Interaction Between Internal Tides and Waves: A Challenge in Predicting NWS Dynamics

Ivica Janekovic

ivica.janekovic@uwa.edu.au

UWA, Pawsey and UWA Shell's chair

Outline

- Introduction
  - basic theory and NWS scene
- Problem
  - IT – wave interactions and effects on waves
- Possible Solution
  - 2-way coupling, advanced modelling
- Conclusion
  - way forward

Introduction

- Well known effect (obs & model)
  - waves alter upper ocean in many ways
    - breaking and nonbreaking turbulence, mixing
    - atmosphere-ocean boundary layer (α*)
    - nonlinear effects and Stokes drift
  - currents influence waves
    - Doppler shift $\omega = \sigma + \mathbf{k} \cdot \mathbf{v}$
    - Stretching / compressing wavelengths, function of current grad
    - Current induced refraction, focusing, wave action advection c_g+u
    - Norway “dangerous seas”

Air-Sea Interface 2025

Theory and previous studies

THE UNIVERSITY OF WESTERN AUSTRALIA

J. Fluid Mech. (1987), *vol.* 177, *pp.* 293–306
Printed in Great Britain

The propagation of short surface waves on longer gravity waves

By M. S. LONGUET-HIGGINS

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, UK, *and* Institute of Oceanographic Sciences, Wormley, Surrey, UK

(Received 18 June 1986)

To understand the imaging of the sea surface by radar, it is useful to know the theoretical variations in the wavelength and steepness of short gravity waves propagated over the surface of a train of longer gravity waves of finite amplitude. Such variations may be calculated once the orbital accelerations and surface velocities in the longer waves have been accurately determined – a non-trivial computational task.

waves on long
s
NS
ırrey

waves of the same type,
; the crests of the longer
roughs. In the present
ıs between the two wave
e shorter wave train are
ssentials from previous
waves is shown to corre-

JPO papers …

The Interaction of Wind-Generated Sea Waves with Tidal Currents

C. E. VINCENT

School of Environmental Sciences, University of East Anglia, Norwich, U.K.

(Manuscript received 12 December 1978, in final form 14 February 1979)

ABSTRACT

The interaction between wind-generated surface waves and tidal currents can be described in terms either of the energy balance of the system or of the conservation of wave action, assuming that the tidal currents are weak. Analytical solutions for the variation in surface wave amplitude and wavenumber are shown for the case where the surface waves are in deep water and are propagating parallel to the direction of tidal wave propagation, using the energy balance approach.

Wave analysis from two adjacent sites in the southern North Sea show that wave heights during two 16-day periods were modulated at a period of 12–13 h and that higher waves were occurring when the waves were propagating in the same direction as the tidal current. A simplified model for the tidal regime in this area was used to compute the theoretical modulation of the wave amplitude from the energy balance equations and these were compared with the observed wave heights. Very good correspondence was found between the phases of the modulations, but the observed wave height variations exceeded those predicted by over 50%. The limitations of this analysis and some possible causes of this underestimation are discussed.

The Influence of Unsteady Depths and Currents of Tides on Wind-Wave Propagation in Shelf Seas

H. L. TOLMAN

Faculty of Civil Engineering, Delft University of Technology

(Manuscript received 3 August 1989, in final form 8 February 1990)

ABSTRACT

The influence of unsteady depths and currents on wind wave propagation on the scale of shelf seas such as the North Sea is investigated. The attention is focused on depth and current variations due to tides, which are essentially stationary at the scale of a single wave but unsteady at the scale of wave propagation. Analytical solutions are derived for changes of monochromatic unidirectional linear waves due to a one-dimensional tide in water with a constant bottom level. It is shown that the change of absolute frequency due to variations of depth and current in time is of the same order of magnitude as the Doppler shift, and that it is not negligible, as assumed in a quasi-stationary approximation. The common quasi-stationary approximation leads to large errors in the predicted change of wave parameters in all situations considered here.

5. Discussion

As indicated in section 3, depths and currents due to tides in shelf seas are essentially an unsteady and inhomogeneous medium for wind wave propagation. Away from the coast interactions due to current variations are dominant over those due to surface level variations. Changes of the absolute frequency ω for the situation considered here [Eq. (33), Fig. 3] are of the same order of magnitude as the Doppler shift k_0U_p, whereas relative changes of the wave amplitude [Eq. (44), Fig. 4] are of the same order of magnitude as the relative current velocity U/c_g. Considering e.g. a current velocity of 1 m s^{-1}, a water depth of 25 m and a wave period of 7 s (which is fairly realistic for the southern North Sea), relative changes of the order of 10% might be expected for these wave parameters.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. C7, PAGES 12,755–12,771, JULY 15, 1991

Effects of the Gulf Stream on Ocean Waves

L. H. HOLTHUIJSEN AND H. L. TOLMAN[1]

Delft University of Technology, Department of Civil Engineering, Delft, Netherlands

In the present study a third-generation numerical wave model is used to study effects of a straight Gulf Stream and a Gulf Stream ring on ocean waves in swell and storm conditions. The model accounts for all relevant processes of propagation, generation, and dissipation of the waves (including current effects) without imposing a priori restraints on the spectral development of the waves. The dominating mechanism affecting the waves appears to be current-induced refraction even though the short-crestedness of the incoming waves tends to mask its effects (also in swell conditions). Depending on wind and wave conditions, refraction may trap locally generated waves in the straight Gulf Stream or it may reflect wave energy back to the open ocean. In the Gulf Stream ring, refraction induces a considerable variation in significant wave height and short-crestedness, but it hardly affects the mean wave direction. In storm conditions the processes of generation and dissipation are considerably enhanced in countercurrent situations and reduced following-current situations.

A Case Study of Wave–Current Interaction in a Strong Tidal Current

DIANE MASSON

Institute of Ocean Sciences, Sidney, British Columbia, Canada

(Manuscript received 6 December 1994, in final form 31 August 1995)

ABSTRACT

During August 1991, a field program was carried out in the vicinity of Cape St. James, off the British Columbia coast, where a strong tidally driven flow interacts with an active wave climate. Surface current maps were obtained from a CODAR-type HF radar (Seasonde) over an area of about 350 km^2 around the cape. A series of Loran-C drifters were also deployed during the experiment and used as ground truth for the radar. A comparison between the drifter and the radar surface currents indicates reasonable agreement.

Wave information was acquired with three Waverider buoys deployed around the cape. A significant modulation of the wave properties at the tidal period was observed for the buoy located in the area where the currents are maximum. The tidally induced changes in the wave field are modeled with a local wave–current interaction model based on wave action conservation and on a high-frequency limiting spectral shape. The model is applied on a period of 11 days for which the wind was relatively steady. The magnitude of the modeled tidal modulation of the wave field is of the same order of magnitude as the measurements but, in general, underestimates the measured tidally induced changes. However, during the first half of the period, the modulation of the total wave energy is significantly out of phase with the buoy data. The effect of refraction by the current on the waves is assessed using a backward ray tracing method and two-dimensional surface current maps. It is proposed that refraction effects are important during the first part of the study period and are a plausible cause for the phase discrepancy between the measurements and the results of the local model.

JGR 2017

THE UNIVERSITY OF WESTERN AUSTRALIA

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2016JC012413

Small-scale open ocean currents have large effects on wind wave heights

Fabrice Ardhuin[1], Sarah T. Gille[2], Dimitris Menemenlis[3], Cesar B. Rocha[2], Nicolas Rascle[1], Bertrand Chapron[1], Jonathan Gula[1], and Jeroen Molemaker[1]

[1]Univ. Brest, CNRS, IRD, Ifremer, Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Brest, France, [2]Scripps Institution of Oceanography, University of California San Diego, La Jolla, California, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Key Points:

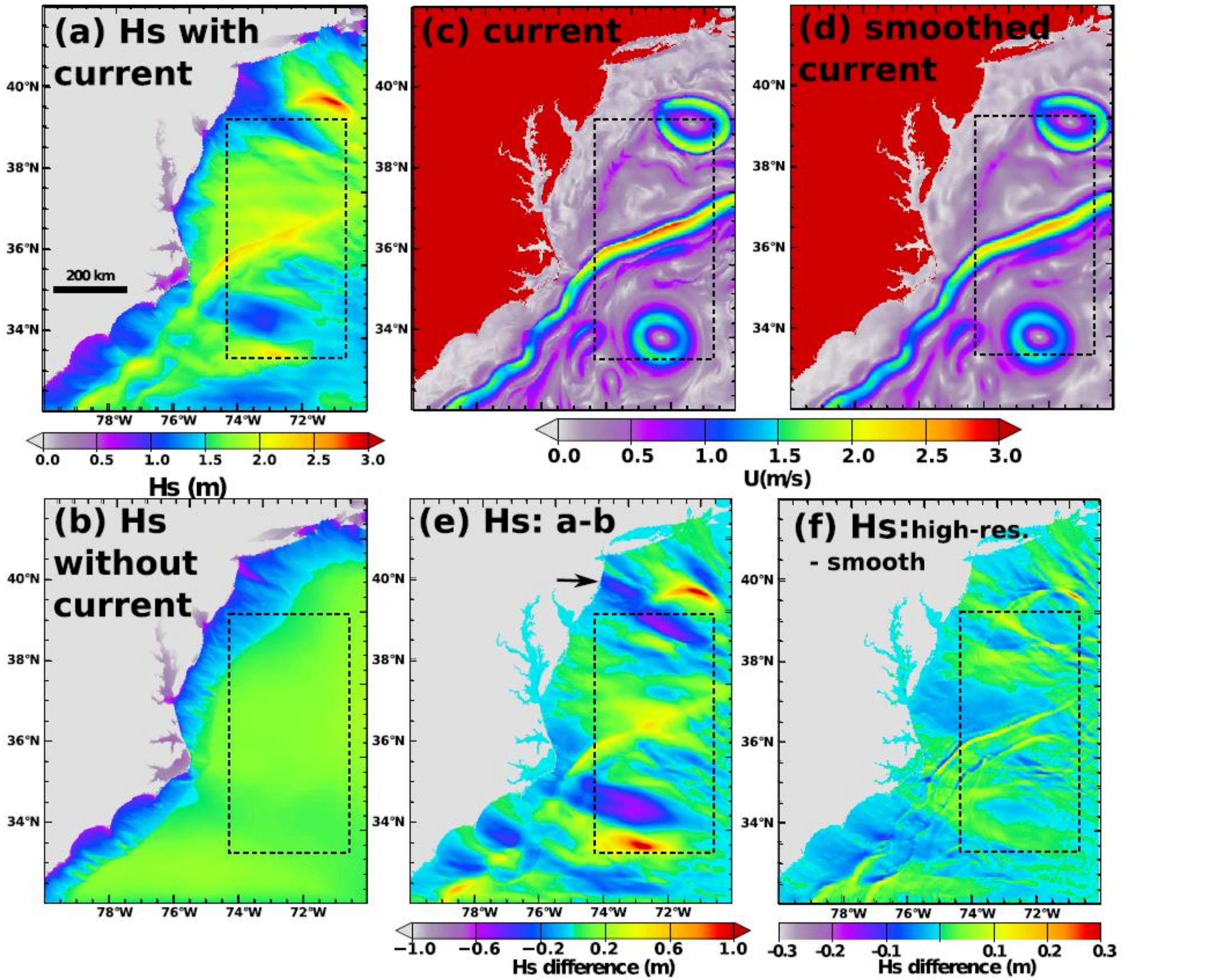
- Wave height gradients at scales under 100 km are determined by currents
- The wave height variance at 10 km scale is proportional to the current spectrum
- If not corrected for by measuring gradients in wave parameters, SWOT error on sea level probably exceed 20% of total allowed error

