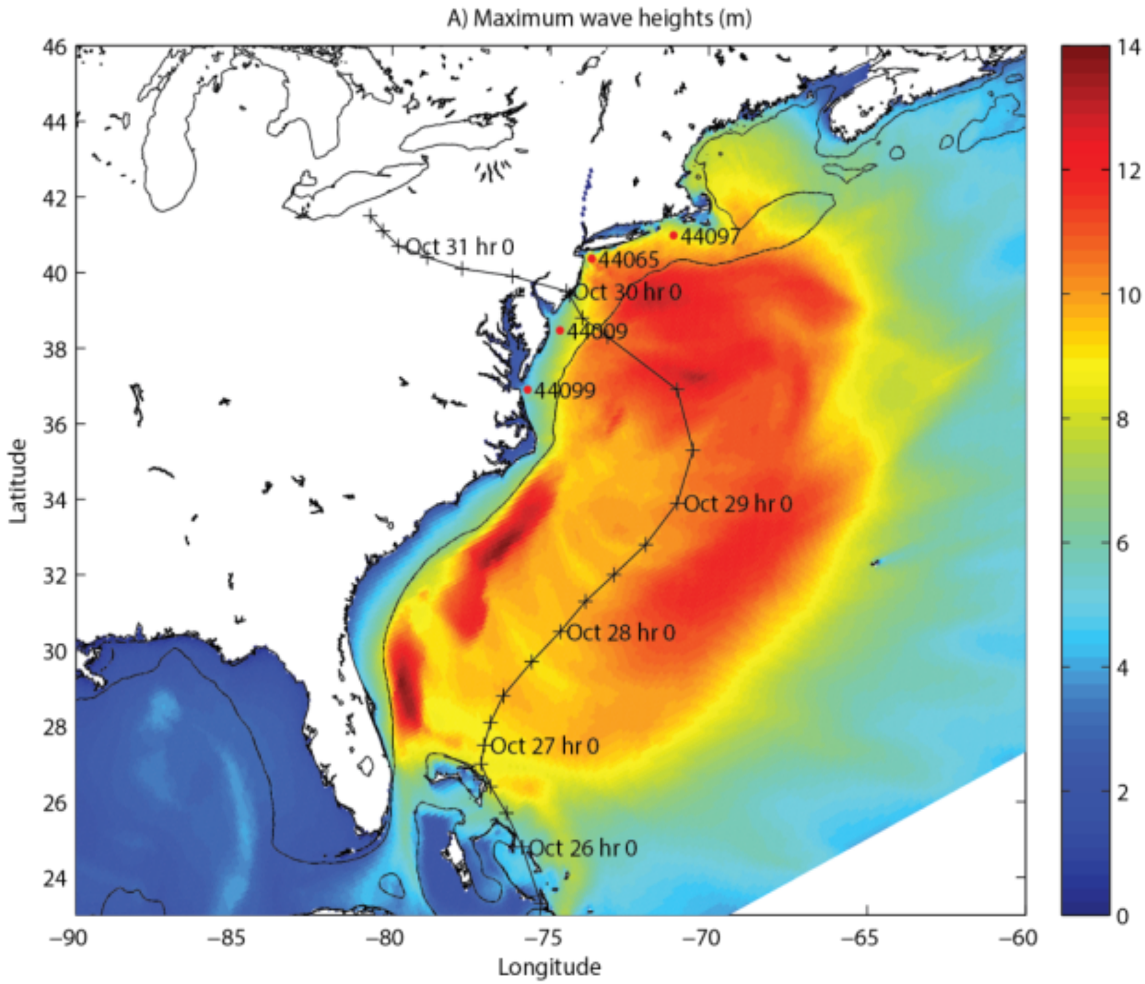
New York Bight grid (700-m res.)

