Wave-current Interaction (WEC) in COAWST

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with
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Jim Thomson
Maitane Olabarrieta
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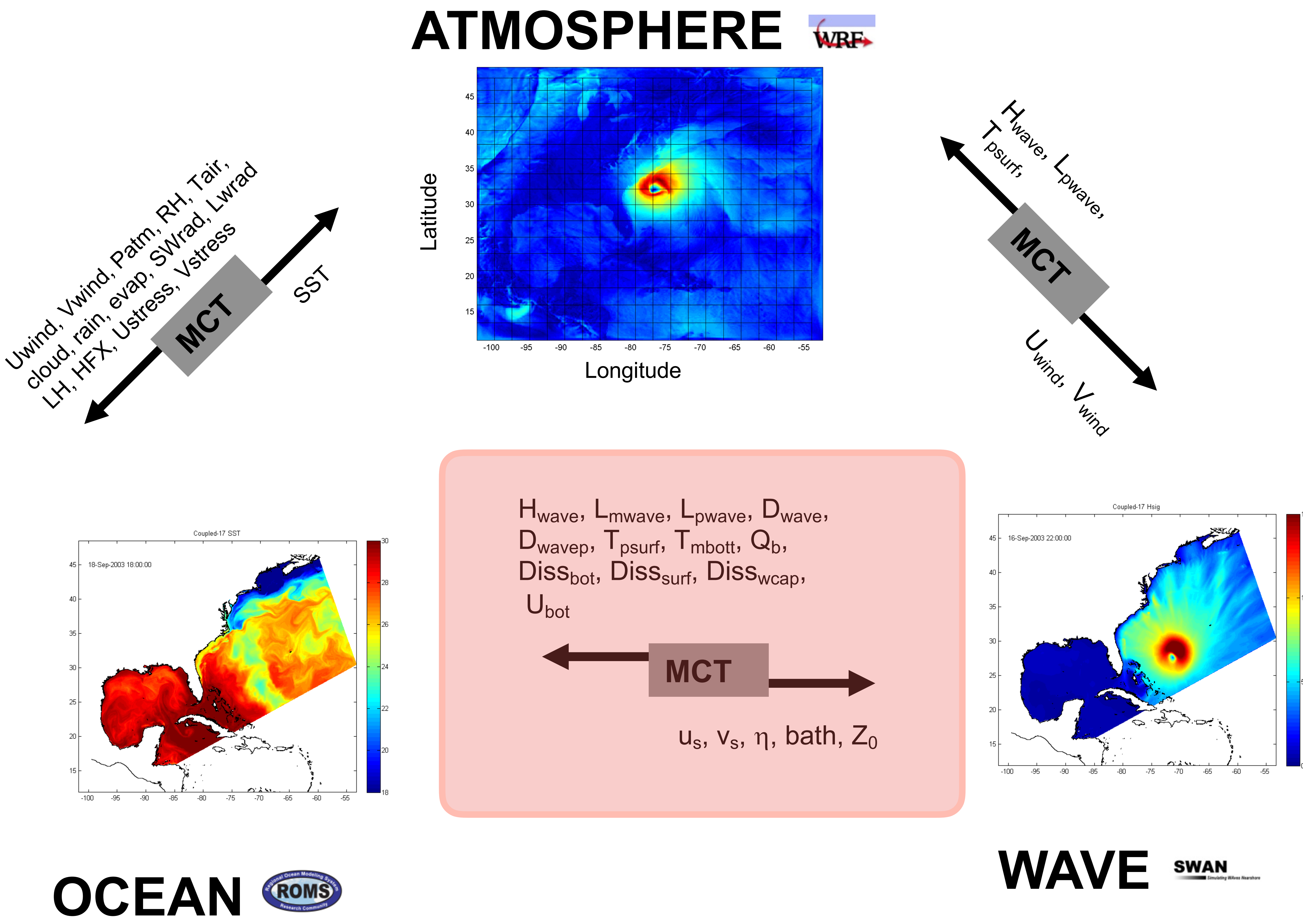
see Kumar et al., 2012:
Implementation of the vortex force formalism in the coupled ocean-atmosphere-wave-sediment transport (COAWST) modeling system for inner shelf and surf zone applications, Ocean Modelling, Volume 47, 2012, Pages 65-95, 10.1016/j.ocemod.2012.01.003.



Warner et al., 2008

Wave-Current Interaction Recipes

Mellor Radiation Stress

*see Kumar et al., 2011

Vortex Force Formalism
(needs wave dissipation)

*see Kumar et al., 2012

cppdefs.h (COAWST/ROMS/Include)	
WEC_MELLOR	Activates Mellor (2011) method for WEC
WEC_VF	Activates McWilliams et al. (2004), Uchiyama et al., 2010 for WEC

Additional Processes

- Roller Model
- Wave-induced Mixing
- Bottom Streaming
- Surface Streaming

Wave-Averaged Eqs. (**WEC_VF**, *e.g.*, Eq 11)

$$\underbrace{\frac{\partial}{\partial t}(H_z u)}_{ACC} + \underbrace{\frac{\partial}{\partial x}(H_z u \cdot u) + \frac{\partial}{\partial y}(H_z u \cdot v) + \boxed{u\frac{\partial}{\partial x}(H_z u^{St}) + u\frac{\partial}{\partial y}(H_z v^{St})}^{\text{C}}}_{HA}$$

$$\underbrace{\frac{\partial}{\partial s}(w_s u) + \boxed{u\frac{\partial}{\partial s}(w_s^{St})}^{\text{C}}}_{VA} \underbrace{- H_z f v}_{COR} - \underbrace{\boxed{H_z f v_{St}}^{\text{C}}}_{StCOR} = \underbrace{\boxed{-H_z\frac{\partial \phi^c}{\partial x}}}_{PG} + \underbrace{\boxed{H_z v^{St}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) - \omega_s^{St}\frac{\partial u}{\partial s}}^{\text{C}}}_{HVF}$$

$$\underbrace{+H_z F^x}_{BF} + \underbrace{\boxed{H_z F^{wx}}^{\text{NC}}}_{BA+RA+Str} \underbrace{+ H_z D^x}_{HM} - \underbrace{\frac{\partial}{\partial s}\left(\overline{u'v'} - \frac{\nu}{H_z}\frac{\partial u}{\partial s}\right)}_{VM}$$

u^{St} = Stokes drift
u = Eulerian mean

Wave-current Interaction Terms	
StCOR	Stokes-Coriolis Force
PG	Pressure Gradient (includes Bernoulli head, quasi-static pressure etc.)
HVF	Horizontal Vortex Force
BA, RA	Breaking and Roller Accelerations
Str	Bottom and Surface Streaming

Breaking Acceleration F_{wx}

Depth-limited Wave-Dissipation Options

- **WEC_VF** option requires depth-limited dissipation to estimate breaking acceleration (similar to radiation stress gradients).

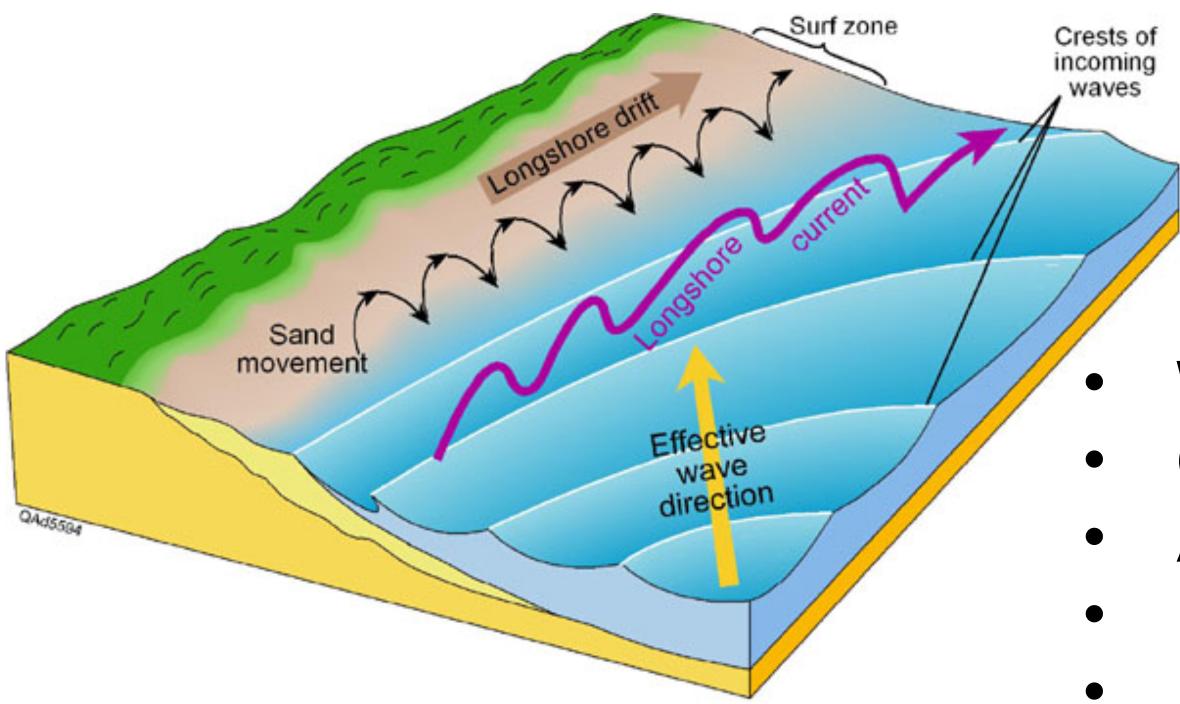
Dissipation Options	
WDISS_THORGUZA	Depth-limited wave dissipation from Thornton & Guza (1983), see Eq. 31.
WDISS_CHURTHOR	Depth-limited wave dissipation from Church & Thornton (1993), see Eq. 32
WDISS_WAVEMOD	Depth-limited wave dissipation from SWAN. Use INRHOG=1

Notes:

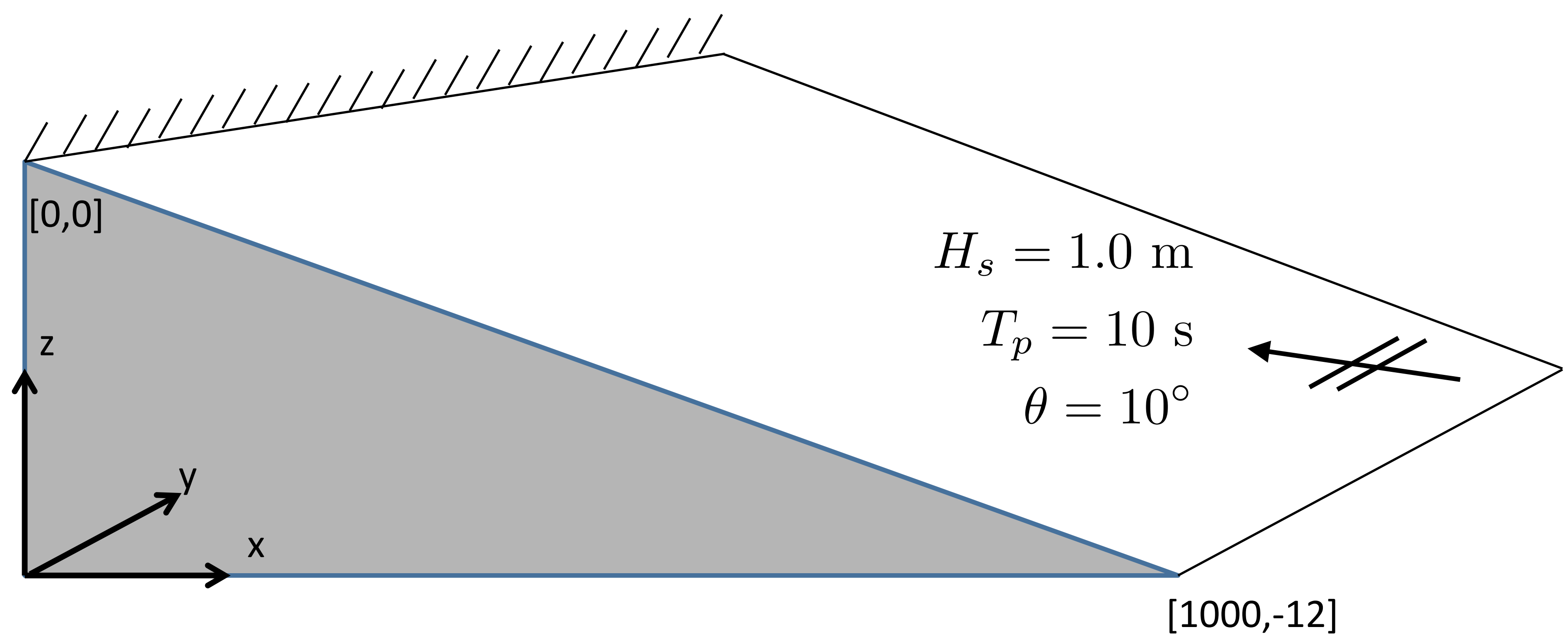
- If no wave-dissipation information available use WDISS_THORGUZA/ CHURTHOR

- If no wave-dissipation module is defined and WEC_VF is still activated, the model expects a forcing file with relevant wave quantities. Codes available for this in /COAWST/Tools/mfiles/

Shoreface Test Case
(Obliquely Incident Waves on a Planar Beach)



- Wave-field computed using SWAN
- One-way coupling (WEC)
- Application Name: SHOREFACE
- Header: COAWST/ROMS/Include/shoreface.h
- Input: COAWST/ROMS/External/ocean_shoreface.in



