

Impacts of Hurricane Irma (2017) on ocean transport processes

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Abstract

In most hydrodynamic model studies, currents and waves are simulated in an uncoupled manner. These modelled currents can then be used to simulate the trajectories of passive drifters (pollutants, sediments, larvae, etc.) without taking wave or wave-current interactions into account. Although this simplification holds for most situations, as the force exerted by waves on currents can be neglected in fair weather conditions, it may lead to significant errors during storm conditions, when currents are strongly influenced by wind-generated waves. In this study, we investigate current-wave interactions in heavy-wind conditions and their impact on transport by coupling the unstructured-mesh hydrodynamic model SLIM with the spectral wave model SWAN. We apply the coupled model in the Florida Reef Tract during Hurricane Irma (Sep. 2017) and show that it successfully reproduces both the observed wave behavior and storm surge during the passage of the hurricane. The modeled currents are

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then used to simulate the trajectories of passive drifters during the passage of the hurricane. Our results show that taking wave force into account induces variations of up 1 m/s in modelled currents on the continental shelf break as well as in the vicinity of reefs and islands. Wave-current interactions can therefore deflect the trajectories of drifting material by up to 10 km on the passage of the storm *Add something?*. These results strongly advocate for the inclusion of wave forces while studying transport processes (sediments, pollutants, larvae, etc.) in heavy-wind conditions.

Keywords:

1. Introduction

Wave-current interactions in coastal areas are of great importance for coastal engineering and management as they play a key role in sediment transport, morphological evolution and pollutant mixing (Bever and MacWilliams, 2013; Li and Johns, 1998). However, these interactions are highly nonlinear and can vary significantly in space and time (Wu et al., 2011). Wave-induced currents are generated by wave radiation stress gradients (Longuet-Higgins, 1970), affecting water levels near shorelines and wave breaking points (Longuet-Higgins and Stewart, 1964). Changes in water levels and currents, in turn, affect the motion and evolution of the waves (Sikirić et al., 2013). Coupled wave-current models are therefore required to correctly represent these complex interactions.

As coastal oceans are characterized by a complex topography with islands, inlets and estuaries, unstructured models are preferred as structured grid models show limitations in resolving topologically-controlled nearshore processes (Wu et al., 2011; Chen et al., 2007). Being able to capture the impact of topology on wave interactions becomes even more important in the case of hurricanes. The strong hurricane-induced winds generate large wind-waves and disturb ocean conditions (Liu et al., 2020) by causing coastal upwellings on continental shelves (Smith, 1982) and inducing strong currents, waves and

21 storm surges in nearshore and coastal regions (Dietrich et al., 2010; Weisberg
22 and Zheng, 2006).

23 South Florida and the Gulf of Mexico are particularly vulnerable to
24 hurricanes (Malmstadt et al., 2009) and modelling studies predict tropical
25 cyclones to increase both in frequency and intensity in this region (Marsooli
26 et al., 2019; Knutson et al., 2010). Accurately representing wave-current
27 interactions under strong winds becomes therefore critical in order to predict
28 hurricane impacts in events such as the Deepwater Horizon oil spill in
29 the Gulf of Mexico in 2010 (Le Hénaff et al., 2012). A better description of
30 the impacts of waves on currents could also improve the accuracy of search
31 and rescue efforts during storms (Breivik et al., 2013) or inform reef managers
32 by better understanding the impact of hurricane-induced currents on larval
33 dispersal (Lugo-Fernández et al., 2001).

34 Individual-based modelling of particulates has been extensively used to
35 study the transport of drifting materials such as pollutants, sediments or
36 larvae (Le Hénaff et al., 2012; Liubartseva et al., 2018; Figueiredo et al.,
37 2013; Frys et al., 2020). Although some of these studies take the impact of
38 waves into account by adding a Stokes drift velocity, *i.e.* the net drift of a
39 floating particle in the direction of the wave propagation (Van Den Bremer
40 and Breivik, 2018), to the Eulerian currents, they usually neglect the wave-
41 induced currents. Such practice is reasonable in the case of fair weather,
42 when wave-induced forces exerted on currents are relatively small, but might
43 lead to significant inaccuracies during storm conditions (Röhrs et al., 2012;
44 Curcic et al., 2016). To assess the importance of wave-current interactions
45 during a tropical cyclone, we investigated the transport of drifting particles
46 on the Florida shelf during Hurricane Irma, one of the strongest and costliest
47 tropical cyclones on record in the Atlantic Basin (Xian et al., 2018), which
48 made landfall in Florida in September 2017.

49 In this study, we developed an unstructured coupled wave-current model of
50 South Florida to simulate the ocean circulation during hurricane Irma. Both

51 modelled currents and waves were validated against field measurements and
52 were then used to simulate the transport of drifting material in the Florida
53 Keys and the Florida inner shelf during the passage of the hurricane. Model
54 outputs were then compared with uncoupled simulation results in order to
55 assess the impact of wave-induced forces and Stokes drift on the modelled
56 currents and transports.

57 **2. Methods**

58 *2.1. Study area and observational data*

59 The large-scale ocean circulation around South Florida is dominated by
60 the Florida Current (FC), which originates from the Loop Current (LC) where
61 it enters the Florida Straits from the Gulf of Mexico, and, downstream, forms
62 the Gulf Stream. The FC is a major western boundary current characterized
63 by spatial variability and meandering, associated with the presence of cyclonic
64 eddies between the core of the current and the complex reef topography of the
65 Florida Reef Tract (FRT) (Lee et al., 1995; Kourafalou and Kang, 2012). The
66 northern half of these reefs are made of early Holocene reef frameworks and
67 indurated sand ridges while the southern part (the Florida Keys) is composed
68 of a chain of limestone islands, fossilized remnants of ancient coral reefs and
69 sand bars (Hoffmeister and Multer, 1968; Shinn, 1988; Lidz and Shinn, 1991).
70 The variability of the FC extends over a large range of spatial and temporal
71 scales, with periods of 30-70 days in the Lower Keys (Lee et al., 1995) and
72 shorter periods of 2-21 days in the Upper Keys (Lee and Mayer, 1977), and
73 exhibits significant seasonal and interannual cycles (Johns and Schott, 1987;
74 Lee and Williams, 1988; Schott et al., 1988). Circulation on the West Florida
75 Shelf (WFS) on the other hand is forced by local winds and tidal fluctuations
76 (Lee and Smith, 2002; Liu and Weisberg, 2012).

77 The state of the ocean around Florida is monitored by an extensive
78 array of tide gauges, current meters and buoys. In this study, we used sea
79 surface elevation measurements from the National Oceanic and Atmospheric

80 Administrations (NOAA) Tides and Currents dataset. These measurements
81 were taken at four locations: two in the Florida Keys (Key West and Vaca Key);
82 one on the eastern coast of Florida (Virginia Key); and one on the western
83 coast (Naples). For the currents, we used ADCP measurements from the
84 University of South Florida's College of Marine Science's (USF/CMS) Coastal
85 Ocean Monitoring and Prediction System (COMPS) for the WFS (Weisberg
86 et al., 2009). More specifically, we used measurements from moorings C10,
87 C12 and C13, respectively located at the 25, 50, and 50 m isobaths of the
88 WFS (Liu et al., 2020). Finally, for the waves, we used measurements from
89 four buoys of the NOAA's National Data Buoy Center (NDBC); two on
90 Florida's eastern shelf and two on the WFS. The locations of all measurement
91 stations are shown in Fig. 1A,C.

