Examination of wave-current interactions over the eastern Canadian shelf under severe weather conditions using a coupled circulation-wave model

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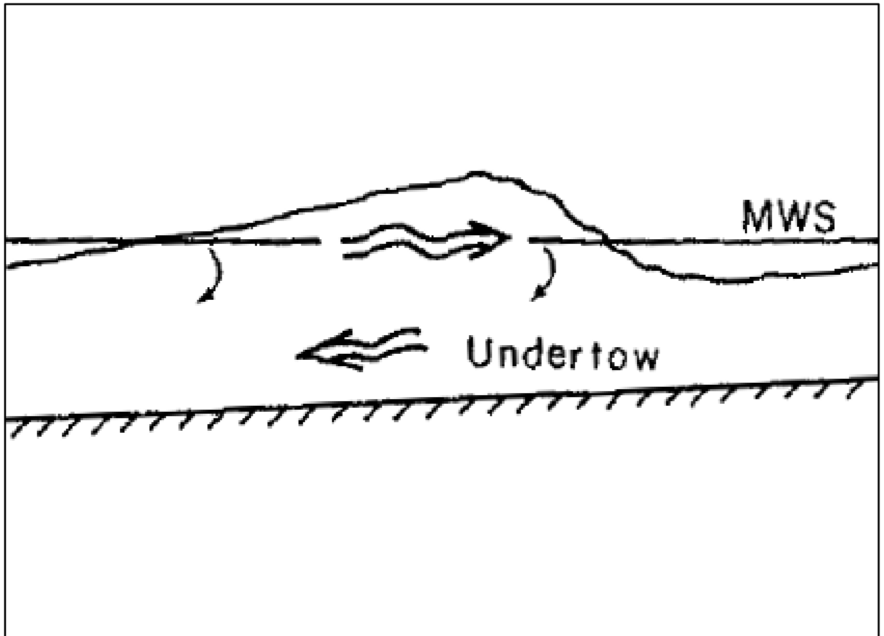
Outline

- **Introduction**
- **A coupled wave-circulation model**
- **Two idealized test cases**
  (a) A plane beach with undertow
  (b) A barred beach with rip current
- **Realistic applications during three storm events**
- **Summary**

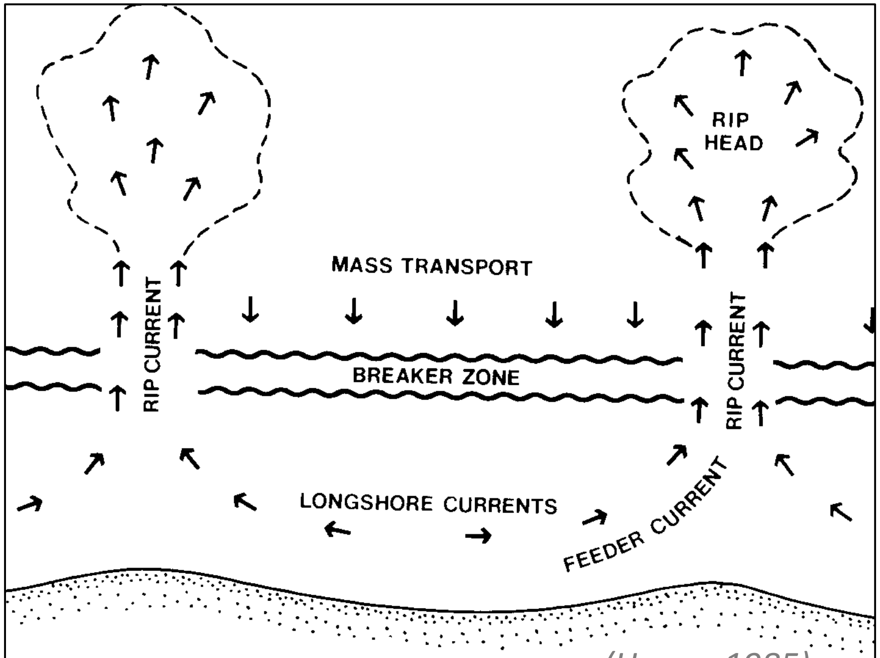
1. Introduction

Sketch of undertow



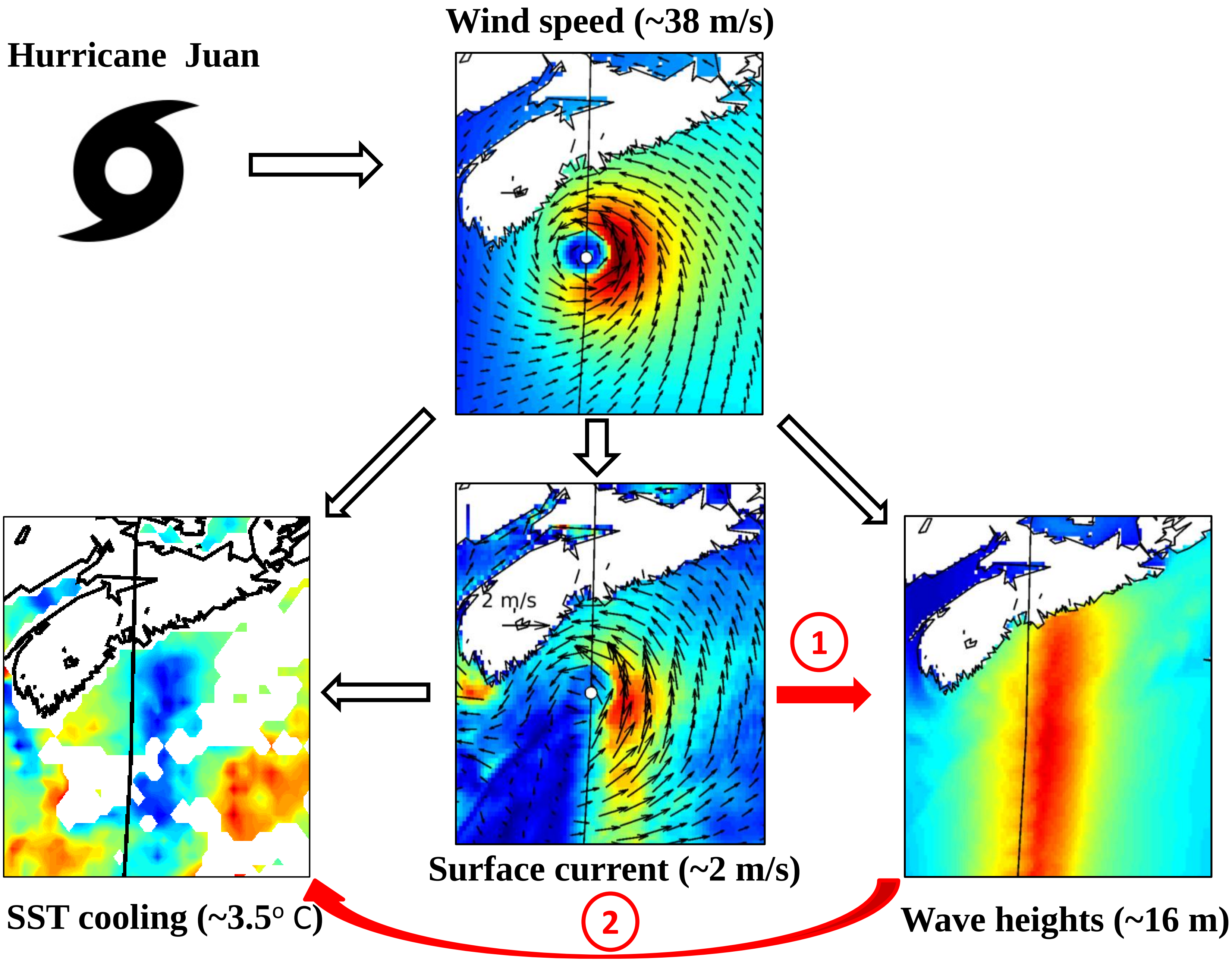
Buhr Hansen & Svendsen (1984)

Sketch of rip current

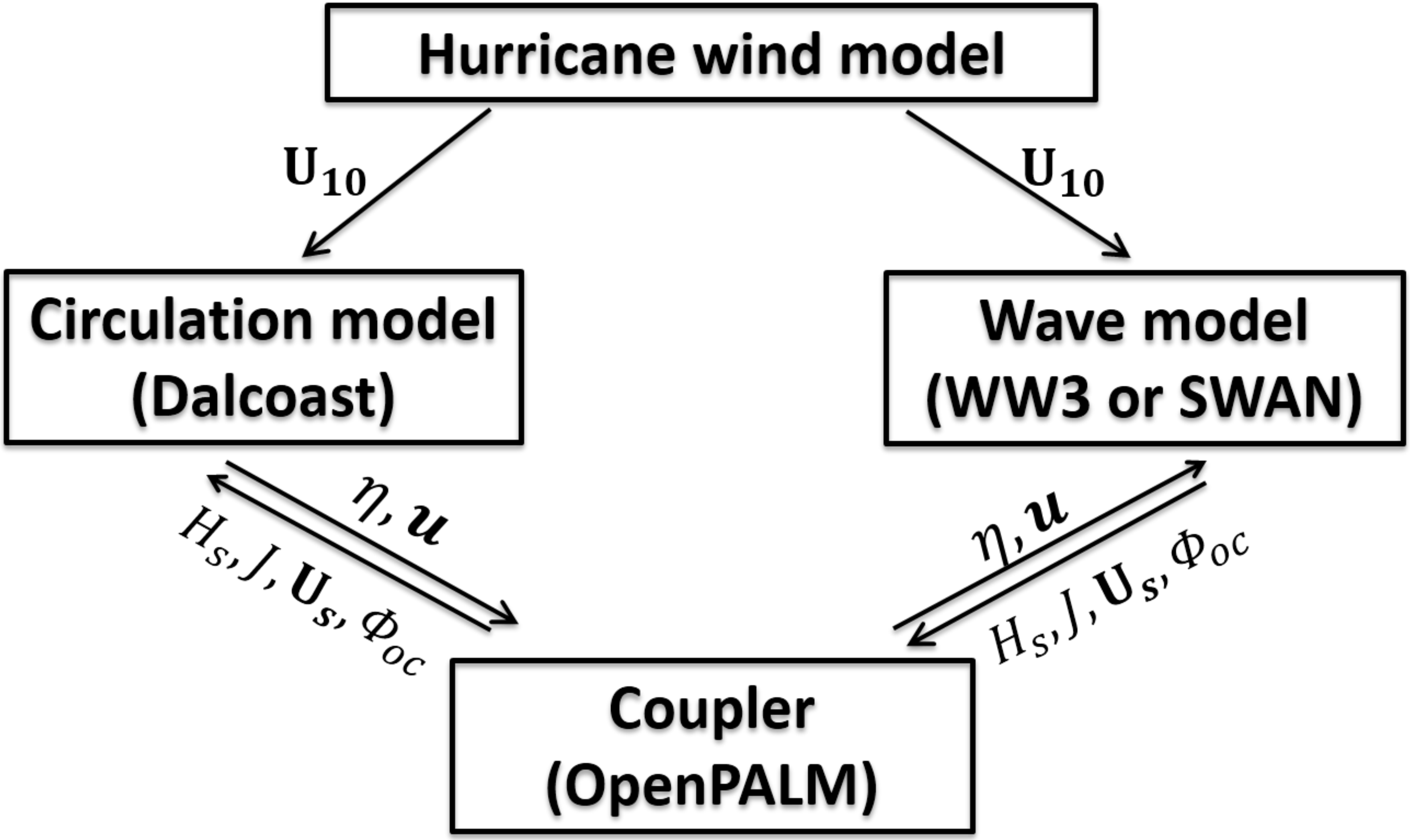


(Hayes, 1985)