Header File
(COAWST/ROMS/Include/shoreface.h)

```
/*
** svn $Id: shoreface.h 429 2009-12-20 17:30:26Z arango $
********************************************************************************
** Copyright (c) 2002-2014 The ROMS/TOMS Group                                **
**   Licensed under a MIT/X style license                                     **
**   See License_ROMS.txt                                                     **
********************************************************************************
**
** Options for Shore Face Planar Beach Test Case.
**
** Application flag:   SHOREFACE
** Input scripts:      ocean_shoreface.h
**                     sediment_shoreface.h
*/

#define ROMS_MODEL
#undef  WEC_MELLOR
#define WEC_VF
#define WDISS_CHURTHOR
#define BOTTOM_STREAMING
#define SURFACE_STREAMING
```

Do not use if not really studying streaming processes

Input File & Breaking Acceleration
(COAWST/ROMS/External/ocean_shoreface.in)

```
! Wec boundary conditions

  LBC(isU2Sd) ==   Gra     Clo     Gra     Gra          ! 2D U-stokes
  LBC(isV2Sd) ==   Gra     Clo     Gra     Gra          ! 2D V-stokes
  LBC(isU3Sd) ==   Gra     Clo     Gra     Gra          ! 3D U-stokes
  LBC(isV3Sd) ==   Gra     Clo     Gra     Gra          ! 3D V-stokes

! Constants used in surface turbulent kinetic energy flux computation.

  CHARNOK_ALPHA == 1400.0d0                ! Charnok surface roughness
 ZOS_HSIG_ALPHA == 0.5d0                   ! roughness from wave amplitude
       SZ_ALPHA == 0.25d0                  ! roughness from wave dissipation
      CRGBAN_CW == 100.0d0                 ! Craig and Banner wave breaking
      WEC_ALPHA == 0.0d0                   ! 0: all wave dissip goes to break and none to roller.
                                           ! 1: all wave dissip goes to roller and none to breaking.
```

Breaking Acceleration Term (part of F_{wx})

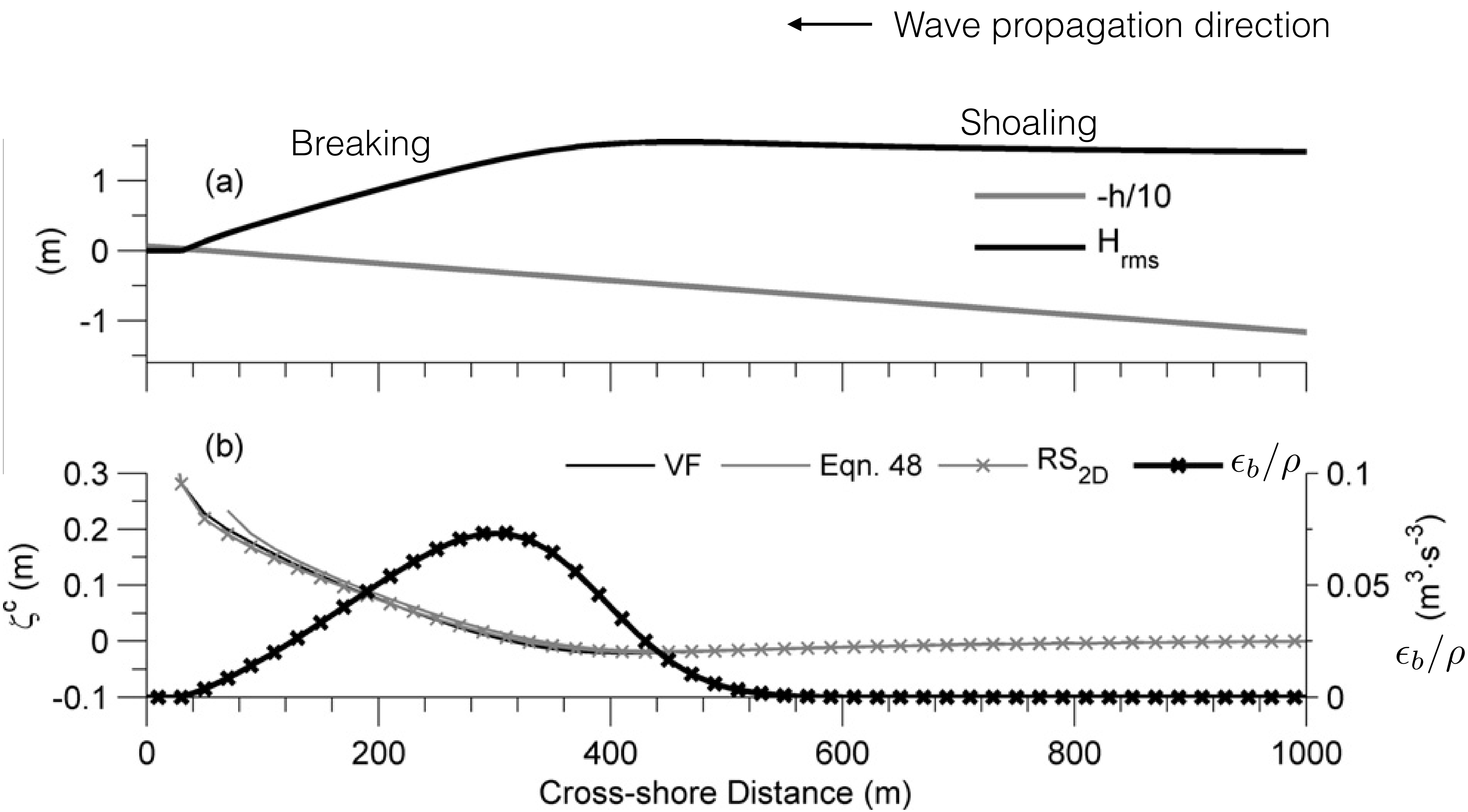
$$B^b = \frac{(1 - \alpha^r)\epsilon^b}{\rho_0 \sigma}\mathbf{k} \cdot f^b(z)$$

ϵ_b = Depth-limited dissipation

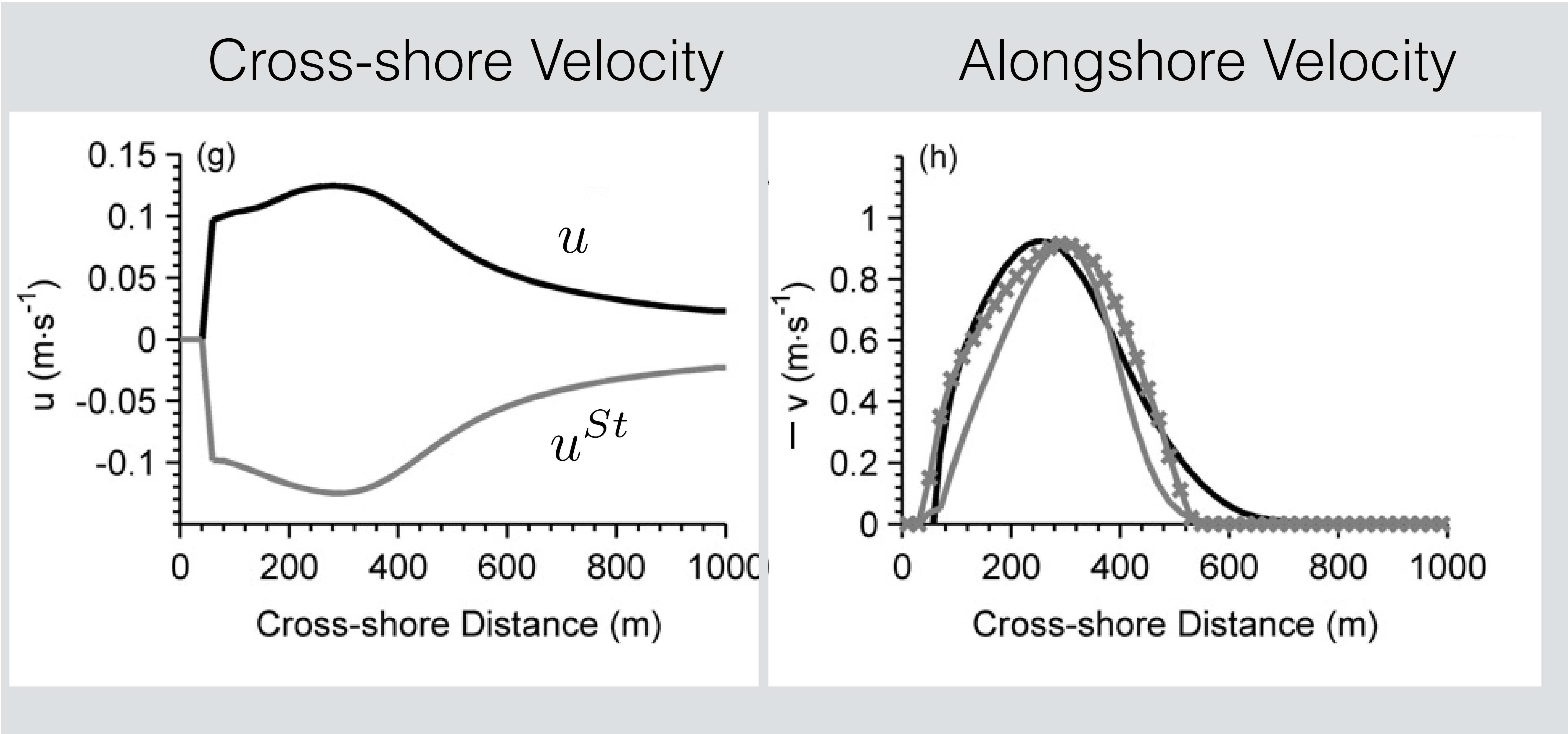
WEC Related OUTPUT
(COAWST/ROMS/External/ocean_shoreface.h)

```
Hout(idU2Sd) == T        ! ubar_stokes       2D U-Stokes velocity
Hout(idV2Sd) == T        ! vbar_stokes       2D V-Stokes velocity
Hout(idU3Sd) == T        ! u_stokes          3D U-Stokes velocity
Hout(idV3Sd) == T        ! v_stokes          3D V-Stokes velocity
Hout(idW3Sd) == T        ! omega_stokes      3D Omega-Stokes velocity
Hout(idW3St) == T        ! w_stokes          3D W-Stokes velocity
Hout(idWamp) == T        ! Hwave             wave height
Hout(idWlen) == T        ! Lwave             wave length-mean
Hout(idWlep) == T        ! Lwavep            wave length-peak
Hout(idWdir) == T        ! Dwave             wave direction
Hout(idWptp) == T        ! Pwave_top         wave surface period
Hout(idWpbt) == T        ! Pwave_bot         wave bottom period
Hout(idWorb) == T        ! Uwave_rms         wave bottom orbital velocity
Hout(idWbrk) == T        ! Wave_break        wave breaking (percent)
Hout(idUwav) == T        ! uWave             wave-depth avgeraged U-velocity
Hout(idVwav) == T        ! vWave             wave-depth avgeraged V-velocity
Hout(idWdif) == T        ! Dissip_fric       wave dissipation due to bottom friction
Hout(idWdib) == T        ! Dissip_break      wave dissipation due to breaking
Hout(idWdiw) == T        ! Dissip_wcap       wave dissipation due to white capping
Hout(idWdis) == T        ! Dissip_roller     wave roller dissipation
Hout(idWrol) == T        ! rollA             wave roller action density
```

Shoreface Test Results



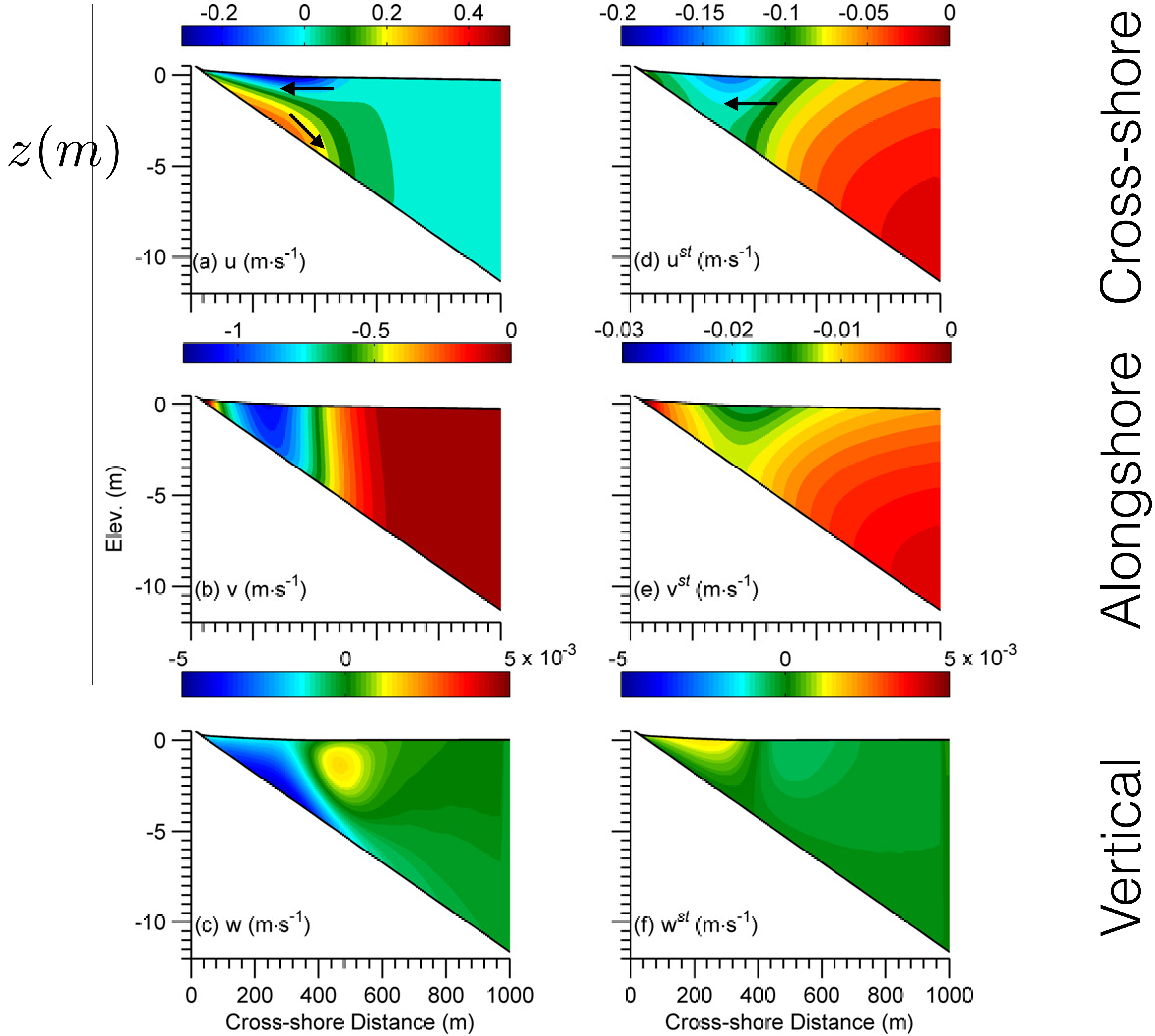
Shoreface Test Results (Depth-averaged)