92 *2.2. Wind and atmospheric pressure during Hurricane Irma*

93 Irma made landfall in Florida on 10 September 2017 as a category 3
94 hurricane, first at Cudjoe Key (Florida Keys) and later on Marco Island,
95 south to Naples (see hurricane track in Fig. 1). It then weakened to a
96 category 2 hurricane as it moved further inland (Pinelli et al., 2018). The
97 storm damaged up to 75% of the buildings at his landfall point in the Florida
98 Keys, making it one of the strongest and costliest hurricanes on record in the
99 Atlantic basin (Xian et al., 2018; Zhang et al., 2019). The strongest reported
100 wind speed was 50 m/s on Marco Island while the highest recorded storm
101 surge was 2.3 m, although larger wind speed likely occurred in the Florida
102 Keys (Pinelli et al., 2018). In order to reproduce the wind profile of Irma in
103 our model, we used high-resolution H*Wind wind fields (Powell et al., 1998).
104 As these data represent 1-min averaged wind speeds, we multiplied them by
105 a factor 0.93 to obtain 10-min averaged wind speeds (Harper et al., 2010),
106 which are more consistent with the time step of our model. Furthermore,
107 H*Wind wind profiles did not cover the whole model extent during the passage
108 of the hurricane and were thus blended within coarser wind field extracted
109 from ECMWF ERA-5 datasets (Fig. 2A). Pressure fields of Irma were also

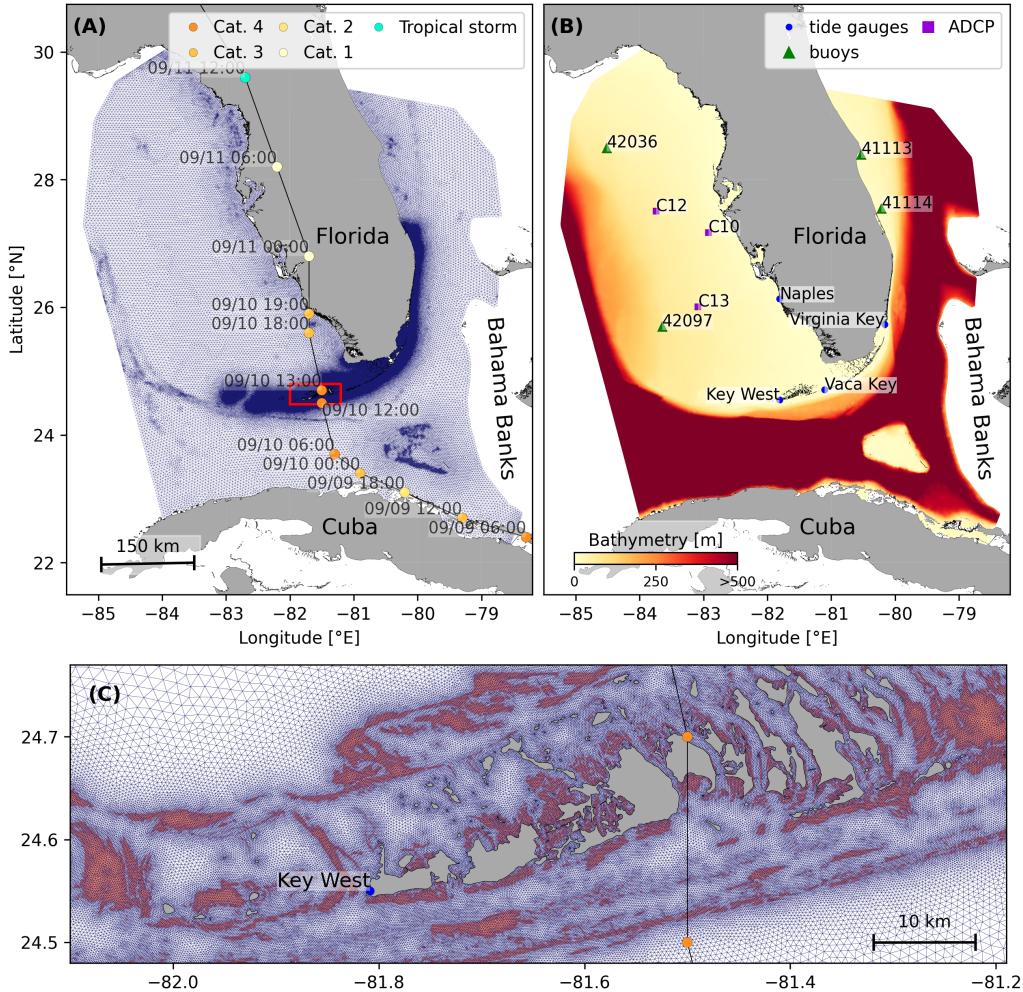


Fig. 1: **A:** Mesh of the computational domain with the trajectory of Irma, category of the hurricane is given by the Saffir-Simpson color scale. **B:** Bathymetry of the domain with the location of stations used for the validation of the model outputs. **C:** Close up view of the Lower Keys area, where the mesh resolution reaches 100m near reefs (shown in dark orange) and islands (highlighted in dark grey)

110 constructed using ERA-5 data. However, the coarse resolution of the dataset
 111 smoothes out the depression at the center of the hurricane, leading to an
 112 underestimation of the pressure gradient (Fig. 2B). To better capture the
 113 central depression of Irma, we built a hybrid pressure field using the position
 114 and the minimal pressure of the core of the hurricane based on its track as
 115 recorded in the HURDAT 2 database (Landsea and Franklin, 2013). Based on
 116 this information, the hybrid pressure field was constructed by combining an
 117 idealized Holland pressure profile (Lin and Chavas, 2012) within the radius of
 118 maximum wind speed of Irma (Knaff et al., 2018) with ERA-5 pressure field.
 119 The transition from the Holland profile to ERA-5 data outside the radius of
 120 maximum wind speed data was performed using a smooth step function (Fig.
 121 2).

122 *2.3. Hydrodynamic model*

123 Ocean currents generated during hurricane Irma around South Florida
 124 were modelled using the 2D barotropic version of the unstructured-mesh
 125 coastal ocean model SLIM¹. The model mesh covers an area similar to the
 126 model extent of Dobbelaere et al. (2020b), that includes the FRT but also the
 127 Florida Straits and part of the Gulf of Mexico (Figure 1). However, this area
 128 has been slightly extended northeastward and westward in order to include
 129 the NOAA-NDBC buoys. Furthermore, to withstand potential cell drying
 130 during the hurricane, we solved the conservative shallow water equations with
 131 wetting-drying:

$$\begin{aligned}
 \frac{\partial H}{\partial t} + \nabla \cdot (\mathbf{U}) &= 0 , \\
 \frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \left(\frac{\mathbf{U}\mathbf{U}}{H} \right) &= -f\mathbf{e}_z \times \mathbf{U} + \alpha g H \nabla(H - h) - \frac{1}{\rho} \nabla p_{\text{atm}} + \frac{1}{\rho} \boldsymbol{\tau}_s \quad (1) \\
 &\quad + \nabla \cdot (\nu \nabla \mathbf{U}) - \frac{C_b}{H^2} |\mathbf{U}| \mathbf{U} + \gamma (\mathbf{U}_{\text{ref}} - \mathbf{U}) ,
 \end{aligned}$$

¹<https://www.slim-ocean.be>

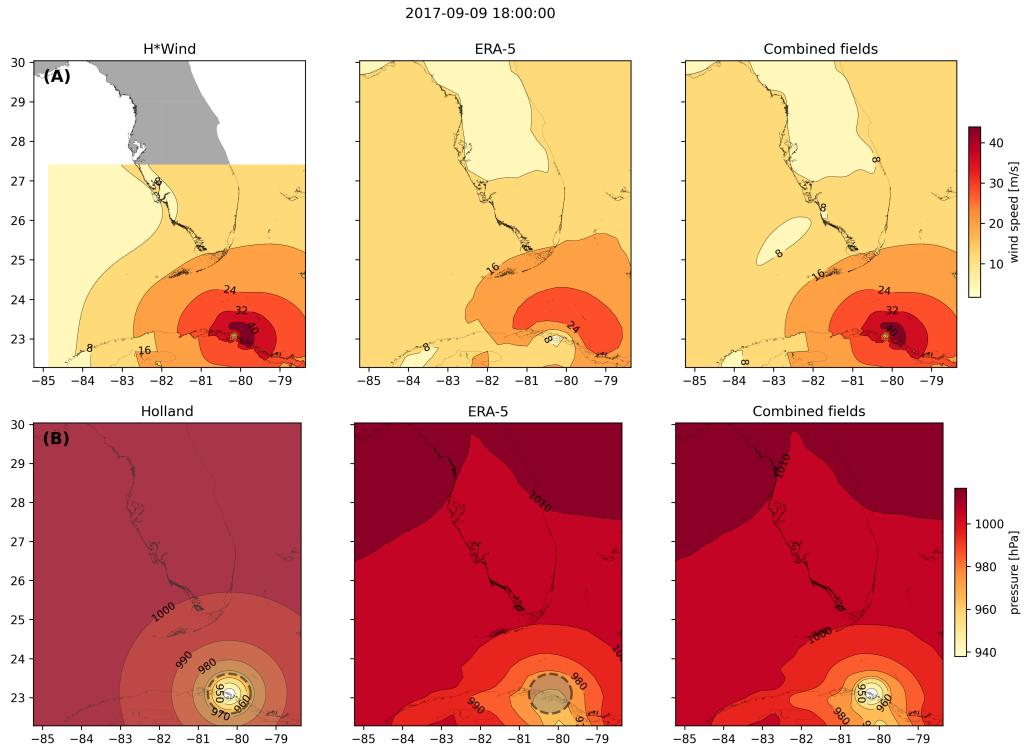


Fig. 2: Snapshot of the hybrid wind and pressure profiles constructed to capture the passage of Hurricane Irma at 1800 UTC 9 September 2017. Wind profiles are obtained by combining high resolution H*Wind with coarse ERA-5 wind fields. Pressure fields are built by combining RA-5 pressure field with an idealized Holland pressure profile based on the track of Irma in the HURDAT 2 database. Holland field was only used within the radius of maximum wind speed (discontinuous grey line) of the hurricane to capture its central depression.