Two major objectives of this study



2. A coupled circulation-wave modelling system



Effects of ocean currents on waves:

Wave action equation $$\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{X} N + \frac{\partial}{\partial k}\dot{k} N + \frac{\partial}{\partial \theta}\dot{\theta} N = \frac{S_{tot}}{\sigma}$$

1. **Relative wind effect:** $\boldsymbol{U_{10}} - \boldsymbol{U}$

2. **Current-induced wave advection:** $\dot{X} = C_g + \boldsymbol{U}$

3. **Current-induced wavenumber shift:** $$\dot{k} = -\frac{\partial \sigma}{\partial D}\frac{\partial D}{\partial s} - \boldsymbol{k} \cdot \frac{\partial \boldsymbol{U}}{\partial s}$$

4. **Current-induced wave refraction:** $$\dot{\theta} = \frac{1}{k}\left(\frac{\partial \sigma}{\partial D}\frac{\partial D}{\partial m} + \boldsymbol{k} \cdot \frac{\partial \boldsymbol{U}}{\partial m}\right)$$

Effects of waves on the 3D circulation:

1. 3D wave forces based on the "Vortex force" formulism

(Bennis et al., 2011)

Momentum equation

$$\frac{\partial \hat{u}}{\partial t} + \hat{u}\frac{\partial \hat{u}}{\partial x} + \hat{v}\frac{\partial \hat{u}}{\partial y} + \hat{w}\frac{\partial \hat{u}}{\partial z} - f\hat{v} + \frac{1}{\rho}\frac{\partial p}{\partial x} = \underbrace{\left[f + \left(\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y}\right)\right]V_s - W_s\frac{\partial \hat{u}}{\partial z}}_{\text{Vortex force}} - \underbrace{\frac{\partial J}{\partial x}}_{\text{Bernouilli's head}} + \underbrace{F_{d,x}}_{\text{Dissipation force}} + F_{m,x}$$

Tracer equation

$$\frac{\partial C}{\partial t} + \underbrace{\frac{\partial(\hat{u} + U_s)C}{\partial x} + \frac{\partial(\hat{v} + V_s)C}{\partial y} + \frac{\partial(\hat{w} + W_s)C}{\partial z}}_{\text{Material advection by Stokes drift}} = 0$$

2. Breaking wave-induced mixing:

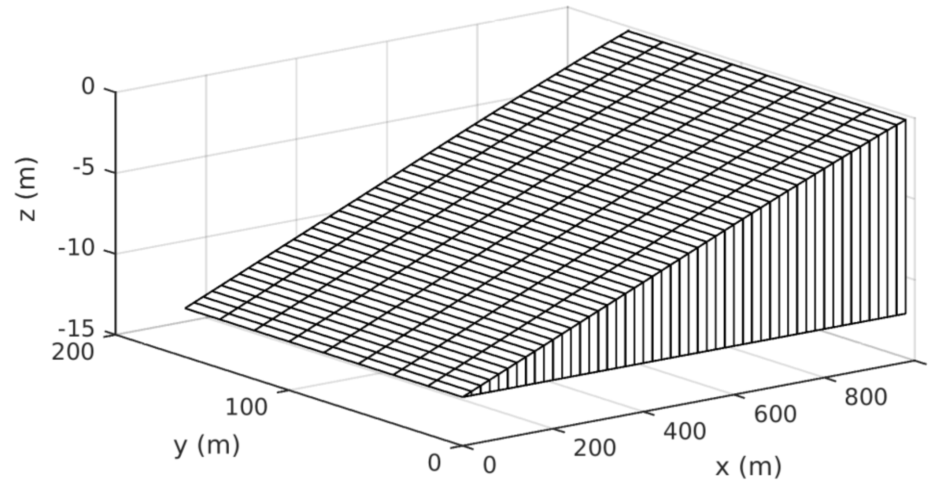
$$K_q\frac{\partial E}{\partial z} = \underbrace{S_{dis}}_{\text{Wave dissipation source term}} \quad at\ z=0$$

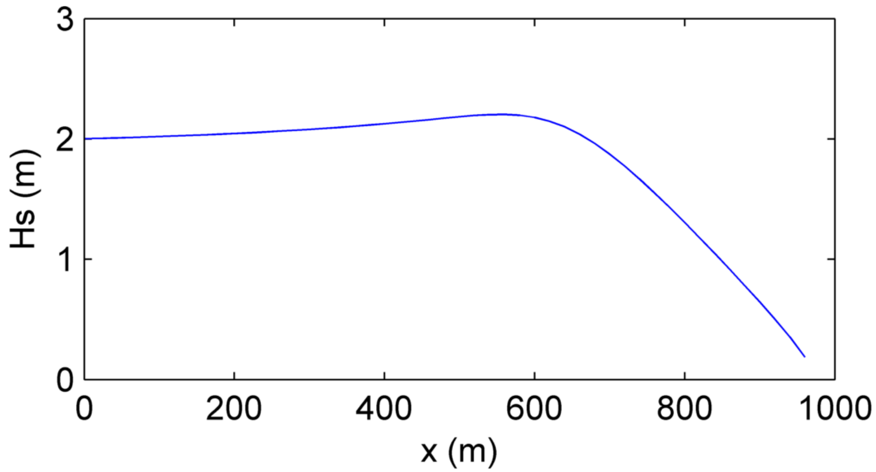
(Craig & Banner, 1994)

3. Two idealized test cases

Test case 1: A plane beach with undertow

- **Bathymetry:**
  1000 x 200 m
  maximum depth: 12 m
- **Wave characteristic:**
  H_s= 2 m
  T_p= 10 s
  θ = 10º
  JONSWAP type spectral wave field
  Computed using SWAN





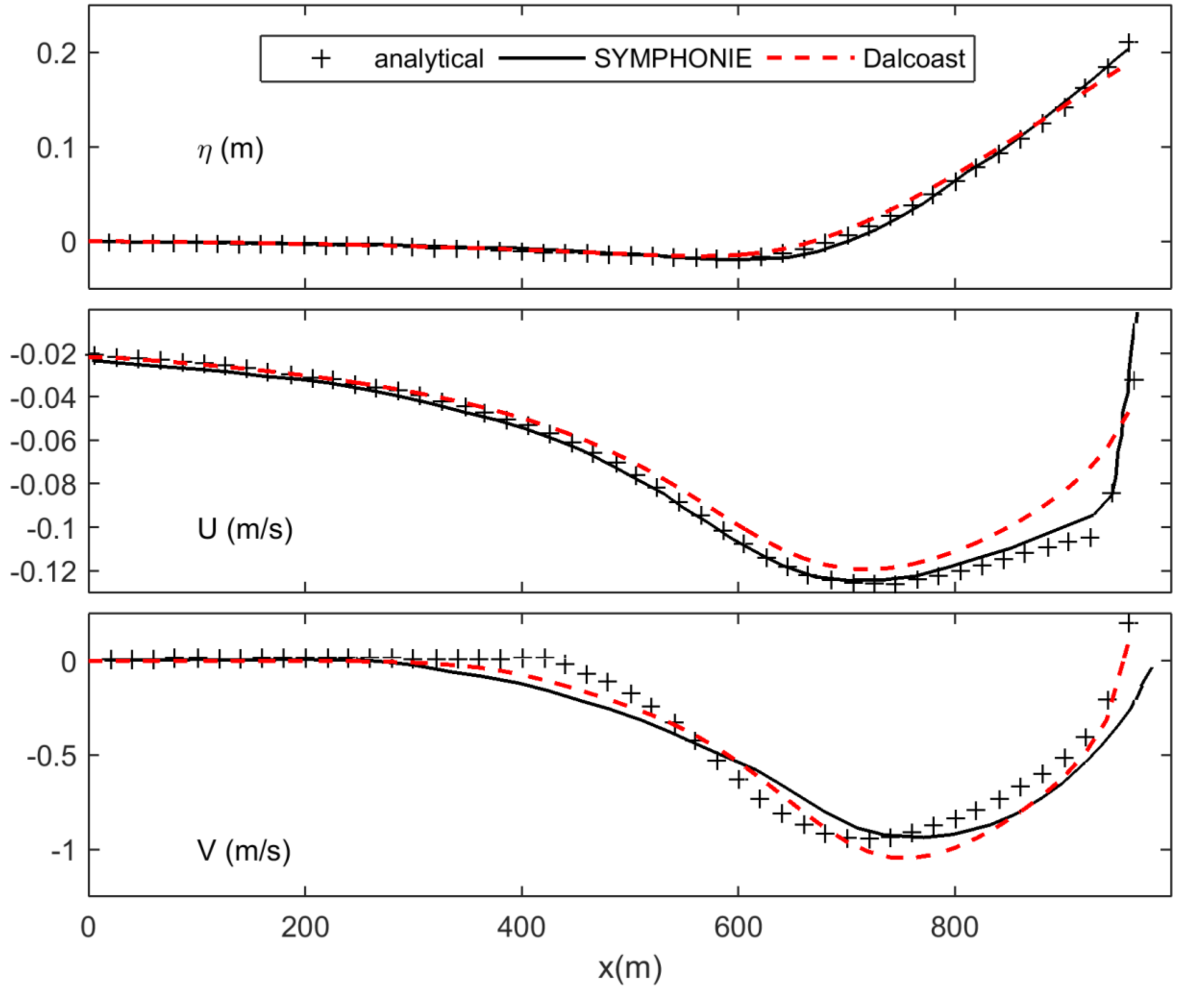
Cross-shore profile of Hs

Results (a):