Correspondence to:
F. Ardhuin,
ardhuin@ifremer.fr

Citation:
Ardhuin, F., S. T. Gille, D. Menemenlis

Abstract Tidal currents and large-scale oceanic currents are known to modify ocean wave properties, causing extreme sea states that are a hazard to navigation. Recent advances in the understanding and modeling capability of open ocean currents have revealed the ubiquitous presence of eddies, fronts, and filaments at scales 10–100 km. Based on realistic numerical models, we show that these structures can be the main source of variability in significant wave heights at scales less than 200 km, including important variations down to 10 km. Model results are consistent with wave height variations along satellite altimeter tracks, resolved at scales larger than 50 km. The spectrum of significant wave heights is found to be of the

Ardhuin, JGR 2017



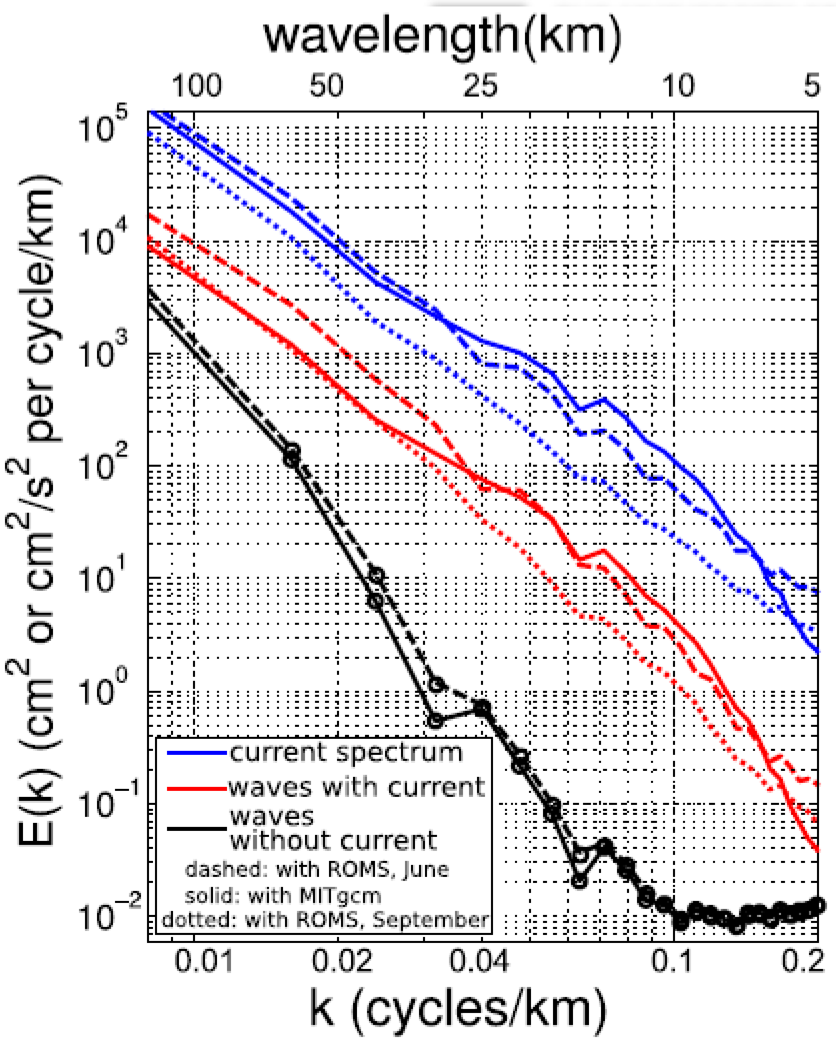


Figure 2. Omnidirectional time-averaged spectra of current and H_s for the Gulf Stream, when current effects of waves are included (in red) or without current effects (black). Dashed or dotted lines and solid lines correspond to currents from ROMS or MITgcm, respectively. Two-dimensional spectra computed over the rectangular box ranging from 74°W to 71°W, and 33.7 to 38.7° were converted to a single dimension by gathering the variance of spectral components of all directions that have the same wavelength.

JPO, 2018

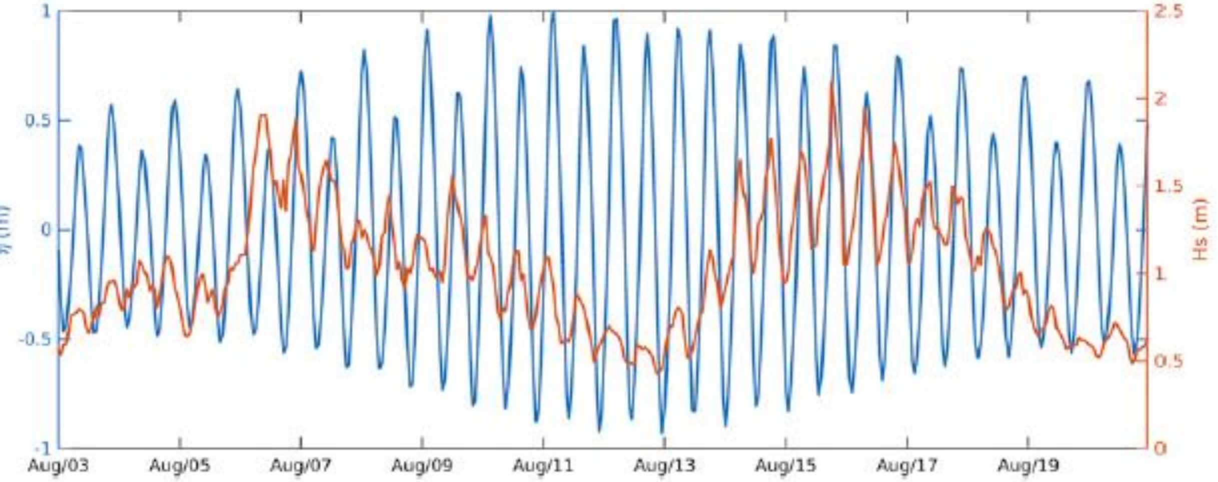


FIG. 5. Time series of predicted tidal elevation (blue) with superimposed time series of observed significant wave height (red) on 3–19 Aug 2010.

Tidal Modulation of Surface Gravity Waves in the Gulf of Maine

PENGCHENG WANG AND JINYU SHENG

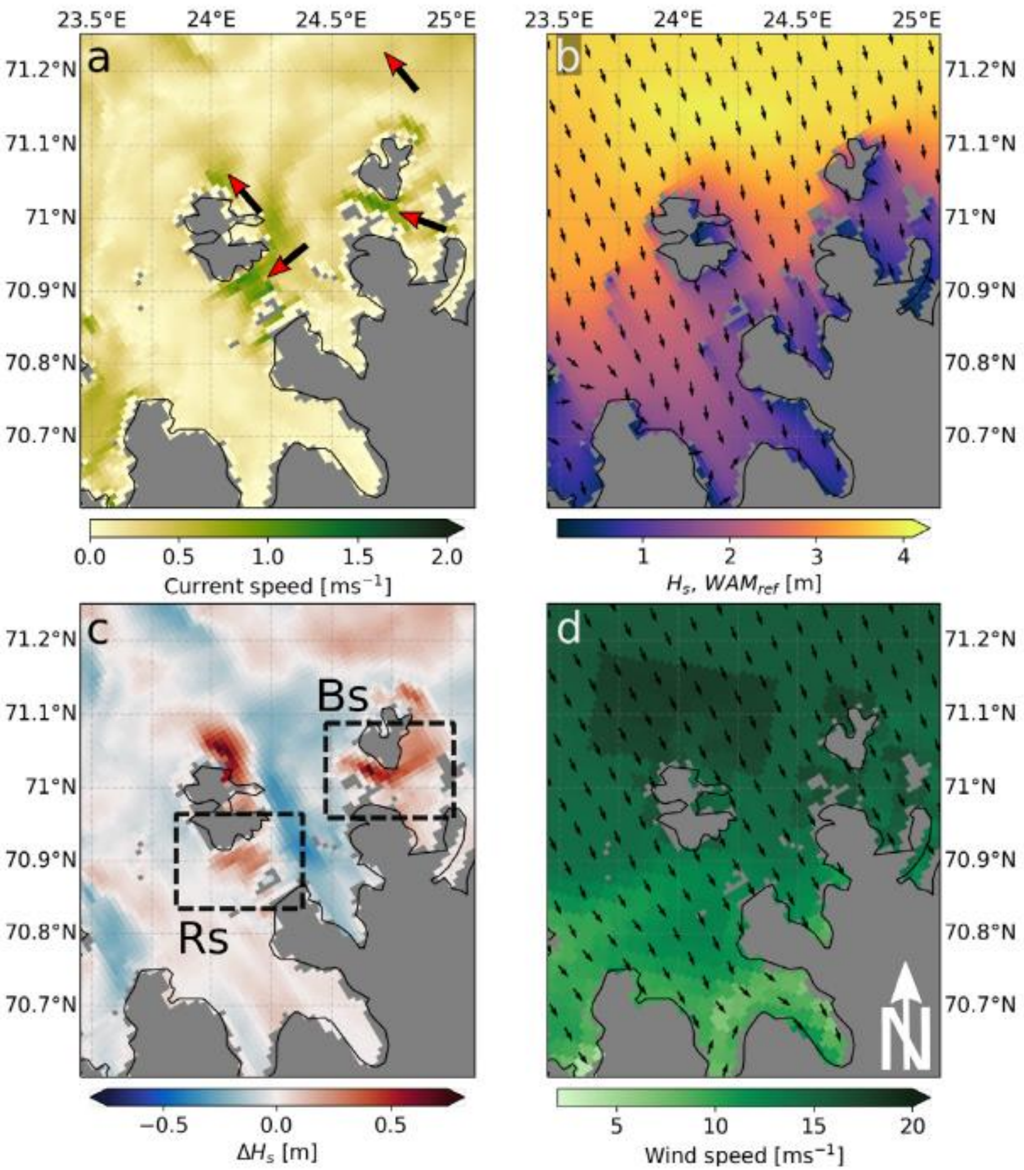
Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

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

ABSTRACT

mines the tidal modulation of surface gravity waves in the Gulf of Maine (GoM) by using ons and numerical model results. Analysis of observational data demonstrates significant l modulations in the mean wave variables for swell-dominated waves in the region. The odulation features significant spatial–temporal variabilities, with large magnitudes near the M. Observations also demonstrate unusual timing of the maximum modulation of significant 1 the following tidal currents. The coupled wave–circulation model successfully reproduces il modulation and the associated spatial–temporal variabilities. Model results demonstrate m H_s modulations are first generated during the maximum flood tide or ebb tide near the M and then propagate onto the inner gulf. Around the mouth of the GoM, tidal currents have adients, resulting in great effects of current-induced convergence, refraction, and wave- e 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.