132 where H is the water column height and \mathbf{U} is the depth-averaged transport;
 133 f is the Coriolis coefficient; g is the gravitational acceleration; h is the
 134 bathymetry; α is a coefficient stating whether the mesh element is wet ($\alpha = 1$)
 135 or dry ($\alpha = 0$) *[add more detail about impact of wetting-drying ?]*; ν is the
 136 viscosity; C_b is the bulk bottom drag coefficient; ∇p_{atm} is the atmospheric
 137 pressure gradient; τ_s is the surface stress, usually due to wind; and γ is a
 138 relaxation coefficient towards a reference transport \mathbf{U}_{ref} . As in Frys et al.
 139 (2020) and Dobbelaere et al. (2020b), SLIM currents were gradually relaxed
 140 towards the operational Navy HYCOM product (GOMl0.04², Chassignet et al.
 141 (2007)) in regions where the water depth exceeds 50m.

142 At very high wind speeds, the white cap is blown off the crest of the waves
 143 (also known as spumes), which has been hypothesized to generate a layer
 144 of droplets that acts as a slip layer for the winds at the ocean-atmosphere
 145 interface (Holthuijsen et al., 2012). This causes a saturation of the wind drag
 146 coefficient for strong winds (Powell et al., 2003; Donelan et al., 2004; Curcic
 147 and Haus, 2020). We take this saturation effect into account by using the wind
 148 drag parameterization of Moon et al. (2007). In this parameterization, the
 149 drag coefficient C_d depends on the wind speed at 10-m height U_{10} according
 150 to:

$$C_d = \kappa^2 \log \left(\frac{10}{z_0} \right)^{-2} \quad (2)$$

151 where κ is the von Karman constant and z_0 is the roughness length expressed
 152 as:

$$z_0 = \begin{cases} \frac{0.0185}{g} U_*^2 & \text{if } U_{10} \leq 12.5 \text{ m/s ,} \\ [0.085(-0.56U_*^2 + 20.255U_* + 2.458) - 0.58] \times 10^{-3} & \text{if } U_{10} > 12.5 \text{ m/s ,} \end{cases} \quad (3)$$

²<https://www.hycom.org/data/goml0pt04>

153 with U_* the friction velocity. The relation between U_{10} and U_* is given by:

$$U_{10} = -0.56U_*^2 + 20.255U_* + 2.458 . \quad (4)$$

154 The mesh resolution depends on the distance to coastlines and reefs
155 following the approach of Dobbelaere et al. (2020b). The mesh is then further
156 refined according to bathymetry value and gradient, as suggested in the
157 SWAN user-guide³. Such an approach improves the model efficiency as the
158 mesh resolution is only increased where required by the currents and waves
159 dynamics. The mesh was generated with the seamsh⁴ Python library, which is
160 based on the open-source mesh generator GMSH (Geuzaine and Remacle,
161 2009). It is composed of approximately 7.7×10^5 elements. The coarsest
162 elements, far away from the FRT, has a characteristic length of about 5 km
163 whereas the finest elements have a characteristic length of about 100 m along
164 the coastlines and over the reefs (Fig 1).

165 *2.4. Wave model*

166 Waves were modelled using the parallel unstructured-mesh version of the
167 Simulating WAves Nearshore (SWAN) model (Booij et al., 1999), one of the
168 most commonly used wave models in coastal areas and inland waters. This
169 model solves the action balance equation (Mei, 1989):

$$\frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot [(\mathbf{c}_g + \mathbf{u})N] + \frac{\partial}{\partial \theta}[c_\theta N] + \frac{\partial}{\partial \sigma}[c_\sigma N] = \frac{S_{in} + S_{ds} + S_{nl}}{\sigma} , \quad (5)$$

170 where $N = E/\sigma$ is the wave action density and E is the wave energy spectrum;
171 θ is the wave propagation direction; σ is the intrinsic wave frequency; \mathbf{c}_g is
172 the wave group velocity, $\mathbf{u} = \mathbf{U}/H$ is SLIM depth-averaged current velocity;
173 c_θ and c_σ are the propagation velocities in spectral space due to refraction
174 and shifting in frequency due to variations in depth and currents; and S_{in} ,

³<http://swanmodel.sourceforge.net/unswan/unswan.htm>

⁴<https://pypi.org/project/seamsh/>

S_{ds}, and *S_{nl}* respectively represent wave growth by wind, wave decay and nonlinear transfers of wave energy through interactions between triplets and quadruplets. The wave spectra were discretized with 48 direction bins and 50 frequency bins logarithmically distributed from 0.03 to 2 Hz. Exponential wind growth was parameterized using the formulation of Janssen (1991), while dissipations by whitecapping and bottom dissipations followed the formulations of Komen et al. (1984) and Madsen et al. (1989), respectively. Coefficients for exponential wind growth and whitecapping parameterizations were based on the results of Siadatmousavi et al. (2011), and significantly differ from SWAN's default settings. By default, SWAN implements the wind input formulation of Komen et al. (1984) and the steepness-dependent coefficient governing dissipation by whitecapping is a linear function of the wave number. In this study, this steepness-dependent coefficient is a quadratic function of the wave number, as it showed better predictions of the significant wave height in the study of Siadatmousavi et al. (2011). The choice of these formulations was motivated by the appearance of numerical instabilities in the region of the Gulf Stream when using SWAN's default parameter values. Finally, wave boundary conditions were derived from WAVEWATCH III (Tolman et al., 2009) spectral outputs at NDBC buoy locations. We selected these datasets as the large number of NDBC buoys around our region of interest allowed for a fine representation of the wave spectra on the boundary of the domain.

Surface waves induce a net drift in the direction of the wave propagation, known as the Stokes drift (Van Den Bremer and Breivik, 2018; Stokes, 1880). This net drift has a significant impact on sediment transport in nearshore regions (Hoefel and Elgar, 2003), on the formation of Langmuir cells (Langmuir, 1938; Craik and Leibovich, 1976) as well as on the transport of heat, salt or pollutants such as oil or micro-plastic in the upper ocean layer (McWilliams and Sullivan, 2000; Röhrs et al., 2012; Drivdal et al., 2014). To correctly model the Stokes drift profile in mixed wind-driven sea and swell

205 conditions, the full two-dimensional wave spectrum must be represented by a
 206 spectral wave model within a wave-current coupling (Van Den Bremer and
 207 Breivik, 2018). We therefore used SWAN modelled spectra to compute the
 208 Stokes drift as follows:

$$\mathbf{u}_s = \int_0^{2\pi} \int_0^{+\infty} \frac{\sigma^3}{h \tanh(2kh)} E(\sigma, \theta) (\cos \theta, \sin \theta) d\sigma d\theta , \quad (6)$$

209 where k is the norm of the wave vector; h is the water depth; and $E(\sigma, \theta)$ is
 210 the wave energy density.

