Tidal Modulations of Surface Gravity Waves in the Gulf of Maine

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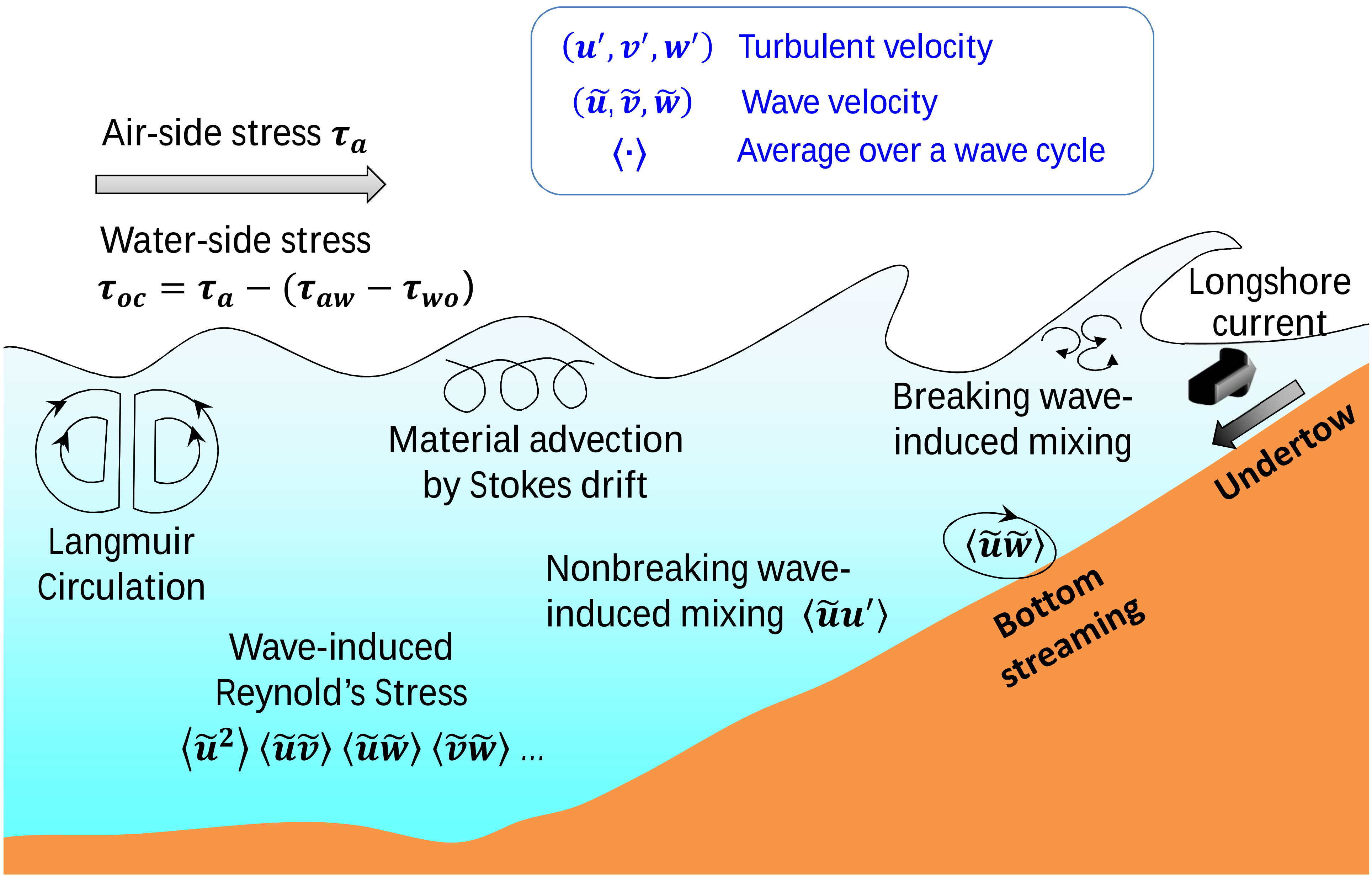
Outline

1. Introduction
2. A coupled wave-circulation model based on POM and WW3
3. Analysis of observational data in the Gulf of Maine (GOM)
4. Numerical model results (Effects of tidal currents on surface waves)
5. Ocean Frontier Institute
6. Summary

1. Introduction

- **Accurate simulation and prediction of 3D currents and surface gravity waves require better knowledge of wave-current interactions (WCIs), particularly over coastal and shelf waters.**
- **Significant progress has been made in the development and applications of coupled circulation-wave models.**
- **WCIs are expected to be large during extreme weather events such as hurricanes or tropical storms, and also large over areas with strong tidal currents.**
- **One would expect that the tidal modulation in the wave height should reach its maximum in the contra tidal currents.**
- **Higher surface waves in the following tidal currents were frequently observed than those in the contra tidal currents.**

A. Effects of waves on currents (WEC)



Effects of waves on the 3D circulation (WEC):

- **3D wave forces based on the "Vortex force" formulism**

(Bennis et al., 2011)

$$\frac{\partial \hat{u}}{\partial t} + \hat{u}\frac{\partial \hat{u}}{\partial x} + \hat{v}\frac{\partial \hat{u}}{\partial y} + \hat{w}\frac{\partial \hat{u}}{\partial z} - f\hat{v} + \frac{1}{\rho}\frac{\partial p}{\partial x} =$$

$$\underbrace{\left[f + \left(\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y}\right)\right]V_s - W_s\frac{\partial \hat{u}}{\partial z}}_{\text{Vortex force}} - \underbrace{\frac{\partial J}{\partial x}}_{\text{Bernouilli's head}} + \underbrace{F_{d,x}}_{\text{Dissipation force}} + F_{m,x}$$

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

- **Wave-enhanced vertical mixing due to wave breaking:**

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

(Craig & Banner, 1994)

B. Effects of currents on waves (CEW)

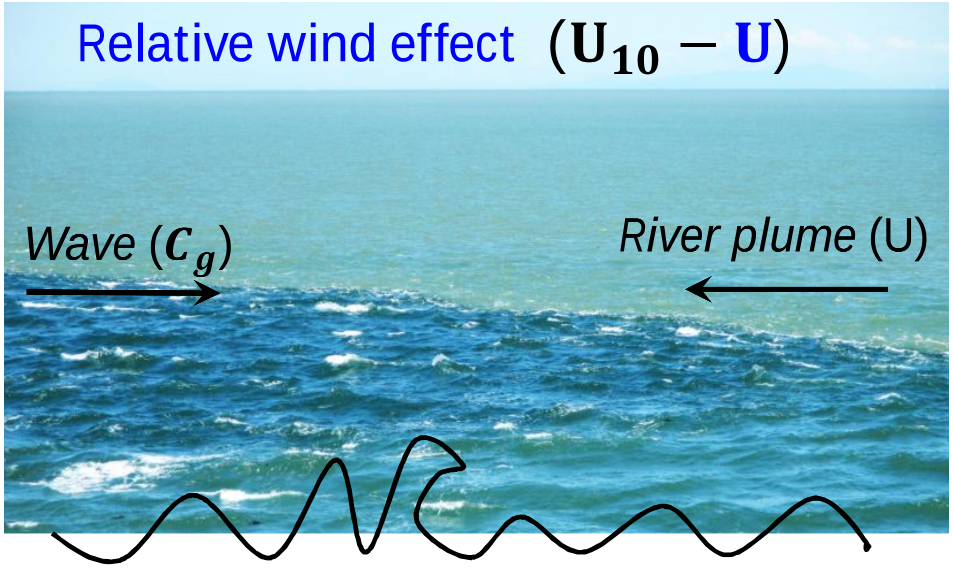
Wave action balance equation:

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \left[(C_g + \mathbf{U})N\right] - \frac{\partial}{\partial k}\left(\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial s} + \mathbf{k}\cdot\frac{\partial \mathbf{U}}{\partial s}\right)N - \frac{\partial}{\partial \theta}\left[\frac{1}{k}\left(\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m} + \mathbf{k}\cdot\frac{\partial \mathbf{U}}{\partial m}\right)\right]N = \frac{S}{\sigma}$$

Current-induced advection

Current-induced wavenumber shift

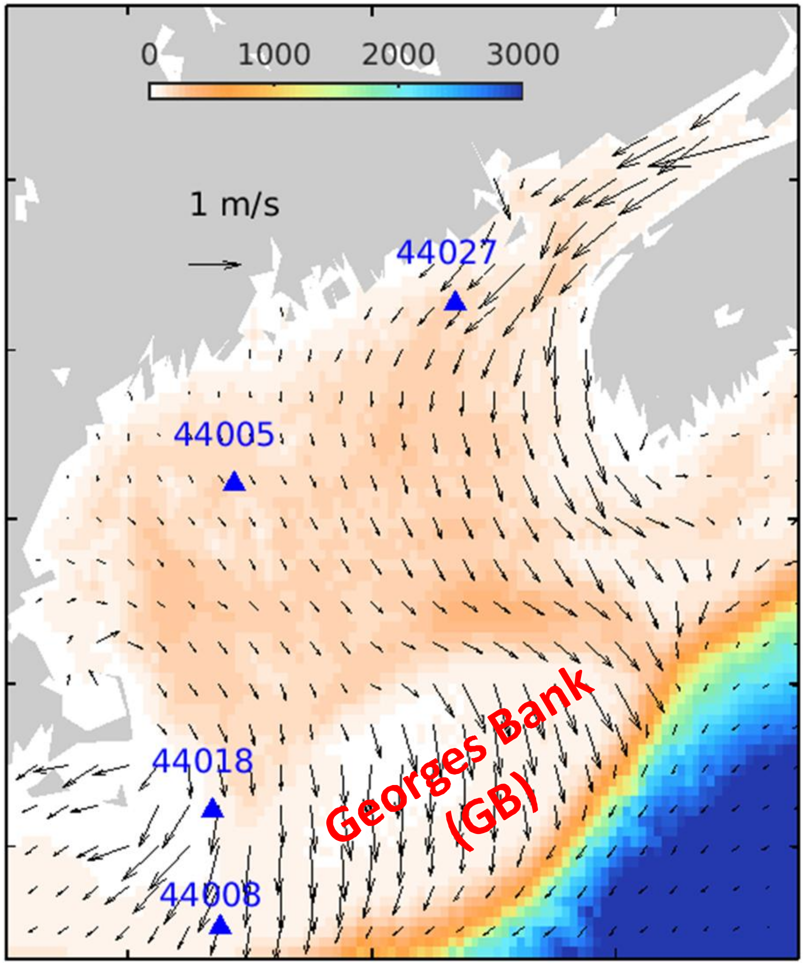
Current-induced refraction

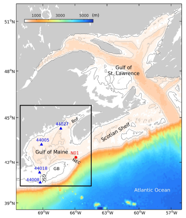


(Strait of Georgia, BC)

