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# Longshore drift produced by climate-modulated monsoons and typhoons in the South China Sea

Patrick Marchesiello<sup>a,c,\*</sup>, Elodie Kestenare<sup>a</sup>, Rafael Almar<sup>a</sup>, Julien Boucharel<sup>b</sup>, Nguyet Minh Nguyen<sup>d</sup>

<sup>a</sup>*IRD/LEGOS, 14 av. Edouard Belin, 31400 Toulouse, France*

<sup>b</sup>*CNRS/LEGOS, 14 av. Edouard Belin, 31400 Toulouse, France*

<sup>c</sup>*CARE center, Ho Chi Minh City Univ. of Technology, HCMC, Vietnam*

<sup>d</sup>*Southern Institute of Water Resources Research, HCMC, Vietnam*

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## Abstract

Monsoons and typhoons impact the tropical coastal zones through their signature on winds and waves, leading to increased vulnerability – through erosion, marine submersion and flooding – of an ever growing coastal population. This study addresses wave-driven coastal impacts in the South China Sea (SCS), particularly along the Vietnam coast. Using 38 years of offshore wave fields from ERA-Interim reanalysis, we assess the seasonal and interannual variability of wave patterns, storminess, and wave-induced alongshore sediment transport (longshore drift). Results suggest a large seasonal coastal impact due to high-energy, north-easterly waves generated by winter monsoon winds. The net annual sediment transport is southward with significant interannual and decadal variations (20% standard deviation with particular years at 40% of the mean), presenting strong correlations with the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) regime changes. The regime shift of 1998, from a warm to a cold PDO phase characterized by more La Niña events, is associated with an increase in winter wave energy and thus higher sediment transport (about 10%). The typhoon activity in the SCS is partly associated with that of the Pacific Northwest basin, but as a large semi-enclosed sea, presents local differences. It is positively correlated with La Niña in summer and with El Niño Modoki in winter. The summer correlation to ENSO phases is opposite to that of the whole Northwest Pacific due to competing local and remote mechanisms driving cyclone formation and trajectory. For the same reason, the effects of ENSO and PDO phases are opposite in the SCS: during

the last cold PDO phase, typhoon frequency was reduced by 20%, with significant net impact on estimated sediment transport. The typhoon contribution to sediment transport is a 15% reinforcement of southward transport due essentially to winter activity. If winter monsoon and typhoons appear to work together on average, their low-frequency variability are out-of-phase. This is particularly clear at decadal scale, as cold PDO phases seem favorable to strong winter monsoon waves but detrimental to SCS typhoon numbers. These results confirm that regional climate variability (together with human factors affecting river sediment supply, coastal management of beach-dune systems, land subsidence, mangrove deforestation) is an essential part of coastal vulnerability that needs to be better assessed.

*Keywords:* longshore drift, wave climate, monsoon, typhoon, ENSO, PDO

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## 1. Introduction

The South China Sea (SCS; or Vietnam East Sea in Vietnam), is the largest semi-enclosed marginal sea in the Northwest Pacific and a source of interest for surrounding countries, including Vietnam, a coastal state within a tropical monsoon area (Fig. 1). Its coastal zone shelters many cities with a growing population that is now threatened by erosion and submersion. Various engineering projects have investigated coastal vulnerability but general assessments on the status of erosion along the Vietnam coast are relying on scarce data (e.g., FAO report by Ngo et al. 2006, and more recently Hue and Thanh 2020) or derived from satellite estimations over the last three decades (Luijendijk et al., 2018). The coast is generally split into three main regions: northern, central (between 11°N and 19°N) and southern. Coastal erosion and accretion are believed to vary from one region to the other according to river sediment supply, lithologic composition of the coast, human factors<sup>1</sup>, and oceanic conditions.

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\*Corresponding author

*Email address:* `patrick.marchesiello@ird.fr` (Patrick Marchesiello)

<sup>1</sup>The list of human factors is long, spanning from the watershed to the coastal zone: dam construction, embankment, irrigation, mining, forest-to-agriculture conversion, groundwater extraction, coastal development (ports, resorts, channel dredging, groins and breakwaters), mangrove deforestation, etc

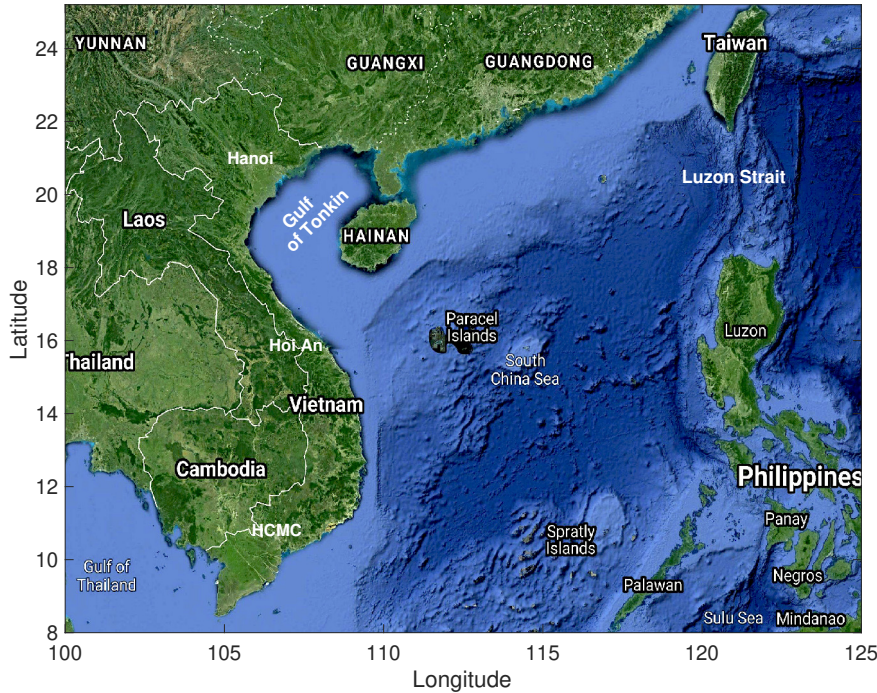


Figure 1: Geographical map of the South China Sea region.

14 The northern region located in the Gulf of Tonkin and protected from most SCS swell  
 15 conditions (Nguyen et al., 2014) is usually associated with sedimentation and will thus be  
 16 discarded in this study. In the central region, erosion has been observed in all coastal  
 17 provinces due to a more direct exposition to swell and local wind waves. Sand being the  
 18 main shore-building material, the strongest erosion is expected to occur in convex coastal  
 19 sections of the coast facing wind and wave direction (Komar, 1976). The main focus of the  
 20 paper will be on the sandy central coast, which has the longest stretch and largest angle  
 21 with dominant incoming swell. We will ignore the Mekong delta coastal zone in the southern  
 22 region, which is also highly vulnerable to oceanic conditions but presents specific conditions  
 23 as a lowland, mud-dominated system (the delta is about 1 m above sea level; Minderhoud  
 24 et al. 2019). In particular, sediment transport mechanisms in the coastal delta are very  
 25 different from a sand-dominated shoreline as they are affected by wide and shallow mudflats  
 26 (Marchesiello et al., 2019).