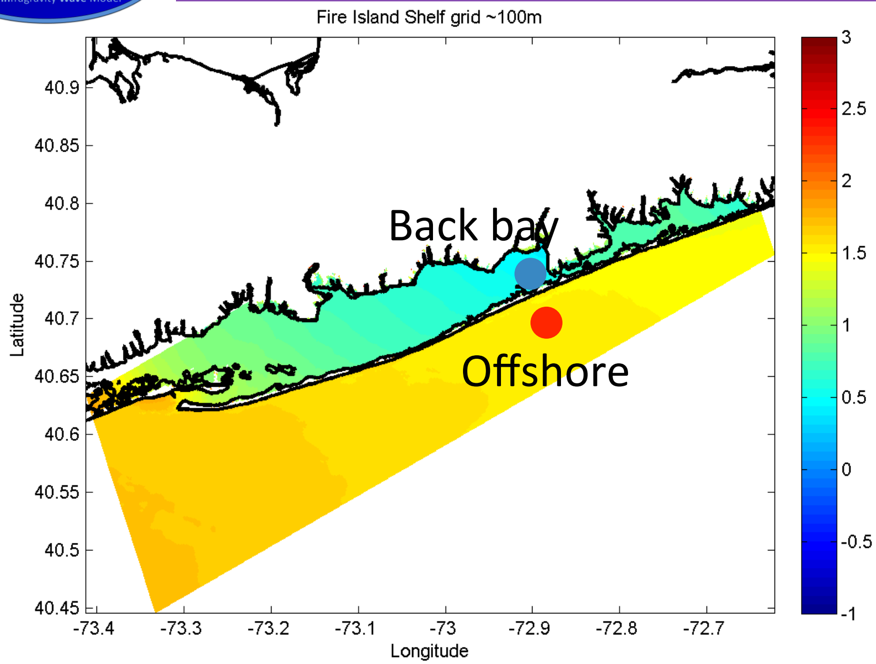


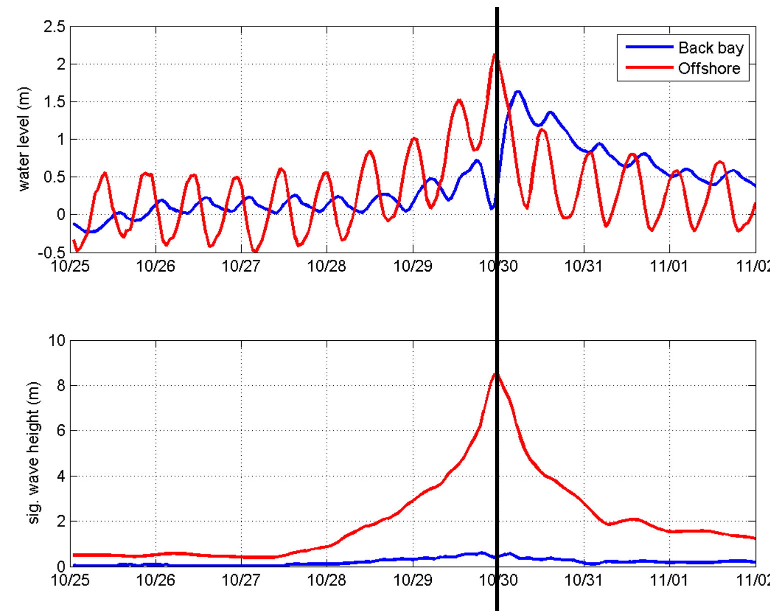
Shelf grid (100-m res.)

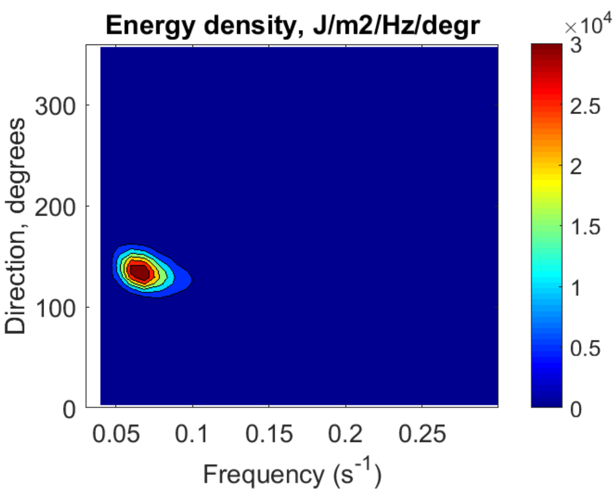


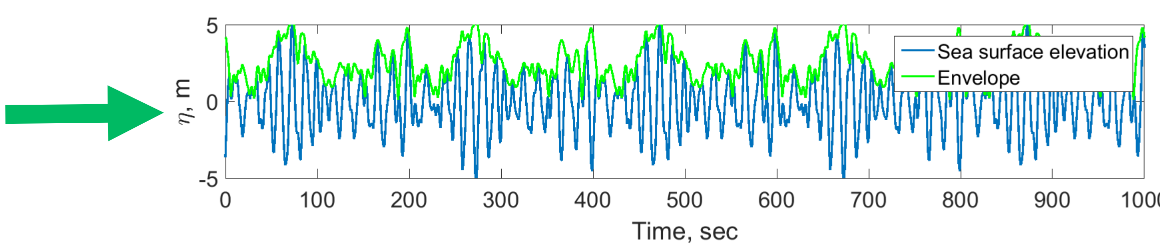
Breach grid (5-10 m res.)