Sea levels

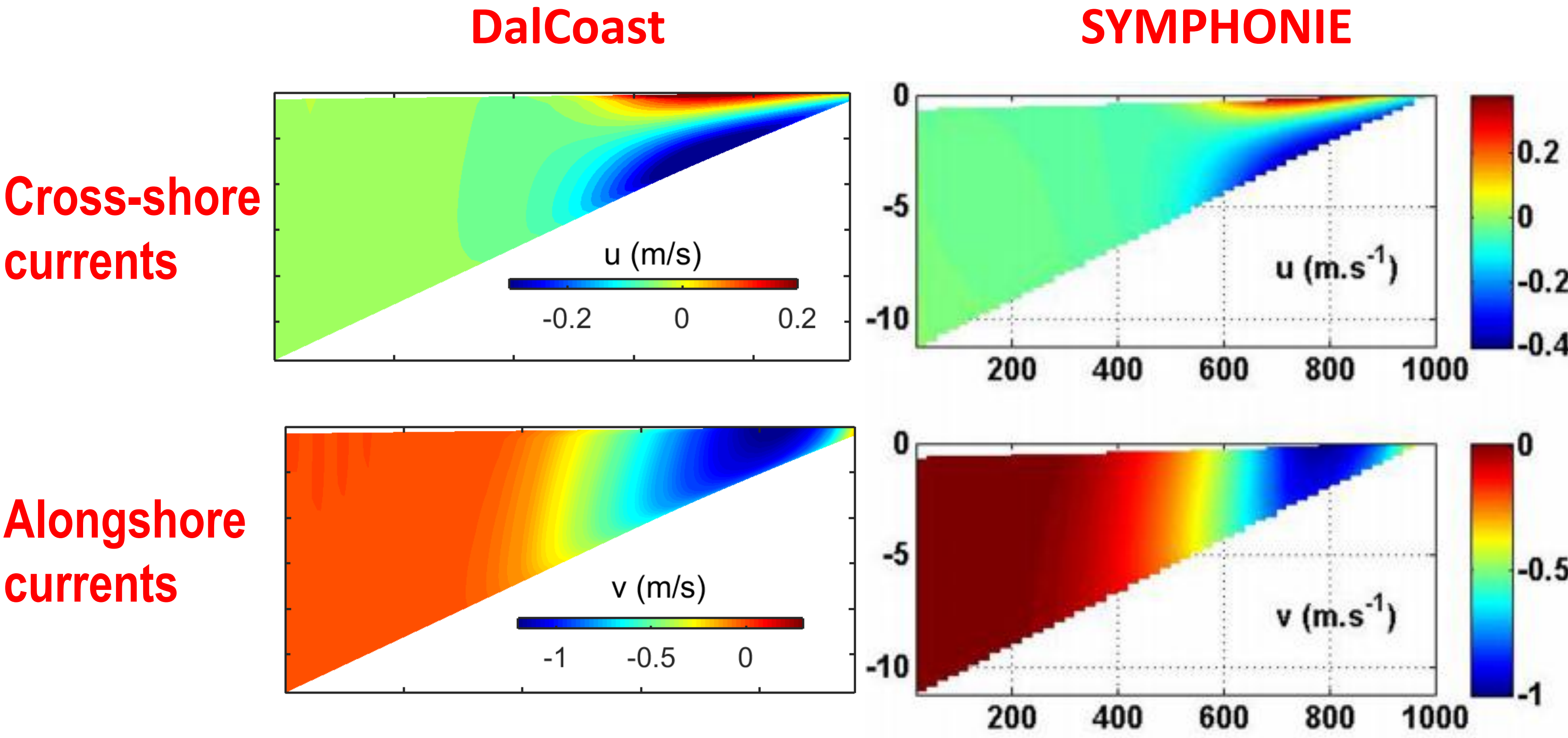
Cross-shore currents

Alongshore currents



Cross-shore profiles of surface elevation and depth-averaged currents in Dalcoast and SYMPHONIE (Michaud et al., 2012)

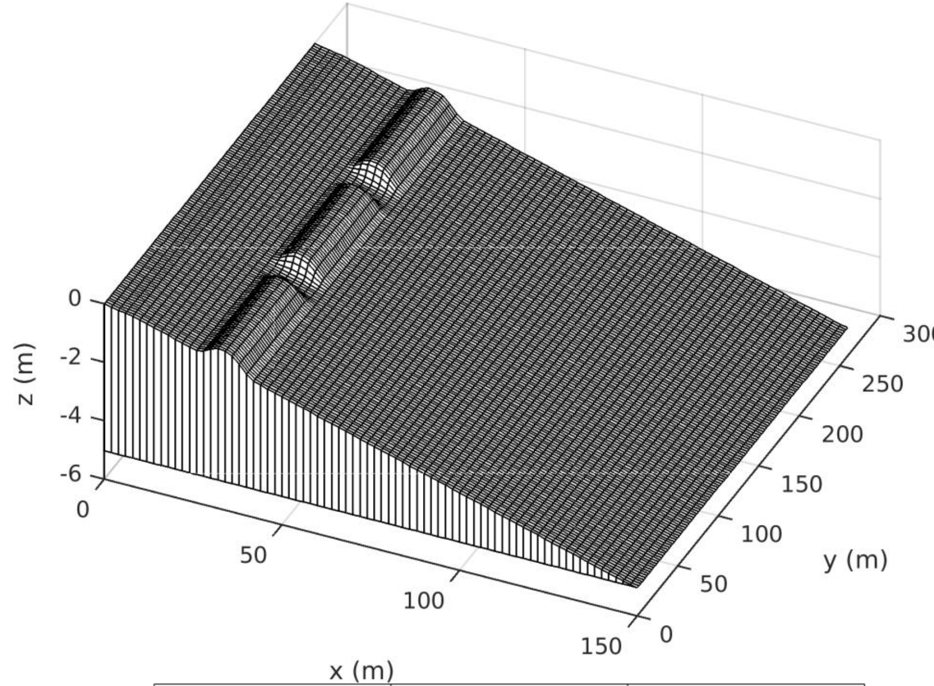
Results (b):

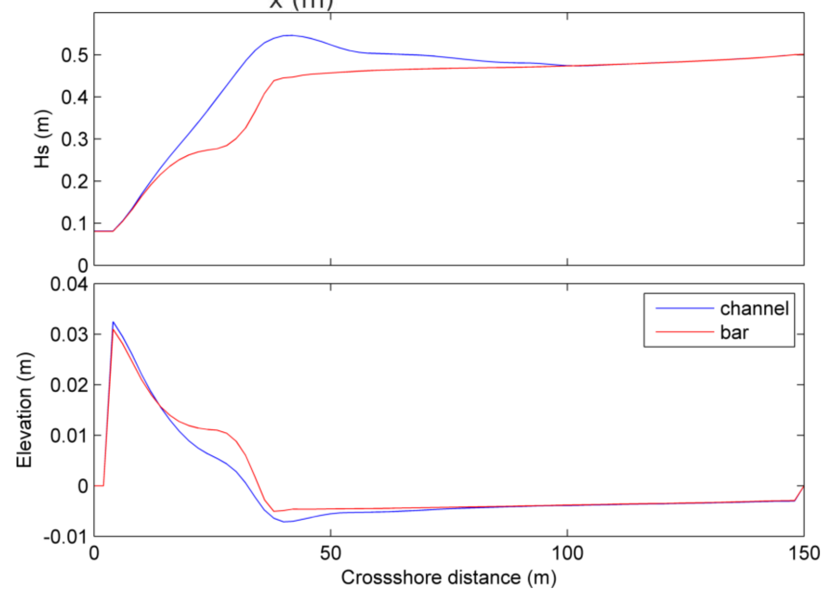


The vertical structure of the cross-shore and alongshore currents in Dalcoast (left) and SYMPHONIE (right)

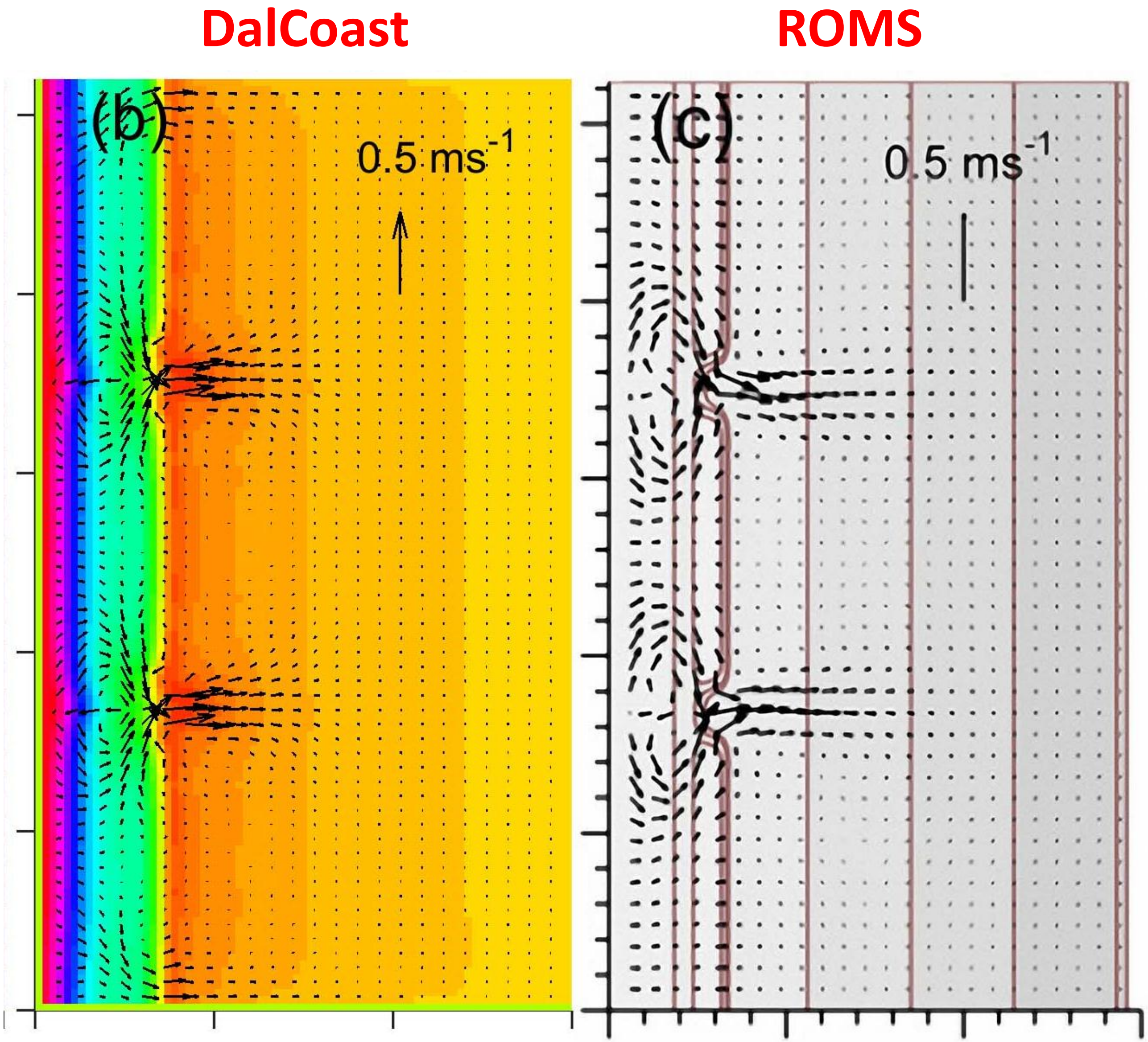
Test case 2: A barred beach with rip current

- **Bathymetry:**
  146 x 262 m, maximum depth: 5 m
- **Wave characteristic:**
  H_s= 0.5 m
  T_p= 3.16s
  θ = 90°
  JONSWAP type spectral wave field
  Two-way coupling (Dalcoast and SWAN)