Current-enhanced wave dissipation

Research Objective and Methods





(Surface ocean currents produced by DalCoast)

Objective:

To examine tidal modulations of surface gravity waves in the Gulf of Maine (GOM) and associated important physical processes

Methods:

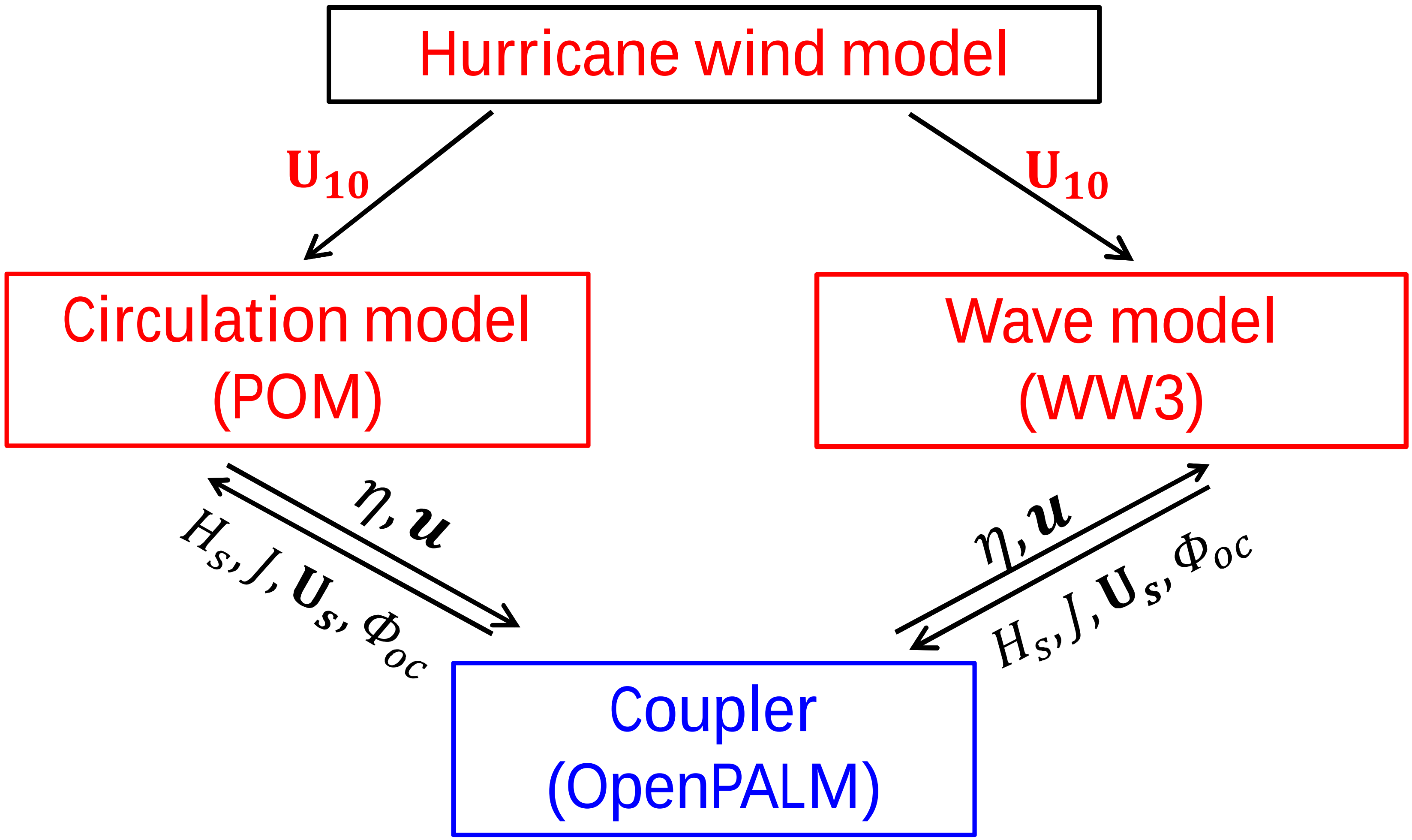
- Buoy observations

  44027 44005 44018 44008

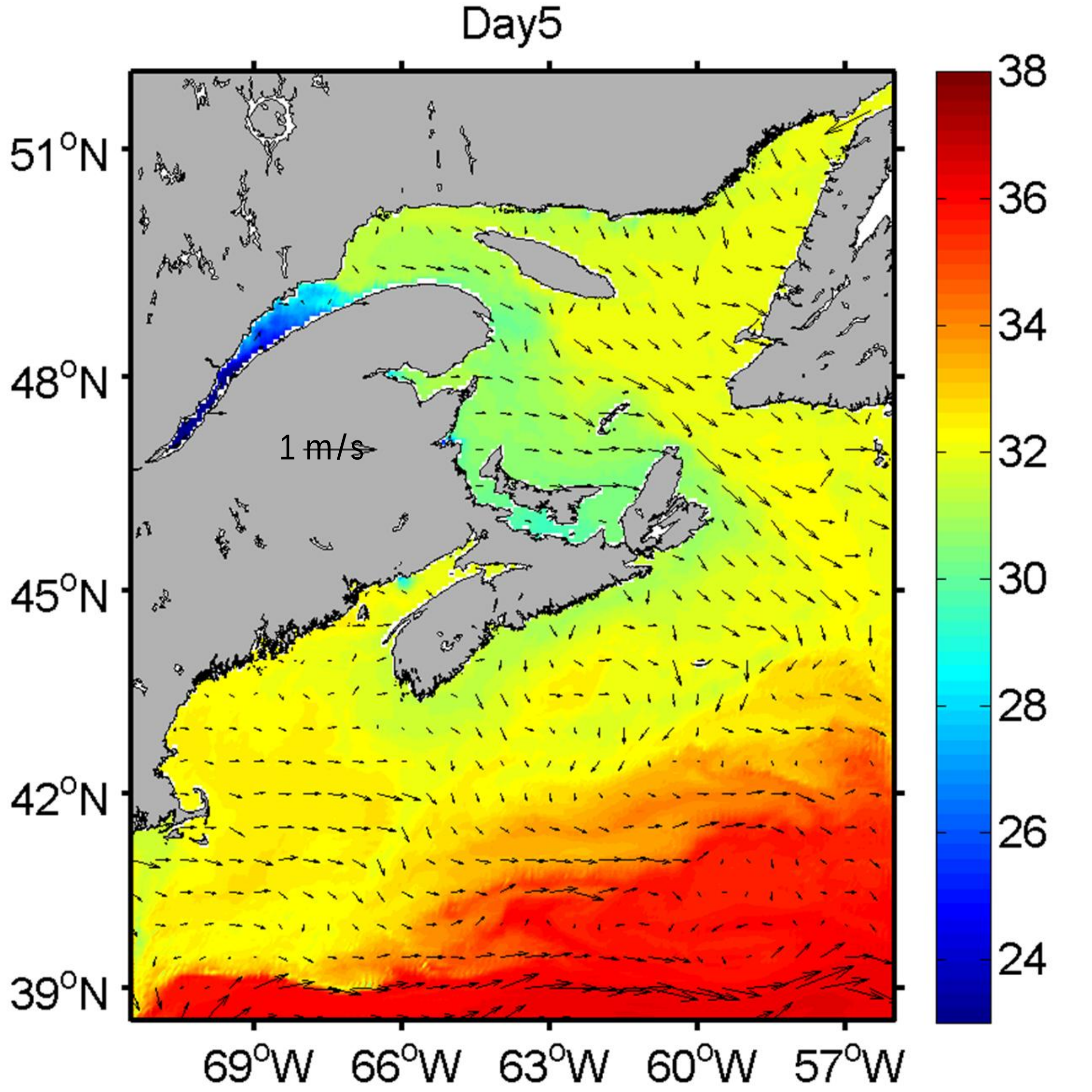
- A coupled wave-circulation model

  Wave model: WAVEWATCH III
  Circulation model: DalCoast

2. Coupled Wave-Circulation Model



Simulated sea surface currents and salinity in 2008 produced by DalCoast based on POM



Application One: Wave-current interactions over the eastern Canadian shelf under three extreme weather conditions

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2016JC011758

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

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Key Points:

- A comparative study of wave-current interactions during three storms
- Application of a coupled model based on a 3D circulation model and a third-generation wave model
- Examining the role of the storm translation speed in wave-current interactions

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Citation:
Wang, P., and J. Sheng (2016), A comparative study of wave-current interactions over the eastern Canadian shelf under severe weather conditions

Abstract A coupled wave-circulation model is used to examine interactions between surface gravity waves and ocean currents over the eastern Canadian shelf and adjacent deep waters during three severe weather events. The simulated significant wave heights (SWHs) and peak wave periods reveal the importance of wave-current interactions (WCI) during and after the storm. In two fast-moving hurricane cases, the maximum SWHs are reduced by more than 11% on the right-hand side of the storm track and increased by about 5% on the left-hand side due to different WCI mechanisms on waves on two sides of the track. The dominate mechanisms of the WCI on waves include the current-induced modification of wind energy input to the wave generation, and current-induced wave advection and refraction. In the slow-moving winter storm case, the effect of WCI decreases the maximum SWHs on both sides of the storm track due to different results of the current-induced wave advection, which is affected greatly by the storm translation speed. The simulated sea surface temperature (SST) cooling induced by hurricanes and SST warming induced