27 Coastal morphological evolution is generally examined at seasonal and synoptic (storm-

28 driven) timescales, while a few studies (Bryan et al., 2008; Mortlock and Goodwin, 2016)  
29 show that morphological adjustment can occur at lower frequencies (and may be larger than  
30 short-term variations). The long-term ocean wave climate has only been recently investi-  
31 gated in the SCS due to limited data before the 1980s (Chu et al., 2004; Mirzaei et al.,  
32 2013). With the development of satellite observation, numerical modeling and data assimi-  
33 lation techniques, reanalyses have progressively been available for marine climate research.  
34 These products show that the SCS coastal region is mostly affected by long-period swells  
35 that travel from the Northeast in winter, although local wind waves have a significant role  
36 as well. Besides a seasonal effect, tropical beaches are also exposed to infrequent short (1–3  
37 days) but paroxysmal typhoons. Almar et al. (2017) show that if a storm can produce strong  
38 offshore sediment transport in Nha Trang (about 16°N), central Vietnam, the beach would  
39 slowly recover under persisting low to moderate waves during the rest of the year. However,  
40 any residual alongshore transport would lead to morphological adjustment. Low-frequency  
41 variability of winds and waves can also impact the coastal zone through modulation of surg-  
42 ing seas and typhoon rainfall and floods. Here, we will focus on longshore sediment transport  
43 and tentatively use it as a climatic index of erosion potential.

44 In this paper, we follow the methodology presented in Almar et al. (2015) for the Gulf of  
45 Guinea in West Africa to connect the large-scale climate variability to the drivers of coastal  
46 vulnerability in Vietnam, as diagnosed by longshore sediment transport. The reliable global  
47 reanalyses from ERA-Interim (ERA-I), covering almost four decades, will bring new insights  
48 on the statistical connection between coastal vulnerability and climate variability, from  
49 typhoon and monsoons intraseasonal events, to seasonal monsoon conditions, interannual  
50 El Niño Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO). This analysis  
51 will also reveal environmental factors that may predominantly affect shoreline variability  
52 in relation with ENSO and PDO. Ultimately, it will help us to foresee changes of coastal  
53 impacts in the coming decade.

## 54 **2. Data and methodology**

### 55 *2.1. Wave reanalysis*

56 We used ERA-I bulk wave parameters (significant height  $H_s$ , peak period  $T_p$  and direc-  
57 tion of both swell and wind waves) extracted from the ECMWF data server on a  $0.5^\circ$  grid,  
58 with a 6-h temporal resolution over the period 1979-2016 (Dee et al., 2011). In ERA-I, the  
59 analysis of surface parameters is performed separately from the main atmospheric analysis.  
60 An optimal interpolation (OI) analysis of ocean wave height is performed using data from  
61 space-borne radar altimeters, when available (starting in 1991). This analysis is then used  
62 to correct the first-guess spectrum, which is generated by the wave forecast model (Lionello  
63 et al., 1992; Dee et al., 2011). The latter consists of a fully coupled wave model (the ECMWF  
64 Wave Atmospheric Model WAM) describing the evolution of two-dimensional wave spectra.  
65 ERA-40 and following ERA-I are the first reanalyses featuring an ocean wind-wave model  
66 coupled to the atmosphere, and the quality of the wave data has been validated against  
67 buoy and altimeter data (Sterl and Caires, 2005; Stopa and Cheung, 2014). There is gener-  
68 ally good correlation between the reanalysis and observational data, apart from the extreme  
69 cases of very high waves ( $H_s > 5$  m) or very small waves ( $H_s < 1$  m), which tend to be  
70 under- or overestimated respectively. These extreme wave conditions are infrequent in the  
71 Vietnam East Sea but not absent, due to tropical storms. The Vietnam coast experiences  
72 8-10 tropical storms each year in average (Wang et al., 2007), which may account for part of  
73 beach erosion as we will discover. Let's keep in mind that the largest storm swell is probably  
74 underestimated in ERA-I data.

### 75 *2.2. Typhoon database and clustering*

76 The trajectories and intensities of typhoons are extracted from the best track archives  
77 provided by NOAA's Tropical Prediction Center. Here we call tropical cyclones (TCs) all  
78 tropical storms with 10-minute maximum sustained winds greater than 17 m/s (34 kn or  
79 63 km/h), while typhoons are mature cyclonic systems with winds greater than 33 m/s (64  
80 kn or 119 km/h). To evaluate cyclonic activity, we use a density index, which is calculated  
81 as the monthly number of TCs in a  $[5^\circ \times 5^\circ]$  sliding box covering the entire North-West

82 Pacific basin at a  $[1^\circ \times 1^\circ]$  resolution. This calculation is detailed in Almar et al. (2019) and  
83 Boucharel et al. (2016) for the Atlantic and Eastern Pacific basins respectively.

84 Following Bell et al. (2019), we applied the probabilistic curve-clustering technique of  
85 Gaffney et al. (2007) to group together TC tracks of similar properties (initial conditions  
86 and track curvature). An advantage of clustering TC tracks is that different but overlapping  
87 track types (with different curvature) can be analyzed separately. Twenty-five cluster runs  
88 were performed for the SCS where the input order of the tracks was randomized and 12  
89 expected maximization starts were used. The cluster run with the smallest trained log-  
90 likelihood value was selected. Linear regression mixture models were fitted to TC tracks  
91 with an objectively determined number of clusters. Bell et al. (2019) find an optimized total  
92 of 9 clusters in the entire Northwestern Pacific (NWP) TC region, including 2 in the China  
93 sea; hence our choice of 2 clusters in this region (Fig. 6b).

### 94 *2.3. Environmental variables*

95 Vertical wind shear (VWS), sea surface temperature (SST), and mid-troposphere rela-  
96 tive humidity are among the most commonly used environmental variables by the scientific  
97 community to assess the environmental control of TC genesis and intensity (Camargo et al.,  
98 2010). The VWS, defined as the environmental horizontal wind difference between 200- and  
99 850-hPa pressure levels (DeMaria, 1996) and relative humidity, averaged between 700- and  
100 850-hPa pressure levels (Kaplan and DeMaria, 2003; Wu et al., 2012), are extracted from  
101 the NCEP/NCAR reanalysis data. The SST is taken from the ECMWF Ocean Reanaly-  
102 sis System 3 (ORA-S4) (Balmaseda et al., 2013). All variables are monthly averaged and  
103 interannual monthly anomalies are computed with respect to a monthly mean climatology  
104 (interannual variability is obtained by averaging monthly anomalies over each year).