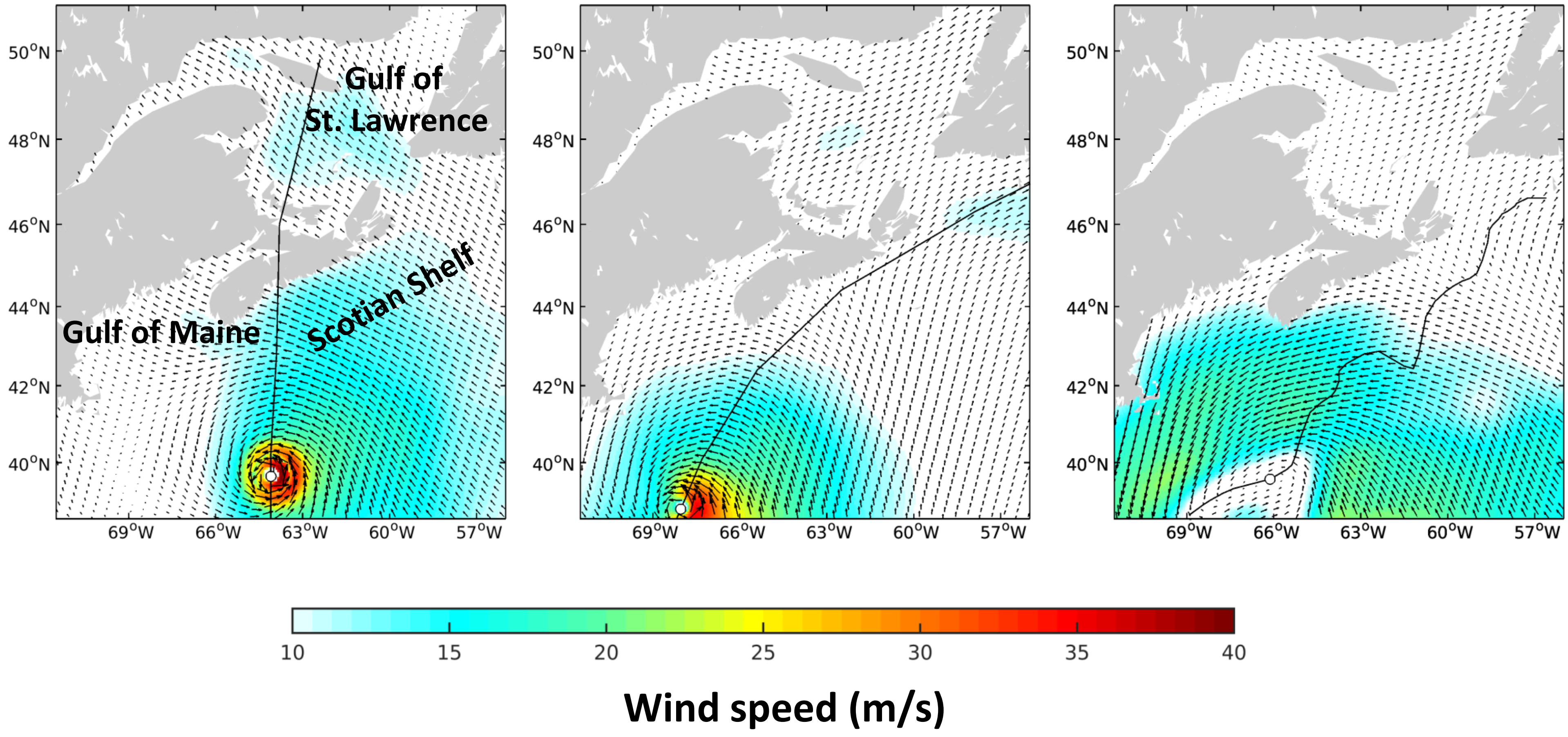
Results:



Depth-averaged currents in Dalcoast (left) and ROMS (Kumar et al., 2011) (right)

4. Realistic applications

#1 Hurricane Juan (2003) **#2 Hurricane Bill (2009)** **#3 Winter storm "White Juan" (2004)**



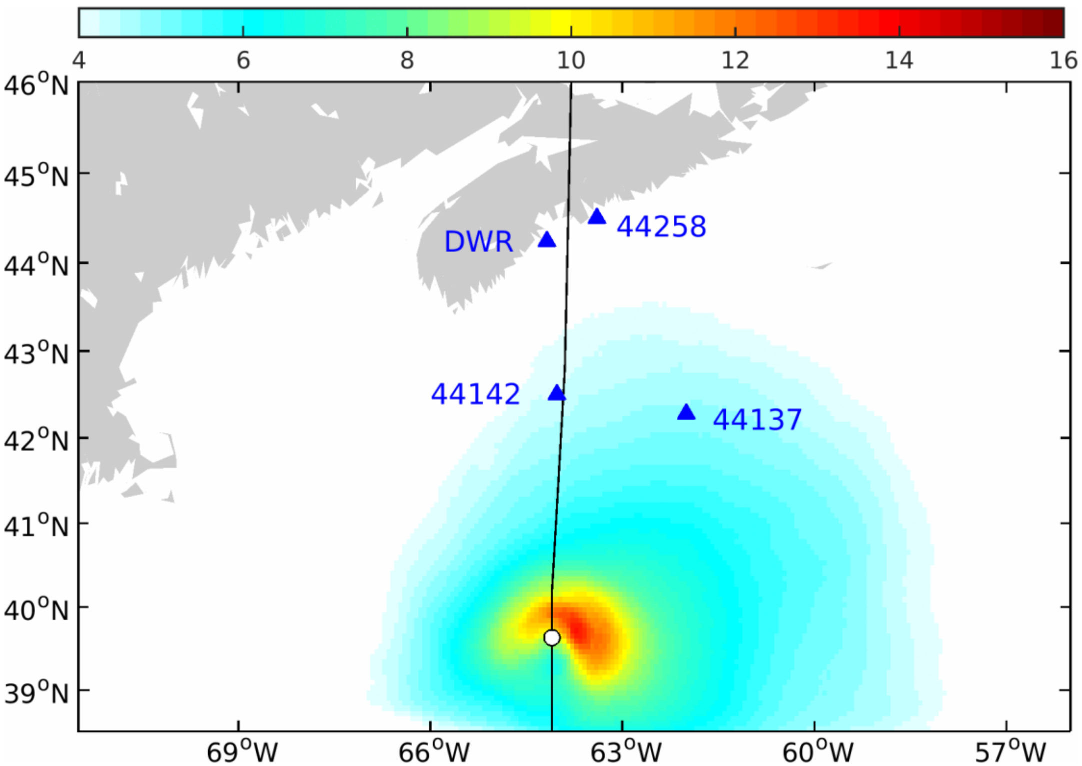
List of numerical experiments

Six major wave-current interaction mechanisms

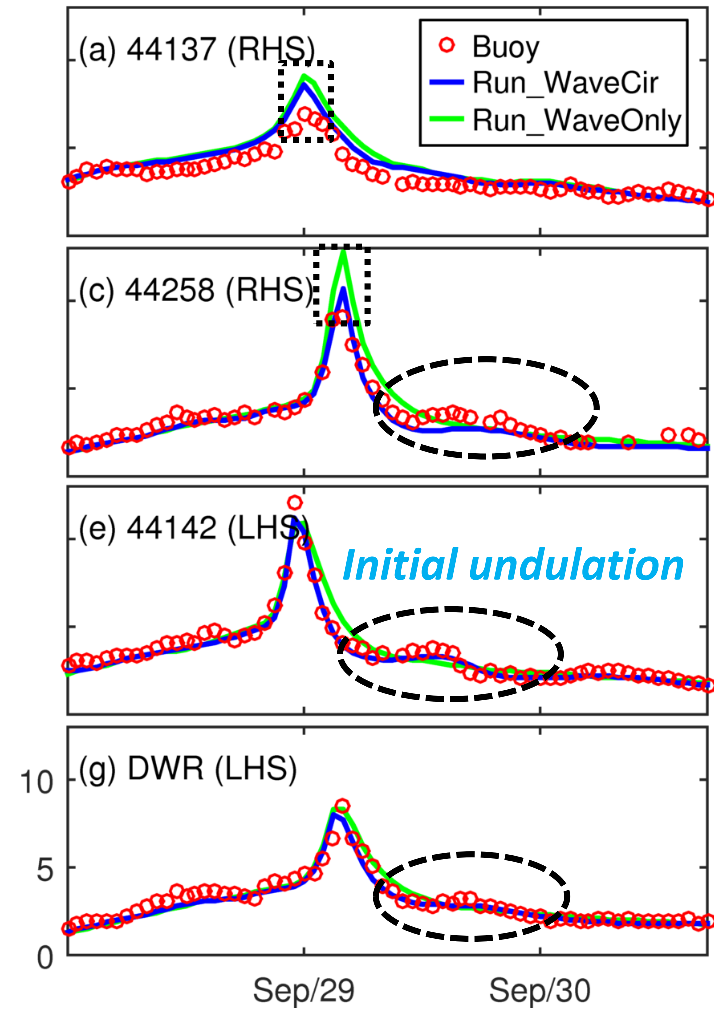
Experiment	Relative wind effect	Current-induced wave advection	Current-induced k shift	Current-induced wave refraction	3D wave forces	Breaking wave-induced mixing
Run_WaveCir	✓	✓	✓	✓	✓	✓
Run_WaveOnly	Wave-only model run					
Run_CirOnly	Circulation-only model run					
Run_WaveU_{10}	✓	✗	✗	✗	✓	✓
Run_WaveC_g	✗	✓	✗	✗	✓	✓
Run_Wavek	✗	✗	✓	✗	✓	✓
Run_Waveθ	✗	✗	✗	✓	✓	✓
Run_CirVF	✓	✓	✓	✓	✓	✗
Run_CirTKE	✓	✓	✓	✓	✗	✓

Process-oriented experiments

4.1 Hurricane Juan



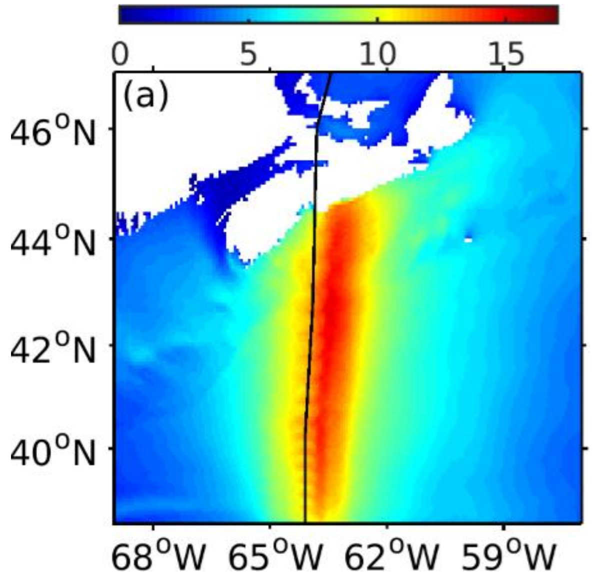
Simulated significant wave heights (m)



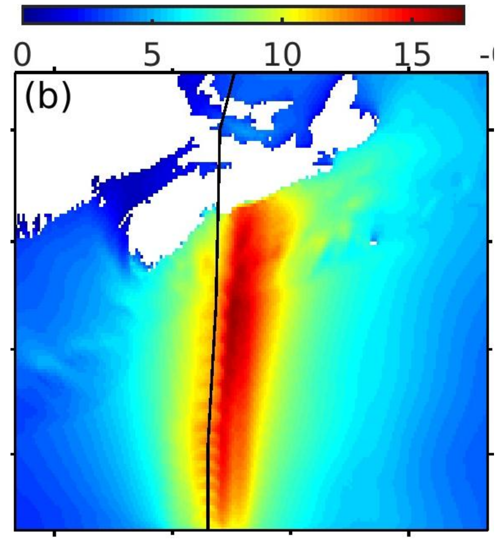
Comparison with observations

The distribution of maximum wave heights (Juan)

Run_WaveCir (coupled model run)

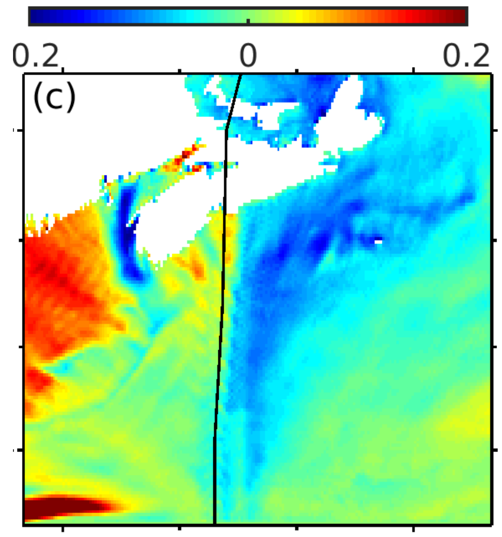


Run_WaveOnly (wave-only model run)