$u^{St} = \text{Stokes drift}$

$u = \text{Eulerian mean}$

Shoreface Test Results



Roller Model Options

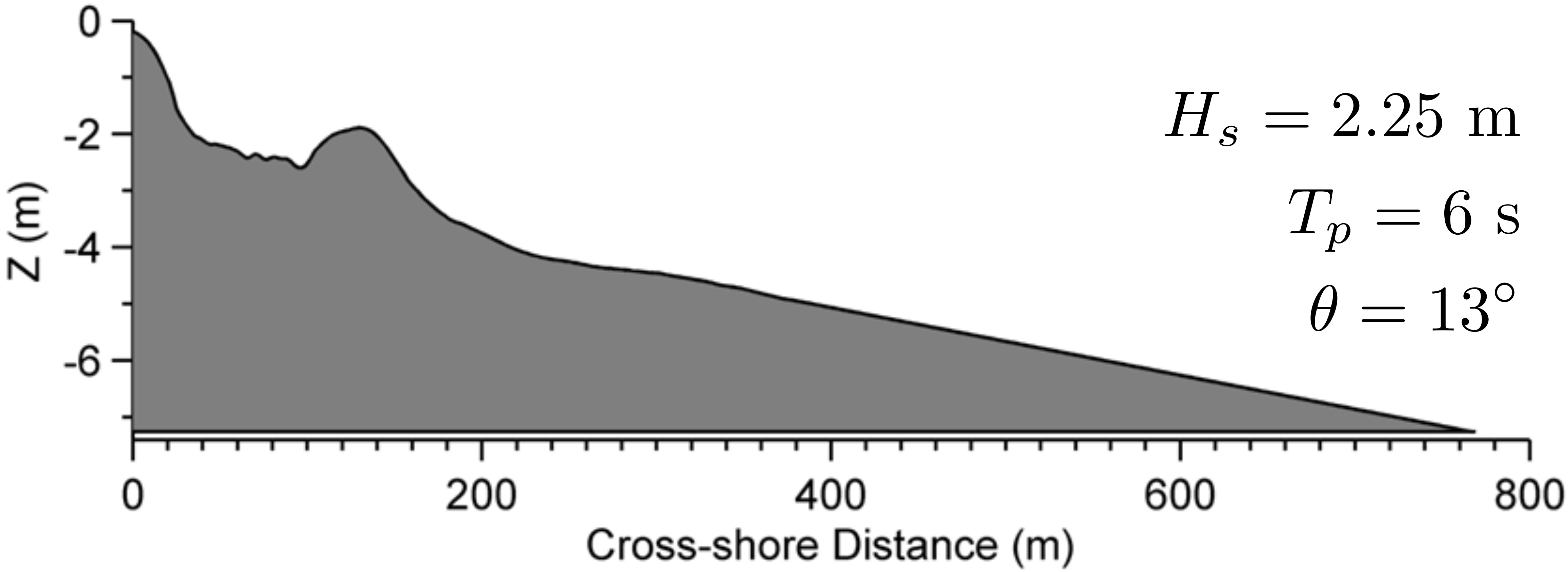
Roller Options	
ROLLER_SVENDSEN	Activates wave rollers based on Svendsen, 1984. See Warner et al. (2008), Eqns. 7 and 10.
ROLLER_MONO	Activates wave roller for monochromatic waves from REF/DIF. See Haas and Warner, 2009.
ROLLER_RENIERS	Activates wave rollers following Reniers et al. (2004). See equations 34-39.

Notes:

- If ROLLER_RENIERS is activated then the parameter wec_alpha in the INPUT file must be changed. For wec_alpha=0 no wave-dissipation goes into creating rollers, while for wec_alpha=1 all wave dissipation creates rollers

```
WEC_ALPHA == 0.0d0                    ! 0: all wave dissip goes to break and none to roller.
                                      ! 1: all wave dissip goes to roller and none to breaking.
```

DUCK'94 Test Case
(Obliquely Incident Waves on a Barred Beach)

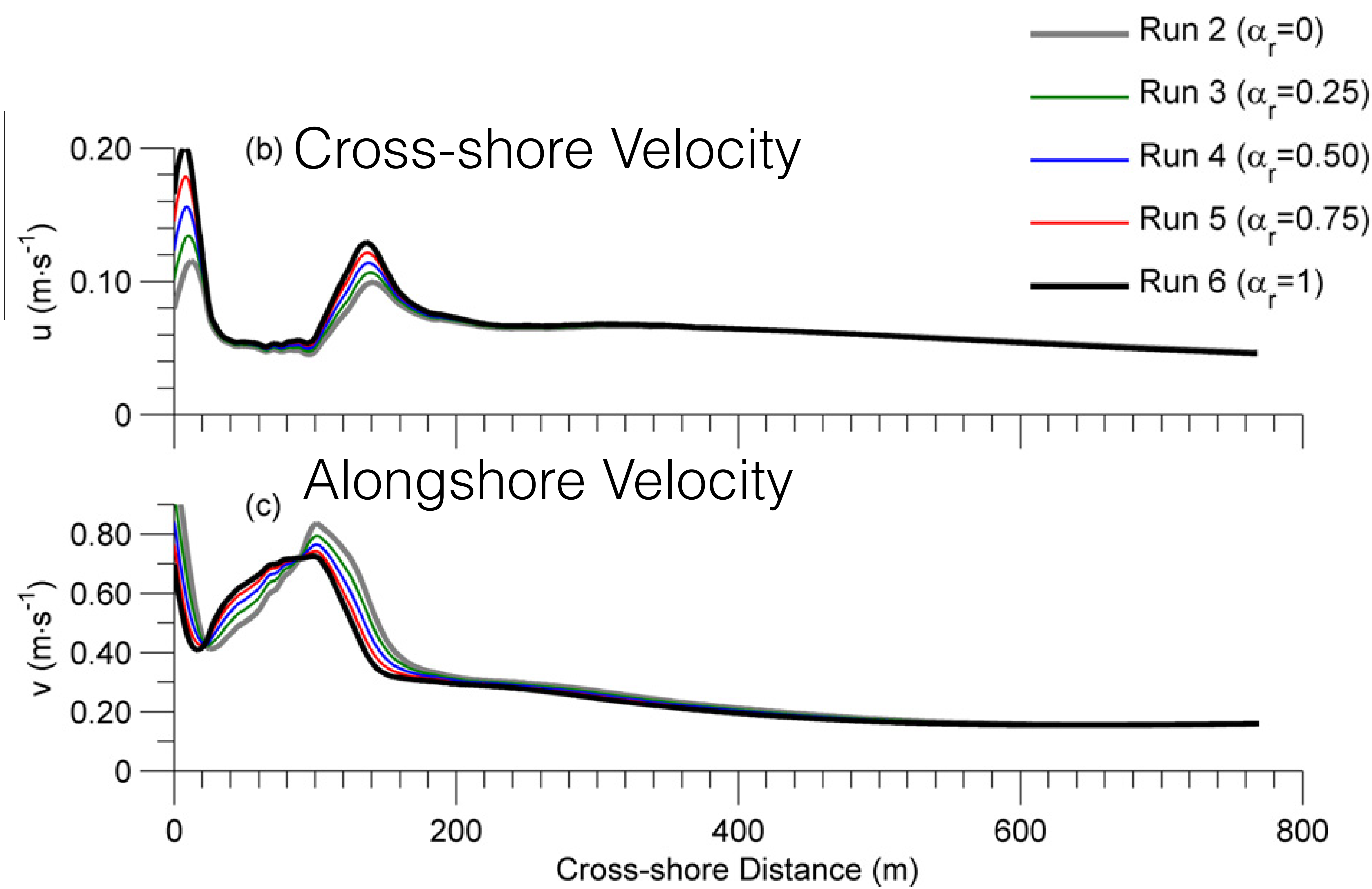


$H_s = 2.25$ m

$T_p = 6$ s

$\theta = 13^\circ$

Roller Reniers Example (DUCK'94)



Wave-induced Mixing (within GLS)

Mixing Options	
TKE_WAVEDISS **ZOS_HSIG**	Inputs part of wave-energy dissipation as near surface TKE. See equations 44-47.
	The option ZOS_HSIG indicates that (a) the surface roughness or mixing length is provided as percent of wave height (see equation 46); (b) the amount of energy as TKE is provided as percent of wave dissipation (see equation 47).

$$K_v \frac{\partial k}{\partial z}\Big|_{z=\zeta} = c_{\epsilon w} \epsilon_w$$

```
ZOS_HSIG_ALPHA == 0.5d0                        ! roughness from wave amplitude
      SZ_ALPHA == 0.25d0                       ! roughness from wave dissipation
```

$c_{\epsilon w}$ (highlighted beside the SZ_ALPHA line)

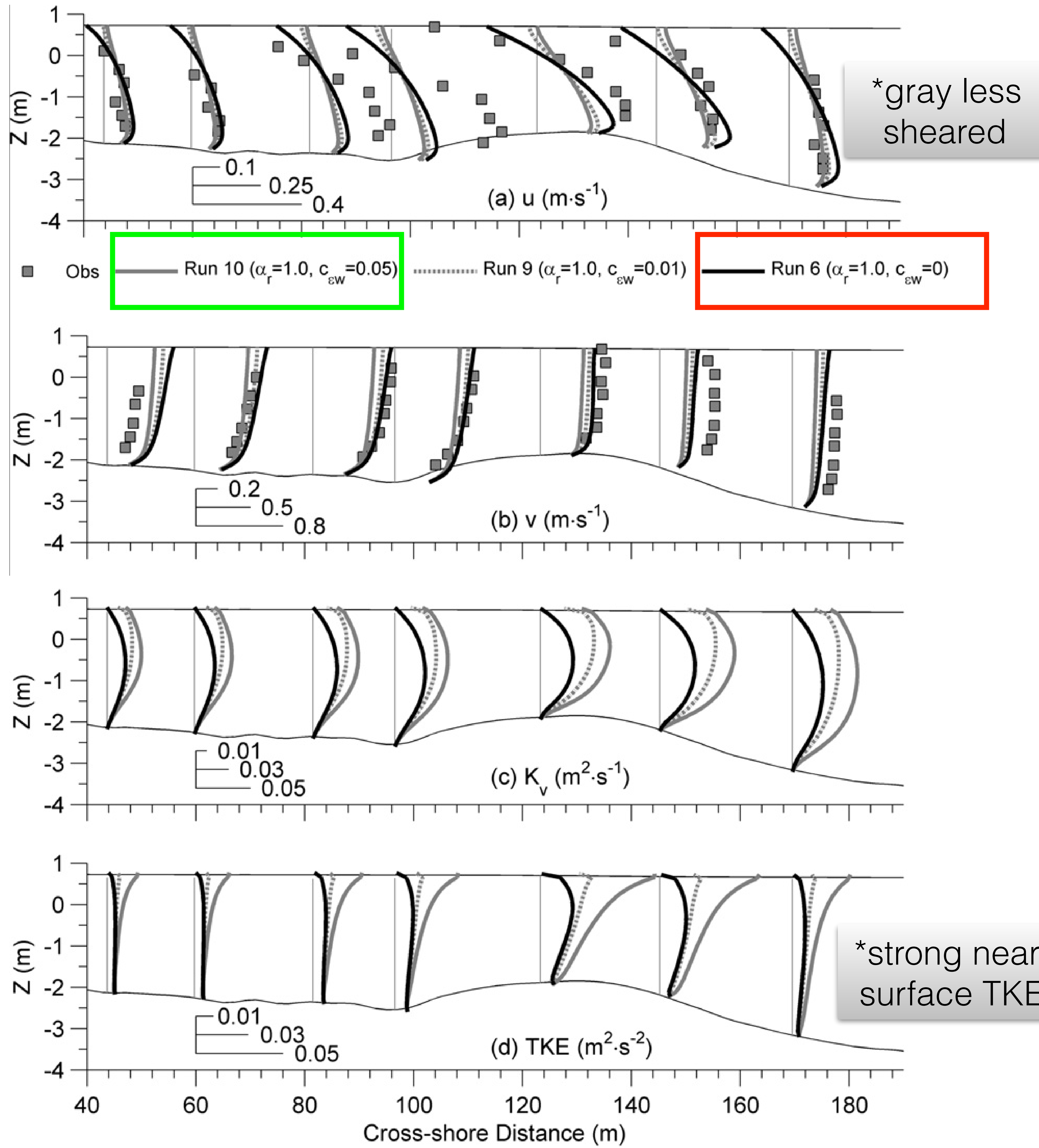
Wave-induced Mixing Example (DUCK' 94)