### 105 *2.4. Sediment transport formulation*

106 Here, as in Almar et al. (2015), we use the relatively recent Kaczmarek et al. (2005)  
107 formula (Eq.1 below) for its suitability in various conditions. The longshore sediment volume

108 transport is computed as:

$$\begin{aligned} Q &= 0.023 - H_b^2 V && \text{if } H_b^2 V < 0.15 \\ Q &= 0.00225 + 0.008H_b^2 V && \text{if } H_b^2 V > 0.15 \end{aligned} \tag{1}$$

109  $H_b$  is the breaking wave height (see below) and  $V$  an estimated surf zone long shore  
110 current derived from the commonly used Longuet-Higgins formula:

$$V = 0.25K_v \sqrt{\gamma g H_b} \sin 2\alpha_b \tag{2}$$

111  $\alpha_b$  is wave angle,  $\gamma = H_b/D_b = 0.78$  the constant breaker index following Battjes and  
112 Janssen (1978),  $g=9.8 \text{ m/s}^2$  the gravitational acceleration,  $D_b$  the local water depth, and  
113  $K_v$  an empirical constant. We use  $K_v = 2.9$ , as in Almar et al. (2015), for wave-dominated,  
114 sandy environments. We calculated monthly and annual values of the longshore sediment  
115 transport associated with the total wave field (wind and swell waves).

116 Note that this estimation of longshore drift can only provide an order of magnitude  
117 rather than an exact quantitative assessment (Pilkey and Cooper, 2002), but the study  
118 focuses on transport sensitivity to oceanic forcing variability. Assuming that coastal erosion  
119 (or accretion) results primarily from the longshore gradient of sediment transport, it should  
120 broadly vary as the sediment transport itself. In this sense, our transport formulation can  
121 be used as a climatic index of erosion potential.

### 122 **3. Results: monsoon and typhoon impacts with ENSO/PDO modulation**

#### 123 *3.1. Monsoons*

124 Waves are generally most energetic in higher latitudes, although the tropical band can  
125 also experience large waves, like those associated with monsoon weather that impact the  
126 coasts of southeastern Asia (Felix et al., 2019). The seasonal climatology of the com-  
127 bined wind sea and swell waves obtained by seasonally averaging all waves over the period  
128 1979–2016 is presented in Figure 2. The wave field reflects the Asian monsoon weather (for a  
129 review, see Chang et al. 2006). Summer monsoon appears to drive low-energy, short-period



130 southwesterly waves. However, the onset of northeast winter monsoon (October-April) re-  
 131 sulting from the formation of the Siberian High leads to high wind conditions, particularly  
 132 off northern and central Vietnam. It can bring strong persistent swell of somewhat lower  
 133 energy but longer duration than tropical storms. Swell and wind waves follow a similar  
 134 seasonal pattern, with swell generally larger than wind waves. In winter, the mean wind  
 135 magnitude over the SCS is about 9 m/s (not shown) and the resulting swell has monthly  
 136 mean significant wave heights of 1-2.5 m for swell propagating from the northeast (50° angle  
 137 to the north) with a mean period of more than 8 s. The winter monsoon swell is associated  
 138 with a long fetch that extends along the SCS and beyond through the Luzon Strait (between  
 139 Taiwan and Luzon island of the Philippines that connects the SCS to the Pacific basin; Fig.  
 140 1). Wind waves present larger intraseasonal variations, especially during winter, for both  
 141 magnitude and direction (not shown).

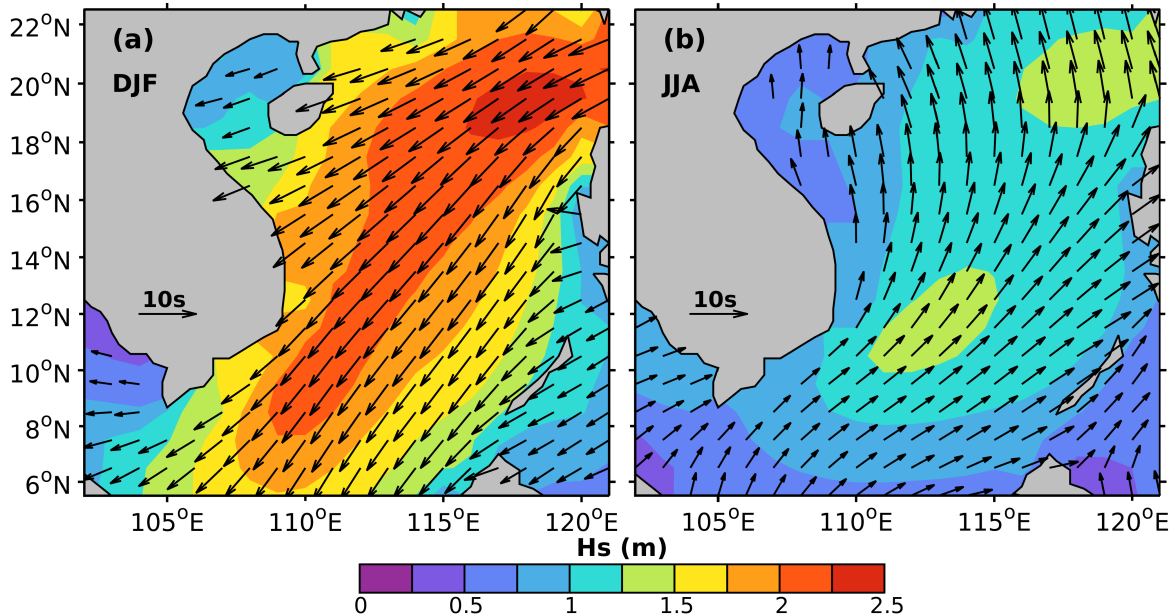


Figure 2: Winter (December-February; left) and summer (June-August; right) wave characteristics: Hs (color); wave direction (vector direction) and period (vector magnitude)

142 As the Siberian High varies on timescales of a few days to a week, surges of northeast

143 winds set in then wane with this cycle (Shoji et al., 2014). ERA-I presents heavy swells  
 144 ( $> 4$  m) during winter monsoon surges (not shown). There is substantial literature on the  
 145 atmospheric cold intrusion — called cold surges — affecting the Southeast Asian coastal  
 146 states every winter (Shoji et al., 2014; Chang et al., 2006), but comparatively little about  
 147 the effect of these energetic events on the sea state (Almar et al., 2017). In contrast during  
 148 summer, weaker southwesterly winds of about 6 m/s dominate over most parts of the SCS,  
 149 consistent with previous studies (Chu et al., 2004; Mirzaei et al., 2013). Although, as already  
 150 mentioned, summer monsoon drives weak southwesterly waves (0.8 m in average), tropical  
 151 storms and typhoons can cause significant wave heights to rise briefly to around 4 m.