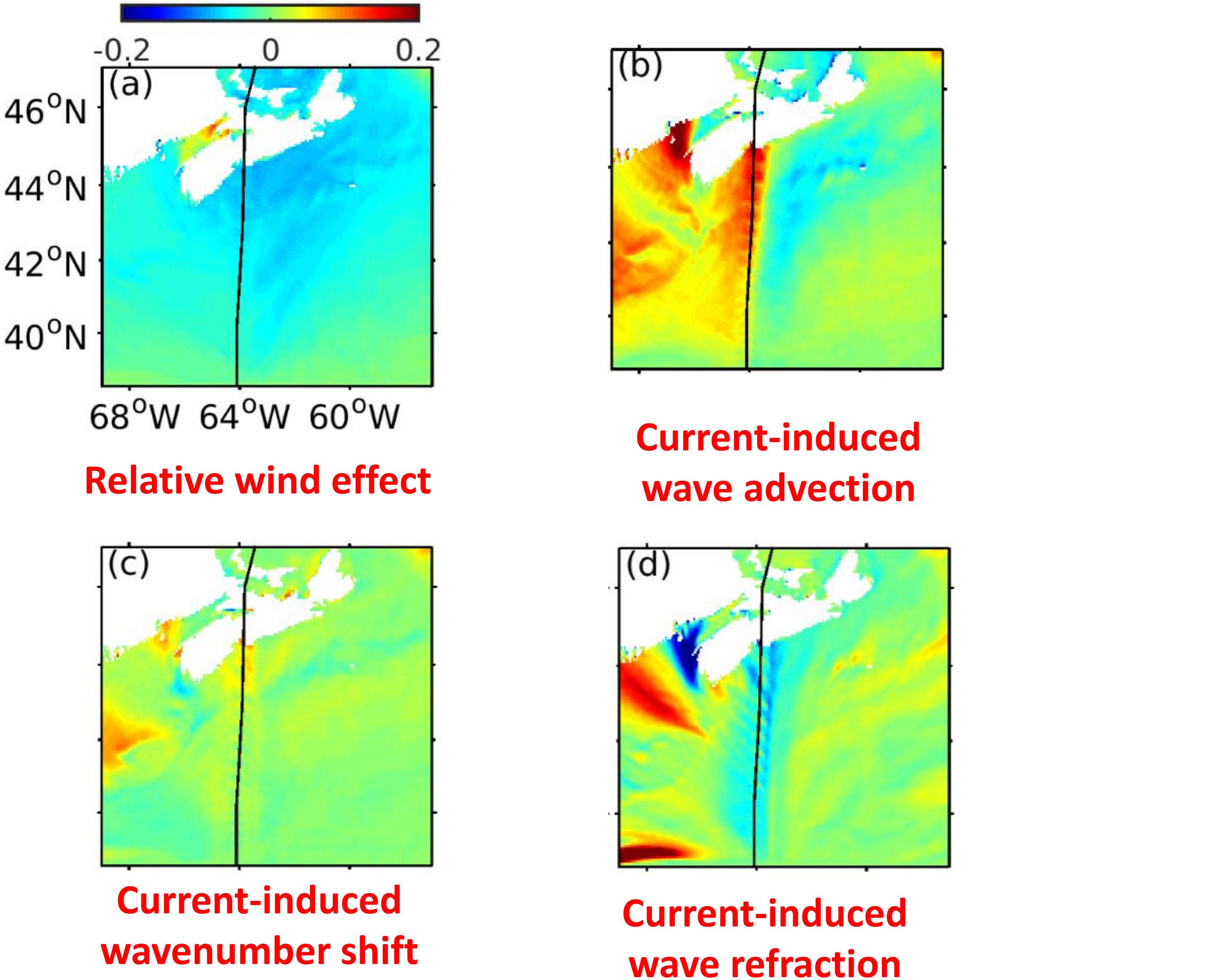


Normalized differences

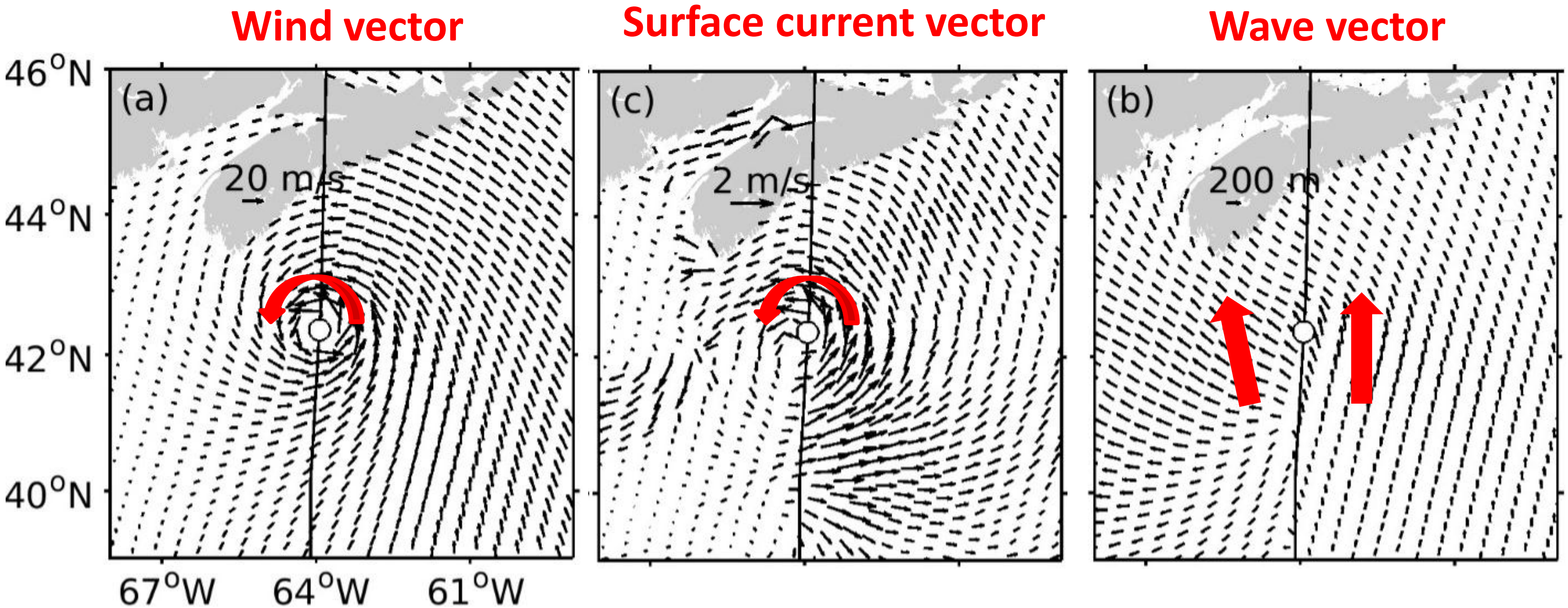
(a-b)/b



The roles of four WCI mechanisms on the distribution of maximum wave heights (Juan)

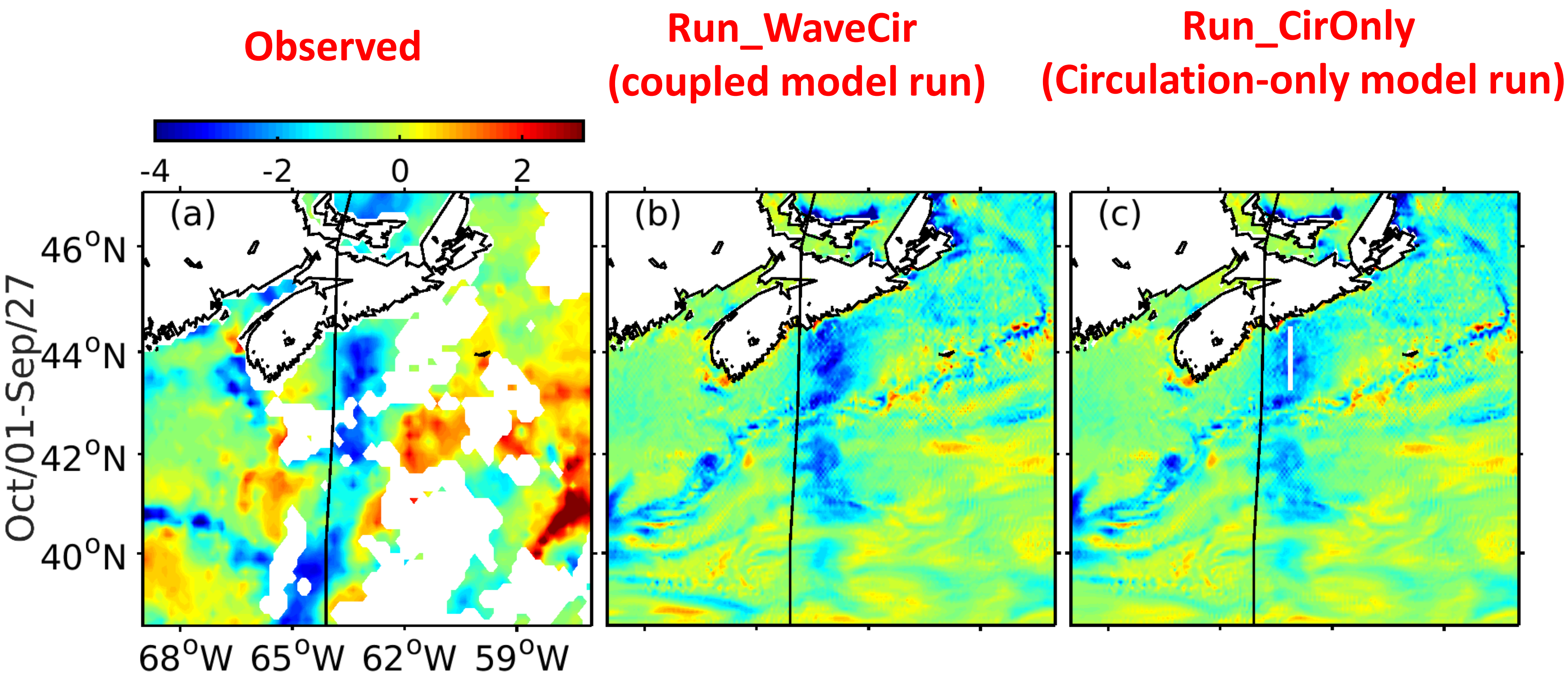


An explanation for the different roles of the WCI mechanisms on maximum wave heights (Juan)