211 *2.5. Coupled model*

212 SLIM and SWAN are coupled so that they run on the same computational
 213 core and the same unstructured mesh. SLIM is run first and passes the
 214 wind velocity (\mathbf{U}_{10}), water level ($\eta = H - h$) and depth-averaged current
 215 ($\mathbf{u} = \mathbf{U}/H$) fields to SWAN, as well as a roughness length (z_0) for the bottom
 216 dissipation formulation of Madsen et al. (1989). This roughness length is
 217 computed from SLIM's bulk drag coefficient C_b following the approach of
 218 Dietrich et al. (2011) so that both models have consistent bottom dissipation
 219 parameterizations. SWAN then uses these quantities to compute the wave
 220 radiation stress gradient, that is then passed to SLIM as the force exerted
 221 by waves on currents $\boldsymbol{\tau}_{\text{wave}}$ (Fig. 3). SLIM then uses this quantity to
 222 update the value of the surface stress $\boldsymbol{\tau}_s$ in Eq. (1), that now becomes
 223 the sum of wind and wave-induced stresses $\boldsymbol{\tau}_s = \boldsymbol{\tau}_{\text{wind}} + \boldsymbol{\tau}_{\text{wave}}$. Here, the
 224 momentum flux from the atmosphere to the ocean is taken as the commonly-
 225 used full wind stress $\boldsymbol{\tau}_{\text{wind}}$. Doing so, we neglect the momentum advected
 226 away from the storm by the waves, leading to a 10-15% overestimation of
 227 the momentum flux in hurricane winds Curcic (2015). Moreover, we followed
 228 the approach of Dietrich et al. (2012) by characterizing the wave-induced
 229 stresses using the radiation-stress representation instead of the vortex-force
 230 representation (McWILLIAMS et al., 2004). Although the later provides a
 231 clearer and meaningful decomposition of the wave-effect, we implemented the

232 first representation for the sake of simplicity as it allows us to provide the
233 whole wave contribution as an additional surface stress to SLIM (Lane et al.,
234 2007).

235 SLIM's governing equations are integrated using an implicit time integra-
236 tion scheme while SWAN is unconditionally stable (Dietrich et al., 2012),
237 allowing both models to be run with relatively large time steps. In this study,
238 the stationary version of SWAN was used, *i.e.* the time derivative of Eq. 5
239 was set to zero. This resulted in reduced scaling and convergence rates than
240 with the nonstationary version of SWAN but increased the stability of the
241 model. The wave spectra at each node of the mesh was saved at the end of
242 each iteration to serve as initial conditions for the next one. Both models
243 were run sequentially using a time step of 600s, so that each computational
244 core was alternatively running either SLIM or SWAN. As in the coupling
245 between SWAN and ADCIRC (Dietrich et al., 2012), both models use the
246 same local sub-mesh, allowing for a one-to-one correspondence between the
247 geographic locations of the mesh vertices. No interpolation is therefore needed
248 when passing the discretised variables from one model to the other, which
249 allows an efficient inter-model communication. However, as SLIM applies
250 discontinuous Galerkin finite element methods, an additional conversion step
251 to a continuous framework was required to transfer SLIM nodal quantities to
252 SWAN.

253 3. Results

254 We first validated the reconstructed atmospheric fields of hurricane Irma
255 as well as the outputs of our coupled jave-current model against field mea-
256 surements. A summary of the error statistics is given in Table 1. We then use
257 the validated model to simulate the transport of passive drifters in the Lower
258 Keys during the passage of Hurricane Irma. These drifters were advected by
259 two sets of currents: (i) the currents from an uncoupled SLIM model run
260 during Irma (SLIM) and (ii) the currents from the coupled SLIM+SWAN

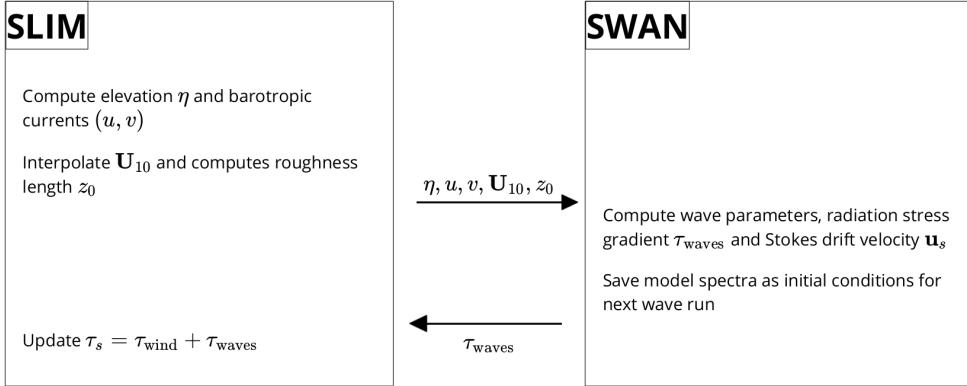


Fig. 3: Schematic illustration of the coupled SLIM+SWAN model.

model (SLIM+SWAN). Furthermore, the depth-averaged Stokes drift was computed using the wave spectra of our coupled model run (Stokes-C) as well as those of an uncoupled SWAN run during the passage of the hurricane (Stokes-U). We then simulated the trajectories of passive tracers during the passage of the Irma in the Lower Keys using different combinations of these fields. These trajectories were finally compared to evaluate the impact of the wave-current interactions and the Stokes drift on the transport processes during a major hurricane.

3.1. Model validation

H*Wind winds and hybrid pressure field agree well with station measurements at Vaca Key station (Fig. 4). The hybrid pressure field shows better agreement with observations than ERA-5 pressure as it successfully reproduces the storm depression. ERA-5 fields, on the other hand, fail to resolve the low pressure at the core of the hurricane due to their coarser grid, leading to an overestimation of 8 mbar of the storm depression. Both H*Wind and ERA-5 agree well with observed wind speeds although both data sets tend to slightly overestimate the width and intensity of the wind peak. However, H*wind profiles show a better match with the timing of the observed peak, as ERA-5 winds tend to anticipate it. H*wind also exhibits a

Validation of atmospheric forcings at Vaca Key station

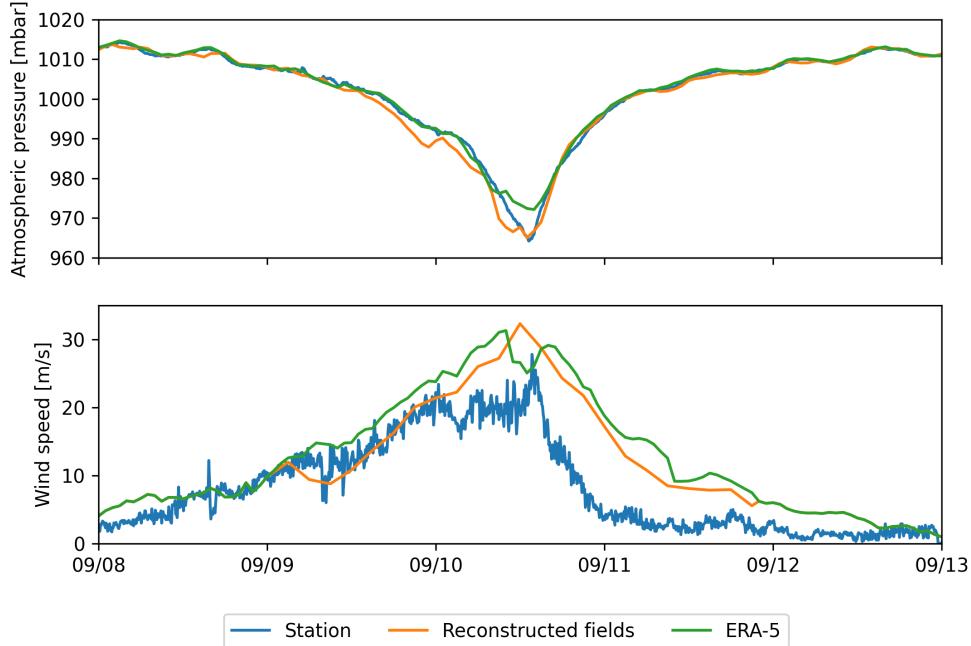


Fig. 4: Comparison of reconstructed wind atmospheric pressure with field measurements and coarser ECMWF ERA-5 profiles at Vaca Key station. The generated hybrid atmospheric forcings better capture the observed storm depression while H*wind winds better match the measured peak in wind speed.

slightly narrower peak in wind speed, which better agrees with observations.
 Hydrodynamic outputs of the coupled wave-current model agree well with tide gauge (Fig. 5) and ADCP measurements (Fig. 6). Despite a slight overestimation of the amplitude of sea surface elevation (1) in fair weather conditions, the timing and amplitude of the storm surges are well reproduced by the coupled model. The largest model error during the surge is an overestimation of 18 cm of the elevation peak at Virginia Key. The fit is especially good at Naples, where both the large positive and negative surges are captured by the coupled model with an error of less than 5 cm. Modelled 2D currents were validated against depth-averaged ADCP measurements at mooring station C10, C12 and C13 (Fig. 6). As in Liu