Cross-shore Velocity

Alongshore Velocity

Vertical eddy viscosity

Turbulent Kinetic Energy



Bottom and Surface Streaming

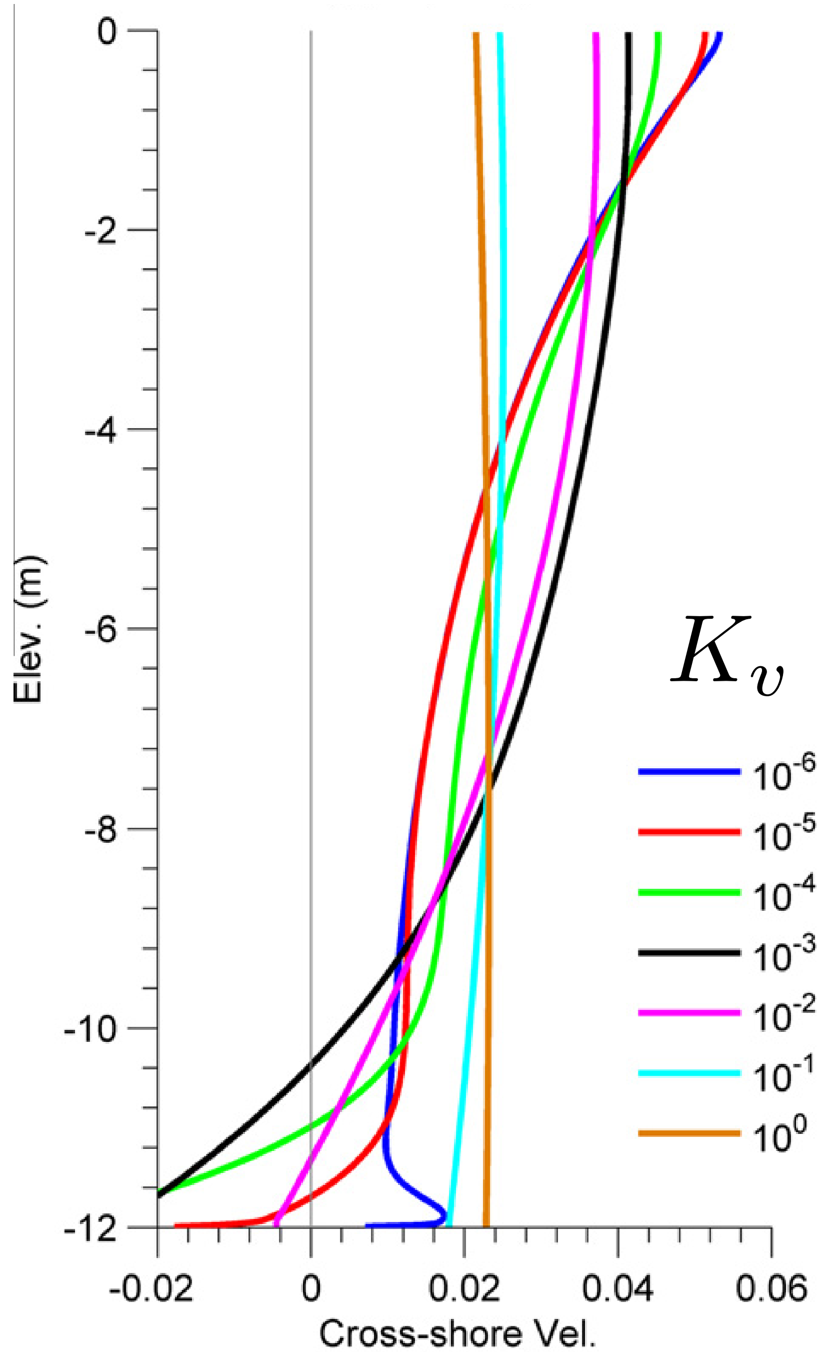
Streaming Options	
BOTTOM_STREAMING	Wave-induced bottom streaming based on Reniers et al. (2004). Requires bottom friction induced wave-dissipation
BOTTOM_STREAMING_ XU_BOWEN	Estimates bottom streaming based on Xu & Bowen (1994)
SURFACE_STREAMING	Estimates surface streaming based on Xu & Bowen (1994)

Notes:

- If BOTTOM_STREAMING_XU_BOWEN is activated, the wave-bottom boundary layer needs to be resolved, which requires very high near-bottom resolution. Suggested **VTRANSFORM=2** and **VSTRETCHING=3**

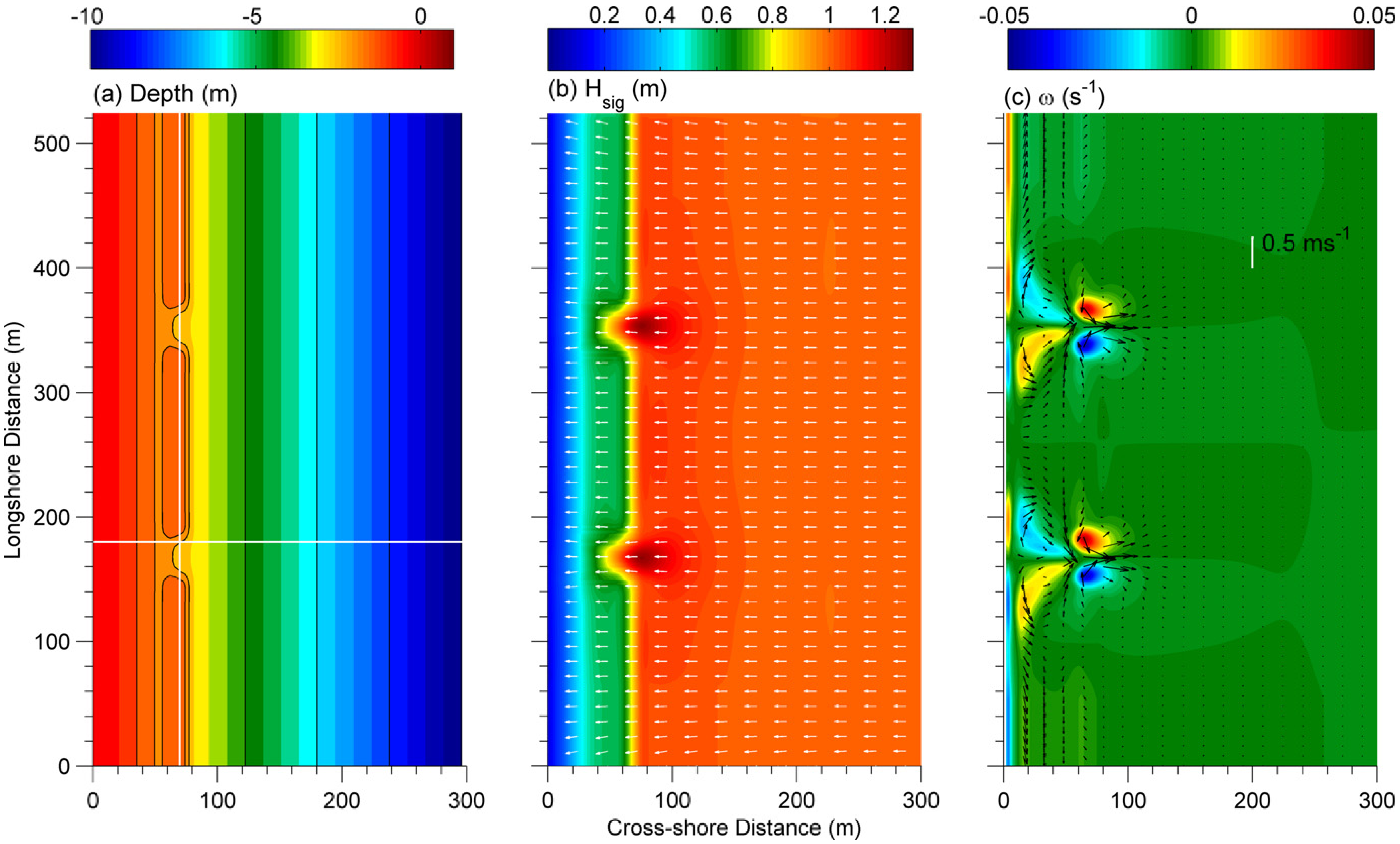
Bottom Streaming (Inner-shelf Undertow)

Offshore-Directed Undertow

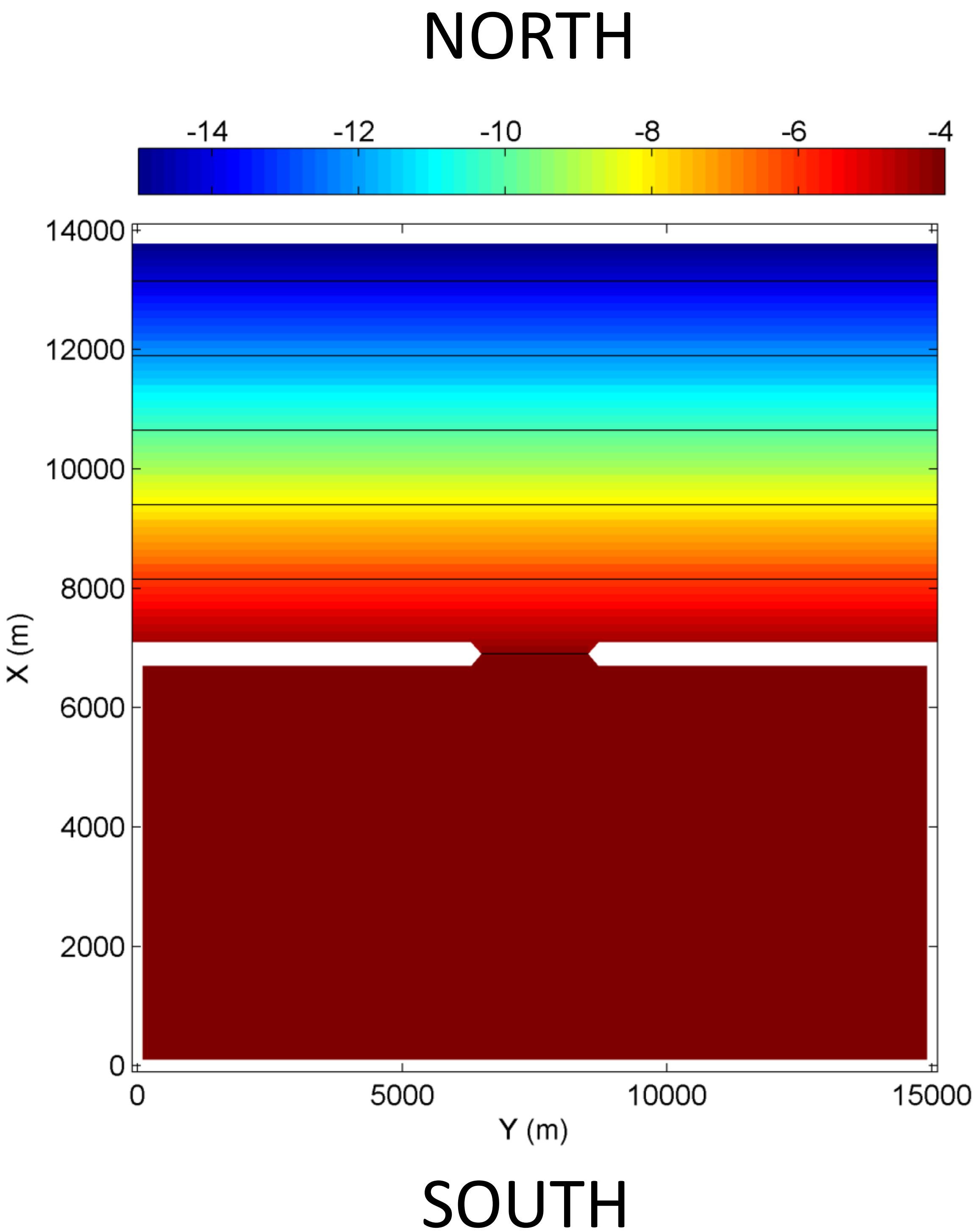


*for small Kv, cross-shore velocity u is sheared and similar to Stokes-drift u^{St} indicating balance between Coriolis and Stokes-Coriolis forces $f_{\mathrm{cor}} u = f_{\mathrm{cor}} u^{\mathrm{St}}$

Rip-Current Dynamics



Inlet Test Case



- Wave field computed using SWAN
- Two way coupling (WEC and CEW)
- Application Name: INLET_TEST

Header file: COAWST/Projects/Inlet_test/Coupled/inlet_test.h

Input file: COAWST/Projects/Inlet_test/Coupled/ocean_inlet_test.in
COAWST/Projects/Inlet_test/Coupled/swan_inlet_test.in
COAWST/Projects/Inlet_test/Coupled/coupling_inlet_test.h

Inlet Test Case- Header File

```
#define ROMS_MODEL
#define SWAN_MODEL
#define MCT_LIB

#define UV_VIS2
#define MIX_S_UV
#define MASKING
#define UV_ADV
#undef  UV_COR
#define TS_MPDATA
#define DJ_GRADPS
#define SPLINES_VDIFF
#define SPLINES_VVISC

#define SOLVE3D
#undef  WEC_MELLOR
#define WEC_VF
#define WDISS_WAVEMOD
#define UV_KIRBY
#define ANA_INITIAL
#define ANA_SMFLUX
#define ANA_FSOBC
#define ANA_M2OBC
```