Norway – Lofoten Maelstorm



Ocean Modelling 176 (2022) 102071

ELSEVIER

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Resolving regions known for intense wave–current interaction using spectral wave models: A case study in the energetic flow fields of Northern Norway

Trygve Halsne [a,b,*], Patrik Bohlinger [a], Kai Håkon Christensen [a,c], Ana Carrasco [a], Øyvind Breivik [a,b]

[a] Norwegian Meteorological Institute, Henrik Mohns Plass 1, Oslo, 0371, Norway
[b] University of Bergen, Allégaten 41, Bergen, 5020, Norway
[c] University of Oslo, Problemveien 7, Oslo, 0315, Norway

Intense Interactions between Ocean Waves and Currents Observed in the Lofoten Maelstrom

ØYVIND SAETRA,[a] TRYGVE HALSNE,[a,b] ANA CARRASCO,[a] ØYVIND BREIVIK,[a,b] TORSTEIN PEDERSEN,[c] AND KAI HÅKON CHRISTENSEN[a]

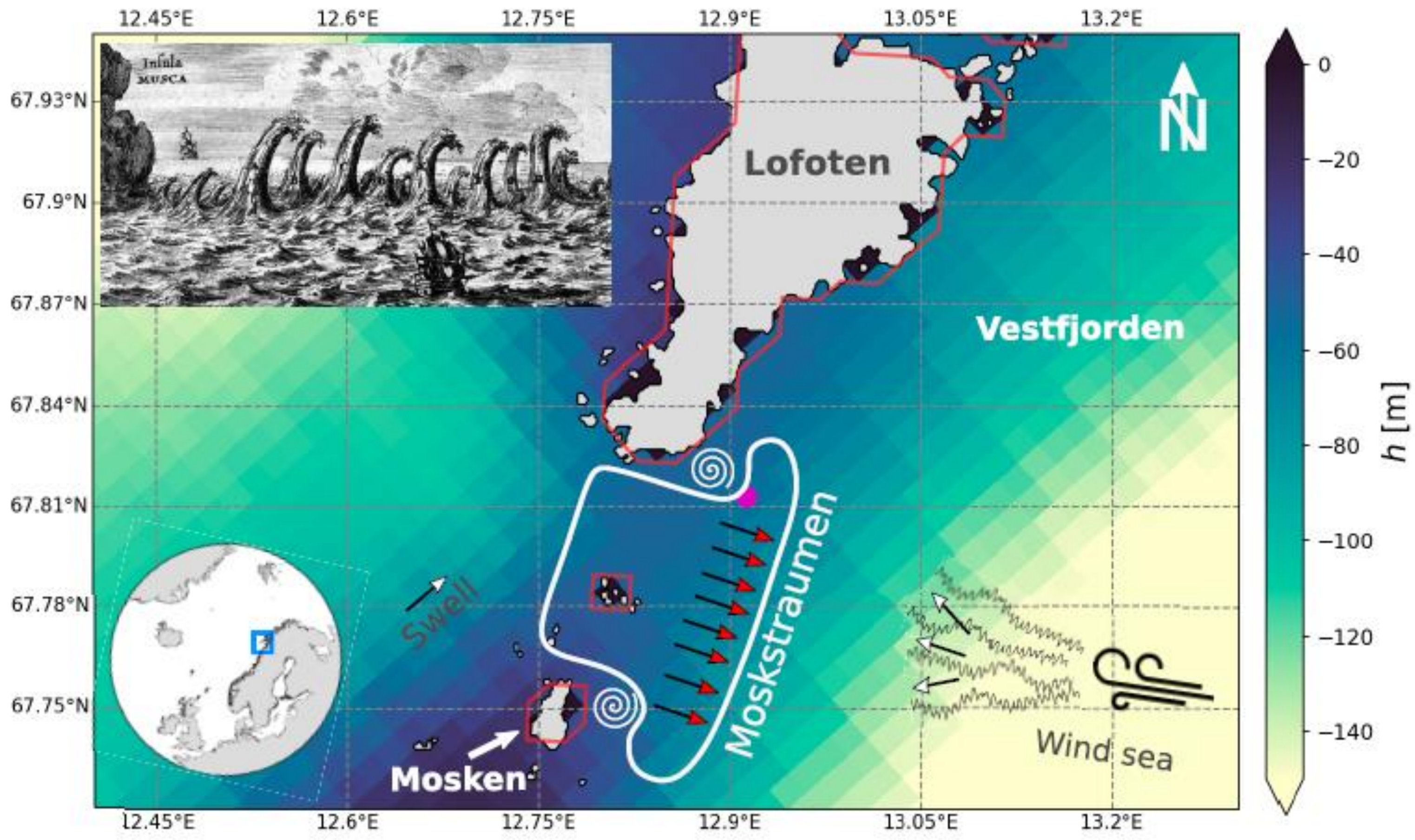


FIG. 1. A cartoon representation of the Moskstraumen tidal current during incoming tide (red colored arrows denote direction), which is located between the southern tip of the Lofoten Peninsula and the island of Mosken in northern Norway. The magenta dot shows the location of the ADCP. Red contours denote the land mask from the

ts in the
py seas
studies
lenging
s of the
ation of
t of the
that the
ng tide.

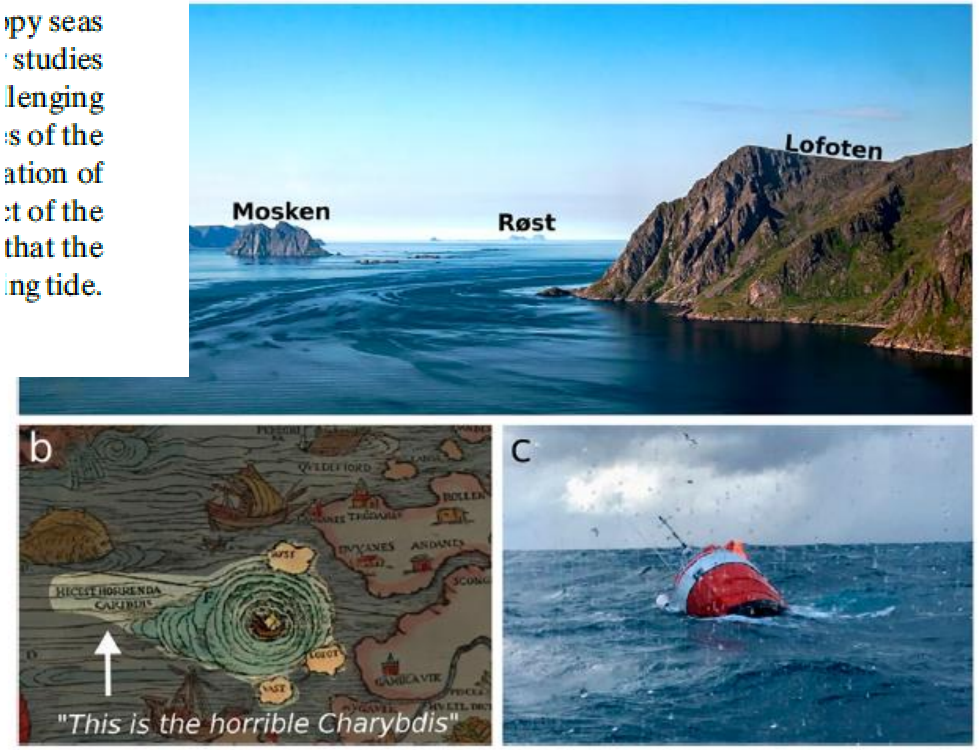


FIG. 1. The many views of Moskstraumen. (a) A photograph of Moskstraumen in the Moskenes Sound from 2009 by Jørn Røssvoll taken from a helicopter. The photograph is most

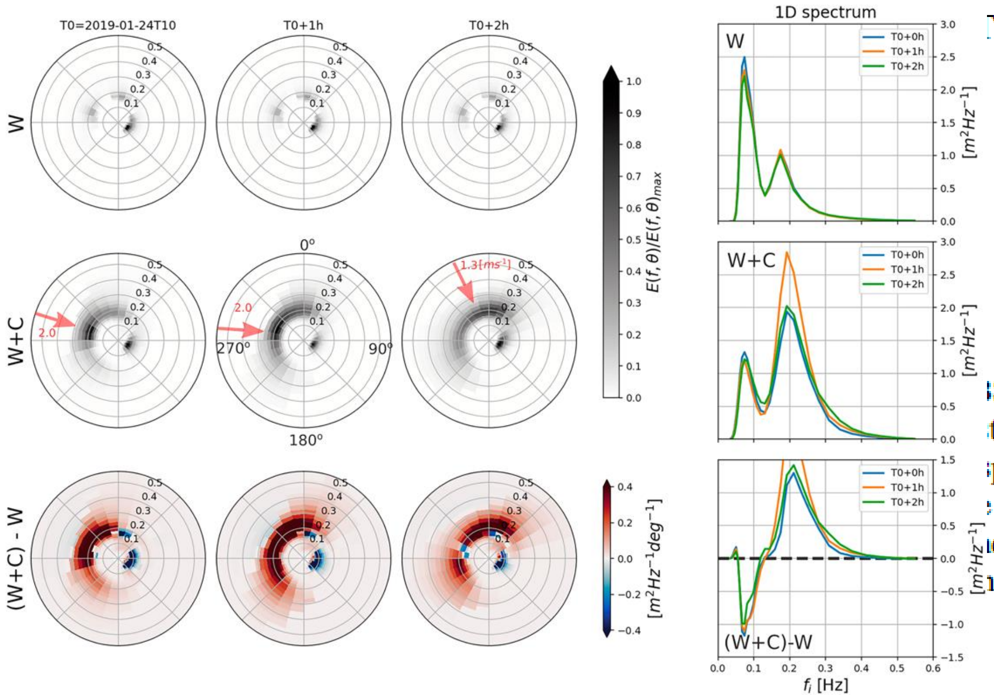
Wave–Tide Interaction for a Strongly Modulated Wave Field

ALLISON HO,[a] SOPHIA MERRIFIELD,[a] AND NICK PIZZO[a]

[a] *Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California*

(Manuscript received 8 August 2022, in final form 2 November 2022)

ABSTRACT: Observations from Coastal Data Information Program (CDIP) moored buoys off the coast of Florida reveal tidally driven wave–current interactions that modify significant wave heights by up to 25% and shift peak periods by up to a second. A case study at Fernandina Beach, Florida, shows surface waves steepening on following tidal currents and becoming less steep on opposing tidal currents, with the largest modulations occurring in the long-period swell band. To



Wave Modulation in a Strong Tidal Current and Its Impact on Extreme Waves

TRYGVE HALSNE,[a,b] ALVISE BENETAZZO,[c] FRANCESCO BARBARIOL,[c] KAI HÅKON CHRISTENSEN,[a,d] ANA CARRASCO,[a] AND ØYVIND BREIVIK[a,b]

[a] *Norwegian Meteorological Institute, Oslo, Norway*
[b] *University of Bergen, Bergen, Norway*
[c] *Institute of Marine Sciences, Italian National Research Council, Venice, Italy*
[d] *University of Oslo, Oslo, Norway*

(Manuscript received 24 March 2023, in final form 30 October 2023, accepted 1 November 2023)

STRACT: Accurate estimates of extreme waves are central for maritime activities, and stochastic wave models are the t option available for practical applications. However, the way currents influence the statistics of space–time extremes spectral wave models has not been properly assessed. Here we demonstrate impacts of the wave modulation caused by of the world's strongest open ocean tidal currents, which reaches speeds of at least 3 m s^{-1}. For a bimodal swell and d sea state, we find that most intense interactions occur when the wind sea opposes the tidal current, with an increase in ificant wave height and spectral steepness up to 45% and 167%, respectively. The steepness modulation strengthens

Quick Theory Recap

- Smooth sailing in case we known ocean currents
  - Ardhuin et al., 2017 – effect of the Gulf stream on WW3
  - Tolman, Vincent, Masson,…
- In case of oscillatory currents (mostly BT tides)
  - Strong tidal currents – i.e. Norway -> large effect
  - Still OK, as we know how to predict barotropic currents

(Problem) baroclinic+tides = IT

THE UNIVERSITY OF WESTERN AUSTRALIA

- Internal tides – hard problem to predict timing
- We can predict some features (statistical way - amp)
  - Problem is random surfacing of internal tides/currents
  - Hard to predict correct phasing (even 4D-Var DA example)
    - complex path in 3D, density variation, topographic effects, remote
  - Strong baroclinic currents at the NWS, WA is ideal testbed
  - Globally: Hawai'i, Tahiti, Macquarie Ridge, Luzon Strait.