A) Maximum wave heights (m)
Latitude
Longitude
46
44
42
40
38
36
34
32
30
28
26
24
−90
−85
−80
−75
−70
−65
−60
Oct 31 hr 0
Oct 30 hr 0
Oct 29 hr 0
Oct 28 hr 0
Oct 27 hr 0
Oct 26 hr 0
44097
44065
44009
44099
14
12
10
8
6
4
2
0









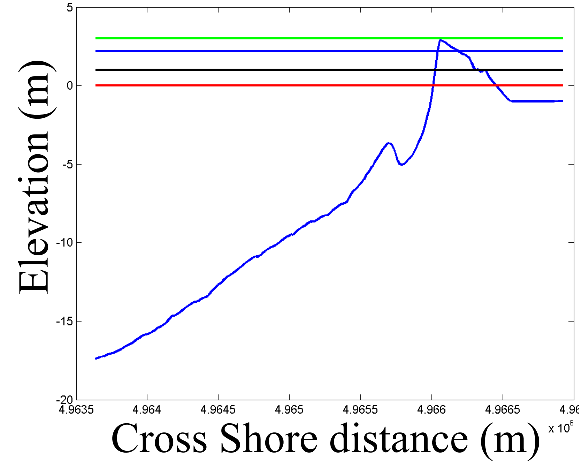
H_{mo}=7.9 m

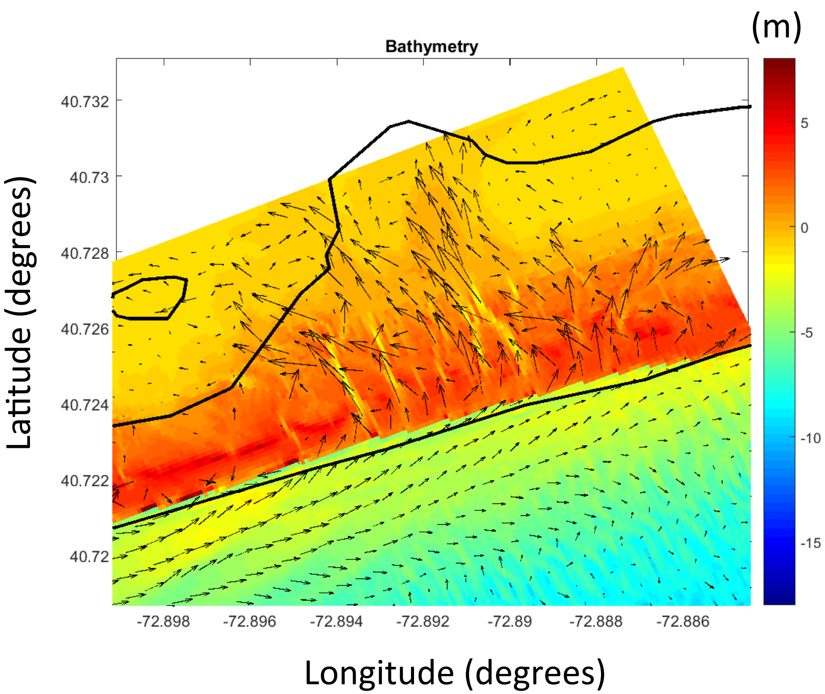
Tp=14 s

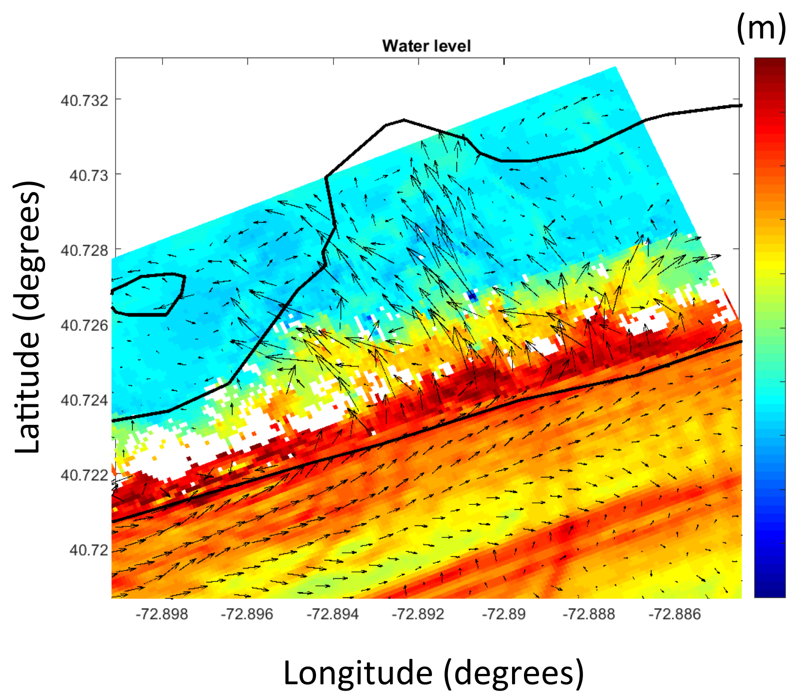
θ= 135 degrees

Infragravity wave (0.8m)
Surge (1.5m)
Tide (1.0m)
MSL (0.0m)

Cross shore profile near breach location







FUTURE PLANS

-Improve the SWAN-INWAVE interface (still developing and testing it).

-INWAVE is not capable of including wave spectral variations along its boundaries and future efforts will be directed to include these capabilities.

- Validate Inwave with more test cases and field data.

- Include the manual in COAWST_User_Manual.doc