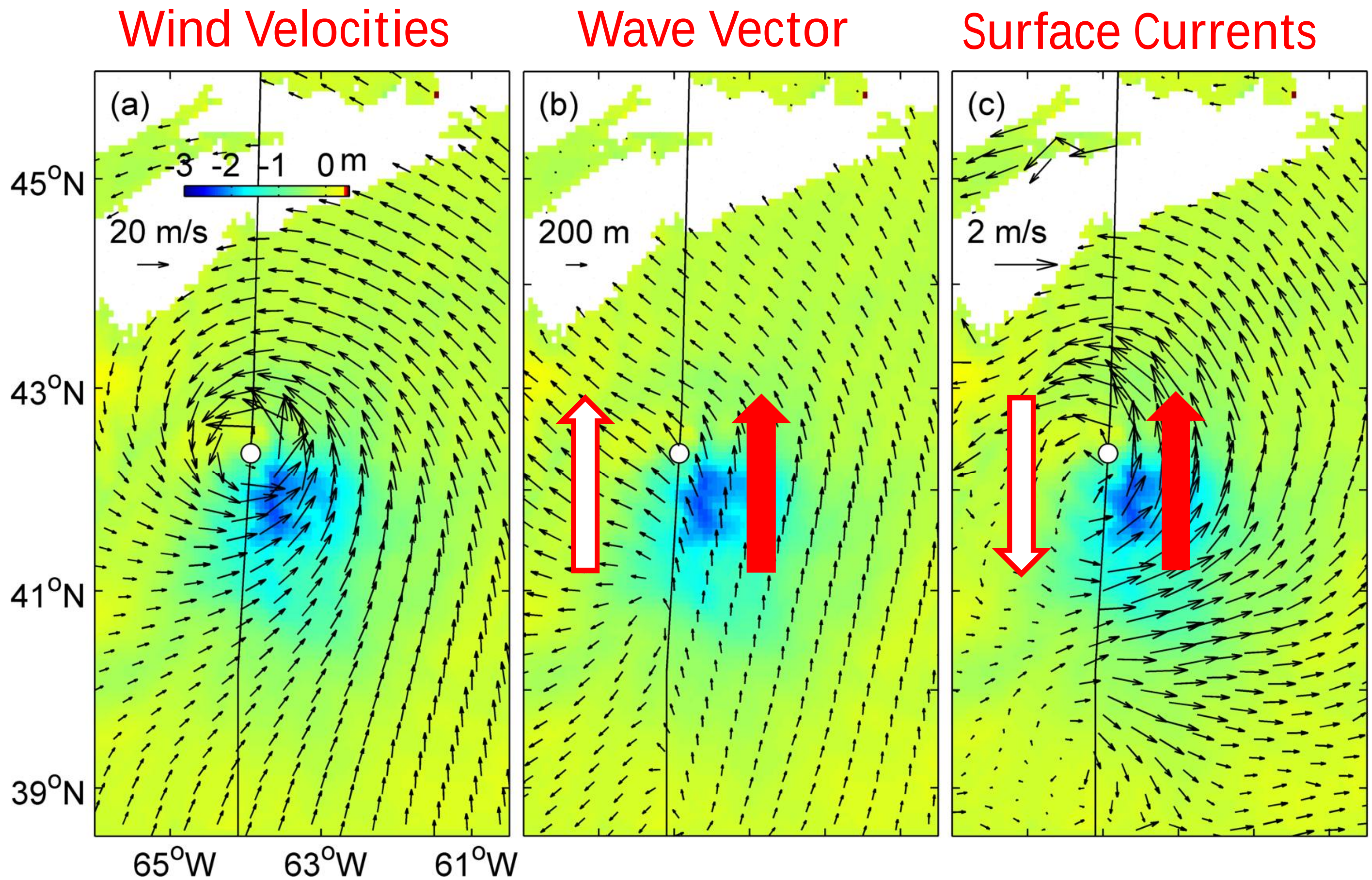

Image: differences in *Hs* due to effect of circulation on waves

- Surface currents reduce the effective wind speeds to waves
- Currents increase the advection velocity of the wave packet

Application Two: Wave-current interactions over the Canadian coastal waters

Contents lists available at ScienceDirect

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Assessing the performance of formulations for nonlinear feedback of surface gravity waves on ocean currents over coastal waters

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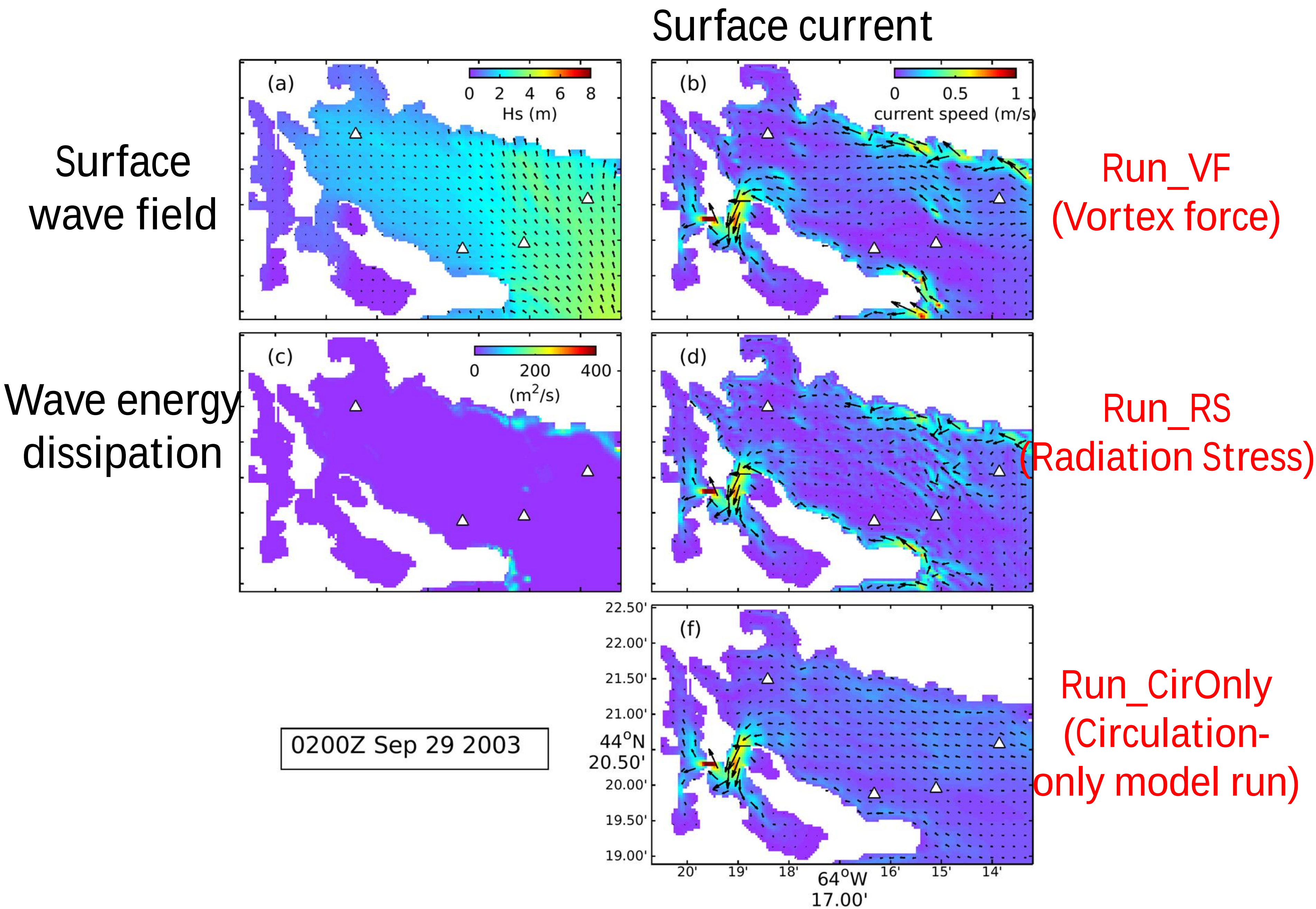
A R T I C L E I N F O

Keywords:
Wave-current coupling
Surface waves
Radiation stress
Vortex force
Coastal circulation
Numerical model

A B S T R A C T

This study presents applications of a two-way coupled wave-circulation modelling system over coastal waters, with a special emphasis of performance assessments of two different methods for nonlinear feedback of ocean surface gravity waves on three-dimensional (3D) ocean currents. These two methods are the vortex force (VF) formulation suggested by Bennis et al. (2011) and the latest version of radiation stress (RS) formulation suggested by Mellor (2015). The coupled modelling system is first applied to two idealized test cases of surf-zone scales to validate implementations of these two methods in the coupled wave-circulation system. Model results show that the latest version of RS has difficulties in producing the undertow over the surf zone. The coupled system is then applied to Lunenburg Bay (LB) of Nova Scotia during Hurricane Juan in 2003. The coupled system using both the VF and RS formulations generates much stronger and more realistic 3D circulation in the Bay



Surface current
Surface wave field
Wave energy dissipation
(a)
0 2 4 6 8
Hs (m)
(b)
0 0.5 1
current speed (m/s)
(c)
0 200 400
(m^2/s)
(d)
(f)
Run_VF
(Vortex force)
Run_RS
(Radiation Stress)
Run_CirOnly
(Circulation-only model run)
0200Z Sep 29 2003
22.50'
22.00'
21.50'
21.00'
44°N 20.50'
20.00'
19.50'
19.00'
20'
19'
18'
64°W 17.00'
16'
15'
14'

Application Three: Tidal modulation of surface waves in the Gulf of Maine.