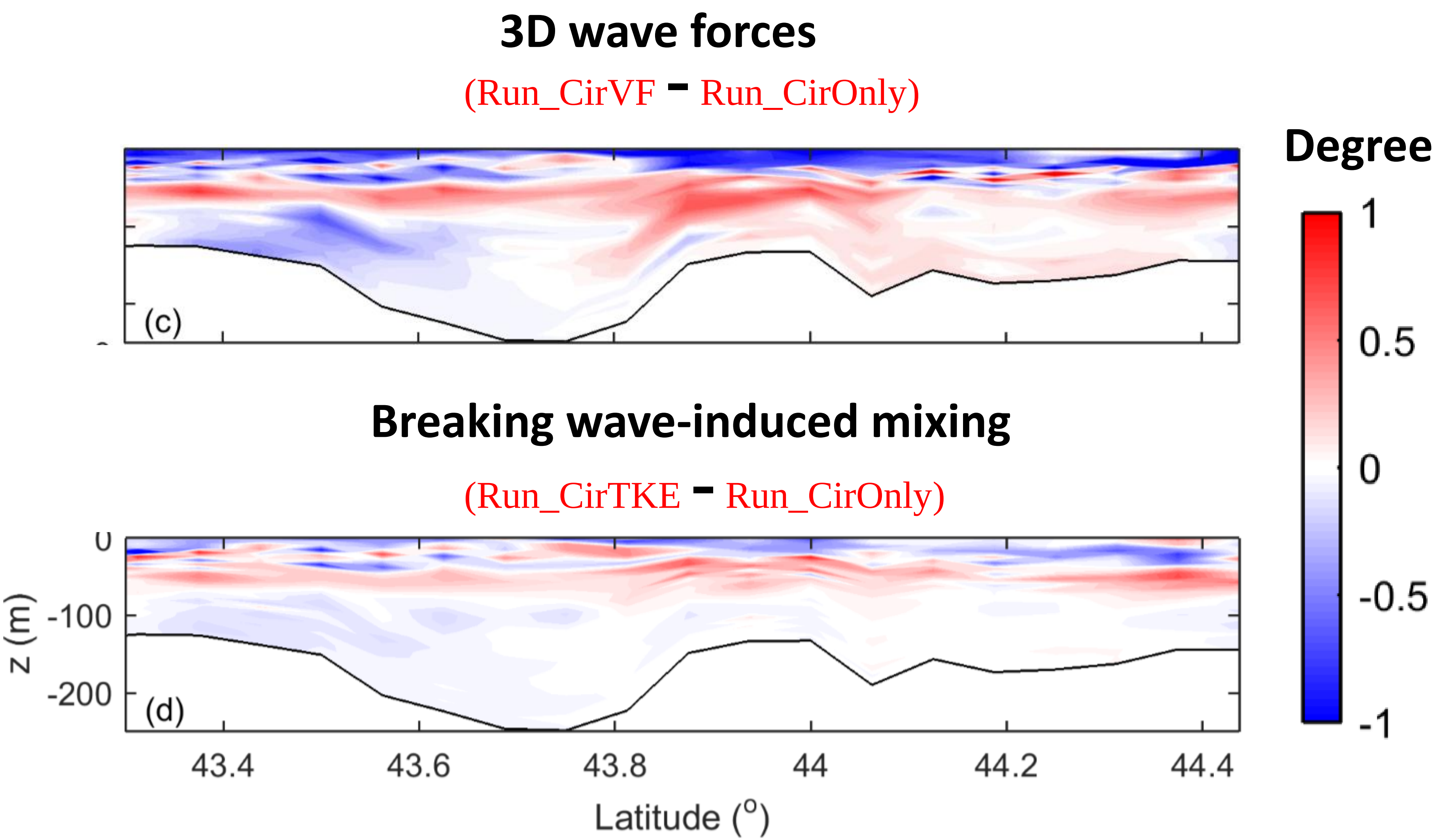
Hurricane translation speed: **9-15 m/s**
Group velocity of dominant swell waves: **9-10 m/s**
The wave field under a fast-moving hurricane is strongly affected by remotely generated swells

Observed and simulated SST change (Juan)

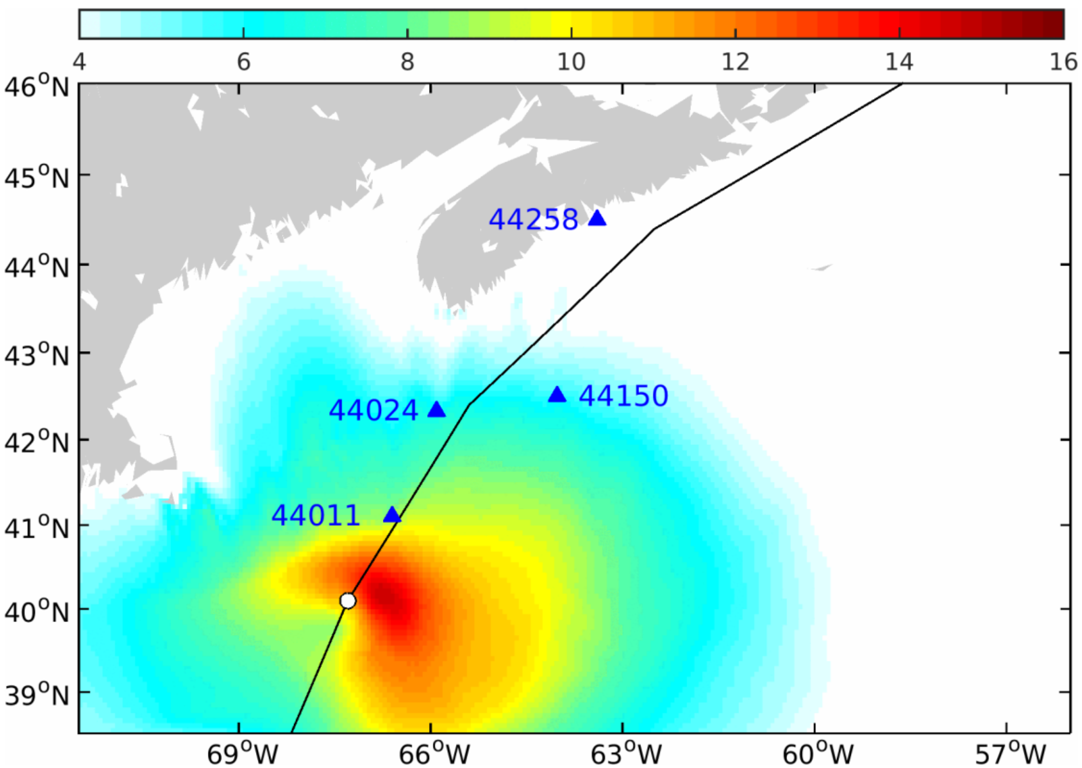


Comparison of SST cooling from (a) satellite data and model results in (b) Run_WaveCir and (c) Run_CirOnly

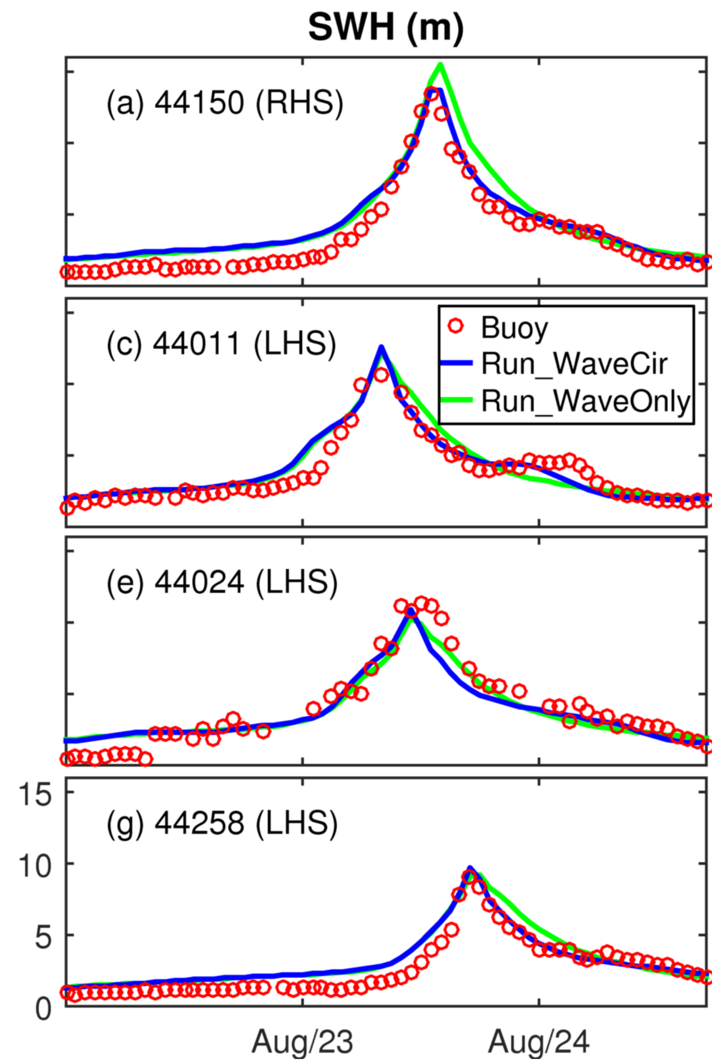
The roles of two WCI mechanisms on the storm-induced temperature changes (Juan)



4.2 Hurricane Bill

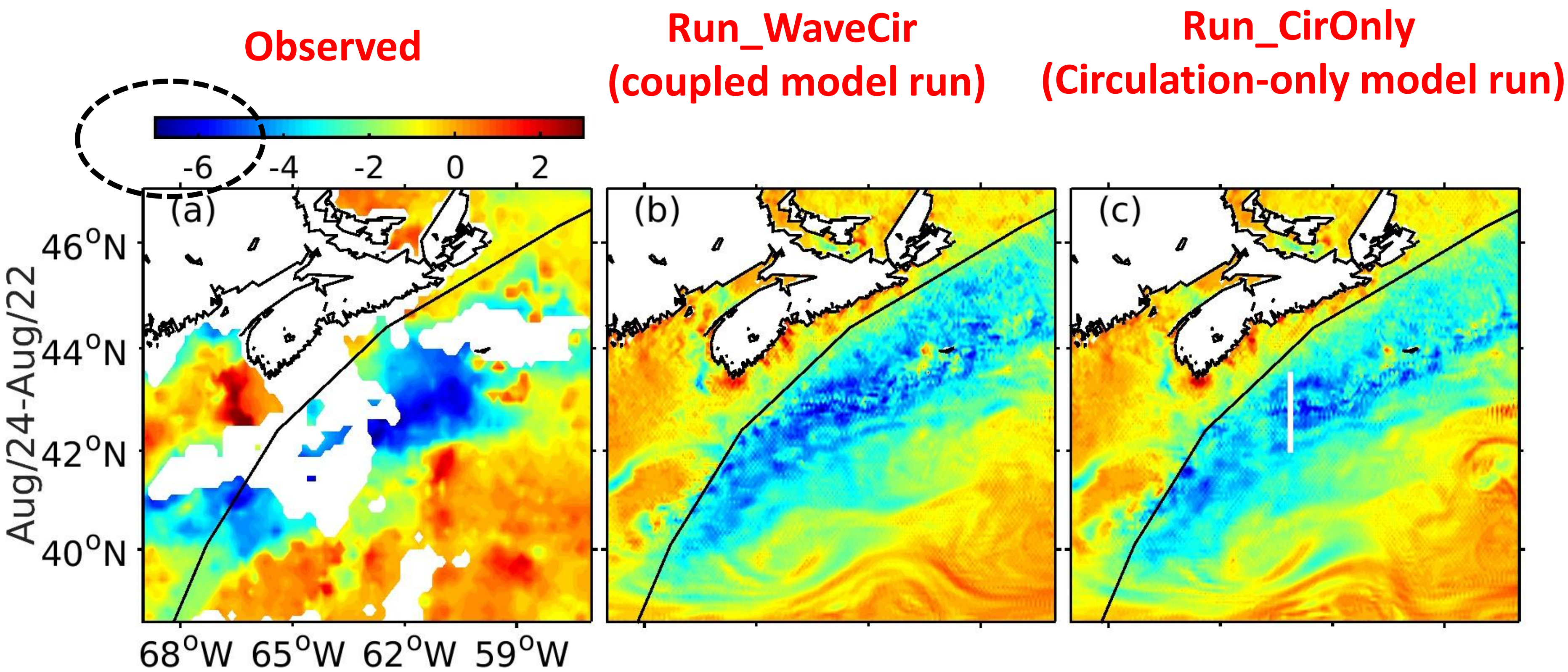


Simulated significant wave heights (m)