Geophysical Research Letters

Oceans | Free Access

Sensitivity of internal tide generation in Hawaii

B. S. Powell, I. Janeković, G. S. Carter, M. A. Merrifield

First published: 24 May 2012 | https://doi.org/10.1029/2012GL051724 | Citations

JOURNAL OF GEOPHYSICAL RESEARCH
Oceans
AN AGU JOURNAL

Free Access

Analysis of four-dimensional variational state estimation of the Hawaiian waters

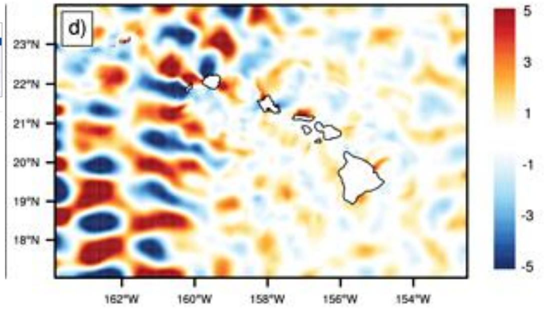
D. Matthews, B. S. Powell, I. Janeković

First published: 09 March 2012 | https://doi.org/10.1029/2011JC007575 | Citations: 29

ELSEVIER
Ocean Modelling
Volume 171, March 2022, 101969

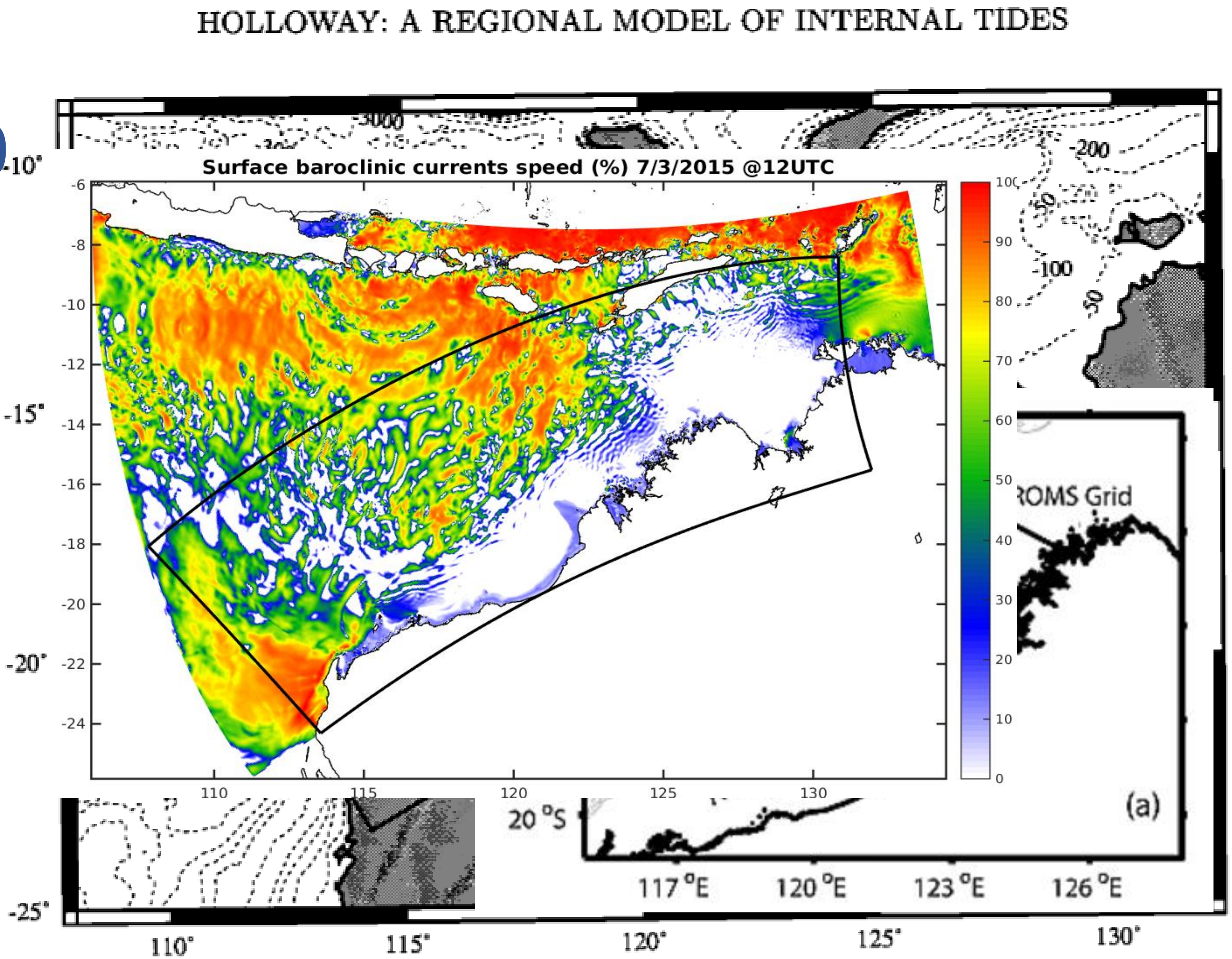
4D-Var data assimilation using satellite sea surface temperature to improve the tidally-driven interior ocean dynamics estimates in the Indo-Australian Basin

I. Janeković, M.D. Rayson, N.L. Jones, P. Watson, C. Pattiaratchi



NWS ... setting the scene

- Peter Holloway, '80
  - 4km POM
- Matt Rayson, 2012
  - 1-3 km ROMS
- ….
- I. Janekovic, '22
  - 2km 4D-Var DA