Tidal Modulation of Surface Gravity Waves in the Gulf of Maine

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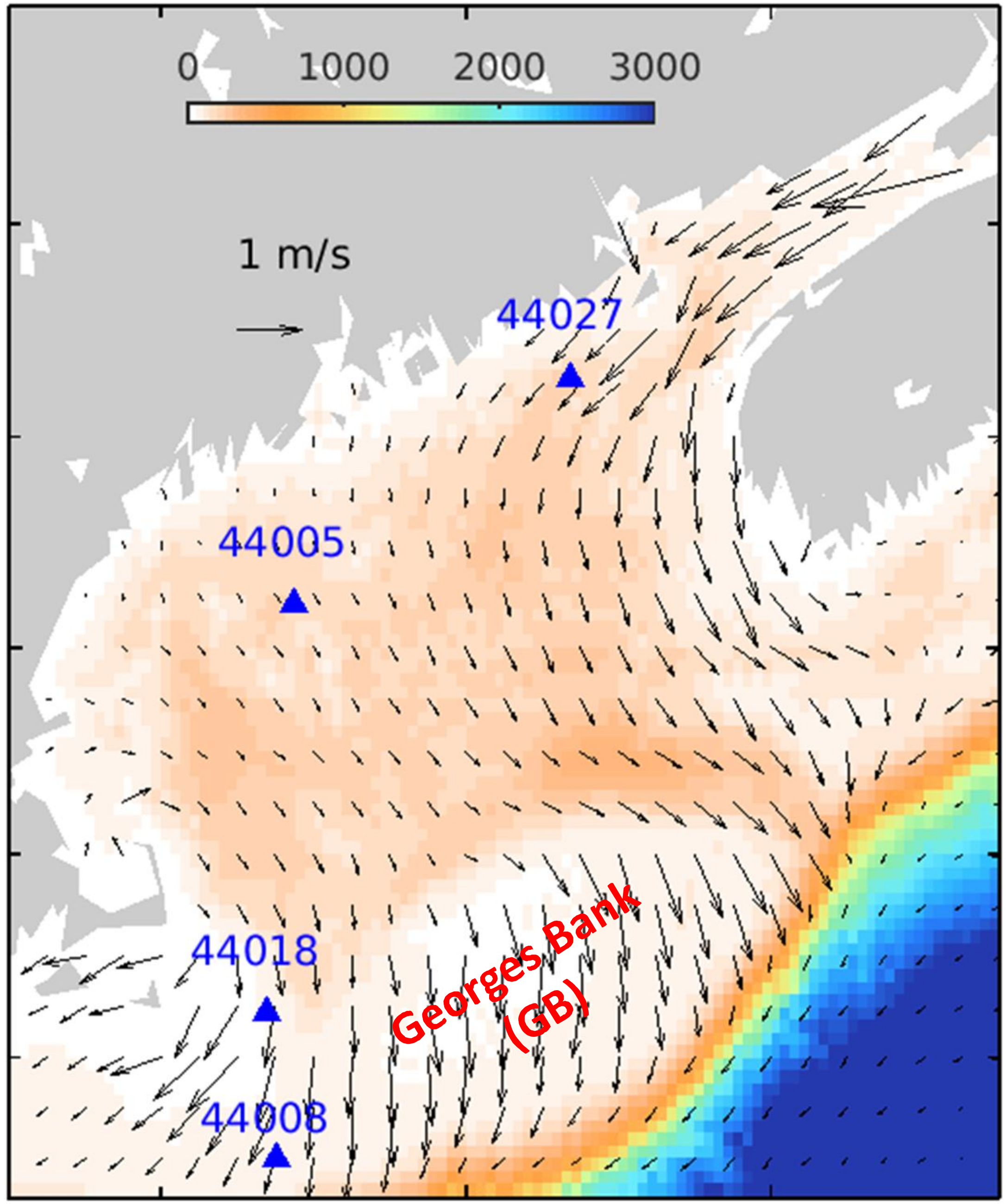
(Manuscript received 28 November 2017, in final form 15 August 2018)

ABSTRACT

This study examines the tidal modulation of surface gravity waves in the Gulf of Maine (GoM) by using in situ observations and numerical model results. Analysis of observational data demonstrates significant semidiurnal tidal modulations in the mean wave variables for swell-dominated waves in the region. The observed tidal modulation features significant spatial–temporal variabilities, with large magnitudes near the mouth of the GoM. Observations also demonstrate unusual timing of the maximum modulation of significant wave height H_s in the following tidal currents. The coupled wave–circulation model successfully reproduces the observed tidal modulation and the associated spatial–temporal variabilities. Model results demonstrate that the maximum H_s modulations are first generated during the maximum flood tide or ebb tide near the mouth of the GoM and then propagate onto the inner gulf. Around the mouth of the GoM, tidal currents have strong spatial gradients, resulting in great effects of current-induced convergence, refraction, and wave-number shift. The tidal modulation in H_s generated by convergence (10%–14%) is less affected by the wave propagation direction than the modulation generated by the wavenumber shift (6%–10%) and refraction (4%–20%). The latter modulation varies significantly with changes in the wave propagation direction. In addition, current-enhanced dissipation becomes important during high winds, which reduces at least one-half of the H_s modulation during the study period. The observed unusual timing of the maximum H_s modulation in the following tidal currents can be mostly explained by the convergence and wavenumber shift associated with wave-energy convergence and energy transfer from currents to waves in spatially decelerating currents.

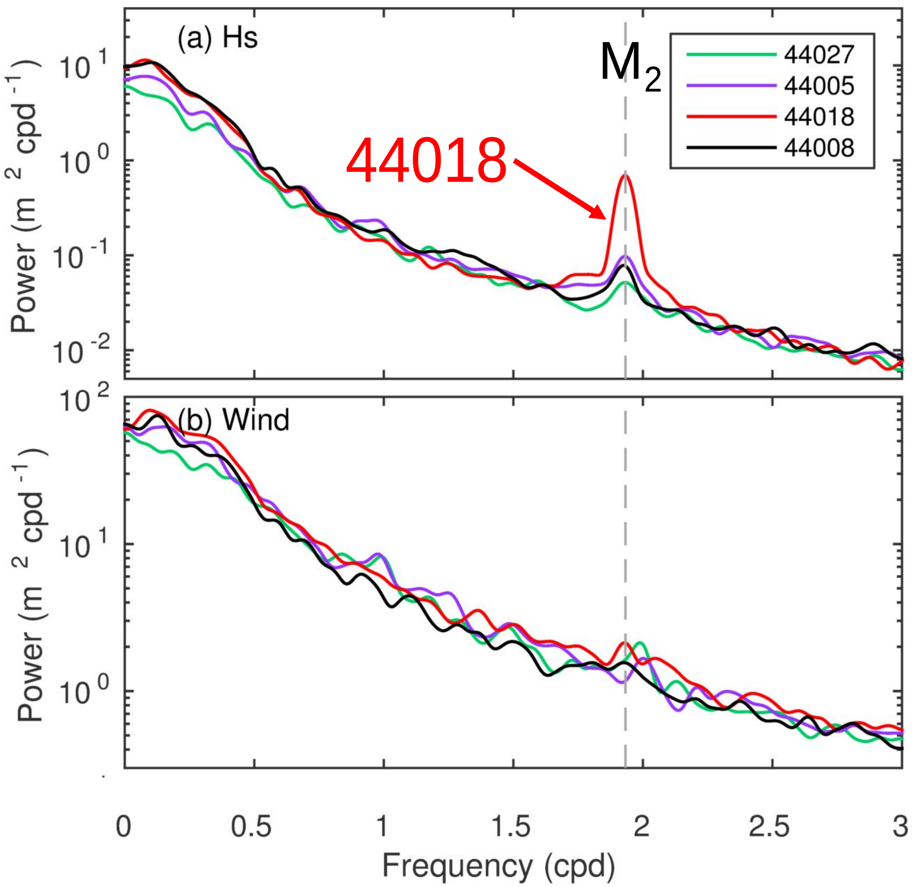
Application Three: Tidal modulation of surface waves in the Gulf of Maine.



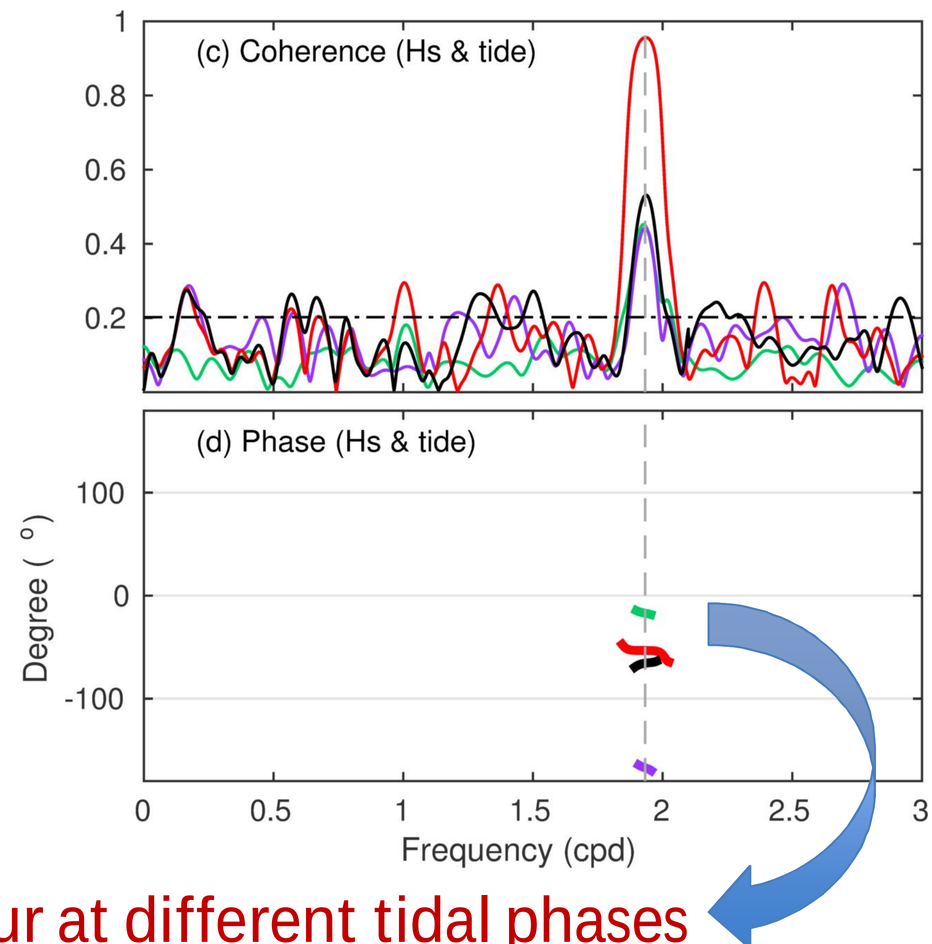
3. Analysis of Observational Data

Spectral content (2008-2010)