Inlet Test Case- SWAN Input File

```
PROJECT 'Inlet Test' ' '
 'INLET test'
 'Bathymetry: flat bottom'
 'COMMENTS'

MODE NONSTATIONARY TWODIMENSIONAL

SET DEPMIN 0.10 INRHOG 1 NAUTICAL
COORDINATES CARTESIAN

&& KEYWORD for number of nested SWAN grids.
NSGRIDS 1

&& KEYWORDS TO CREATE AND READ COMPUTATIONAL GRID &&
CGRID CURVILINEAR 76 71 EXC 9.999000e+003 &
        CIRCLE 36 0.04 1.0 20
READGRID COORDINATES 1 'Projects/Inlet_test/Coupled/inlet_test_grid_coord.grd' 4 0 0 FREE

&& KEYWORDS TO CREATE AND READ BATHYMETRY GRID &&
INPGRID BOTTOM CURVILINEAR 0 0 76 71 EXC 9.999000e+003
READINP BOTTOM  1 'Projects/Inlet_test/Coupled/inlet_test_bathy.bot' 4 0 FREE

&& KEYWORD TO CREATE CURRENT GRID &&
INPGRID CURRENT CURVILINEAR 0 0 76 71 EXC 9.999000e+003              &
        NONSTAT  20000101.000000 25 DAY 20000126.000000

&& KEYWORD TO CREATE WATER LEVEL GRID &&
INPGRID WLEV CURVILINEAR 0 0 76 71 EXC 9.999000e+003                 &
        NONSTAT  20000101.000000 25 DAY 20000126.000000

&& KEYWORD TO CREATE BOTTOM FRICTION GRID &&
INPGRID FRIC CURVILINEAR 0 0 76 71 EXC 9.999000e+003                 &
        NONSTAT  20000101.000000 25 DAY 20000126.000000

&& BOUNDARY FORCING &&
BOUNDPAR1 SHAPESPEC JONSWAP 3.3 PEAK DSPR DEGREES
BOUNDPAR2 SEGMENT IJ 0 71 76 71 CONSTANT PAR 1.0 10.0 0. 20.
```

Inlet Test Case- Coupling File

```
! Number of parallel nodes assigned to each model in the coupled system.
! Their sum must be equal to the total number of processors.

NnodesATM =  0                    ! atmospheric model
NnodesWAV =  1                    ! wave model
NnodesOCN =  1                    ! ocean model

! Time interval (seconds) between exchange of fields between models.

  TI_ATM2WAV =     0.0d0              ! atmosphere to wave coupling interval
  TI_ATM2OCN =     0.0d0              ! atmosphere to ocean coupling interval
  TI_WAV2ATM =     0.0d0              ! wave to atmosphere coupling interval
  TI_WAV2OCN =   600.0d0              ! wave to ocean coupling interval
  TI_OCN2WAV =   600.0d0              ! ocean to wave coupling interval
  TI_OCN2ATM =     0.0d0              ! ocean to atmosphere coupling interval

! Enter names of Atm, Wav, and Ocn input files.
! The Wav program needs multiple input files, one for each grid.

   ATM_name = namelist.input                                   ! WRF input file
   WAV_name = Projects/Inlet_test/Coupled/swan_inlet_test.in   ! wave model
   OCN_name = Projects/Inlet_test/Coupled/ocean_inlet_test.in  ! ocean model

! Sparse matrix interpolation weights files. You have 2 options:
! Enter "1" for option 1, or "2" for option 2, and then list the
! weight file(s) for that option.

   SCRIP_WEIGHT_OPTION = 1
!
! Option 1: IF you set "SCRIP_WEIGHT_OPTION = 1", then enter name
!           of the single netcdf file containing all the exchange
!           weights. This file is created using the code in
!           Lib/SCRIP_COAWST/scrip_coawst[.exe]

   SCRIP_COAWST_NAME = Projects/Inlet_test/Coupled/scrip_weights_inlet_test.nc
```

Running Inlet Test Case

```
./coawst.bash –j N
```

np = number of processors
coawstM = Executable created after compilation
Input file = Projects/Inlet_Test/Coupled/coupling_inlet_test.in

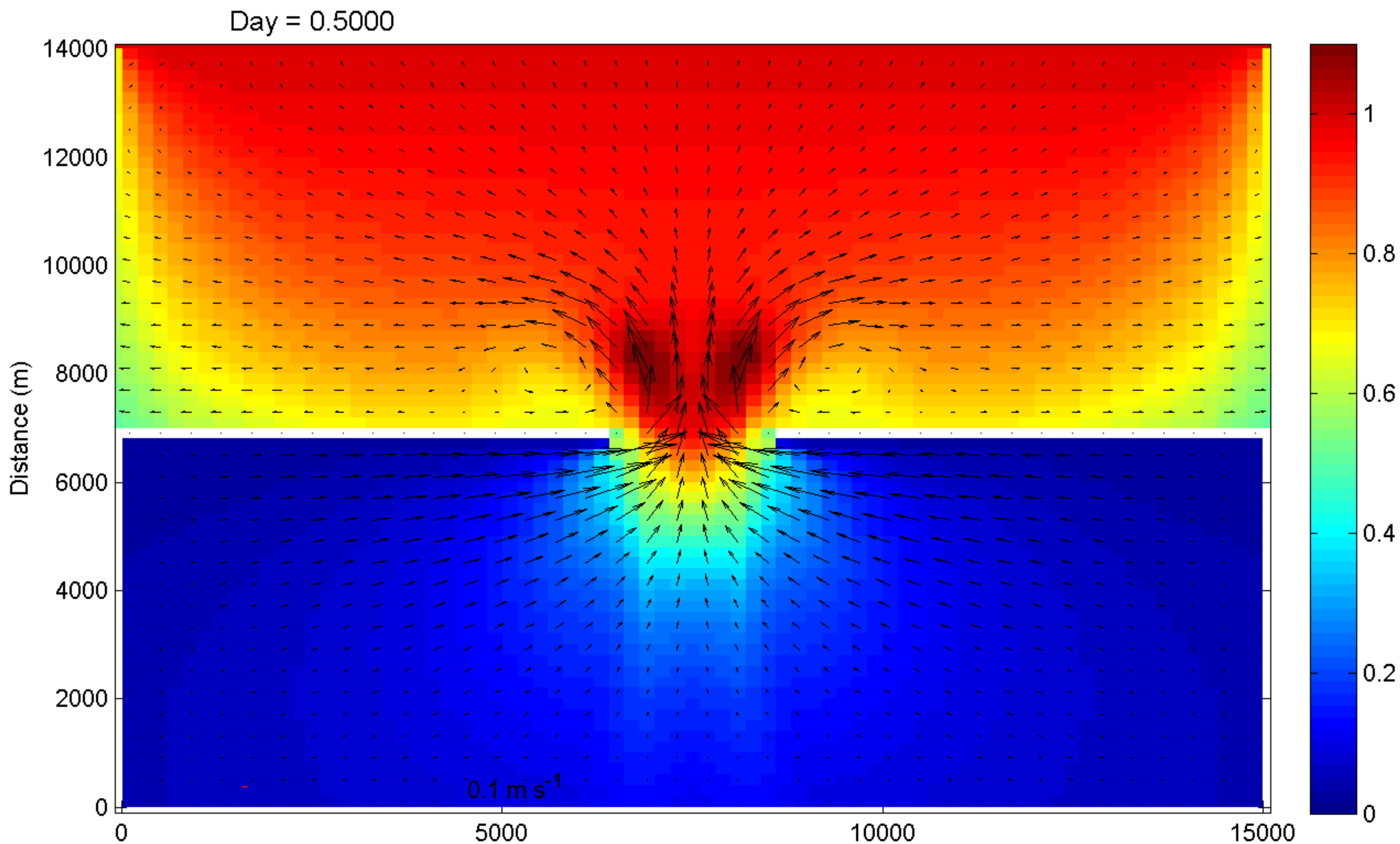
<u>Serial</u>

```
./coawstS.exe Projects/Inlet_test/Coupled/coupling_inlet_test.in
```

<u>Parallel</u>

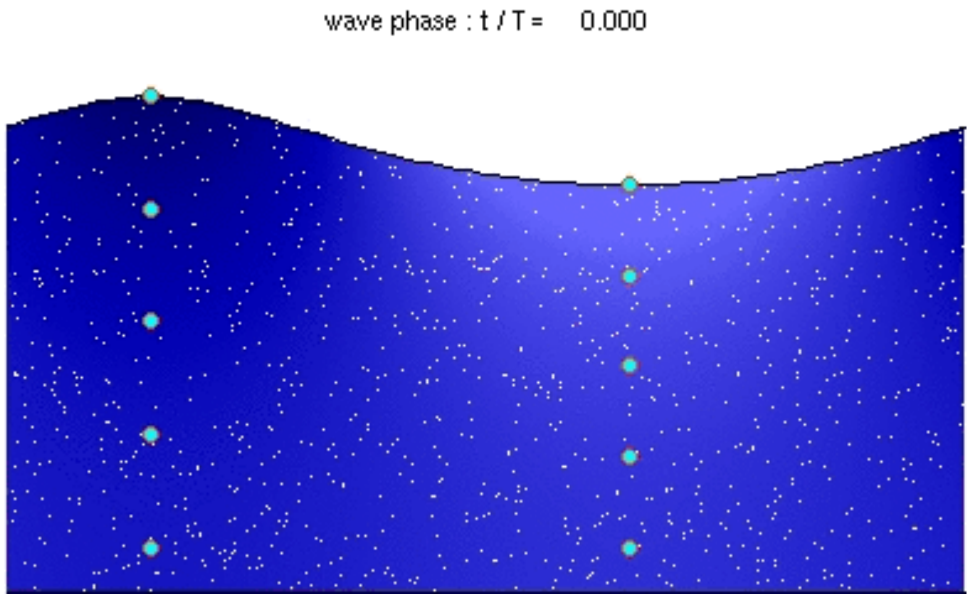
```
mpiexec/run -np 4 ./coawstM.exe Projects/Inlet_test/Coupled/coupling_inlet_test.in
```