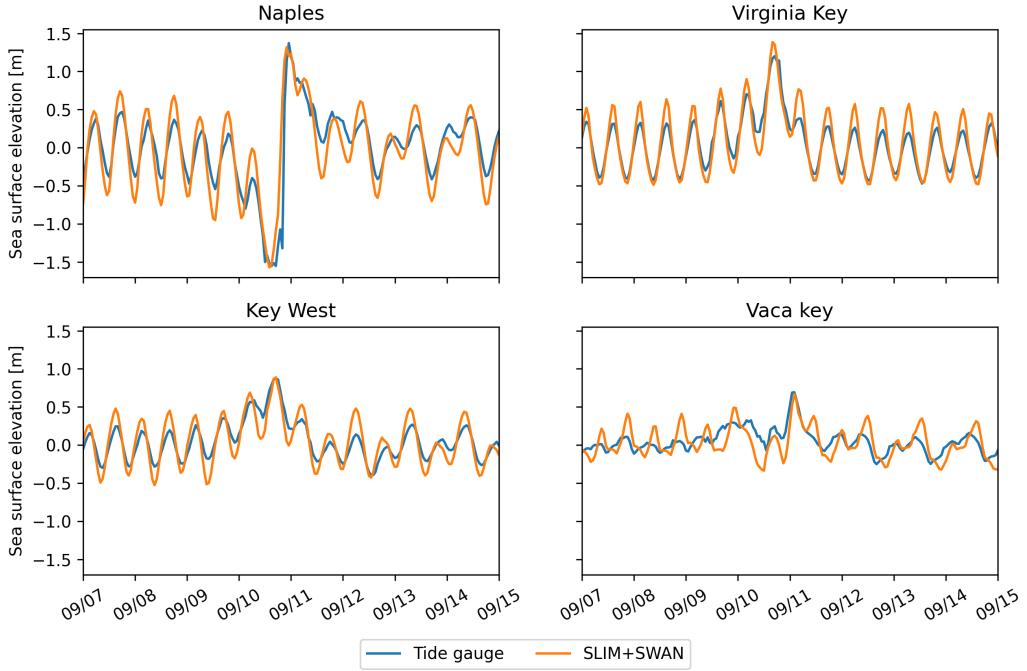


Fig. 5: Comparison of modelled sea surface elevation with all 4 tide gauge measurements (see Fig. 1B for their location). Timing and amplitudes of the storm surges are well reproduced by the model

et al. (2020), we performed the vector correlation analysis of Kundu (1976) to compare modelled and observed current velocity vectors. Correlation coefficients (ρ) between simulated and observed depth-averaged currents were 0.84, 0.74 and 0.73 at the C10, C12 and C13 locations, respectively. Average veering angles were computed as well and were below 12° , as in (Liu et al., 2020). Furthermore, Table 1 indicates that our model tends to produce larger prediction errors on the northward component of the depth-averaged currents than the eastward one. As expected from a depth-averaged model, the best fit with observations is obtained at the shallowest mooring C10, located on the 25 m isobath, with an average veering angle of 6° and smaller error statistics (Table 1).

The simulated significant wave height agrees well with observations on

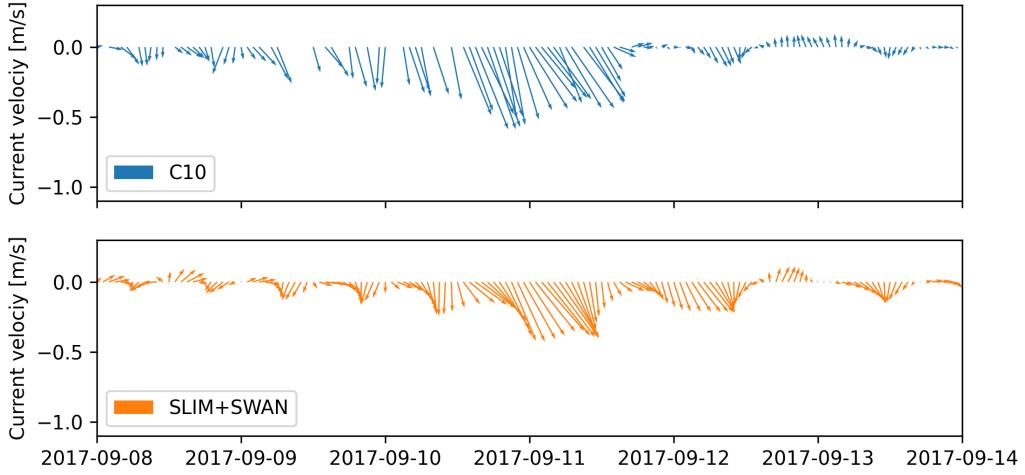


Fig. 6: Comparison of modelled current velocity with observed velocity at mooring C10 (see Fig. 1B for its location). Modelled current velocities agree well with observations, with a correlation coefficient of 0.83 and an average veering angle of 6° .

the WFS, where errors on the peak value do not exceed 5% (Fig. 7). On Florida's eastern shelf, errors are slightly larger and reach 20%. Although the model outputs agree well with observations, a lag in significant wave height is observed for all 4 buoys. Moreover, the peak in significant wave height tends to be underestimated at buoys 41113 and 41114, located on the East Florida Shelf. Other wave parameters were better reproduced by the model on the WFS as well (see buoy 42036 in Fig. 7 and Table 1).

3.2. Impact of waves on currents and transport

We evaluated the impact of wave-current interactions on modelled currents during the passage of Irma in the Lower Keys, between Sept. 7 and 13, 2017. First, we computed the maximum difference between currents modelled by SLIM and SLIM+SWAN during this period (Fig. 8A). The largest differences in current speed were observed over the reefs, on the shelf break and around islands. They can locally reach 1 m/s, with the coupled model SLIM+SWAN yielding the largest amplitudes. The regions where the differences are the largest experience the largest wave-induced stress τ_{wave} (Fig. 8B), as wave

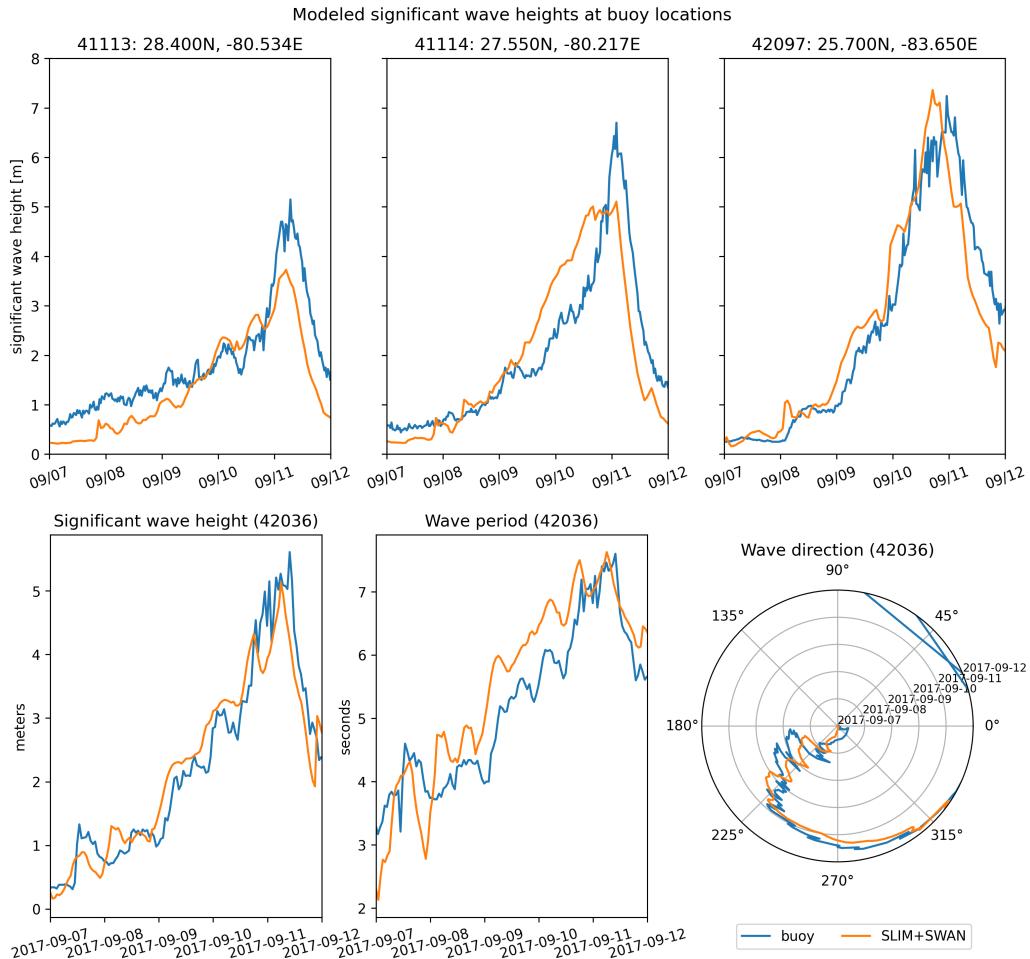


Fig. 7: Comparison of modelled wave parameters with observation at the 4 buoys location (locations shown in Fig. 1B). Modelled significant wave height agrees well with field measurement.