Power spectra of significant wave height (Hs) and wind

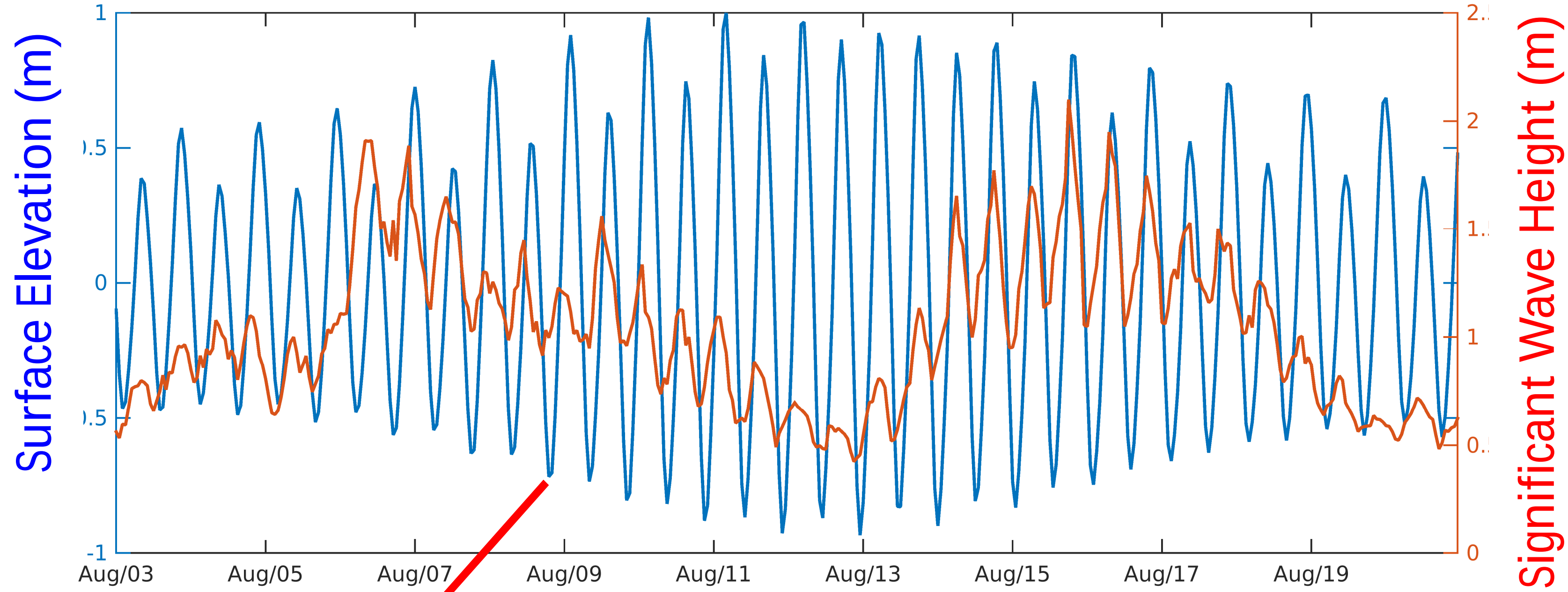


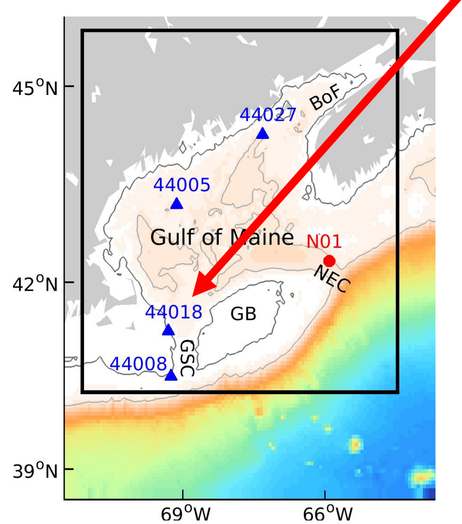
Cross-spectra analysis of Hs and tidal elevation



The maximum Hs modulations occur at different tidal phases

Time series of tidal elevation and SWH (Hs) at 44018





There exists a consistent phase relationship between these two signals, with the maximum $\boldsymbol{H_s}$ modulation occurring during the rising tide. Tidal elevation is calculated from OTIS dataset.

4. Numerical Model results

- Effects of ocean currents on ocean waves are implemented through the wave action balance equation:

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \left[\left(C_g + \underbrace{\mathbf{U}}_{} \right) N \right] - \frac{\partial}{\partial k} \left(\frac{\partial \sigma}{\partial d} \frac{\partial d}{\partial s} + \mathbf{k} \cdot \underbrace{\frac{\partial \mathbf{U}}{\partial s}}_{} \right) N - \frac{\partial}{\partial \theta} \left[\frac{1}{k} \left(\frac{\partial \sigma}{\partial d} \frac{\partial d}{\partial m} + \mathbf{k} \cdot \underbrace{\frac{\partial \mathbf{U}}{\partial m}}_{} \right) \right] N = \frac{S}{\sigma}$$

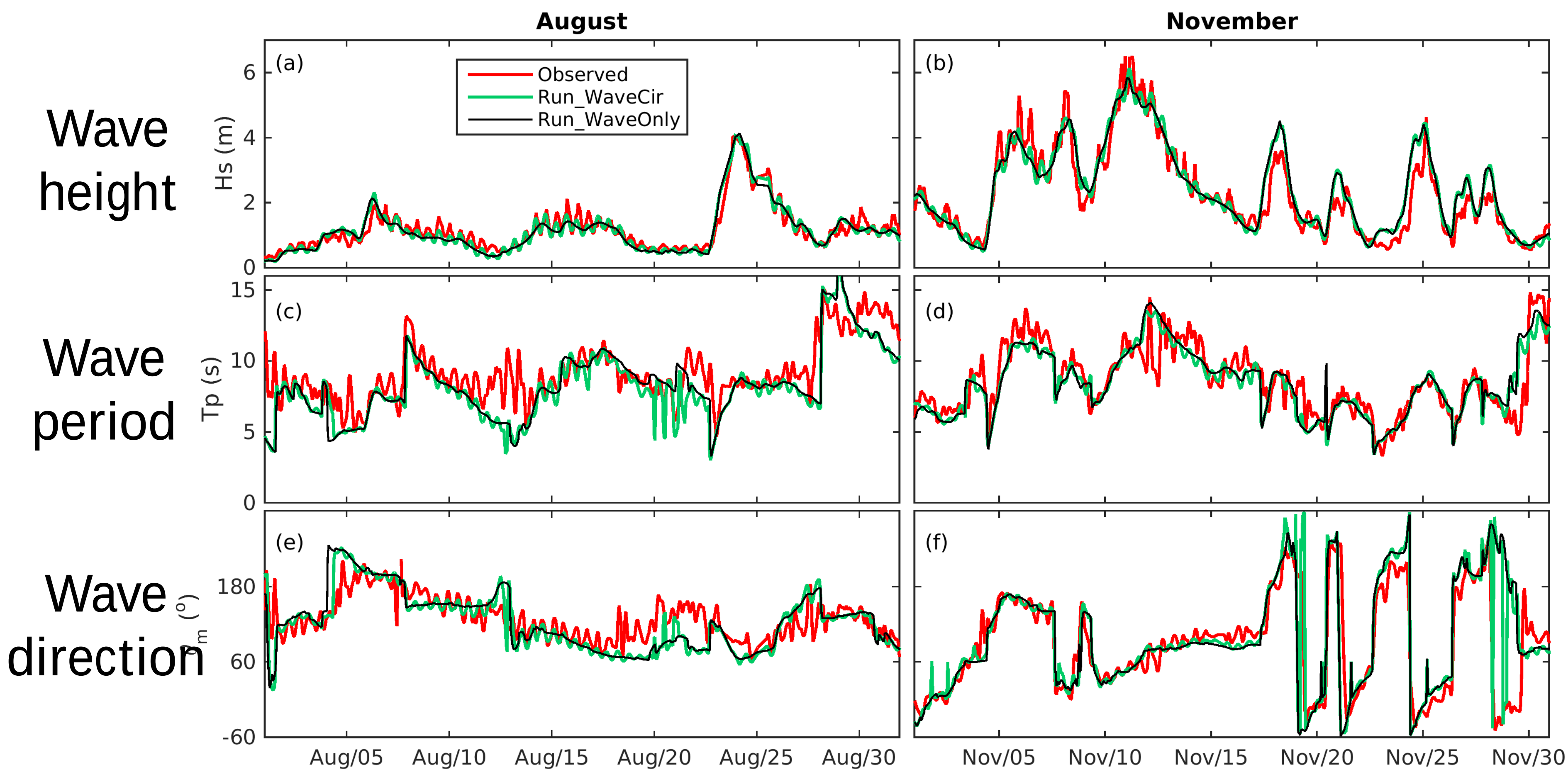
Current-induced advection | **Current-induced wavenumber shift** | **Current-induced refraction**

- List of five numerical experiments

Experiment	Current-induced advection	Current-induced wavenumber shift	Current-induced refraction
Run_WaveCir	✓	✓	✓
Run_WaveOnly		Wave-only model run	
Run_WaveC_g	✓	×	×
Run_Wavek	×	✓	×
Run_Waveθ	×	×	✓