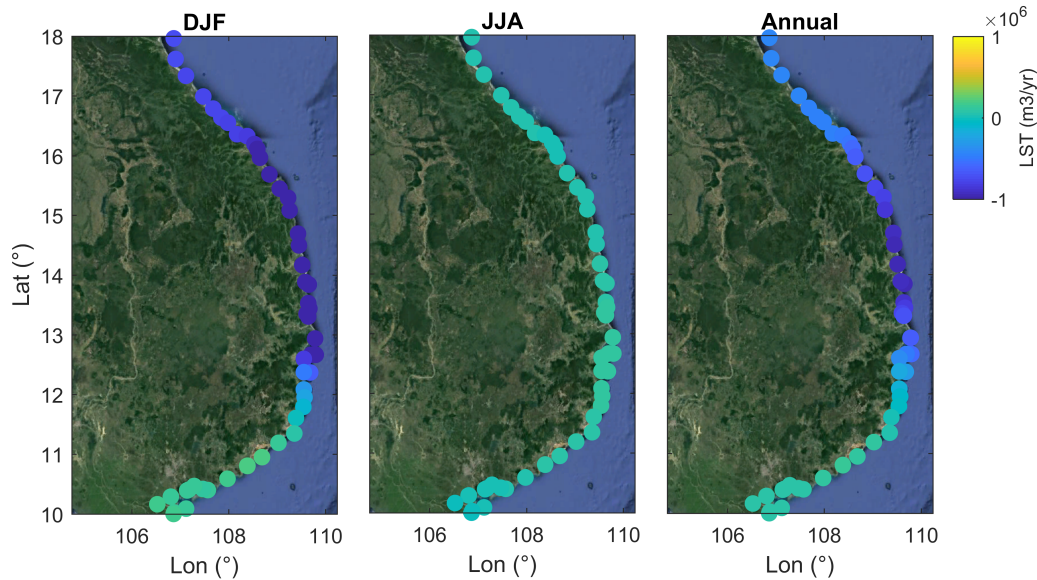


Figure 3: Winter (DJF), Summer (JJA), and Annual mean longshore sediment transport along the Vietnam coast calculated from ERA-I wave fields and Kaczmarek formulation. Southward transport is negative.

### 152 3.1.1. Mean, seasonal and interannual sediment transport

153 We now evaluate the wave-induced longshore sediment transport along the Vietnamese  
 154 coast. According to the Kaczmarek formulation, the oblique strong winter swell largely  
 155 dominates an annual mean southward sediment transport of about 0.5-1 million  $\text{m}^3/\text{year}$   
 156 over the central coast (Fig. 3). This is a relatively high value generally associated with drift-  
 157 aligned beach morphology (Bird, 2005) and consistent with long sandy shores characteristic

158 of Vietnam’s central coast (Hue and Thanh, 2020).

159 There are large seasonal and interannual variations in sediment transport. Interannual  
160 variations have a standard deviation of about 20 % of the mean (Fig. 4) and present signif-  
161 icant correlations (about 55%) with Nino3.4 index anomalies<sup>2</sup>, one of the most commonly  
162 used indices to characterize the El Niño Southern Oscillation (Trenberth and Stepaniak,  
163 2001). El Niño events are characterized by surface warming of the central and eastern  
164 tropical Pacific Ocean and weakening of equatorial trade winds that occur every few years.  
165 Alternating warm El Niño and cold La Niña phases, referred to as ENSO, represent the  
166 largest year-to-year fluctuation of the global climate system (McPhaden et al., 1998). Fig-  
167 ure 5 presents El Niño and La Niña wind patterns constructed from composites of all positive  
168 and negative ENSO events during 1979-2016. In the SCS, the negative ENSO phase (La  
169 Niña) produces a cyclonic anomaly in the wind regime. Therefore, La Niña events are as-  
170 sociated with increased winter monsoon wave energy (not shown) and resulting southward  
171 longshore transport anomalies (of about 40% for the 1999 and 2011 episodes compared to the  
172 annual mean). Conversely, El Niño events produce weaker waves and transport, particularly  
173 during the strong El Niño events of 1997 and 2015.

### 174 3.1.2. Decadal modulation

175 At longer time scales, Figure 4 also reveals a PDO signature, i.e. the dominant mode of  
176 climate variability at decadal time scales in the North Pacific (Mantua et al., 1997; Mantua  
177 and Hare, 2002). Sediment transport time series exhibit a shift around the strong 1997-98  
178 El Niño event. During the first part of the record (1979 to 1998), PDO is in its warm  
179 phase, characterized by a cooler Northwest Pacific ocean and stronger El Niño events with  
180 more frequent occurrence of the Eastern Pacific (EP) type. Typically, EP Niños exhibit an  
181 intense warming pattern confined to the Eastern Pacific, while Central Pacific (CP) Niños

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<sup>2</sup>The Nino3.4 index is based on tropical Pacific SST anomalies averaged over the central equatorial Pacific [5N-5S, 170W-120W], where key ocean-atmosphere interactions for ENSO occur. Anomalies are computed using a 5-month running mean, and El Niño or La Niña events are defined when these anomalies exceeds  $\pm 0.4C$  for a period of six months or more.