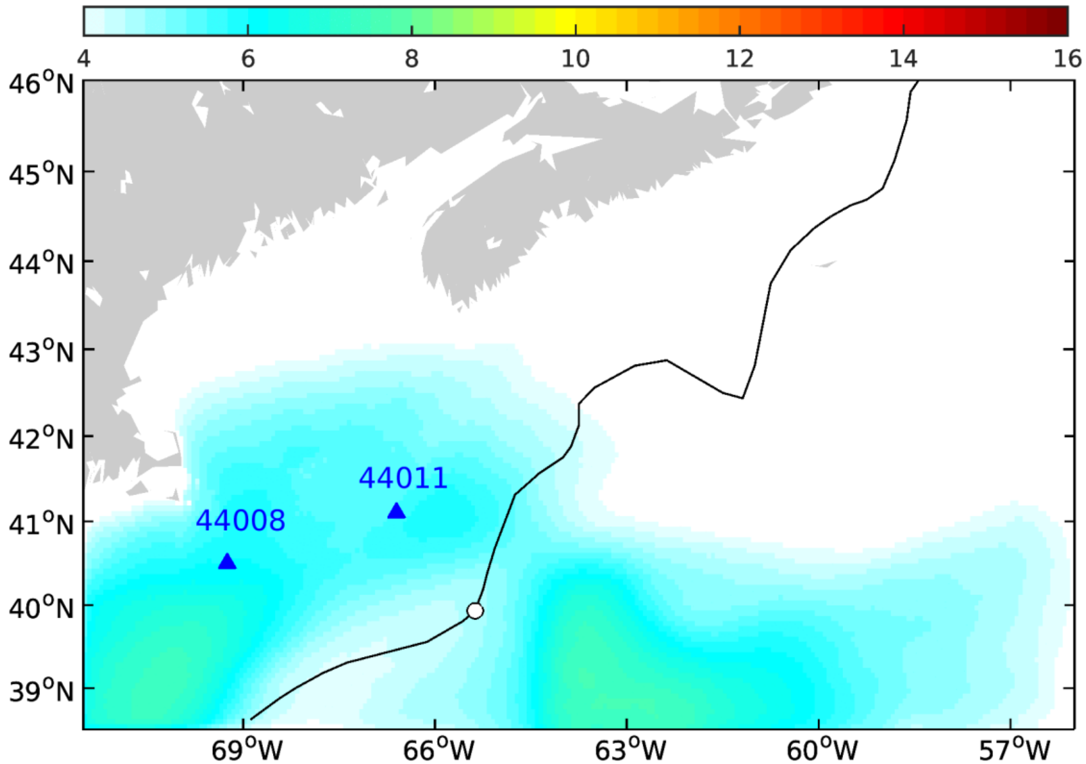
Comparison with observations

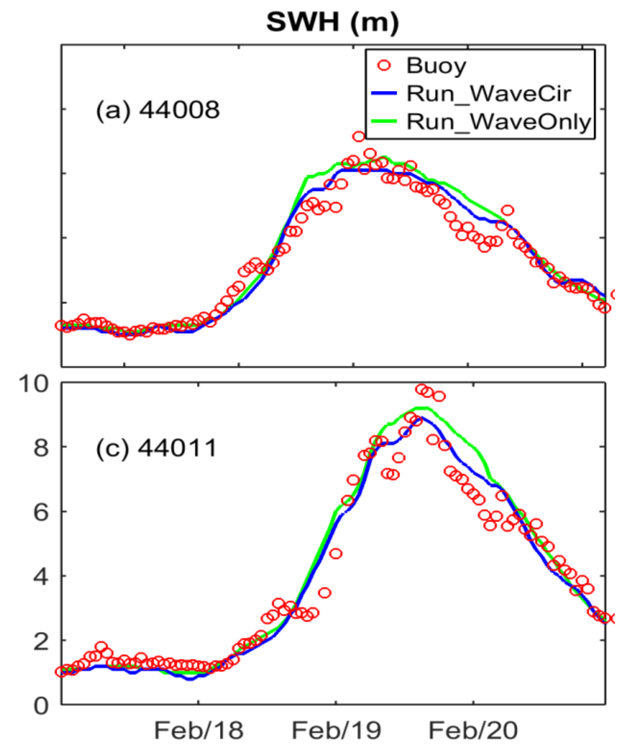
Observed and simulated SST change (Bill)



Comparison of SST cooling from (a) satellite data and model results in (b) Run_WaveCir and (c) Run_CirOnly

4.3 Winter storm "White Juan"



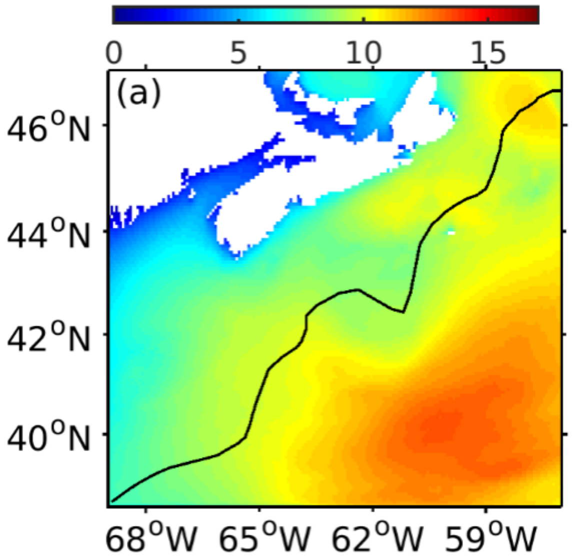


Simulated significant wave heights (m)

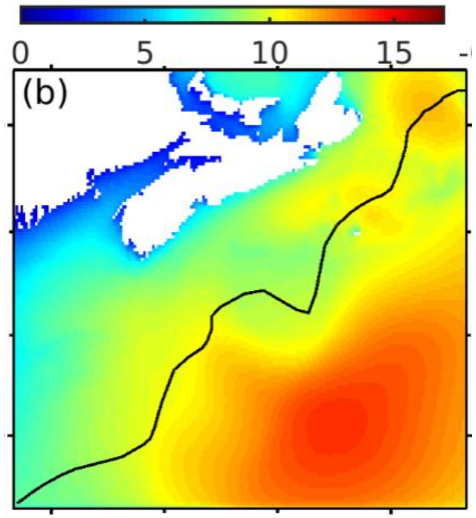
Comparison with observations

The distribution of maximum wave heights (White Juan)

Run_WaveCir
(coupled model run)

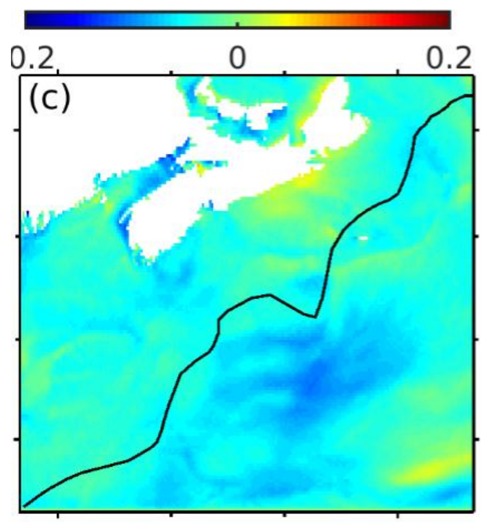


Run_WaveOnly
(wave-only model run)