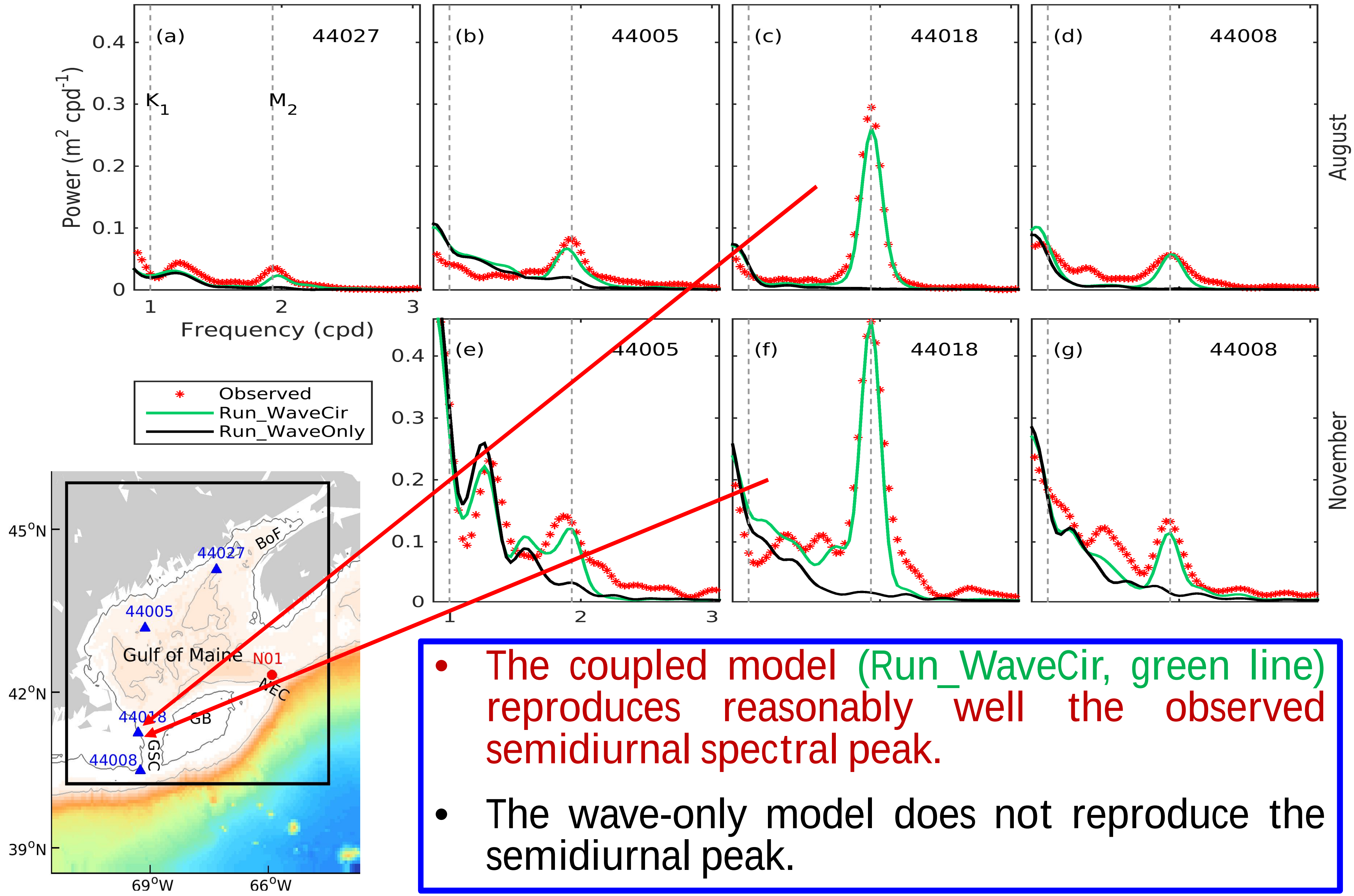
Process-oriented experiments

Time series of observed (red) and simulated (green, black) mean wave variables at buoy 44018



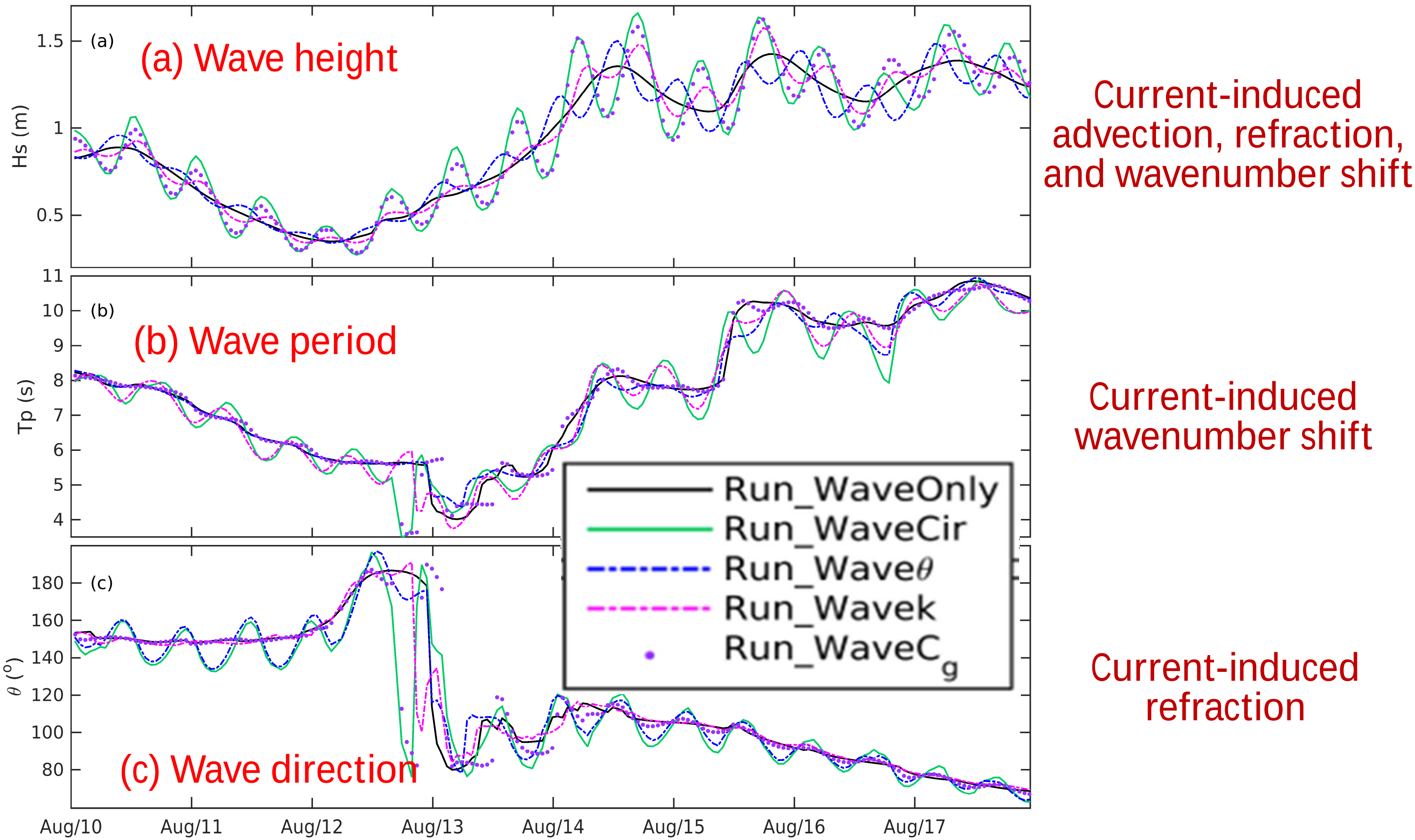
- The coupled model (Run_WaveCir, green line) reproduces reasonably well the observed tidal modulations of mean waves variables.
- The wave-only model does not generate tidal modulations.

Observed (red) and simulated (green, black) power spectra of Hs



- The coupled model (Run_WaveCir, green line) reproduces reasonably well the observed semidiurnal spectral peak.
- The wave-only model does not reproduce the semidiurnal peak.

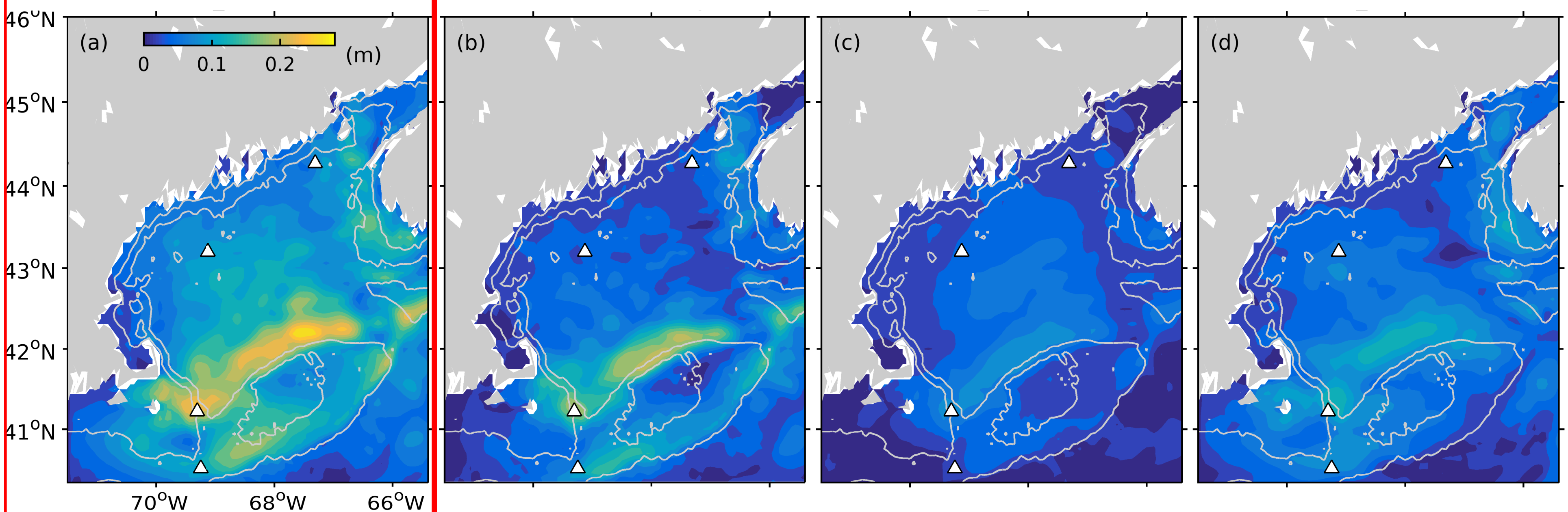
Physical processes for modulations of three mean wave variables



Simulated mean wave variables in the wave-only, fully coupled, and process-oriented model runs at buoy 44018 on August 10-17, 2010

Amplitudes of tidal modulations in Hs (August, 2010)