Station	Variable	Bias	MAE	RMSE
Vaca Key	sse (m)	n/a	0.12	0.16
	U_{10} (m/s)	1.51	1.85	2.61
	p_{atm} (hPa)	-0.21	0.59	1.03
Key West	sse (m)	n/a	0.11	0.13
Virginia Key	sse (m)	n/a	0.10	0.13
Naples	sse (m)	n/a	0.18	0.23
C10	u (m/s)	-0.006	0.04	0.05
	v (m/s)	0.02	0.06	0.08
C12	u (m/s)	-0.01	0.06	0.07
	v (m/s)	0.06	0.09	0.11
C13	u (m/s)	0.004	0.06	0.08
	v (m/s)	0.04	0.06	0.08
41113	H_s (m)	-0.35	0.40	0.51
	T_m (s)	-2.18	2.47	3.13
41114	H_s (m)	-0.21	0.53	0.68
	T_m (s)	-1.69	2.53	3.15
42036	H_s (m)	-0.03	0.26	0.36
	T_m (s)	0.04	0.65	0.77
42097	H_s (m)	-0.15	0.40	0.57
	T_m (s)	0.02	0.62	0.74

Table 1: Error statistics comparing SLIM+SWAN simulated quantities with the measured sea surface elevation (sse), eastward and northward depth-average current velocities (u,v), significant wave height (H_s), and zero-crossing mean wave period (T_m). Model bias, mean absolute error (MAE), and root mean squared error (RMSE) are listed by variable (unit) and value.

319 breaking and wave slowing down over rough seabed induce variations of the
320 wave radiation stress (Longuet-Higgins and Stewart, 1964). Wave-induced
321 differences in current speed were amplified by the action of the wind stress
322 τ_{wind} (Fig. 8C). Wind speeds were larger in the front right quadrant of the
323 hurricane (Zedler et al., 2009), yielding larger differences on the right-hand
324 side of the storm trajectory. This is especially clear in the area between
325 the Florida Keys and the Everglades, where relatively small values of τ_{wave}
326 nonetheless produce current speed differences of up to 0.5 m/s because of the
327 wind stress.

328 To quantify the impact of these differences in the velocity fields, we
329 compared the trajectories of passive particles advected by the uncoupled
330 SLIM and coupled SLIM+SWAN currents during the passage of Irma in the
331 Lower Keys (Fig. 9). Particles were released on the inner and outer shelves
332 at the points highlighted in red and blue dots in Fig. 9A on Sept. 7 at 0000
333 UTC and then tracked until Sept. 15. These areas were constructed using
334 backtracking methods (Dobbelaeere et al., 2020a) to ensure that the release
335 particles would intersect the path of Irma during its passage through the
336 Florida Keys. We first defined two 25km^2 circular regions on the trajectory of
337 the hurricane (see red and blue circles in Fig. 9A). Particles within these two
338 regions were then tracked backward in time using uncoupled SLIM currents
339 from the exact time of the passage of the hurricane until Sept. 7 at 0000
340 UTC. Their positions at the end of the backward simulation (see red and blue
341 particle clouds in Fig. 9) corresponds to the initial condition of the forward
342 transport simulations described below.

343 We compared the trajectories of particles originating from these regions
344 and advected forward in time by different sets of currents: (i) uncoupled SLIM
345 currents alone; (ii) coupled SLIM+SWAN currents; (iii) SLIM currents with
346 the addition of the depth-averaged Stokes drift computed with the coupled
347 wave-current model (Stokes-C); (iv) SLIM+SWAN currents with StokesC;
348 and (v) SLIM currents with the depth-averaged Stokes drift computed with

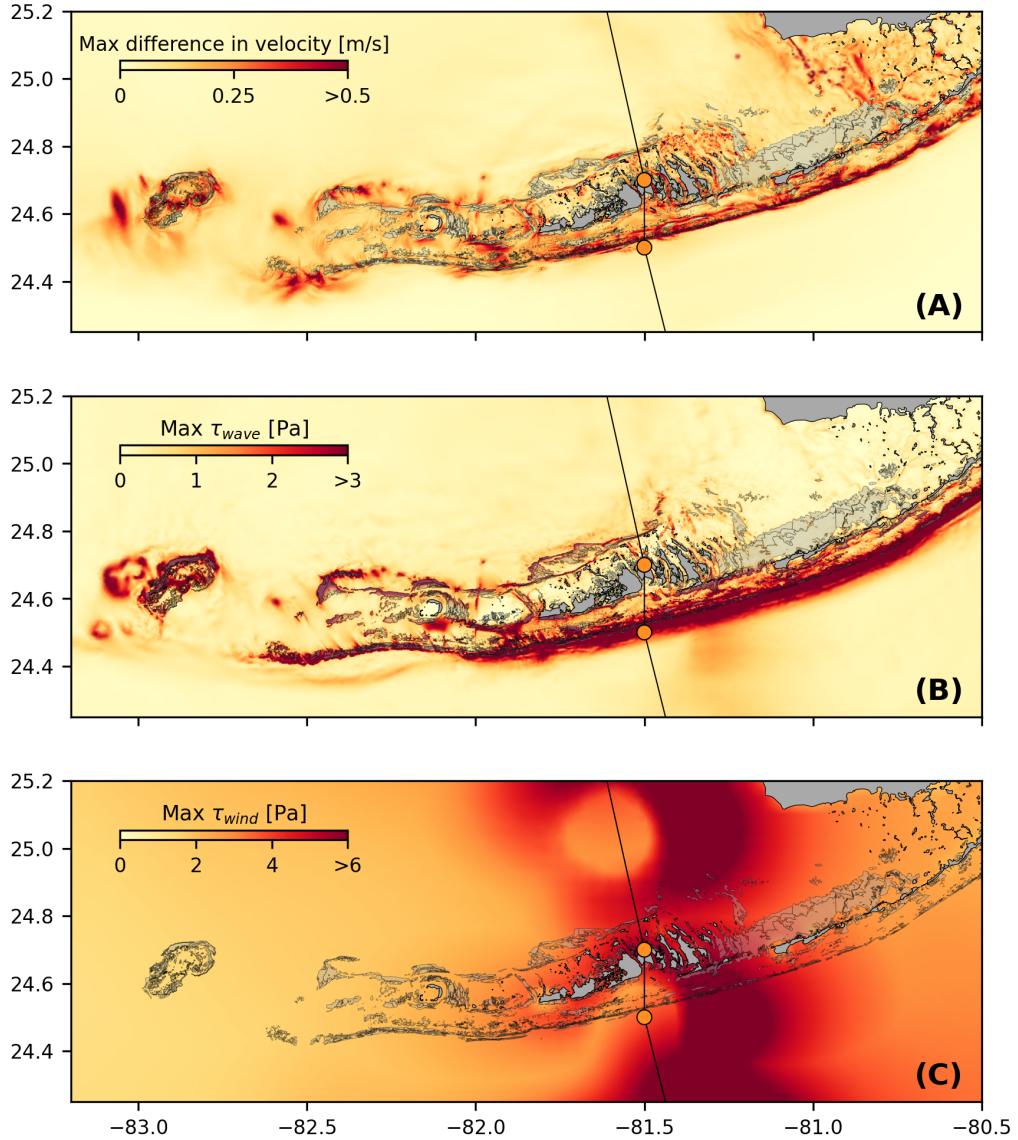


Fig. 8: Maximum difference between SLIM and SLIM+SWAN currents (A) during the passage of Irma in the Lower Florida Keys, along with the maximum wave radiation stress gradient τ_{wave} (B) and wind stress τ_{wind} (C) generated by the hurricane. Wave-induced stress yields difference larger than 0.5 m/s in current velocities.