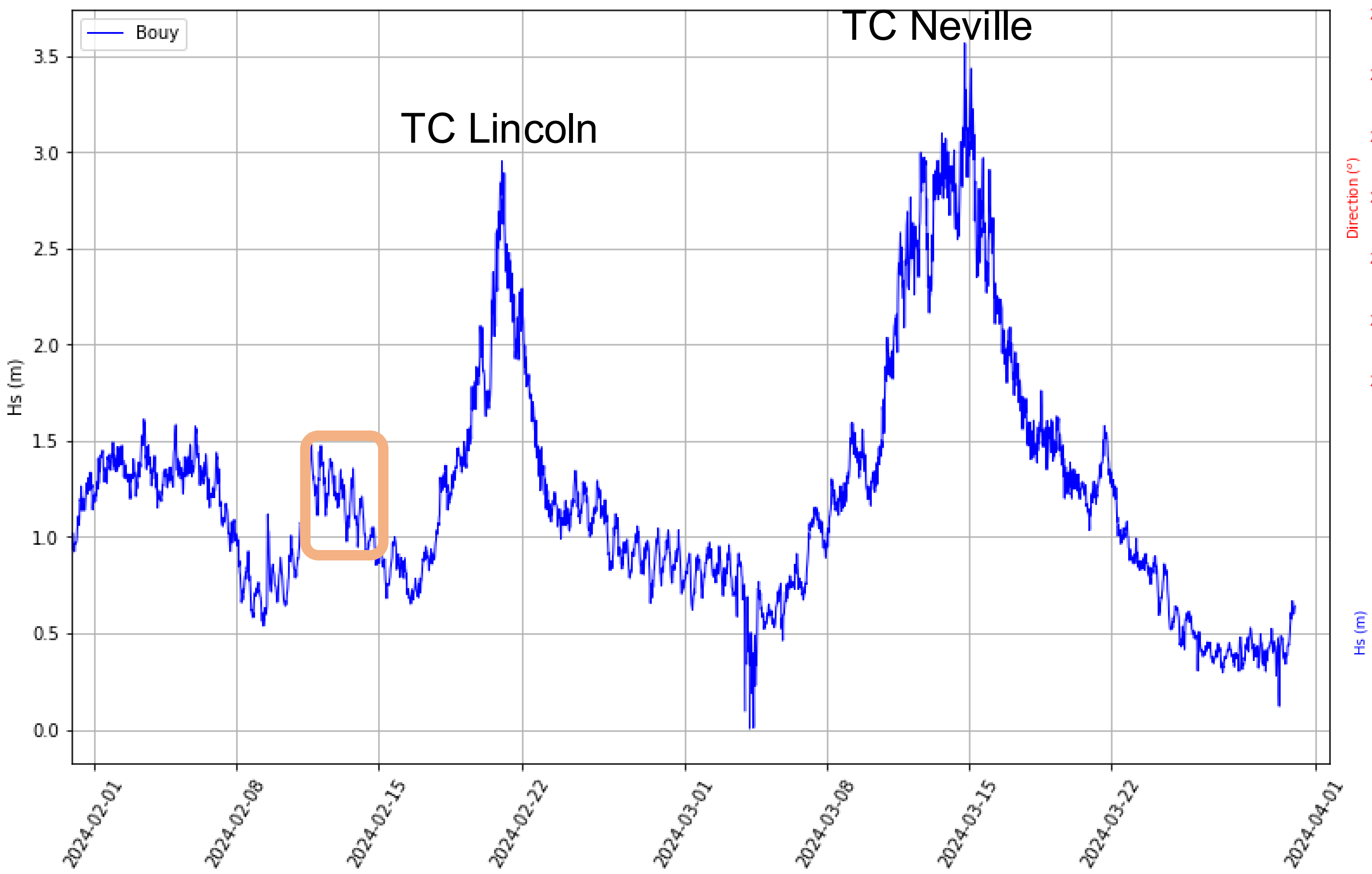
Observations & models

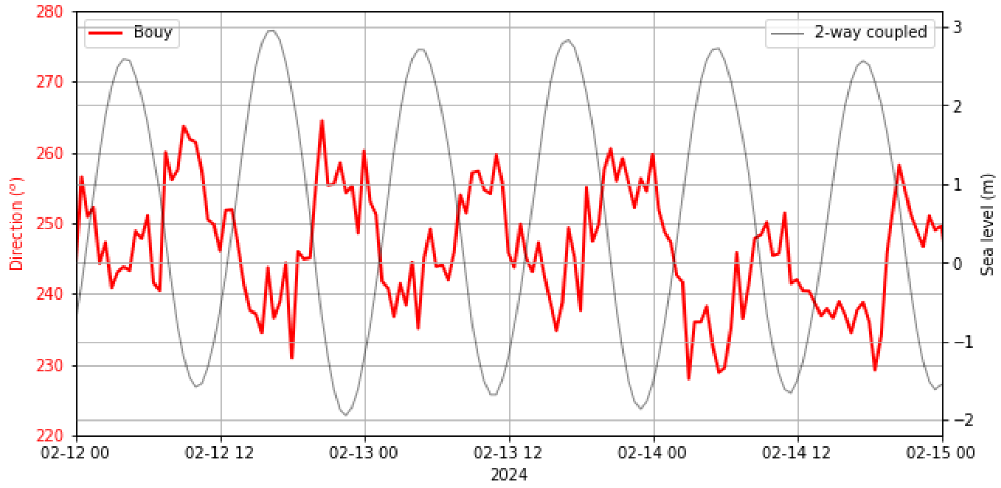
THE UNIVERSITY OF WESTERN AUSTRALIA

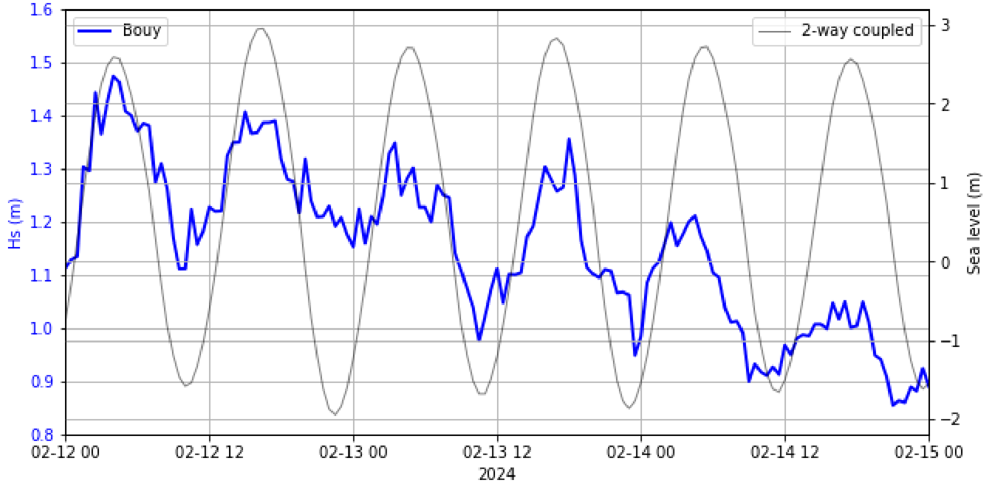
- Shows strong tidal modulation, during the summer
  - not only for Hs but direction as well (critical for operations)
- Modern models (ROMS, WW3, …)
  - even 4DVar-DA is not the silver bullet
- Realistic forcing, supercomputer, ….
- Still struggling to predict correct dynamics
- Exchange of info btw different models was missing

PAWSEY supercomputing centre

Semi-diurnal wave modulation







2-way coupling - digital twin

THE UNIVERSITY OF WESTERN AUSTRALIA

- Focus on wave-current interaction, complete system uses atmosphere model as well (2-way & 3 models)
- Ocean component – ROMS – Vortex force
  - modifying turbulence due to waves
  - surface drag and momentum exchange
  - using wave info (Hs, L, Dir, Tp, diss & breaking)
- Wave component – WW3 or SWAN
  - receive surface V, zeta
  - Cg+U, Doppler shift
  - refraction, focusing…

Geophysical Research Letters

Research Letter | Open Access

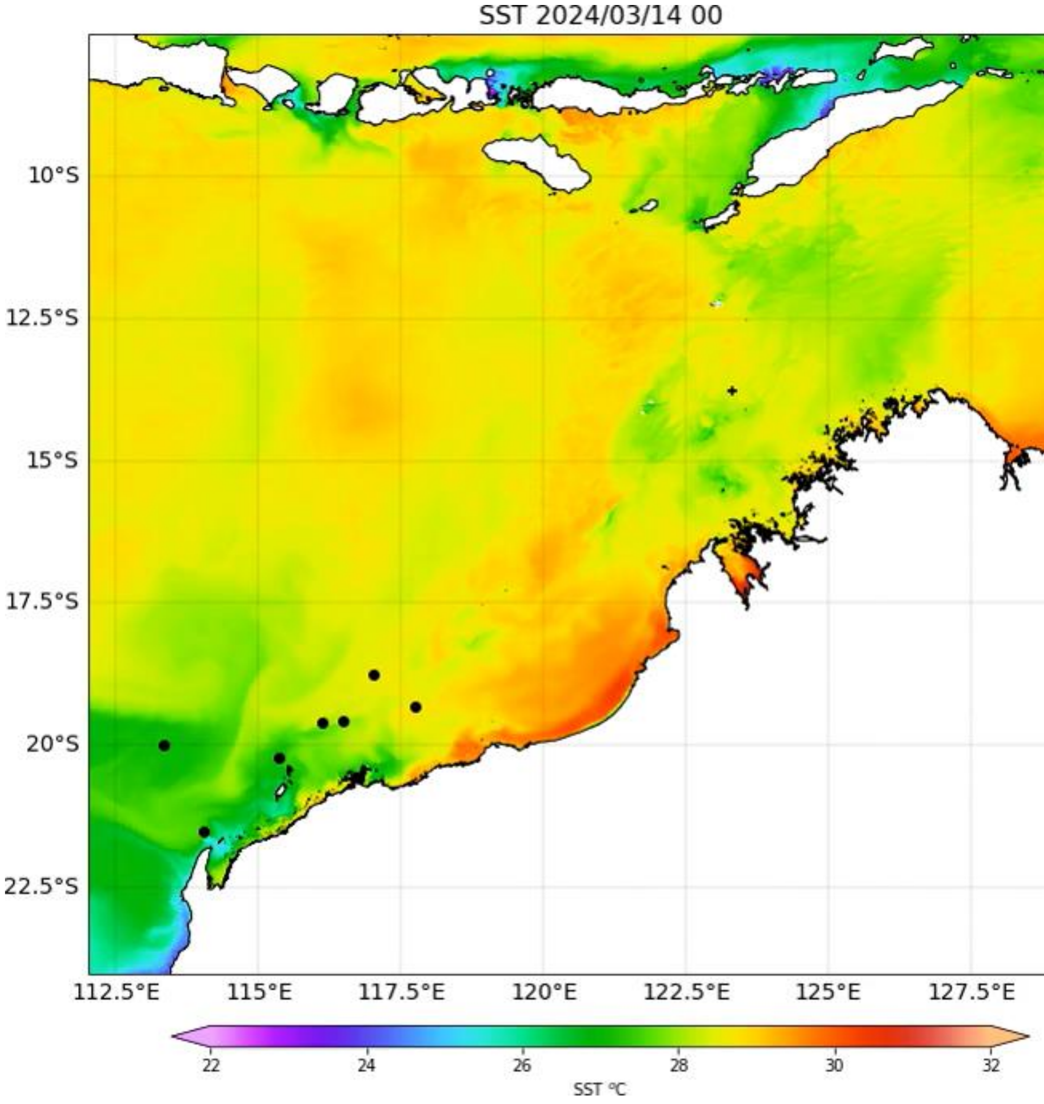
Tropical Cyclone Modeling With the Inclusion of Wave-Coupled Processes: Sea Spray and Wave Turbulence

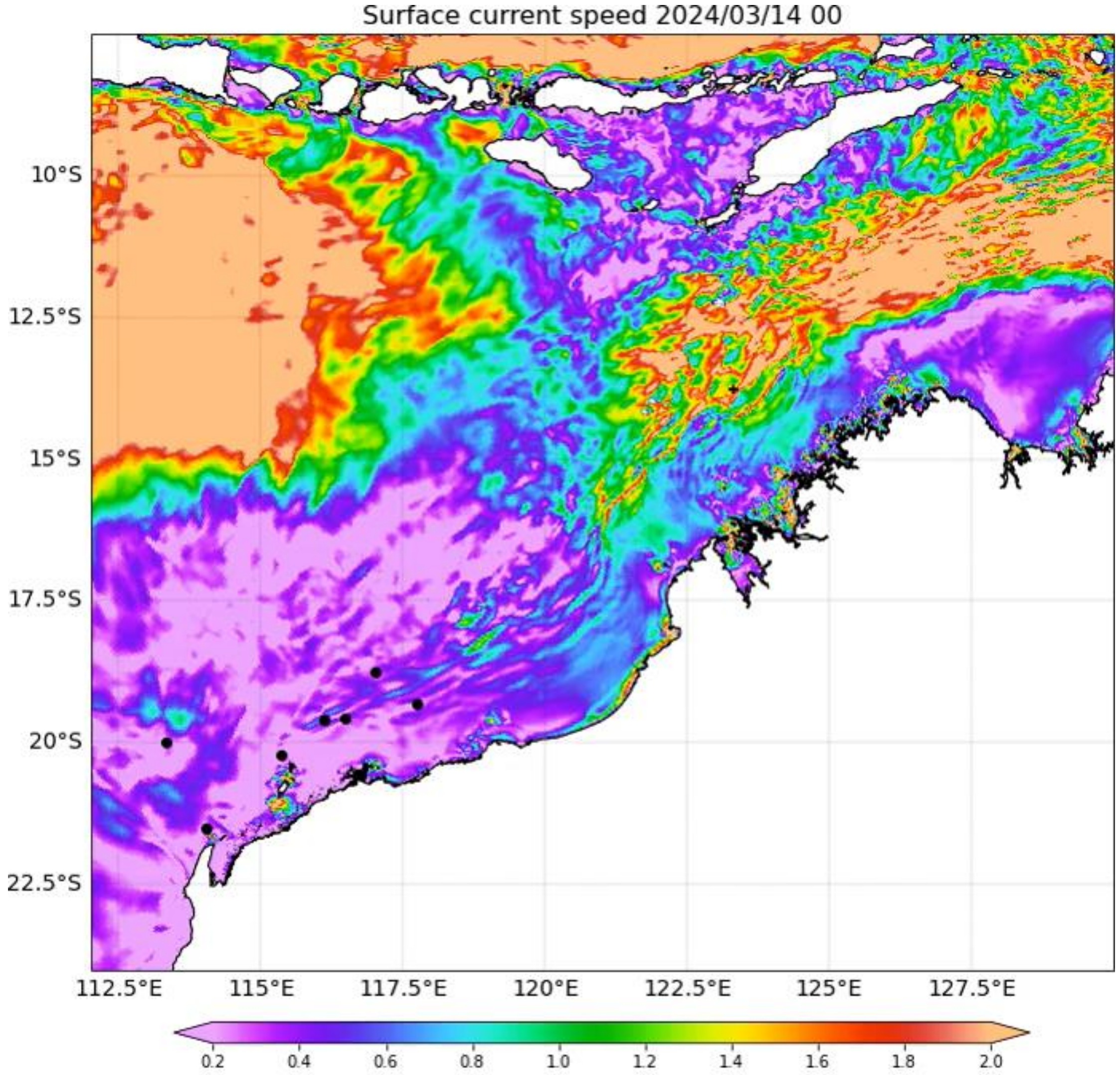
Xingkun Xu, Joey J. Voermans, Wenqing Zhang, Biao Zhao, Fangli Qiao, Qingxiang Liu, Il-Ju Moon, Ivica Janekovic, Takuji Waseda, Alexander V. Babanin