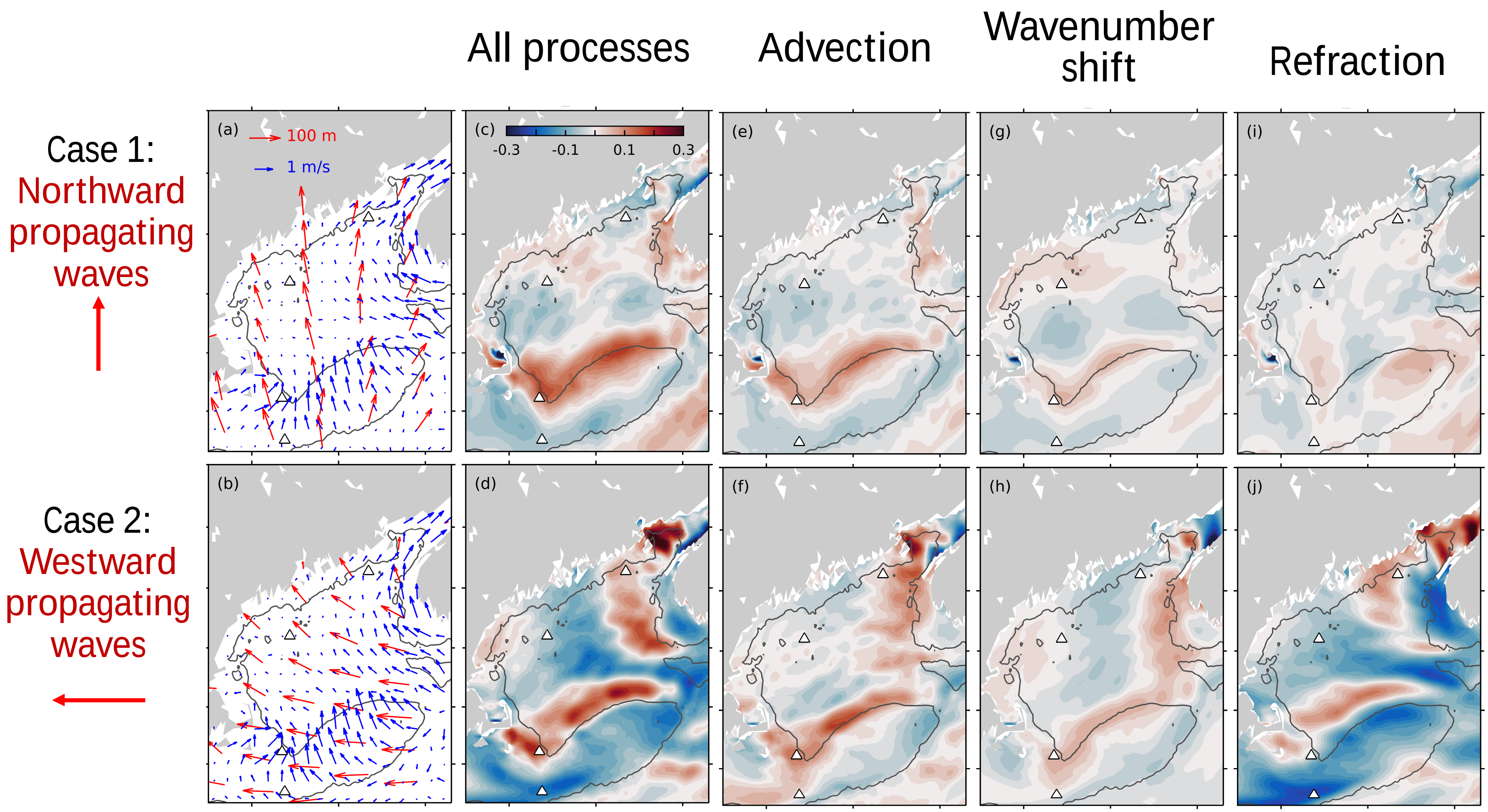
All processes | Current-induced advection | Current-induced wavenumber shift | Current-induced refraction



Both the current-induced advection and wavenumber shift contribute to the H_s modulation over the inner and outer edges of GB.

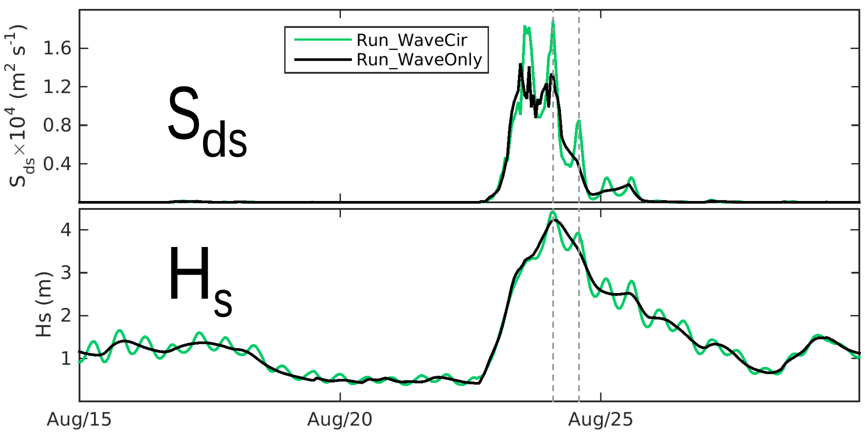
The refraction effect contributes to the H_s modulation over GB and areas behind GB.

Distributions of percentage changes in Hs (color image) induced by three major processes in two cases at the maximum flood



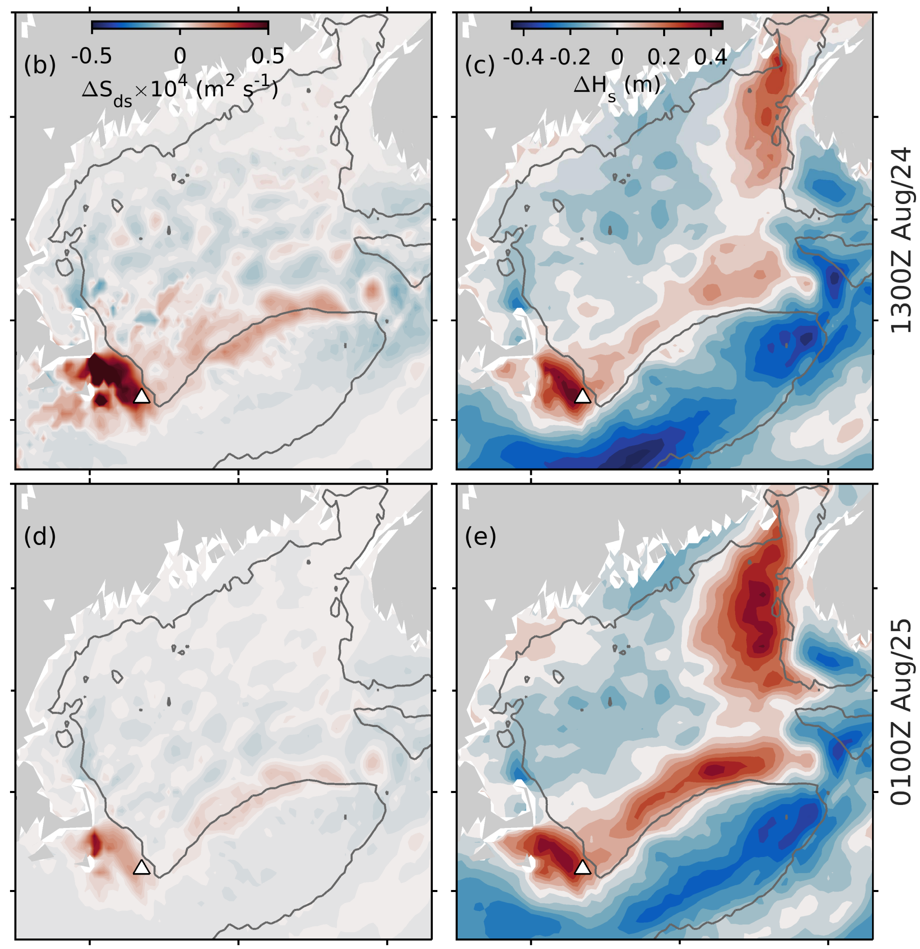
The modulations of H_s due to wavenumber shift and refraction vary with the change in wave propagation directions.

Contribution from current-enhanced wave dissipation (S_{ds})



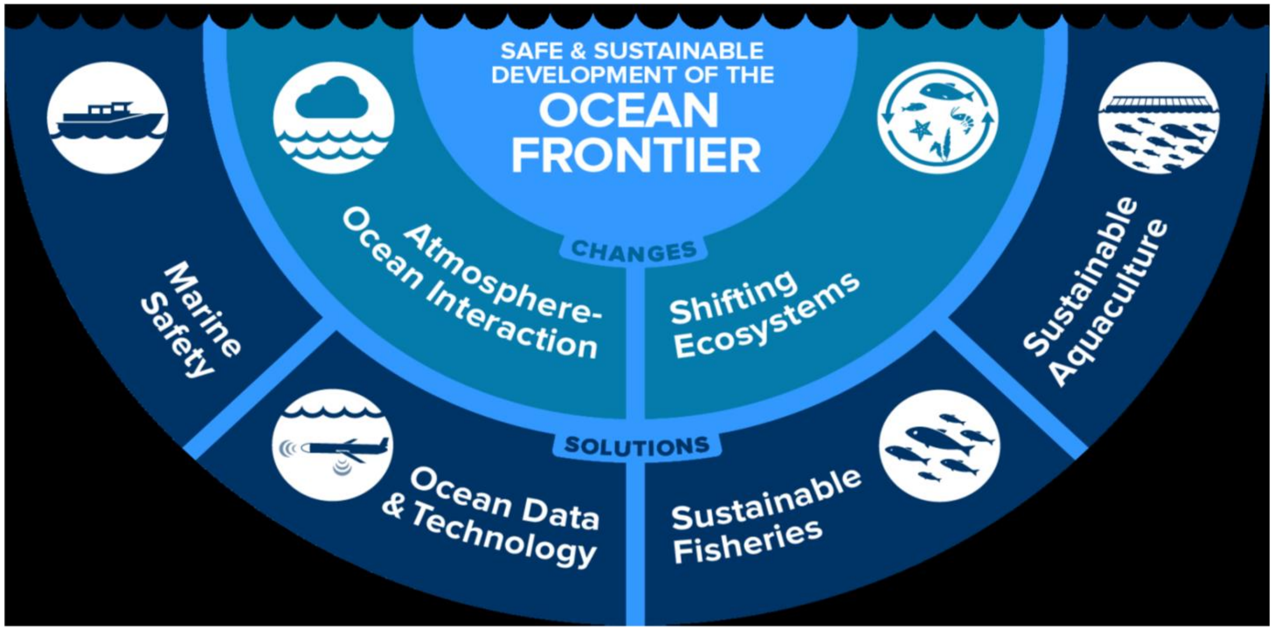
changes in S_{ds}

Changes in H_s



The current-enhanced dissipation (whitecapping dissipation term) becomes important during high winds, which can reduce at least half the Hs modulation over areas behind GB, but has negligible effect on their phases.