349 the uncoupled wave model (Stokes-U). Particles trajectories are compared by
350 computing the distances between the centers of mass of the particle clouds
351 through time. The main result coming out of this analysis is that the waves
352 play a significant role on the transport processes during and after the passage
353 of hurricane Irma. Comparison of SLIM and SLIM+SWAN highlights that
354 wave-current interactions alone yield differences of up to 5 km between the
355 modelled trajectories on the passage of the hurricane. These differences exceed
356 10 km on the outer shelf when Stokes drift is taken into account (see 'SLIM
357 vs SLIM+SWAN+Stokes-C' and 'SLIM vs. SLIM+Stokes-C' in Fig. 9B).

358 The impact of the waves on the transport processes differs significantly
359 between the inner and outer shelves, with wave-induced differences in tra-
360 jectories 4 to 5 times larger on the outer shelf. Furthermore, the distances
361 between the centers of mass of the clouds of particles tend to stabilize on
362 the inner shelf after the passage of Irma, while they keep increasing on the
363 other shelf up to two days after the passage of the hurricane when taking
364 Stokes drift into account. These distances then stabilize for about a day
365 before they start decreasing (see top right panel of Fig. 9B). However, when
366 considering wave-current interactions alone (SLIM vs. SLIM+SWAN), this
367 decrease in distances occurs just after the passage of Hurricane Irma. These
368 larger distances between the modeled trajectories on the outer shelf can be
369 explained by the larger waves, current velocities and spatial variability in this
370 region. Furthermore, the fact that the differences between SLIM alone and
371 model runs including Stokes drift keep increasing after the passage of Irma
372 indicates that the impact of the hurricane on the wave field was still significant
373 on the outer shelf up to 2 days after it crossed the Florida Keys.

374 Comparison of 'SLIM vs. SLIM+SWAN' with the other curves in Fig
375 9B indicates that the effect of the Stokes drift dominates the impact of the
376 radiation stress gradient and the wave-current interactions. Nonetheless,
377 'SLIM vs. SLIM+SWAN' yields values similar to the other two curves on
378 the outer shelf on the passage of Hurricane Irma. This suggest that the

379 impact of waves on currents induce effects similar to the impact of the Stokes
380 drift on the outer shelf during the passage of hurricane Irma . However,
381 comparing SLIM and SLIM+SWAN both on the inner and other shelf, we
382 see that this impact is negligible during the rest of the simulation. Moreover,
383 comparison of Stokes-U and Stokes-C (bottom panels of Fig. 9B) indicates
384 that the difference between the trajectories of particles advected by the two
385 Stokes drift do not exceed 2 km, with larger discrepancies on the outer shelf.
386 The sudden increase of 'SLIM+Stokes-C vs SLIM+Stokes-U' curves on the
387 passage of Irma (and two days after on the outer shelf) and their stabilization
388 afterwards suggest that taking wave-currents interactions into account when
389 modeling waves mostly has an impact during (and directly after) the passage
390 of the hurricane.

391 4. Discussion

392 We developed a coupled wave-current model to study the impact of
393 waves on transport processes during Hurricane Irma. In order to accurately
394 represent the wind and pressure profiles of te hurricane, we built hybrid fields
395 by combining coarser ERA-5 data with high-resolution H*Wind data for
396 the wind speed and idealized Holland profiles for the pressure. Comparing
397 these hybrid profiles with field observations showed that they were better at
398 reproducing the observed central depression of the hurricane as well as the
399 peak in wind speed than ERA-5 data. Using these hybrid fields as forcings,
400 our coupled model accurately reproduced the storm surge at NDBC buoy
401 locations and produced currents and wave parameters in good agreement
402 with field observations, especially on the WFS. The modelled currents and
403 Stokes drift were then used to evaluate the impact of waves on the trajectory
404 of passive drifters on the passage of the hurricane through the Florida Keys.
405 Our results show that neglecting wave effects can induce differences of up
406 to 1 m/s in modelled current velocities, leading to variations of more than
407 10 km in modelled trajectories. These differences in modelled trajectories

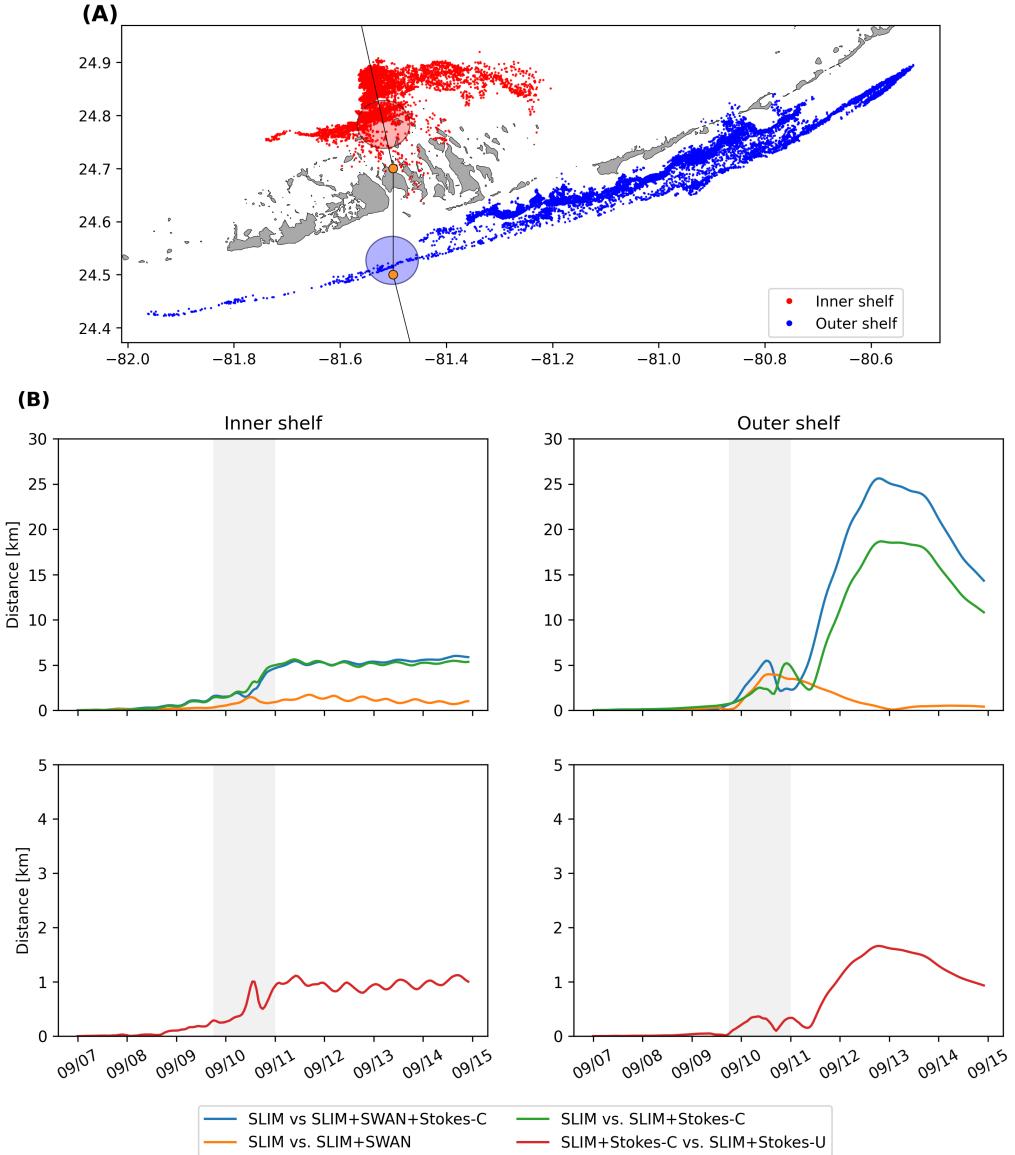


Fig. 9: **A:** Release regions of the passive particles on the inner and outer shelves (red and blue clouds) obtained by backtracking particles released in the red and blue circular areas during the passage of Irma. **B:** Difference between the centers of mass of the particle clouds released from the regions highlighted in **A** and advected by different combinations of coupled and uncoupled velocity fields. **Matthieu:** prsenter plus d'informations sur la Figure 8, notamment les nuages de points issus des deux simulations (SLIM et SLIM+SWAN+Stokes-C), ainsi que les centres de masses correspondants. Ca devrait permettre de soutenir la partie rsultats.