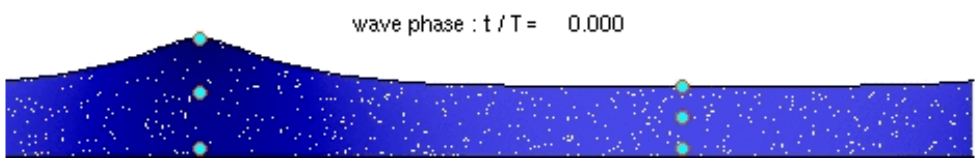
Output Inlet Test Case



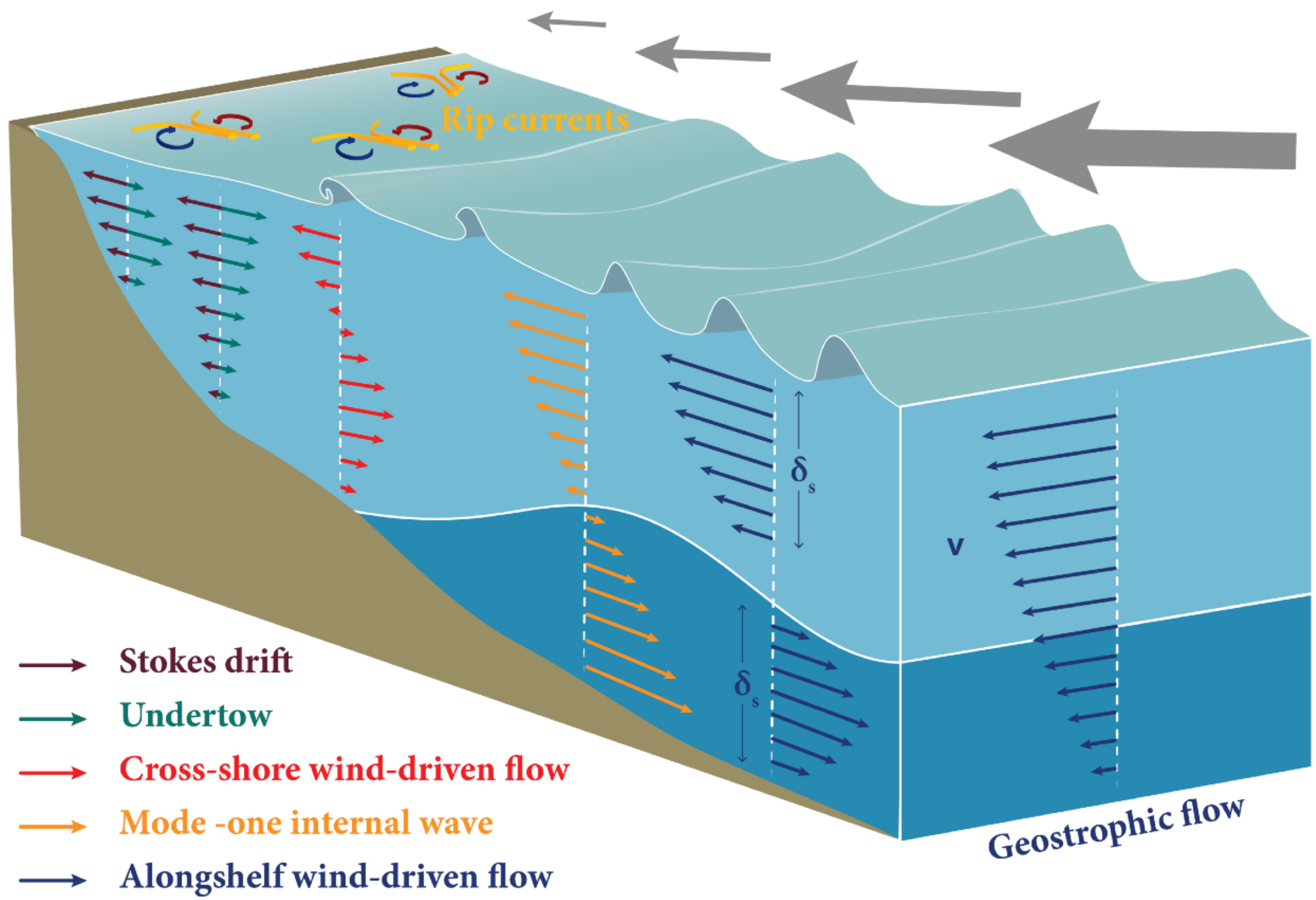
Updated Stokes Drift in COAWST

with Guoqiang Liu, Ramsey Harcourt





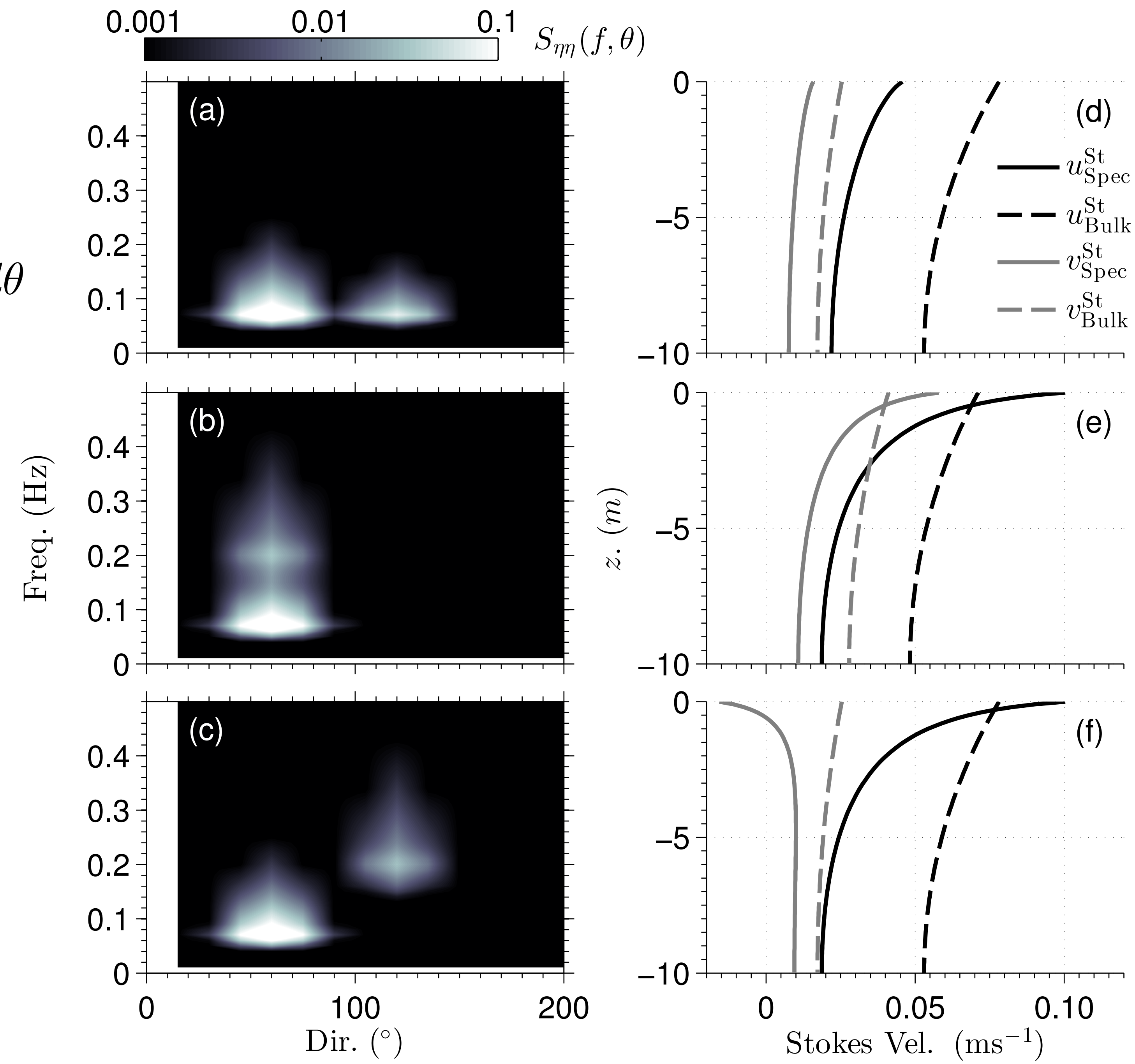
- Vortex Force
- Langmuir Turbulence
- Cross-shore Transport



Bulk & Spectral Stokes Drift Formulations

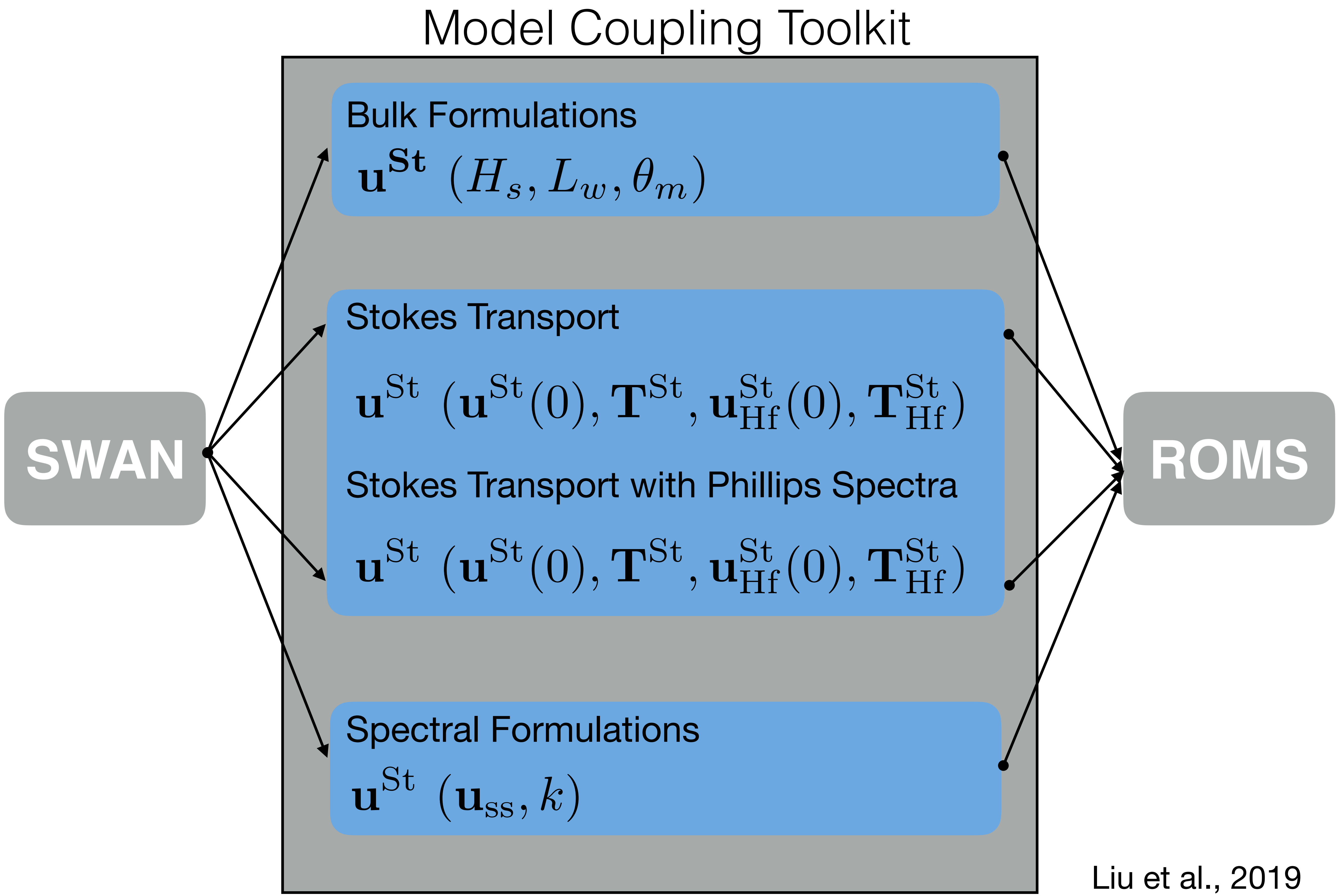
$$\mathbf{v}^{\mathrm{St}} = \frac{H_s^2\omega}{16}\frac{\cosh(2k_{\mathrm{m}}(z+h))}{\sinh^2(k_{\mathrm{m}}h)}\mathbf{k}_{\mathrm{m}}$$

$$\mathbf{v}^{\mathrm{St}} = \int_0^{\infty}\int_{\theta=0}^{\theta=2\pi}\sigma\mathbf{k}S_{\eta\eta}(f,\theta)\frac{\cosh(2k(z+h))}{\sinh^2(kh)}df\,d\theta$$