5. Ocean Frontier Institute



- Dalhousie University, Memorial University and University of PEI recently received $93.7 millions for the Ocean Frontier Institute.
- Title: Safe and Sustainable Development of the Ocean Frontier
- The main objective of this research program is to have an integrated set of 17 research modules focused on: atmosphere-ocean interactions, shifting ecosystems, sustainable fisheries, sustainable aquaculture, marine safety, and ocean data capture and integrated information technology tools.

Research Module F:

Cooperative Model Framework for the NWA and CAG

Module Leads:

Jinyu Sheng and Katja Fennel, Dalhousie University

Collaborating Researchers (with direct participations):

Youyu Lu	Senior Scientist at BIO of DFO, Adjunct at DAL
Will Perrie	Senior Scientist at BIO of DFO, Adjunct at DAL
Entcho Demirov	Associate Professor, MUN
Eric Oliver	Emerging Researcher at DAL

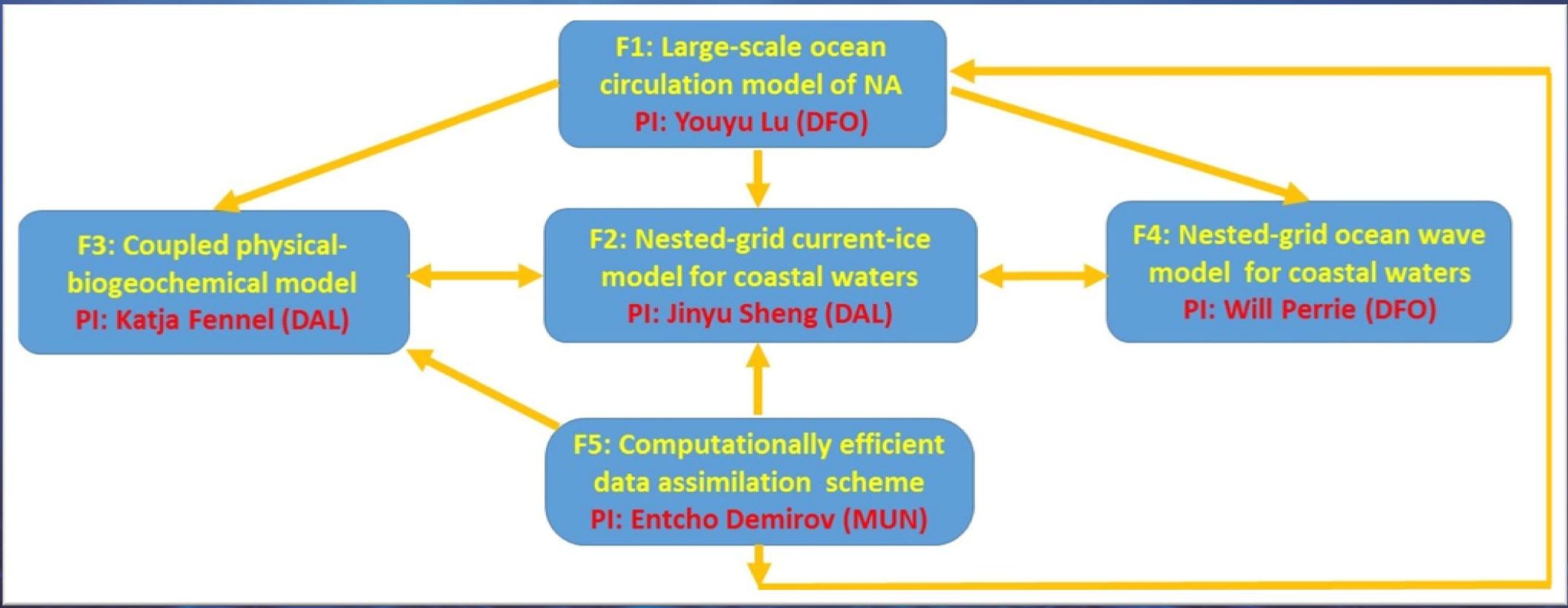
Overarching Objectives of Module F:

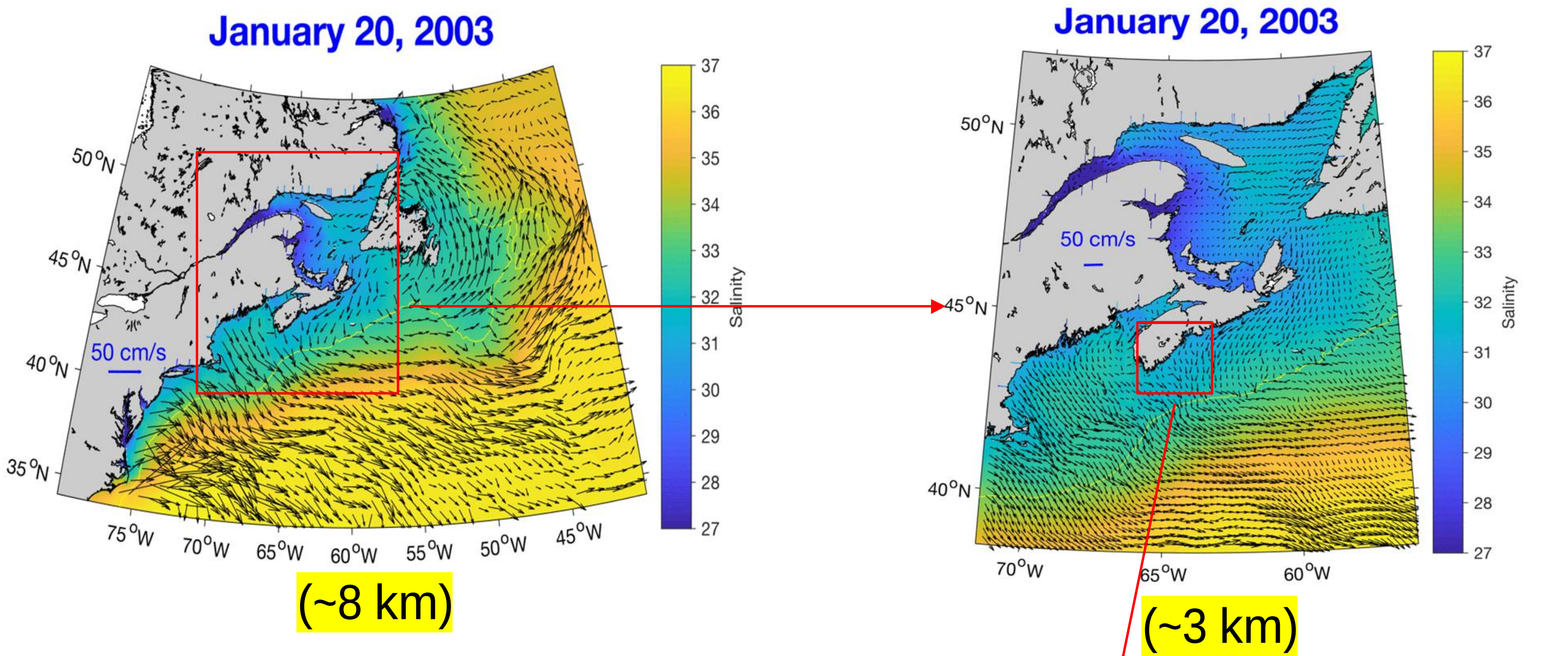
a) Develop and calibrate an integrative, multi-scale, physical-biogeochemical model framework for the NWA

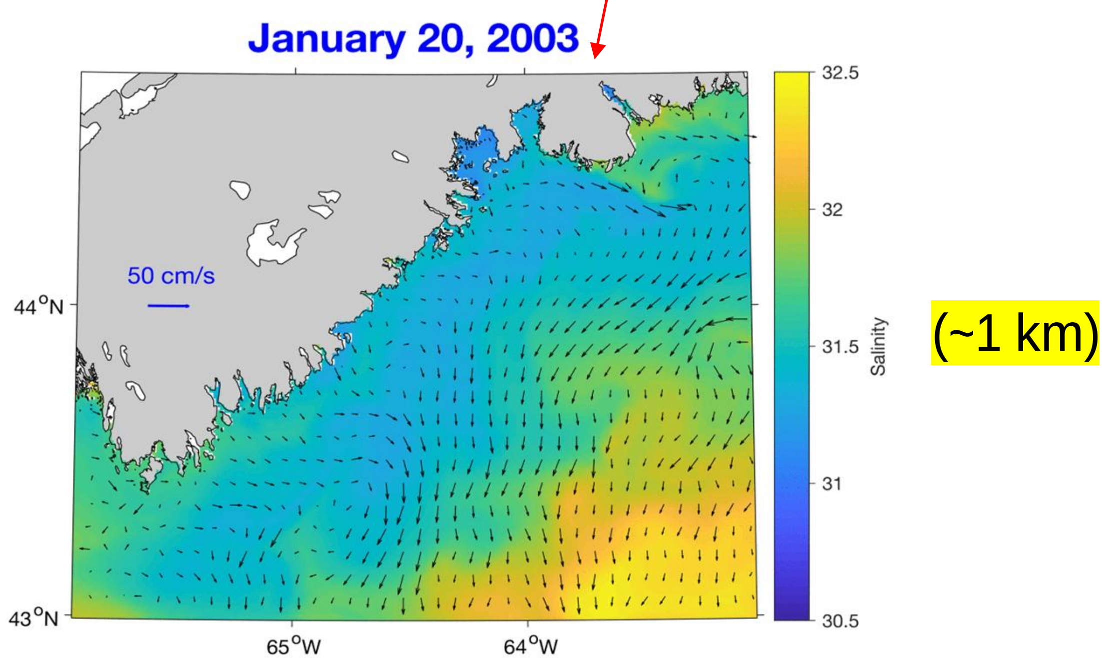
b) Simulate physical and biogeochemical conditions and extreme events in the past and future using the model framework

c) Assimilate observations into the models

d) Investigate the effect of climate change on shifting ecosystem







A 3-level nested grid modelling system for the eastern Canadian shelf based on ROMS

Thank you!