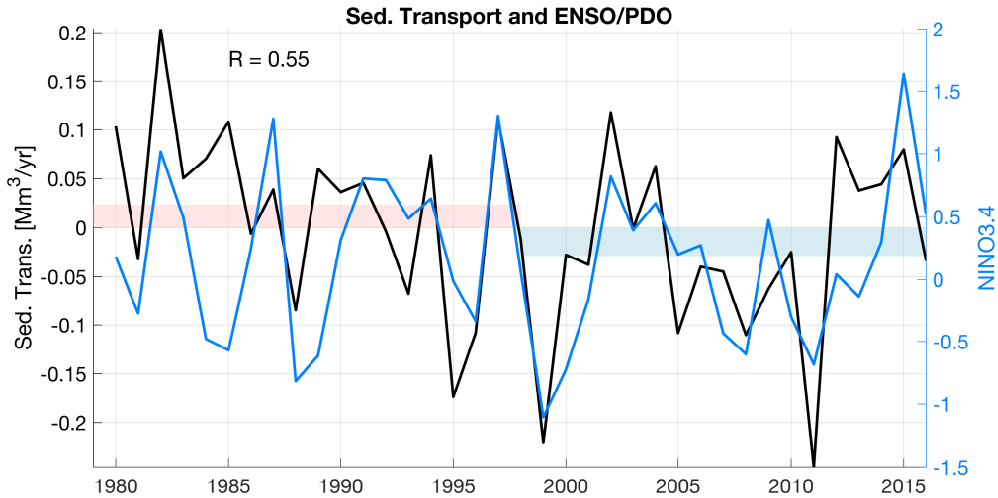


Figure 4: Yearly anomalies of longshore sediment transport along the central coast (around Hoi-An) calculated from ERA-I wave fields and Kaczmarek formulation (the mean southward transport shown in Fig. 3 is removed and the standard deviation of interannual variations is about 20% of this mean). Transport anomalies are compared with interannual (ENSO: Nino3.4 index anomaly) and decadal (PDO) variability. The correlation with Nino3.4 is about 55% (with 95% confidence). For the relation with PDO, the mean sediment transports over the warm (1979-1998) and cold (1999-2016) PDO phases are shown with light red and blue colors, indicating northward (southward) anomalies. The transport increased in average by about 10% of the mean between PDO phases (3 times larger than the standard error on the mean).

182 (or El Niño Modoki) are characterized by moderate warming around the dateline (Capotondi  
 183 et al., 2015). These different flavors of events, which express ENSO diversity, have distinct  
 184 features, impacts and remote connections. The second half of the record (1999 to 2016) is  
 185 marked by a negative PDO phase, which favors frequent and strong La Niña events due  
 186 to a warmer ocean background in the Northwest Pacific. During this recent cold phase,  
 187 there were twice as many years with southward sediment transport anomalies in central  
 188 Vietnam and the transport increased in average by  $0.05 \text{ Mm}^3/\text{yr}$  between the two phases (3  
 189 times larger than the standard error on the mean), i.e., about 10% of the mean transport.  
 190 Therefore, in the SCS, the two most recent decades are characterized by a cold PDO phase  
 191 that promoted higher wave energy due to an enhanced La Niña effect on winter monsoon  
 192 activity, increasing the general southward sediment transport along Vietnam. We conclude  
 193 that decadal/multi-decadal variations (associated with PDO and more generally any ENSO

194 low-frequency modulation) can be a major driver of erosion processes along the Vietnamese  
 195 coast.

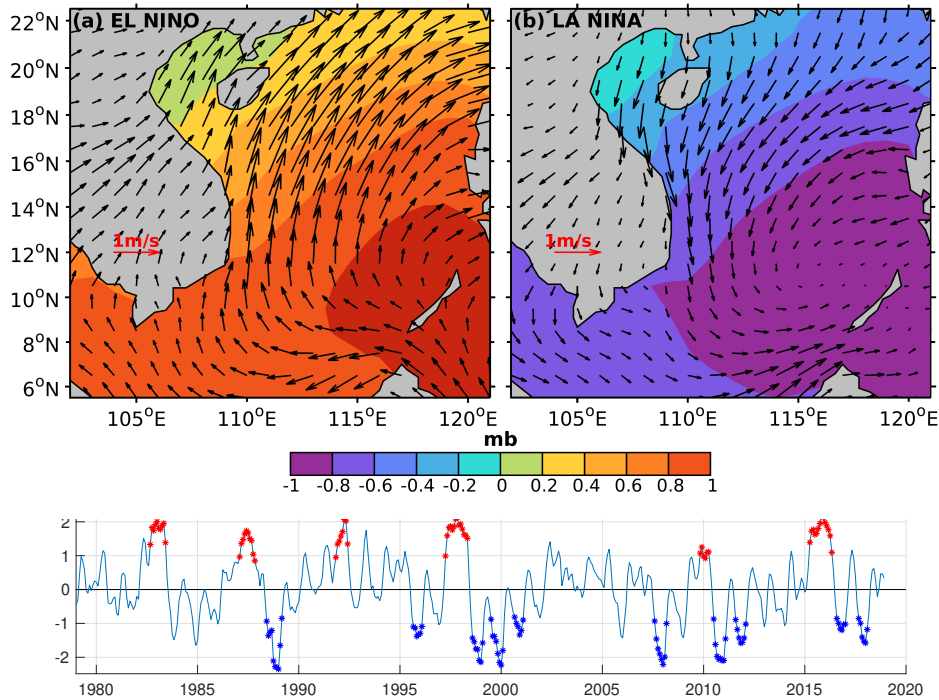


Figure 5: Wind anomalies related to El Niño (left) and La Niña (right), constructed from composites of events: wind magnitude and direction anomaly (vector); surface air pressure anomaly (color). The bottom panel presents the Nino3.4 index anomaly (detrended) with El Niño (red dots) and La Niña (blue dots) events used in the composites. The warm and cold PDO phases before or after 1998 are marked by a prevalence of El Niño and La Niña events respectively.

### 196 3.2. Typhoons

197 The Northwestern Pacific ocean is the most active tropical cyclone basin in the world  
 198 with an annual average of about 25 TCs, i.e., a third of global activity (Lin et al., 2020). As  
 199 a reminder (methodology section), we call TCs all tropical storms with 10-minute sustained  
 200 wind speed greater than 17 m/s (34 kn or 63 km/h), while typhoons are stronger cyclonic  
 201 systems with winds greater than 33 m/s (64 kn or 119 km/h). Over the SCS, the annual  
 202 mean TC number in our data is about 10, comprising 6 typhoons. Of these storms, about  
 203 a third is generated locally, as in Wang et al. (2007). TCs generated over the NWP are

204 strongly influenced by the large-scale atmospheric circulation and oceanic environment (Lin  
 205 et al., 2020), but TCs generated over the SCS are subject to a more local set of dynamical  
 206 and thermodynamical factors, which may be at odds with the large-scale influence (Elsner  
 207 and Liu, 2003; Ling et al., 2015). Our results confirm and further refine these findings.