Kumar et al., 2017

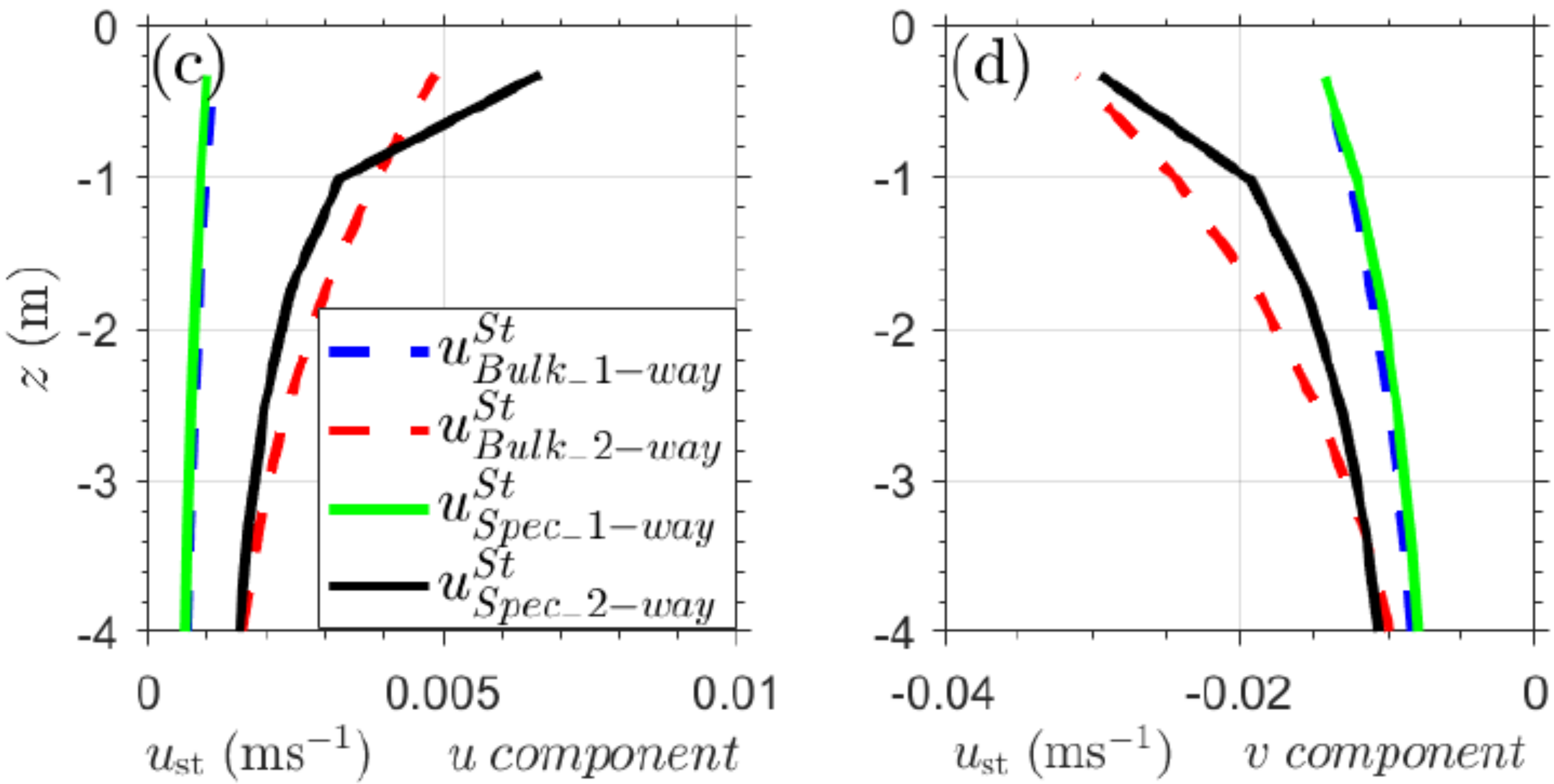
Updating Stokes Drift in COAWST



Liu et al., 2019

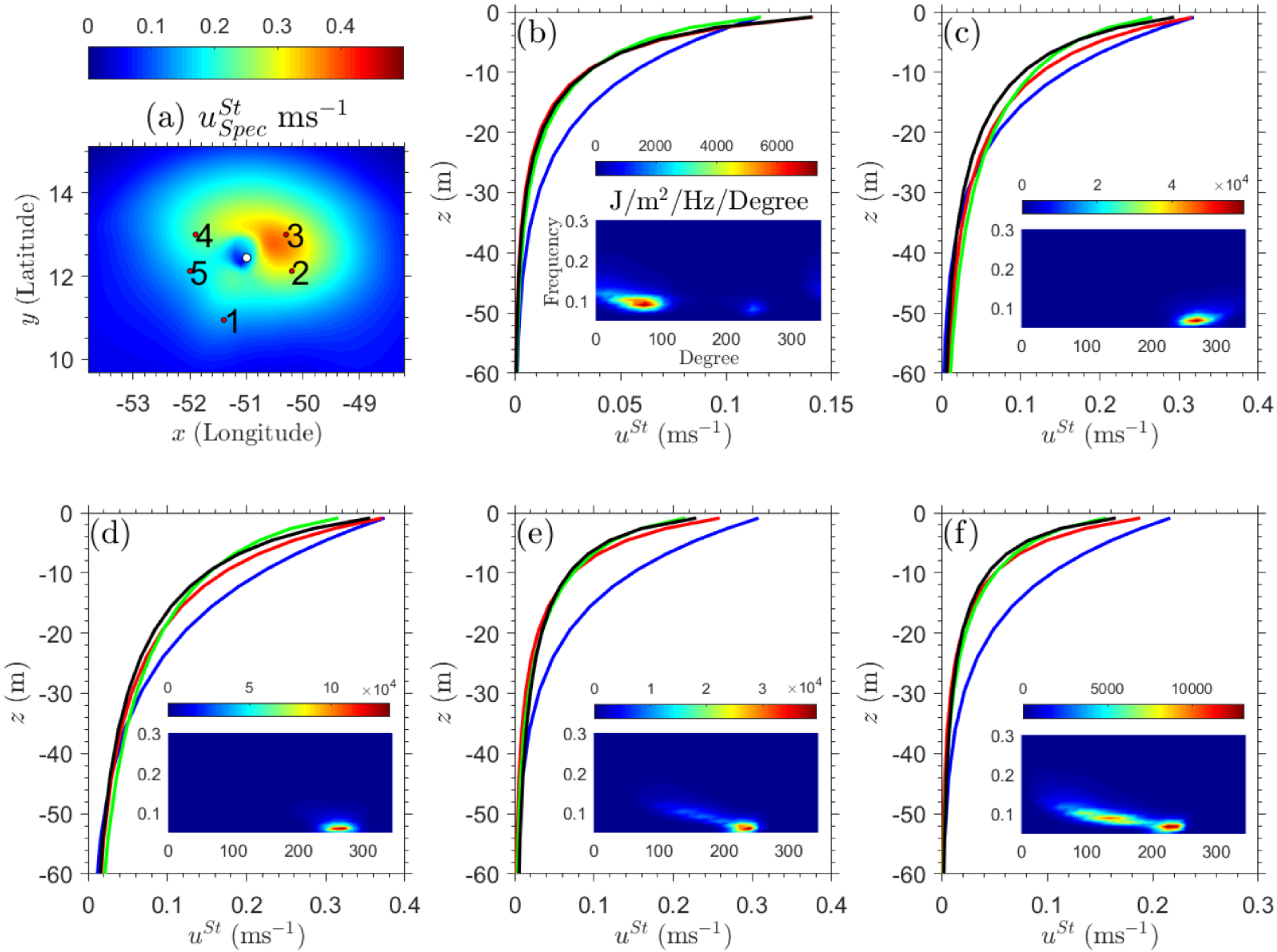
Inlet Test Case Results

Comparison between Bulk and Spectral Formulations



Liu et al., 2019

Idealized Hurricane Test Case



Liu et al., 2019

Second-Moment Closure Modification: Craik-Leibovich Vortex Force

Hydrostatic Primitive Equations

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} + 2\epsilon_{ijl}\Omega_j U_l = -\frac{1}{\rho_0}\frac{\partial P}{\partial x_i} - g_i \frac{\rho}{\rho_0} - \frac{\partial}{\partial x_j}\left(\overline{u_j u_i} - \nu \frac{\partial U_i}{\partial x_j}\right)$$

Traditional Reynolds Stress

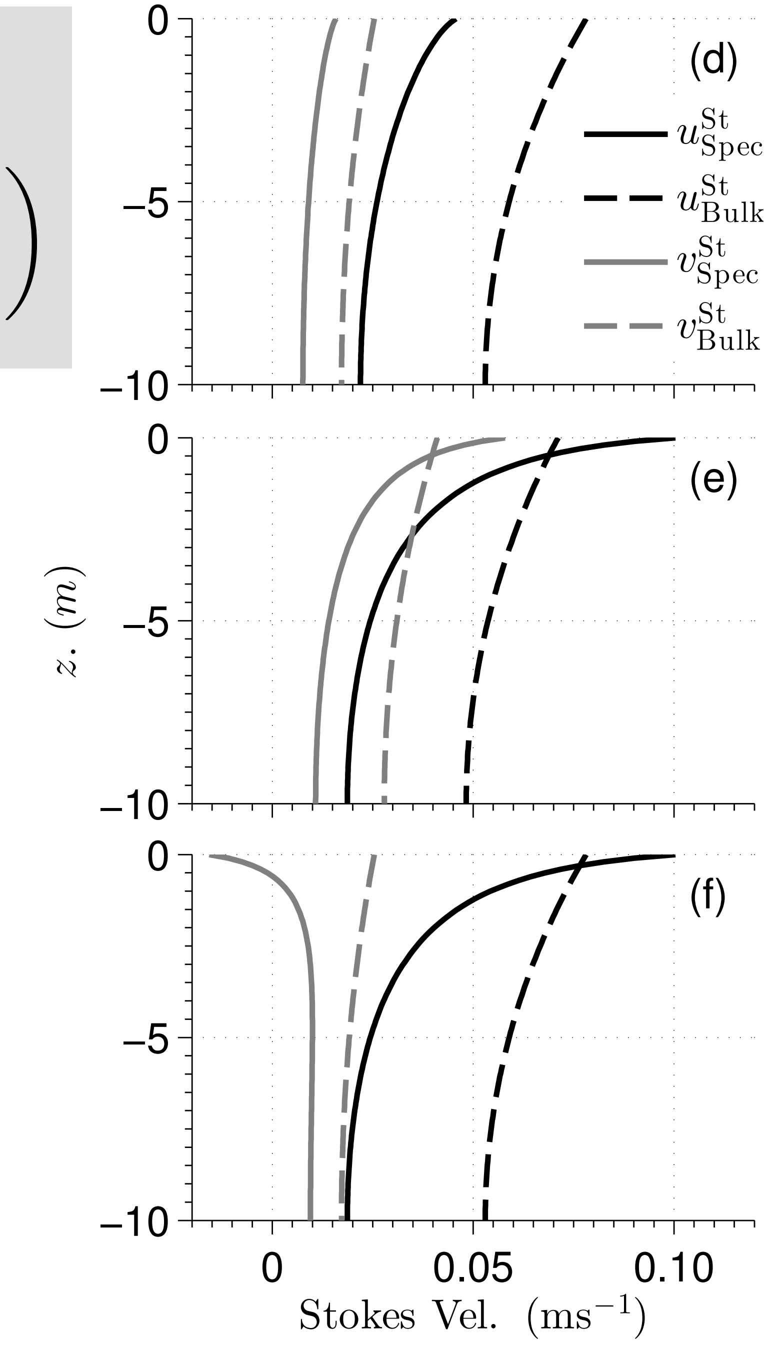
$$\overline{u'w'} = -K_M \frac{\partial U}{\partial z} \qquad \overline{v'w'} = -K_M \frac{\partial V}{\partial z}$$

$$K_M = c\sqrt{2kl}S_M$$

Reynolds Stress with C-L Vortex Force

$$\overline{u'w'} = -K_M \frac{\partial U}{\partial z} - K_M^S \frac{\partial U^{\mathrm{St}}}{\partial z} \qquad \overline{v'w'} = -K_M \frac{\partial V}{\partial z} - K_M^S \frac{\partial V^{\mathrm{St}}}{\partial z}$$

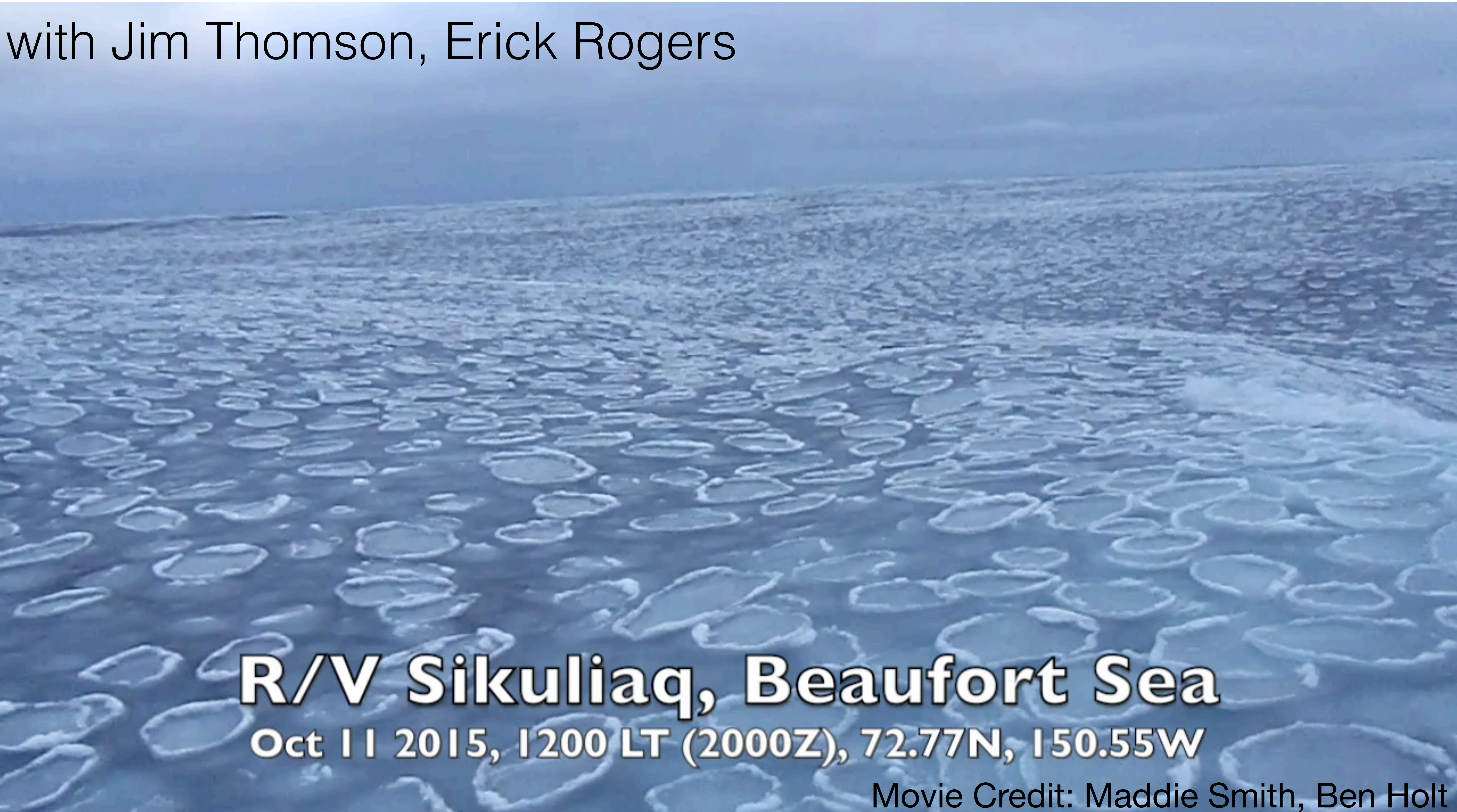
$$K_M = c\sqrt{2kl}S_M \qquad K_M^S = c\sqrt{2kl}S_M^S$$



Harcourt, 2013, 2015
Zheng et al., ……….