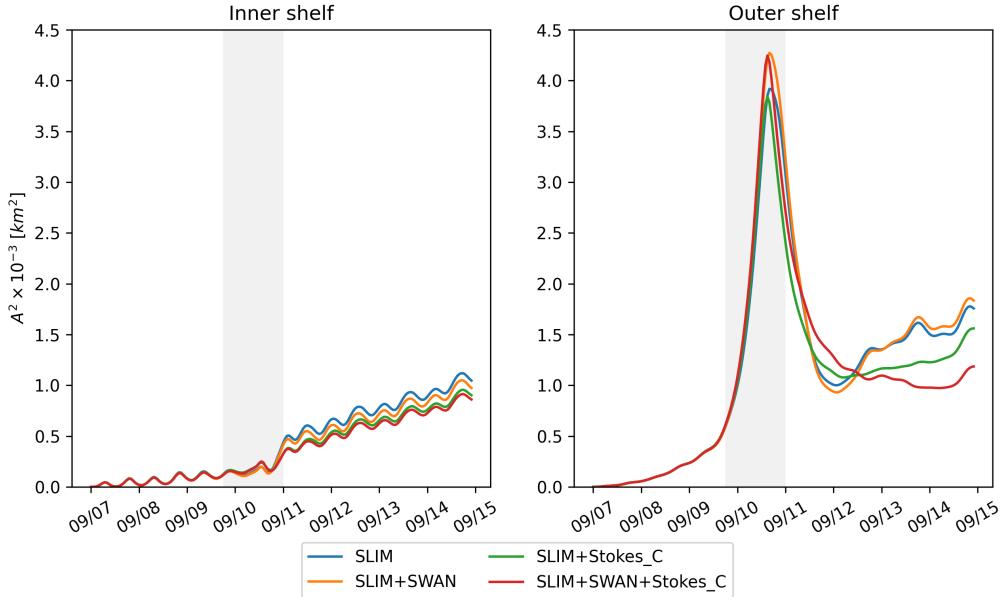


Fig. 10: Dispersion of particles with different velocity fields → not sure to know what to say about that...

were significantly larger and required more time to stabilize on the outer shelf. The impact of the Stokes drift dominates the effects of wave-current interactions through the radiation stress gradient, except at the moment of the passage of the hurricane, when both contributions yield similar impacts. Finally, neglecting wave-current interactions when computing Stokes drift lead to variations of up to 2 km in modelled trajectories on the passage of the hurricane.

[Paragraph on atmospheric forcings ?]

Despite slightly overestimating the amplitude of the sea surface elevation in fair weather conditions, the coupled model reproduces well the timing and amplitude of the observed storm surge (Fig. 5). All elevation peaks are captured with a 4% accuracy at every stations except Virginia key, where the surge was overestimated by about 15%. Such accuracy is key to predict the damages caused by the hurricane, as most destroyed and severely damaged

422 buildings in the Florida keys during Hurricane Irma were caused by storm
423 surge and waves (Xian et al., 2018). Furthermore, the high resolution of
424 model in the regions captures flow accelerations between islands and reefs,
425 allowing for a precise representation of the surge risk in the Florida Keys. In
426 addition to accurately capture positive surges, the model also reproduced the
427 observed negative surge in Naples with an error of about 1%. This result is
428 of interest from a biological point of view as negative surges, although less
429 studied, affect water exchanges between the estuaries and the coastal ocean
430 and disturb the benthic ecosystems (Liu et al., 2020). Such rapid decrease
431 in water level followed by a positive surge cause massive freshwater inflows,
432 generating a significant decrease in water salinity (Wachnicka et al., 2019).

433 Strong currents such as the Gulf Stream affect waves through refraction
434 over gradients in current velocity, shoaling and breaking of opposing waves
435 or lengthening of following waves (Hegermiller et al., 2019). Under hurri-
436 cane conditions, these interactions can cause numerical instabilities in the
437 wave model if appropriate parameterizations and model resolution are not
438 applied. Hegermiller et al. (2019), for instance, used a 5-km model grid and
439 48 directional bins to capture spatial gradients in wave height induced by
440 wave-currents interactions in the Gulf Stream during Hurricane Matthew
441 (2016). These guidelines were followed when defining the coarsest resolution of
442 the model mesh as well as the spectral discretization of SWAN. Boundary con-
443 ditions and directional spreading of the incident waves also play a significant
444 role when modeling wave-current interactions at meso- and submesoscales
445 (Villas Bôas et al., 2020), which motivated our choice of imposing full spectra
446 on the boundary of the wave model instead of bulk parameters. Finally,
447 SWAN default parameterizations for wind energy input and whitecapping
448 caused numerical instabilities by overestimating wave growth and steepness on
449 the boundary of the Gulf Stream on the passage of Irma. This overestimation
450 was solved by using the parameterization of Siadatmousavi et al. (2011). The
451 parameters used in this study were calibrated on the Northern Gulf of Mexico,

which might explains that our model better reproduces wave parameters at buoys 42036 and 4207, located on the WFS (see Fig. 7 and Table 1). However, these calibrated parameters might underestimate wind-induced wave growth might underestimate Florida's eastern shelf. Consequently, incident wave do not receive enough energy to grow after breaking on the bank boundary, leading to the underestimation of the significant wave height at buoys 41113 and 41114 (Fig. 7). A more extensive calibration study might therefore be necessary to achieve good agreement with field measurements on both sides of Florida. Nonetheless, as this study focuses on the wave produced by Irma, which made landfall on the western coasts of Florida, the use of parameterizations calibrated for the Gulf of Mexico seems reasonable.

Fig. 9 showed fairly different behaviors on the inner and outer shelves on the passage of Irma. The fact that the impact of waves is less important on the inner shelf can be explained by the sheltering of the inner shelf due to reefs and islands as well as wave breaking on the shelf break. The inner shelf hence experiences weaker waves and currents, inducing weaker and more localized transport. Furthermore, the impact of winds on waves is reduced in shallower areas under the action of depth-induced breaking. This might explain why differences between particle trajectories stabilize on the inner shelf just after the passage of Hurricane Irma. However, the Florida Keys still experienced strong winds after the passage of the core of the hurricane, which generated high waves in the deeper areas. This might explain why the differences on between the modelled trajectories kept increasing on the outer shelf under the action of strong Stokes drift up to two days after the passage of the hurricane.

Differences between the trajectories of particles advected by SLIM+Stokes-C or SLIM+Stokes-U, don't exceed 2 km (Fig. 9). This suggest that taking wave-currents interactions into account when computing Stokes drift, even under hurricane conditions yields a limited impact. Furthermore, the curves 'SLIM vs. SLIM+SWAN+Stokes-C' and 'SLIM vs. SLIM+Stokes-C' show

482 similar values, which seems to indicate that wave impact of currents is limited
483 on the inner shelf. This would suggest that it is not necessary to take
484 wave-current interactions into account when modeling the trajectories of
485 tracers in shallow, sheltered areas such as the inner WFS during a hurricane.
486 Uncoupled currents with uncoupled Stokes drift should give a reasonably
487 accurate approximation of the transport processes. However, this does not
488 hold for deeper regions, as highlighted by the differences between 'SLIM vs.
489 SLIM+SWAN+Stokes-C' and 'SLIM+Stokes-C' in the outer shelf.

- 490 • Broad perspective \Rightarrow not limited to FL, mention search and rescue

491 **5. Conclusion**

492 **Acknowledgments**

493 Computational resources were provided by the Consortium des Équipements
494 de Calcul Intensif (CÉCI), funded by the F.R.S.-FNRS under Grant No.
495 2.5020.11. Thomas Dobbelaere is a PhD student supported by the Fund for
496 Research training in Industry and Agriculture (FRIA/FNRS).

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