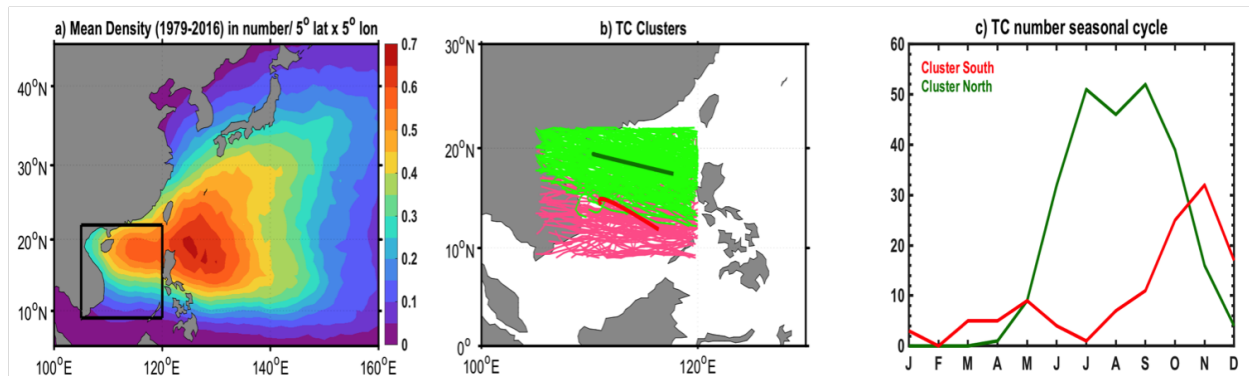


Figure 6: TC density and clustering in the SCS; a) mean annual storm density over the period 1979-2016 in the northwestern Pacific basin; b) TC tracks of the two main clusters in the SCS: green tracks for Cluster North in northern SCS; and red tracks for Cluster South in southern SCS (mean tracks of each cluster are superimposed in bold lines); c) monthly TC frequency for each cluster.

208 Figure 6a shows the mean annual TC density over the period 1979-2016 in the NWP  
 209 basin. TC activity is largest in the northern part of the SCS, locally generated or resulting  
 210 from TCs in the NWP that are taking a straight westward route though the Philippines  
 211 archipelago. To refine these statistics, we applied the probabilistic curve-clustering technique  
 212 presented in the methodology section. Two clusters are selected in the SCS (Fig. 6b). It  
 213 appears that the dominant cluster (green) mainly accounts for northern TC tracks, which  
 214 prevail in summer (Fig. 6c), while the second cluster (red) is representative of southern  
 215 tracks that occur more often in the early winter season (Nov-Dec) as wind shear and cold  
 216 SST become detrimental to TC intensification in the northern SCS (Wang et al. 2007; these  
 217 conditions spread south as winter progresses). These clusters will be referred to as "Cluster  
 218 North" and "Cluster South" respectively in the remainder of the paper. Typhoon Linda is  
 219 an infamous member of Cluster South as it made landfall in the Mekong delta in November  
 220 1997 and was declared the worst storm in recent Vietnam history due to human loss in this

221 vulnerable low-level elevation zone (Anh et al., 2017).

### 222 3.2.1. Interannual modulation

223 Figure 7 presents a time series of SCS TC number from 1979 to 2016, showing large  
224 interannual and decadal variability. The correlation between TC count and Nino3.4 is -0.33  
225 (with 95% confidence) and is therefore out of phase with variability in the whole Pacific  
226 basin (Zhao and Wang, 2019). To explain this result, previous studies hypothesized various  
227 ENSO-TC relationship mechanisms (e.g., Ling et al. 2015; Wang et al. 2007), one of them –  
228 called ENSO-typhoon hypothesis – standing out by successfully relating SCS TC activity to  
229 changes in NWP TC tracks (Elsner and Liu, 2003). The hypothesis states that TC formation  
230 during an El Niño event shifts eastward, with more typhoons tending to head north and  
231 staying away from the SCS. On the contrary, La Niña events would be more favorable to  
232 straight-line TC tracks resulting in more SCS TCs (despite generating less TCs in the Pacific  
233 basin).

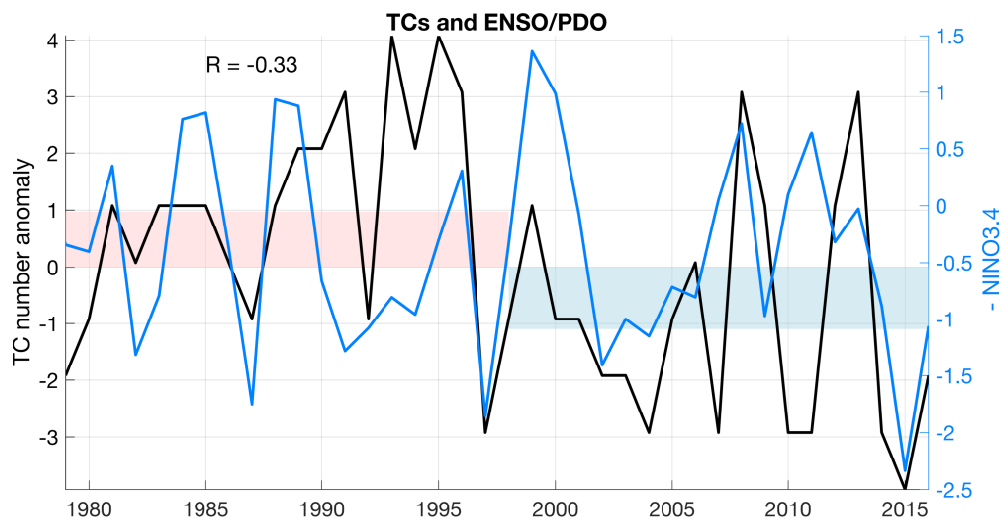


Figure 7: Annual TC numbers anomaly in the SCS during 1979-2016, compared with the negative of Nino3.4 index anomaly. The correlation between TC count and Nino3.4 is -0.33 with 95% confidence. Mean numbers for the warm (1979-1998) and cold (1999-2016) PDO phases are shown in light red and blue shades respectively. There is a difference of 2.1 TCs between phases, much larger than the standard error on the mean of 0.35 TC/yr.

234 The out-of-phase relationship with the Pacific basin-scale interannual forcing is confirmed

235 in Figure 8, showing composites of TC density anomalies during the various phases and  
236 flavors of ENSO. SCS TC activity varies oppositely with that in the NWP. During EP Niño  
237 (La Niña), SCS TC density decreases (increases) in the northern SCS, contrarily to the  
238 open-ocean region (the NWP cyclogenesis region is between 120-180E and extends beyond  
239 the region shown in Fig. 8). However, the SCS TC density increases in the southern SCS  
240 during CP Niños (in phase with the open ocean). This result is substantiated by a regression  
241 of SST onto SCS TC density for each cluster (Fig. 9). It unambiguously confirms that TC  
242 activity in northern and southern SCS is modulated by different ENSO phases. However,  
243 the ENSO-TC correlation remains low in the SCS. The overall Nino3.4-TC correlation is  
244 significant but not high at -33%, while TC frequency is correlated at 60% to CP Niños in  
245 the NWP, outside the SCS.