Twin exp. 1/1-4/2024

- E0: standard model ROMS & SWAN uncoupled
- E1: 2-way coupled system, exchange info 30min
- E2: The same as E1 but currents for exchange = 0
- E1 & E2 kept wave influence inside ROMS
- Nested model into NEMO, ERA5, tides, 2km, 30σ, …

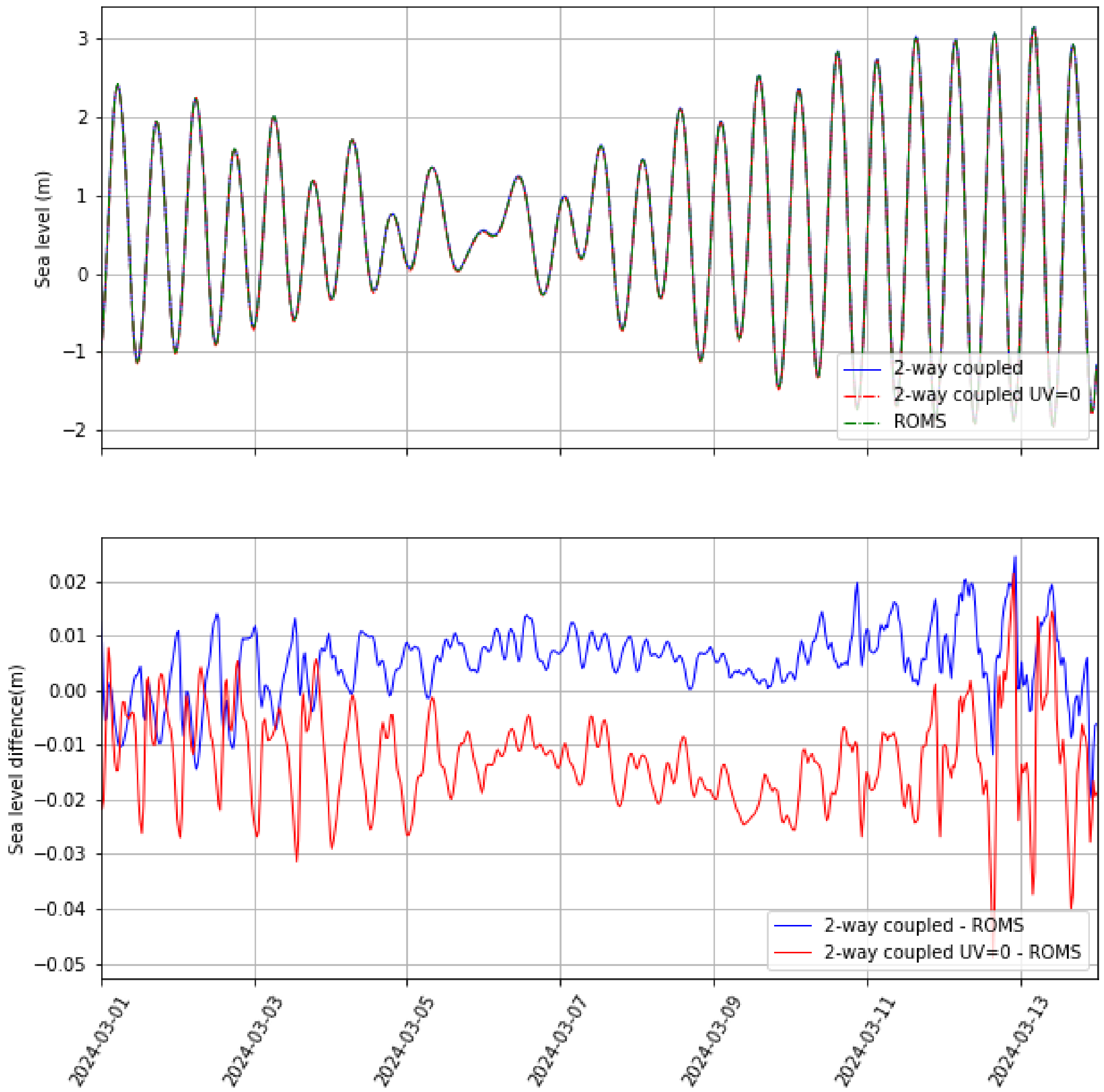
Complex dynamics



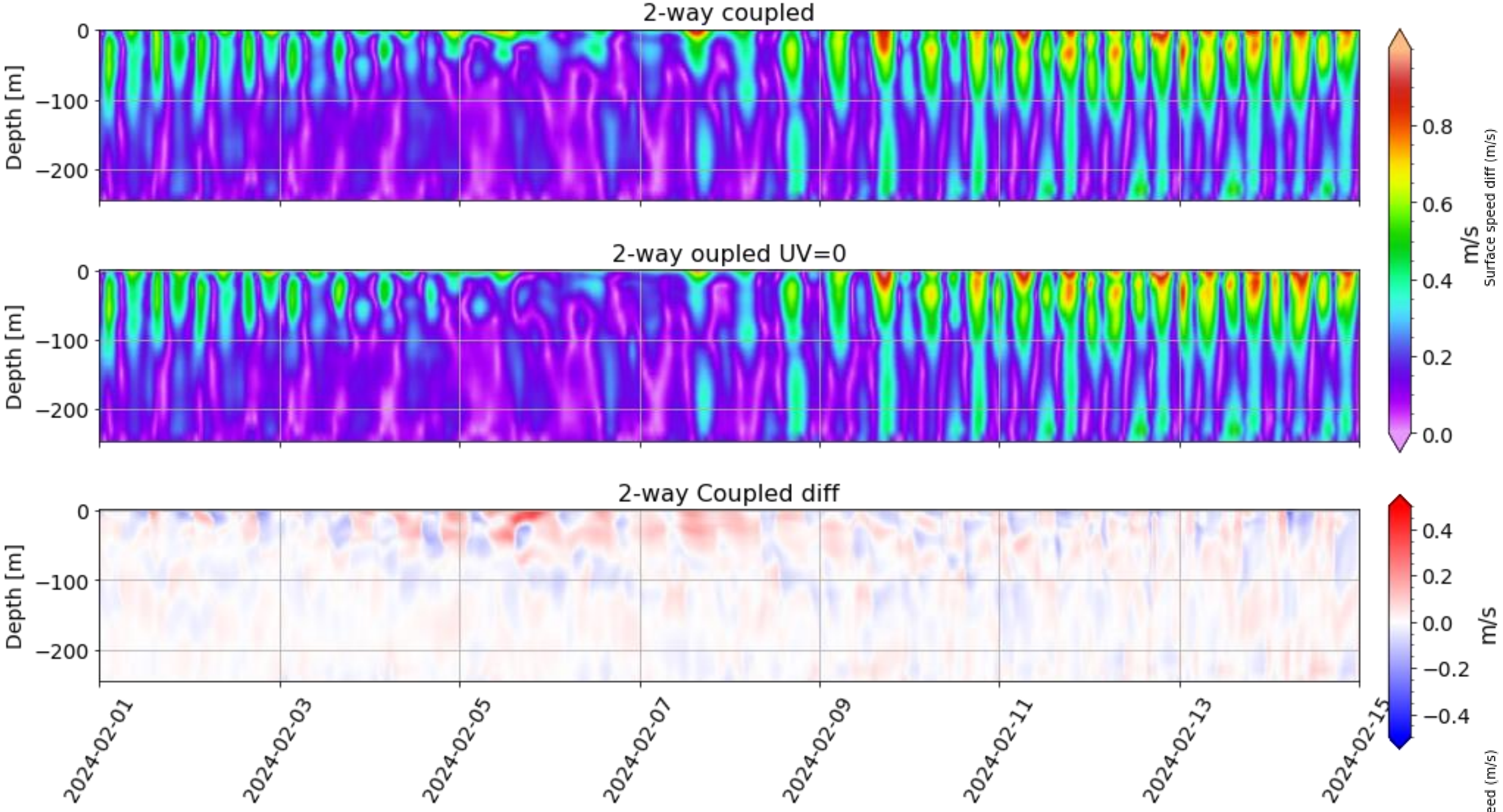


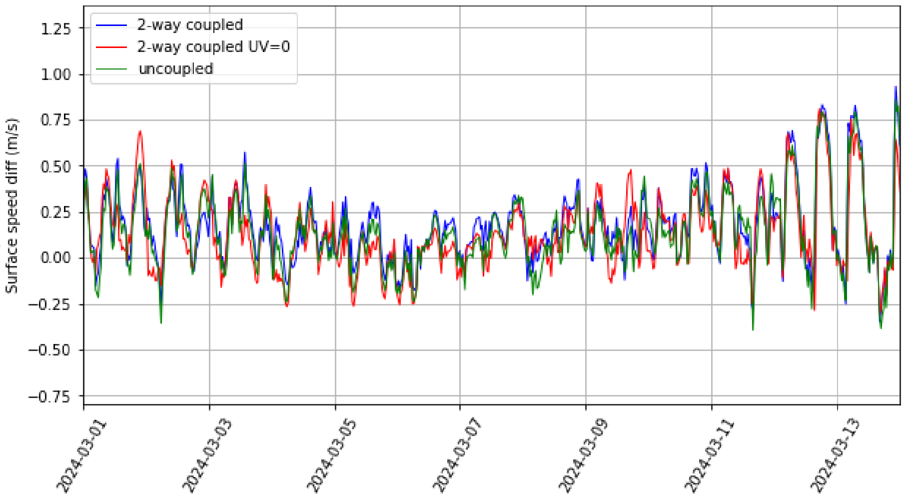
Sea level – E0, E1, E2

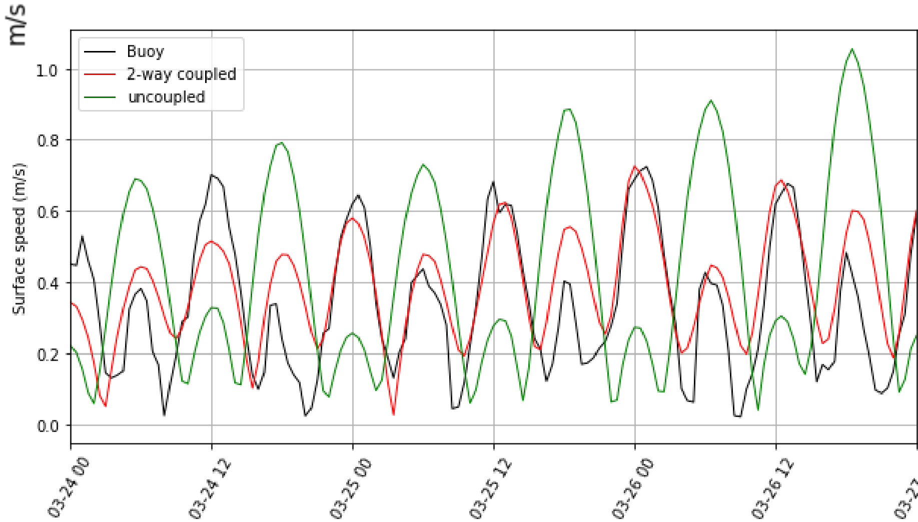
- Not so different - a few cm
- It is fine for deep locations
- Along coast different story