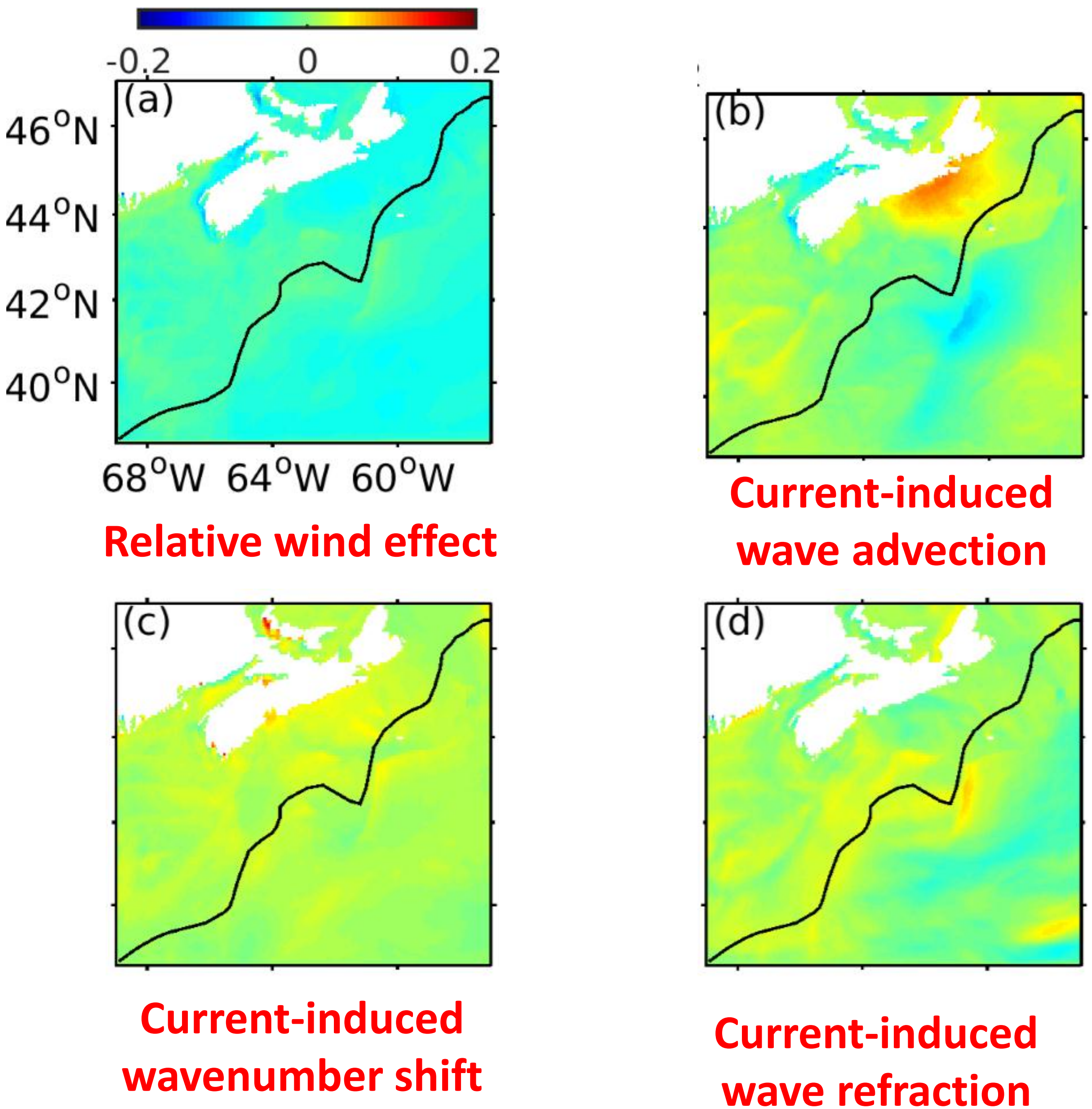


Normalized differences

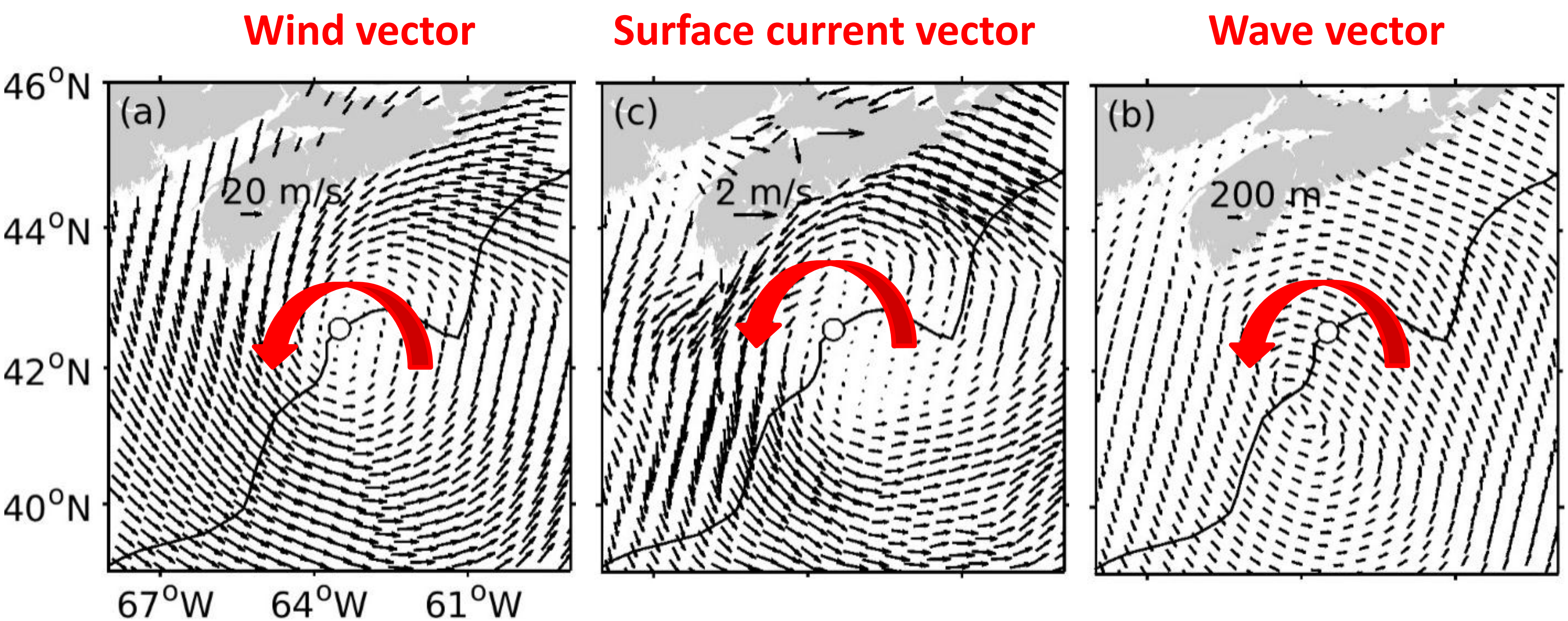
(a-b)/b



The roles of four WCI mechanisms on the distribution of maximum wave heights (White Juan)



An explanation for the different roles of the WCI mechanisms on maximum wave heights (White Juan)

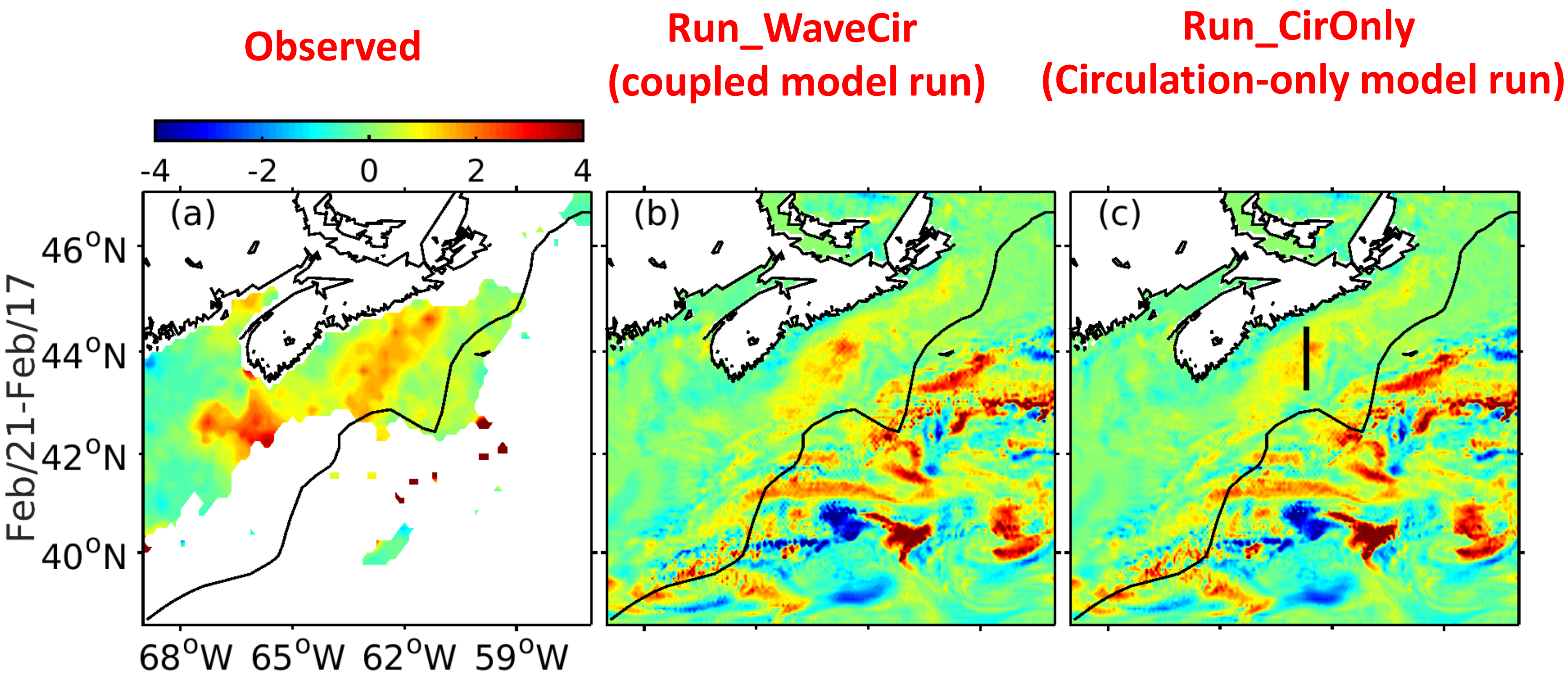


Storm translation speed: ~5 m/s

Group velocity of dominant swell waves: 9-10 m/s

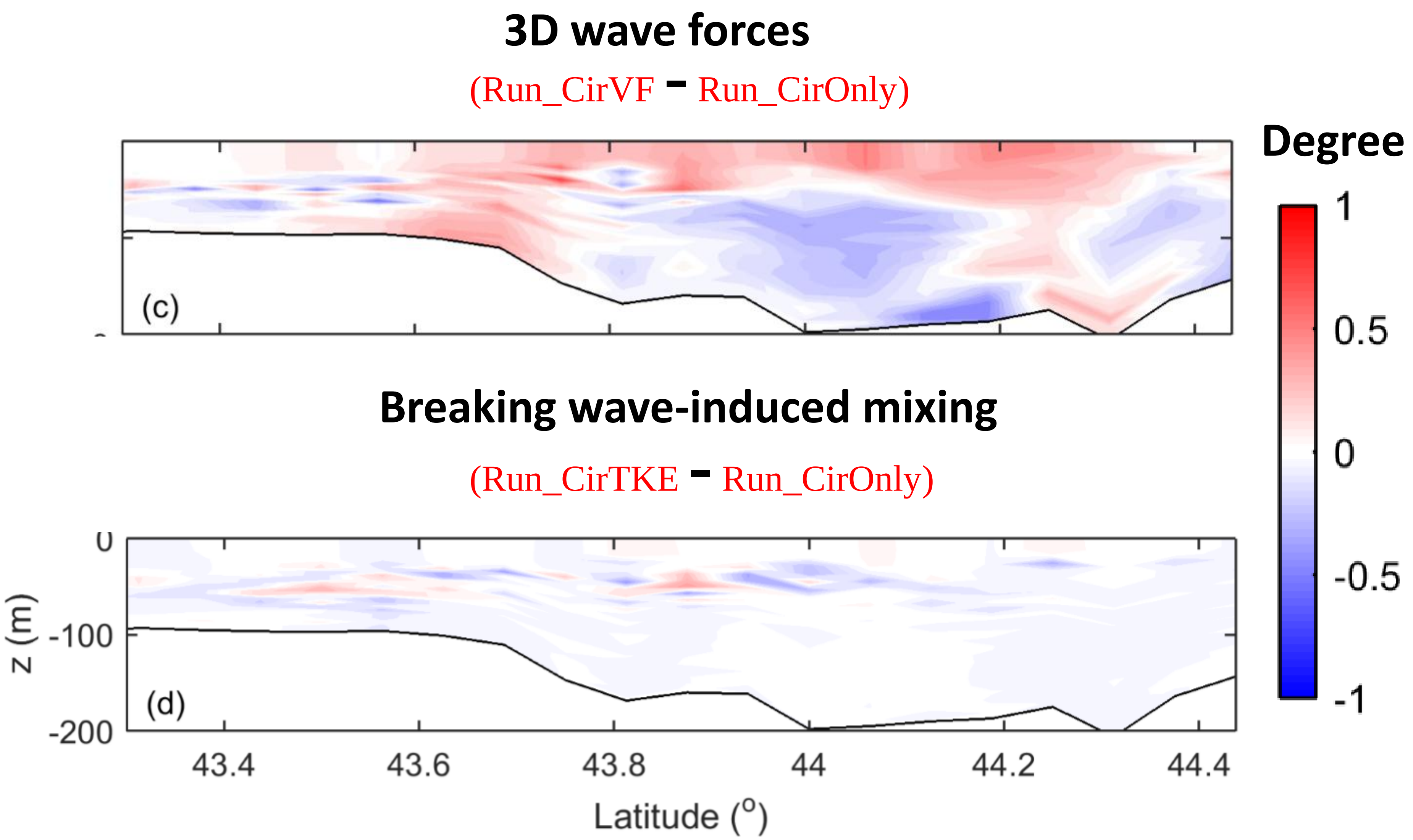
The wave field under a slow-moving winter storm is strongly affected by locally generated waves

Observed and simulated SST change (White Juan)



Comparison of SST change from (a) satellite data and model results in (b) Run_WaveCir and (c) Run_CirOnly

The roles of two WCI mechanisms on the storm-induced temperature changes (White Juan)



5. Summary

- **Development, validation and application of a coupled wave-circulation model during three storm events.**
- **Three major WCI mechanisms on waves are identified during three storm events: the relative wind effect, current-induced wave advection and refraction.**
- **The 3D wave forces can affect the vertical mixing and temperature changes up to 200 m in all three storm cases. The effect of the breaking wave-induced mixing depends on the background stratification in the upper ocean layer.**


Thank you!