246 The out-of-phase relationship associated with the ENSO-typhoon hypothesis can blur  
247 the correlation between ENSO and SCS TC activity, but that can be accentuated by other  
248 causes. For example, part of the interannual variability may be stochastic and associated  
249 with mesoscale interactions during cyclogenesis (Jourdain et al., 2011; Menkes et al., 2012;  
250 Simpson et al., 1997) – as opposed to cyclogenesis environmental factors. Another cause  
251 of a weak ENSO control is another out-of-phase relationship between SCS TCs generated  
252 locally (a third of all SCS TCs) and remotely in the NWP (Ling et al., 2015). According to  
253 Ling et al. (2015), an eastward shift of the western Pacific subtropical high would reduce the  
254 number of TCs entering the SCS but favor in the same time local environmental factors of  
255 cyclogenesis (essentially a weaker wind shear). A regression of wind shear onto TC number  
256 in the NWP, outside the SCS (not shown), seems to confirm this possibility. Therefore, the  
257 TC track deviations described in the ENSO-typhoon hypothesis may be opposed by local  
258 environmental factors, reducing linear correlations even further.

### 259 *3.2.2. Decadal modulation*

260 Interestingly, a stronger and opposite relationship prevails between SCS TC frequency  
261 and decadal environmental forcing, compared with interannual forcing. A regime shift co-  
262 incidental with the PDO phase transition of 1998 is clearly reflected in the SCS TC count



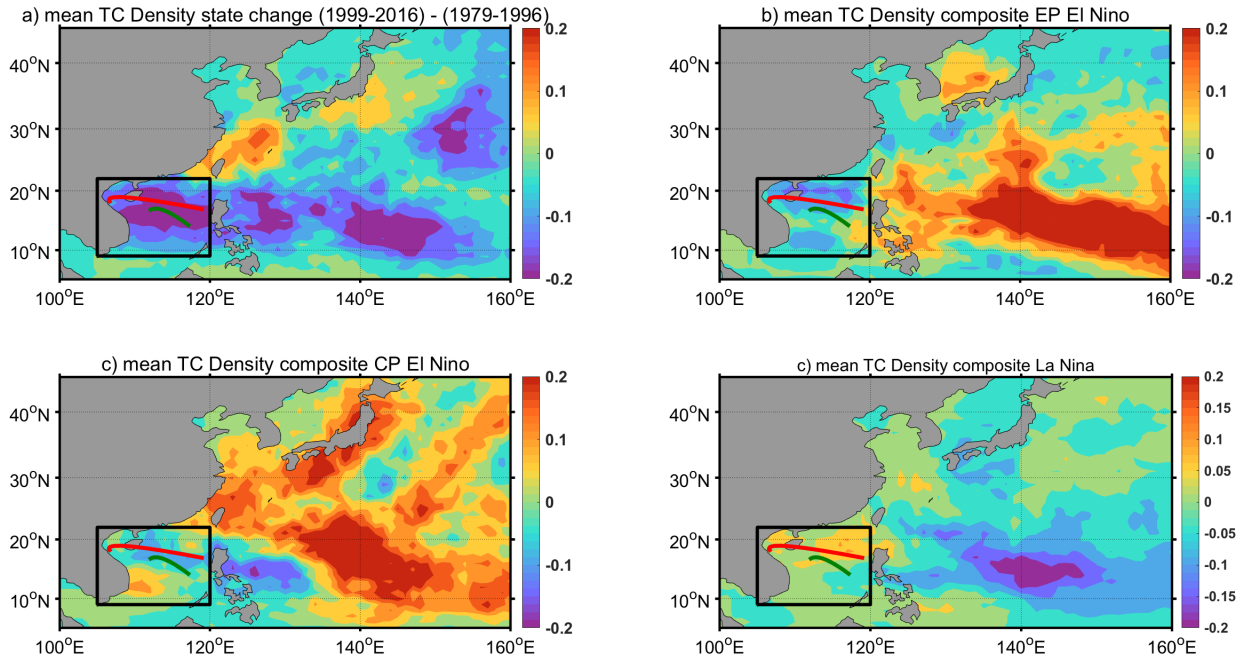


Figure 8: Composite of TC density anomalies (TC number anomalies per  $5^{\circ} \times 5^{\circ}$ ). a) Differences between warm and cold PDO phases; b) EP Niño; c) CP Niño; d) La Niña. ENSO Events are chosen according to the Climate Prediction Center classification. Composites are for the summer-fall TC season (May-December); EP El Niño years: 1982, 1986, 1987, 1991, 1997, 2015; CP El Niño years: 1990, 1995, 2002, 2004, 2009; La Niña years: 1983, 1984, 1988, 1989, 1995, 1996, 1998, 1999, 2001, 2007, 2008, 2010, 2011, 2012. Mean tracks for northern and southern clusters are shown in red and green respectively.

263 (Fig. 7) – as also recently observed in Zhao and Wang (2019) but for the whole NWP basin.  
 264 The warm PDO phase of 1976-1997 met with an averaged 9.9 TCs per year in the SCS,  
 265 but only 7.8 TCs per year during the cold phase of 1999-2016, representing a significant  
 266 2.1 TCs/yr or  $\sim 23\%$  difference between the two phases (the standard error of the mean  
 267 is 0.35 TC/yr). Paradoxically, the cool phase is characterized by both more La Niña and  
 268 CP Niño events and fewer EP Niños, which is favorable to SCS TCs at interannual time  
 269 scales (for both Cluster North and South). Therefore, PDO has an overwhelming influence  
 270 over ENSO on SCS TC frequency. It cannot simply be expressed as an addition of ENSO  
 271 events of the same phase (Warm PDO/El Niño; cold PDO/La Niña) since, on the contrary,  
 272 it has an opposite effect to these events. The main reason may lie in the PDO singularity