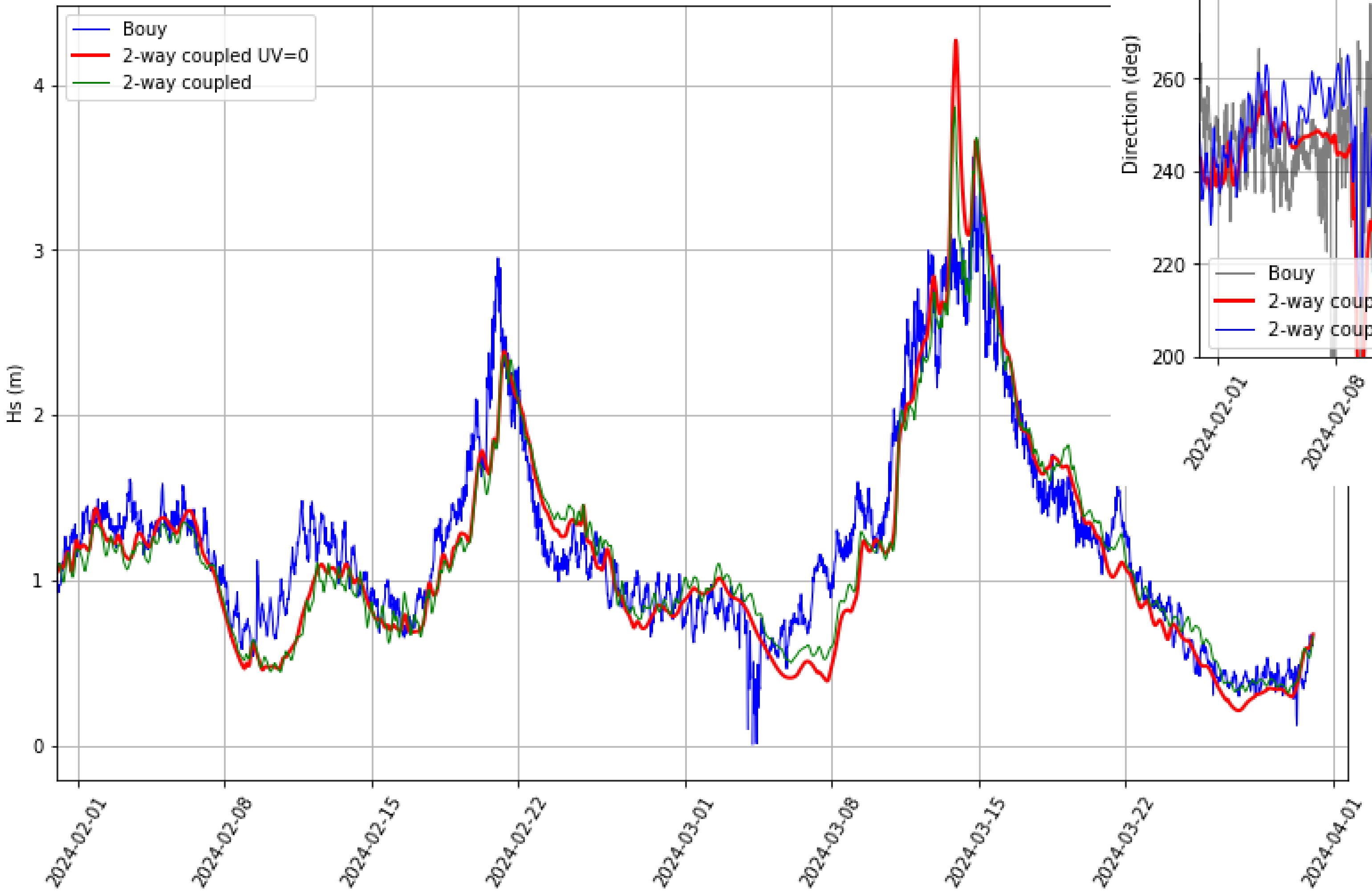
Currents E0, E1, E2

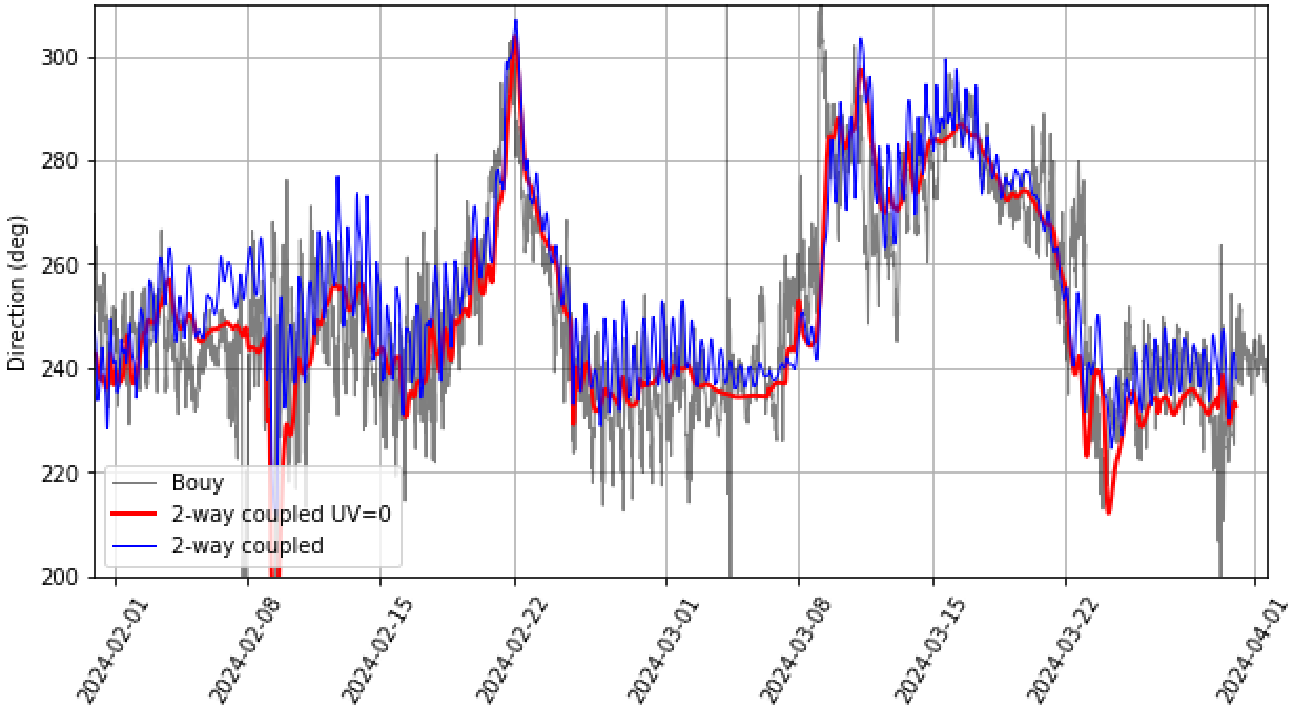






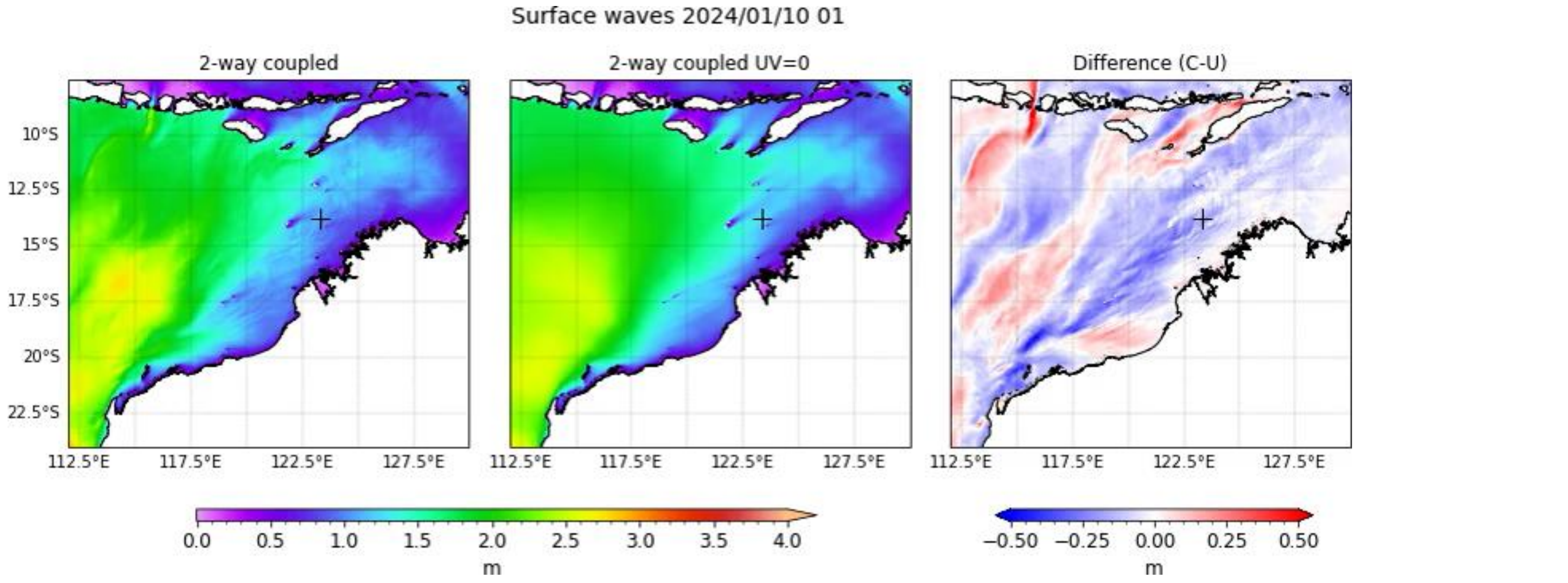
Waves – a bit different story





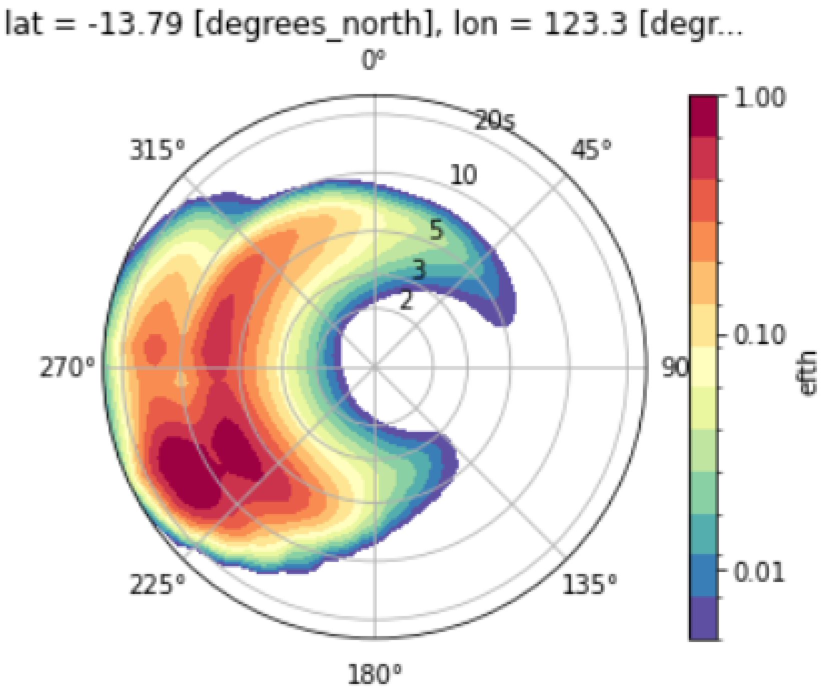
Hs for E2, E1 and E2-E1

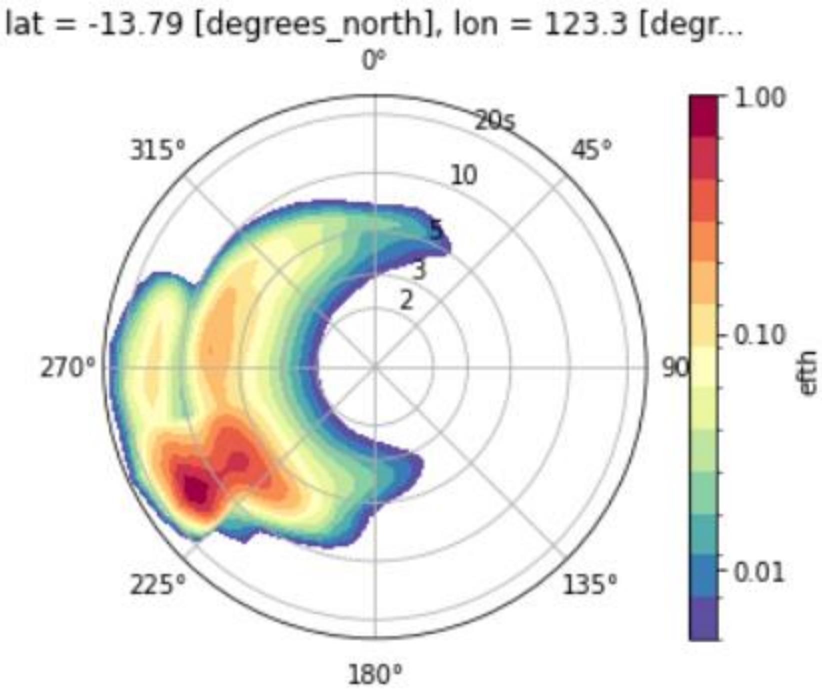
- Depends on location and current strength
- Difference almost as in Ardhuin paper (Gulf Stream)



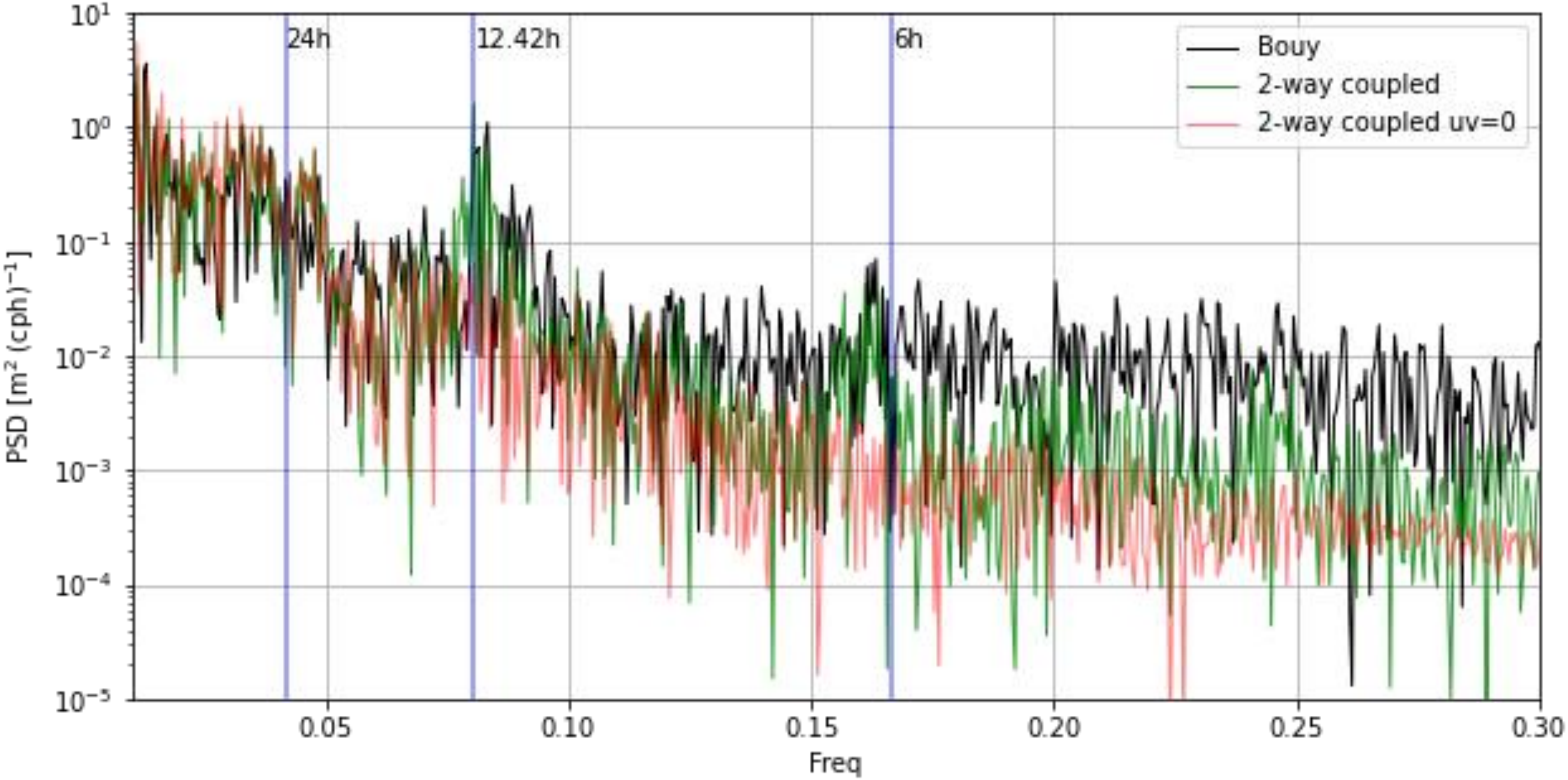
Wave spectra at single point

```
dset_c.isel(lat=0, lon=0).sel(time=slice('2024-02-01','2024-03-01')).mean(dim="time").spec.plot(as_period=True,
                                                                    normalised=True, cmap="Spectral_r", radii_labels_size=10);
```



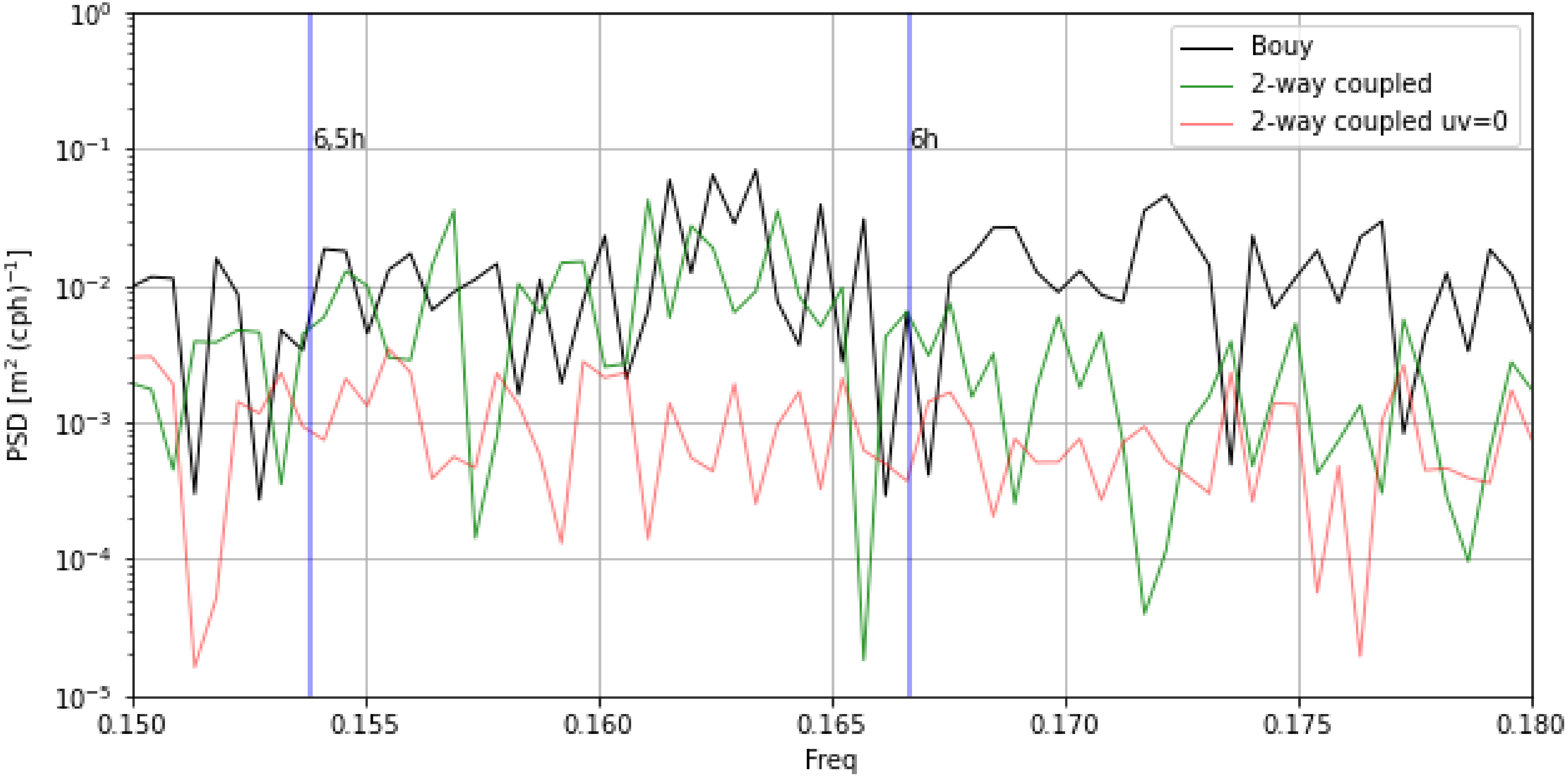


Hs and PSD



24h
12.42h
6h
Bouy
2-way coupled
2-way coupled uv=0
PSD [m² (cph)⁻¹]
Freq
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.05
0.10
0.15
0.20
0.25
0.30

Hs PSD zoom



Bouy
2-way coupled
2-way coupled uv=0
6.5h
6h
PSD [m² (cph)⁻¹]
Freq
0.150
0.155
0.160
0.165
0.170
0.175
0.180

Conclusion (work in progress)

THE UNIVERSITY OF WESTERN AUSTRALIA

- Even we use sophisticated models still hard to fcst
- Wave modulation in semi-diurnal and 6h band
  - Hs can vary up to 10-15%
  - Direction up +/- 10 degrees (up to 20)
  - 2D spectra quite different
- Variability - specific for location/currents (BT/BC)
- 2-way coupling helps with observed modulation PDS
- Using 4D-Var together with 2-way coupled waves?