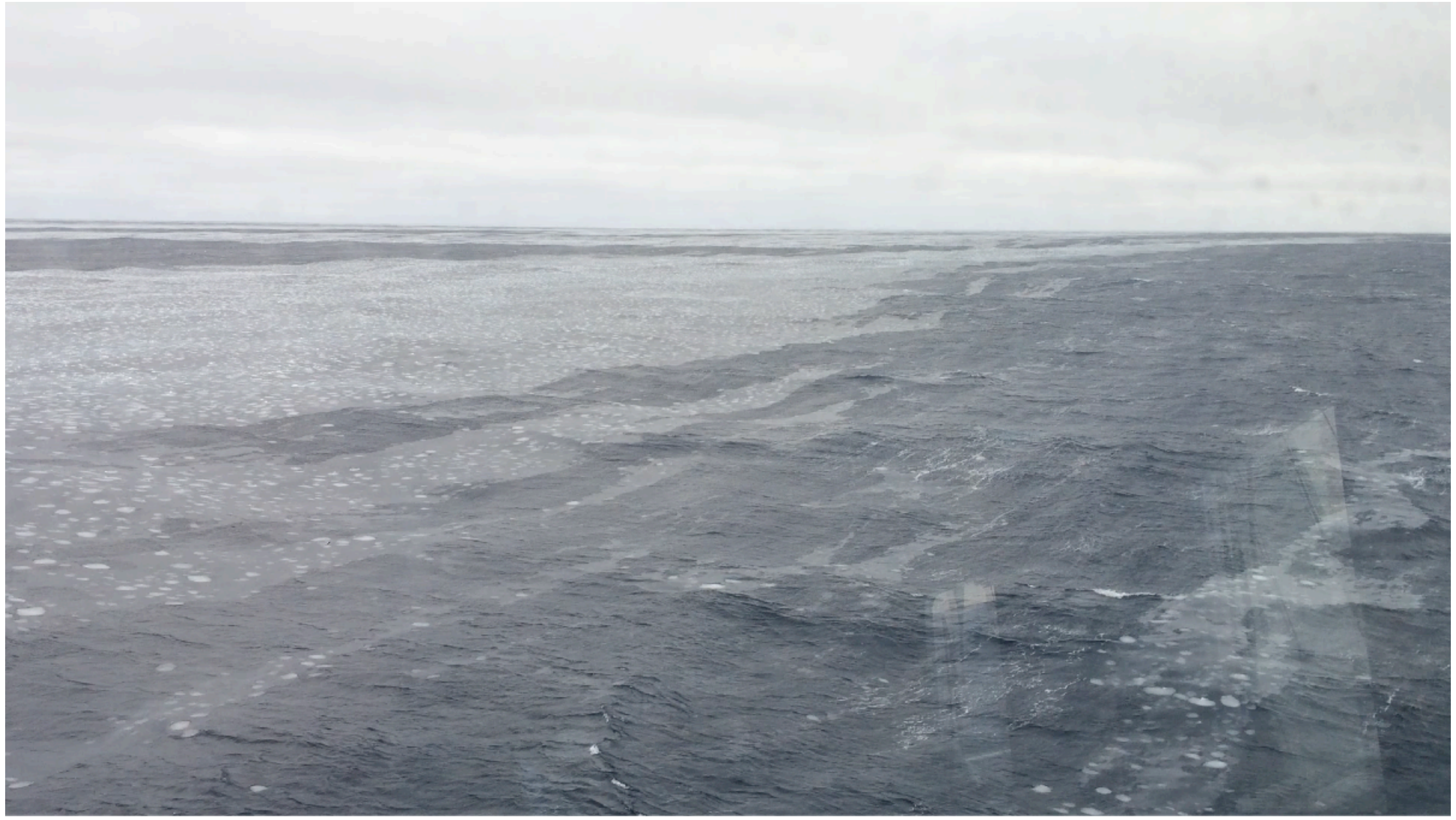
Coastal Ocean Dynamics in the Arctic (CODA)

with Jim Thomson, Erick Rogers

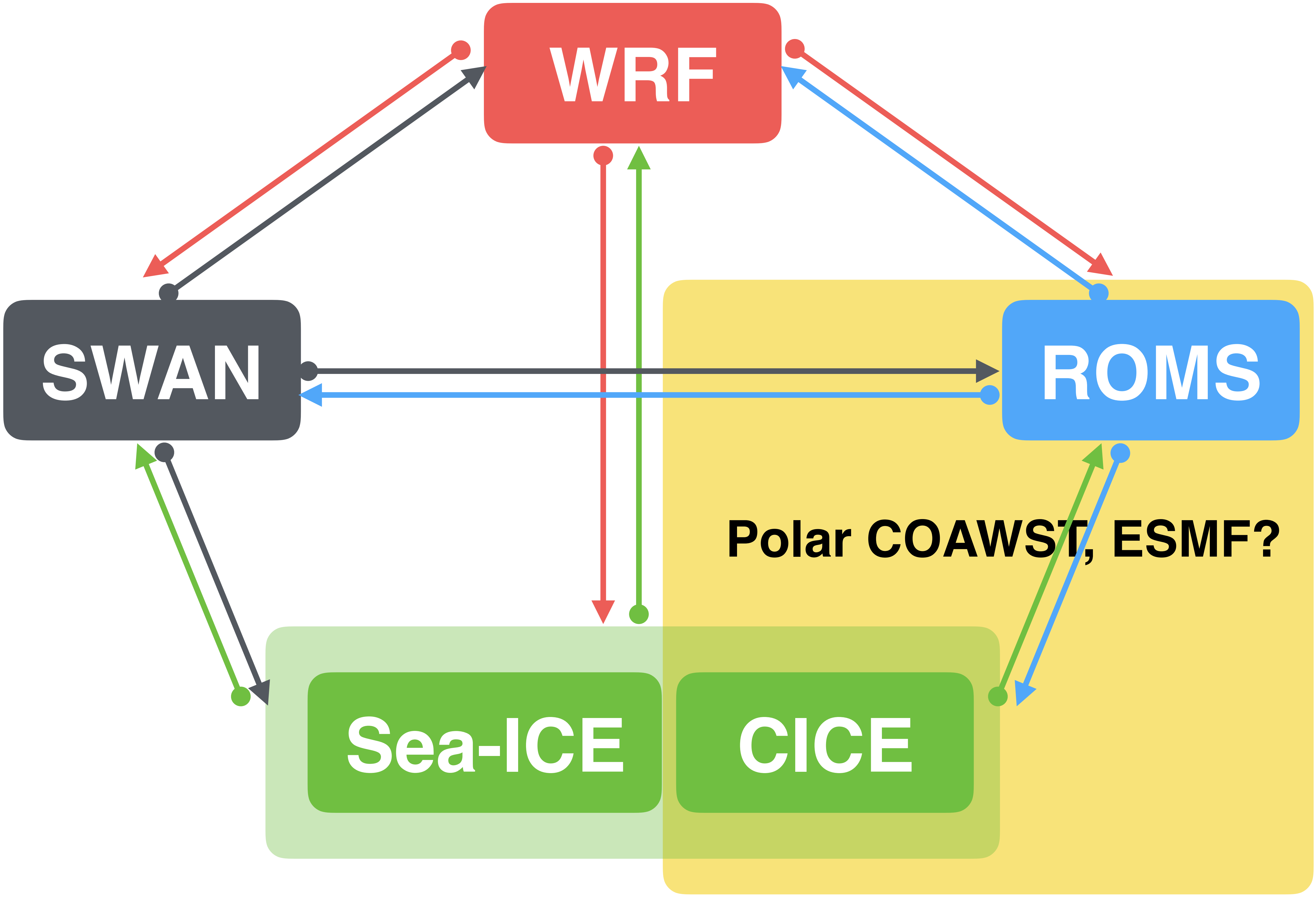


Movie Credit: Maddie Smith, Ben Holt

Wave-Ice Interaction



Modeling Wave-Ice Interaction- COAWST



SWAN with ICE

Action (N)-Balance Equation

$$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c}N = \frac{S_{\mathrm{tot}}}{\sigma}$$

$$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c}N = \frac{1}{\sigma}\left(S_{\mathrm{in}} + S_{\mathrm{nl3}} + S_{\mathrm{nl4}} + \overbrace{S_{\mathrm{ds,w}} + S_{\mathrm{ds,b}} + S_{\mathrm{ds,br}}}^{S_{\mathrm{ds}}}\right)$$

Action (N)-Balance Equation with ICE

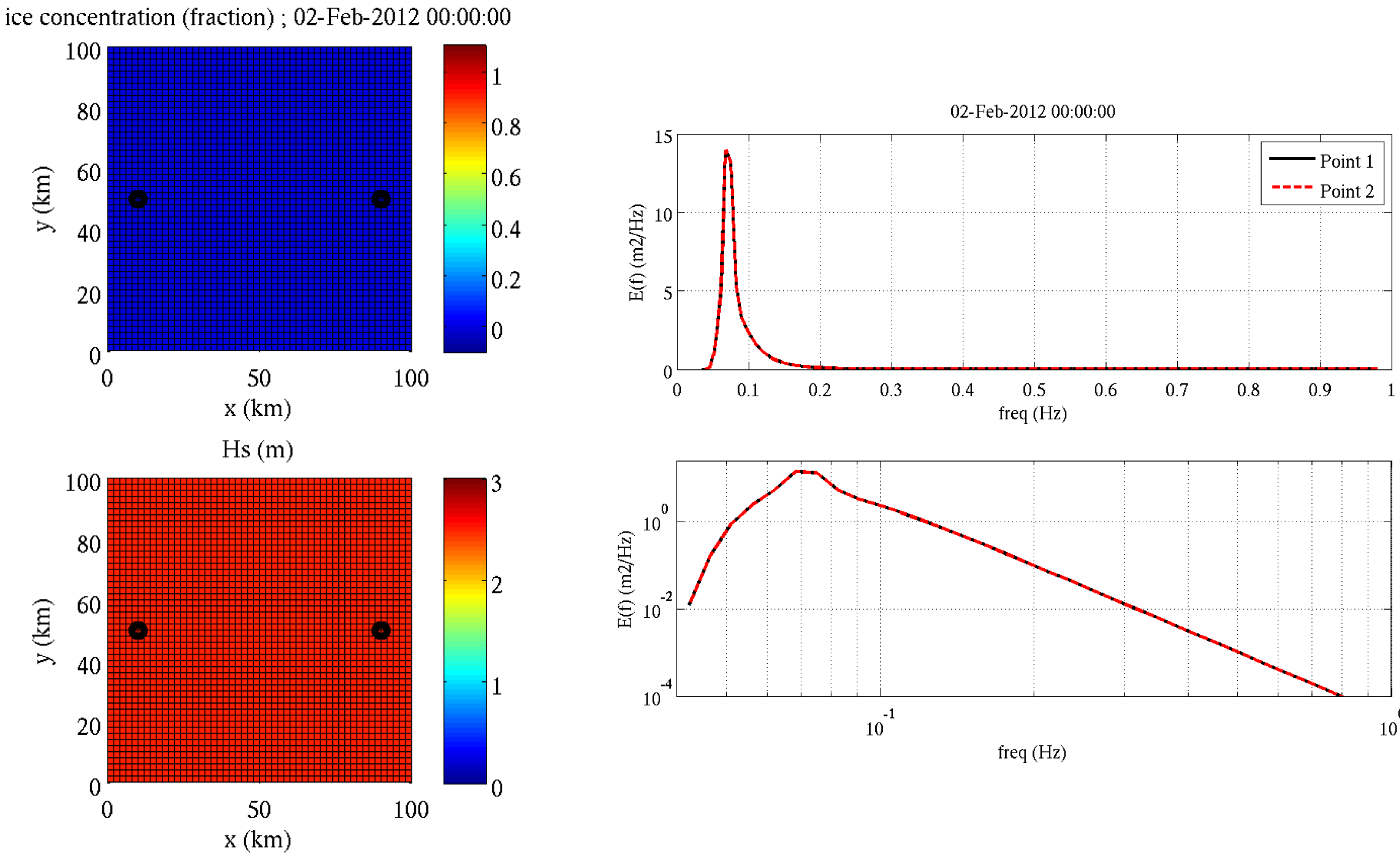
$$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c}N = \frac{1}{\sigma}\left(S_{\mathrm{in}}(1-\alpha) + S_{\mathrm{nl3}} + S_{\mathrm{nl4}} + S_{\mathrm{ds}} + S_{\mathrm{ice}}\right)$$

$$D_{\mathrm{ice}} = \frac{S_{\mathrm{ice}}}{E} = -C_g\alpha$$

$$\alpha = C_0 + C_1 f + C_2 f^2 + C_3 f^3 + C_4 f^4$$

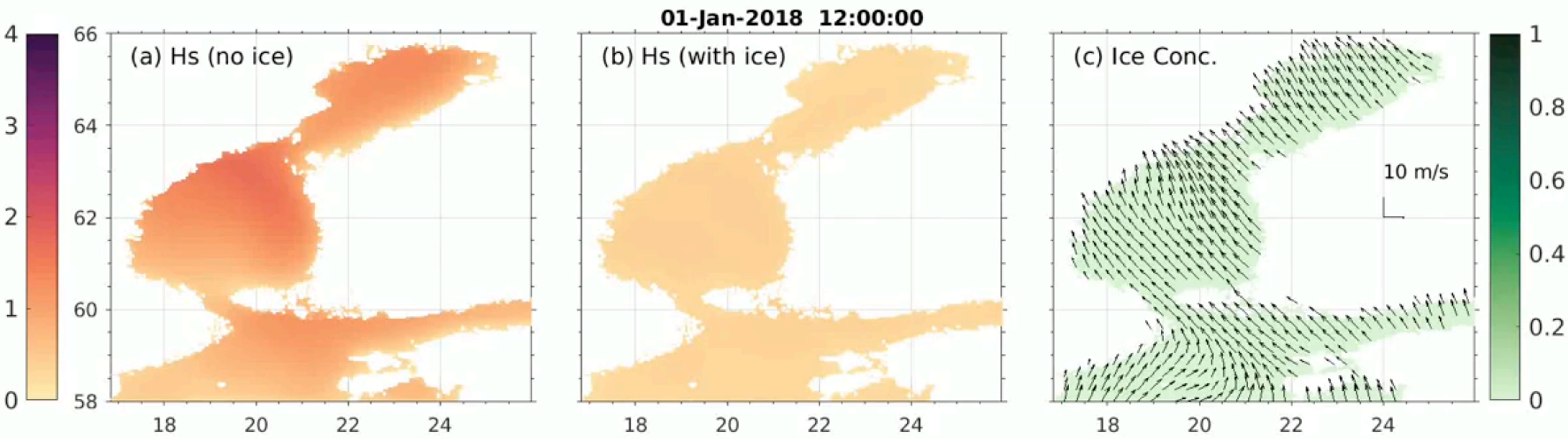
Rogers et al., 2013

Idealized Examples



Rogers et al., 2019

Realistic Examples (Gulf of Bothnia)



Kumar et al., 2019