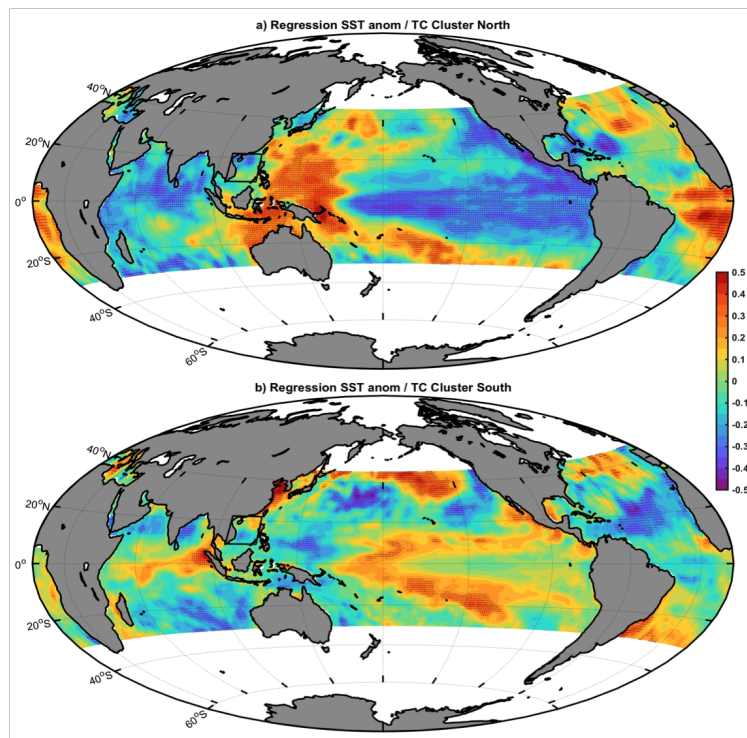


Figure 9: Regression of Pacific SST onto SCS TC number time series for: a) Cluster North, showing a pattern characteristic of La Niña; b) Cluster South, showing a pattern characteristic of CP Niño. Dots indicate significance at the 95% confidence level (Student t-test)

273 regarding its vertical wind shear pattern in the Central Pacific (Fig. 10). The difference  
 274 between warm and cool PDO phases shows very unfavorable wind shear in the recent cold  
 275 phase at longitudes 150-180E (latitudes 10-20N), where a large part of NWP cyclogenesis  
 276 occurs (see also Zhao and Wang 2019).

277 In conclusion, our results show that the SCS is in line with the whole NWP cyclogenesis  
 278 basin at decadal timescales (as *a priori* expected as two thirds of SCS TCs originate from this  
 279 basin), with significant decrease of TC frequency during the last cool PDO phase. However,  
 280 at interannual timescales, out-of-phase relationships between local and remote conditions  
 281 make predictions of cyclogenesis over the SCS particularly challenging. In addition, TC  
 282 activity in the northern and southern SCS (summer and winter respectively) is modulated by  
 283 different ENSO phases, which makes it even more confusing. The relations are summarized  
 284 in Table 1.

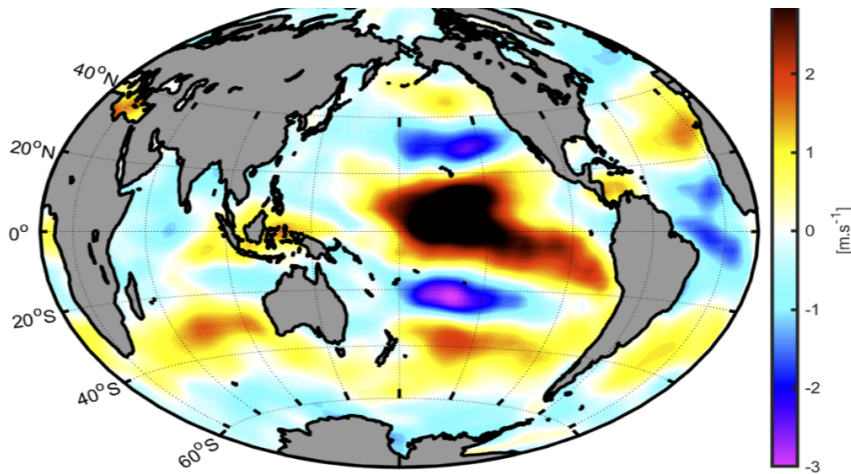


Figure 10: Difference of vertical wind shear between cold (1999-2016) and warm (1979-1996) PDO phases. The dateline is in the center of the map.

### 285 3.2.3. Sediment transport contribution

286 The impact of TCs in terms of longshore sediment transport can be computed by ex-  
 287 tracting wave conditions during TC activity. To that end, we compose our proxy of coastal  
 288 vulnerability during days when TC from each cluster are present in the SCS (Fig. 11).  
 289 Interestingly, the largest contribution to the longshore sediment transport is given by Clus-  
 290 ter South, contrarily to the monsoon effect, and is located along the northern and central  
 291 coast (the effect in the southern region is weak and similar for the two clusters). This result  
 292 can be associated with the northern side of TCs, which is the most favorable to generate  
 293 swell traveling toward the coast of Vietnam and southern China (the southern side possibly  
 294 affecting Malaysia and the Philippines). We thus expect a larger impact of Cluster North  
 295 along the Chinese coast, further north.

296 A quantitative comparison between Typhoon and monsoonal effects around Hoi An (Fig.  
 297 12) shows that TCs contribute about 15% of the net annual sediment transport to the south.  
 298 The main contribution is by Cluster South during the start of winter monsoon (from October  
 299 to December), which adds up to the large winter monsoon southward transport. Cluster  
 300 North only contributes a small fraction of transport in summer. Because Cluster South is  
 301 the dominant driver, the variability of TC-induced sediment transport is correlated with

<b>TC Count</b>	EP Niño	CP Niño	La Niña	Warm PDO	Cold PDO
SCS	–	–	+	++	--
N. SCS	–	–	+	++	--
S. SCS	No	+	No	++	--
NWP	+	+	–	++	--

Table 1: Summary of qualitative TC relationship to ENSO and PDO signals for the whole South China Sea (SCS), the northern and southern subregions (N. SCS and S. SCS) and for the Northwest Pacific basin (NWP). + (–) signs mean positive (negative) correlations, and ++ (--) means strong correlations.

302 CP Niños, while the transport driven by winter monsoon is better correlated with La Niña  
303 events (Table 1). Therefore, CP Niños tend to modulate the effects of TCs and monsoons on  
304 sediment transport in opposite directions. Similarly at decadal scale, the effect of TCs and  
305 monsoons on sediment transport are also out-of-phase, as the cold PDO phase is detrimental  
306 to TC numbers in the SCS (for both clusters) but favorable to strong winter monsoon waves.

#### 307 4. Conclusion

308 Northeast wind monsoon winds are stronger than summer monsoon winds. Accordingly,  
309 the highest waves reaching central Vietnam are from the northeast, which suggests that  
310 southward longshore transport occurring during winter plays a dominant role in the total  
311 sediment budget of central Vietnam. Our estimations show that the annual mean wave  
312 energy drives a total longshore sediment transport (longshore drift) in central Vietnam of  
313 about 0.5-1 Mm<sup>3</sup>/year to the south. We also provide a description and quantification of  
314 multi-decadal longshore drift. It shows that strengthening or weakening of the monsoon  
315 winds associated with ENSO and PDO phases may have a direct impact on these transports  
316 and thus on the erosion process in the region.

317 The role of ENSO and longer time scales, such as PDO regime shifts, on coastal sediment  
318 transport in the SCS has never been identified to our knowledge. The recent decades since  
319 1998 corresponds to a cool PDO phase resembling La Niña pattern, which induces an increase

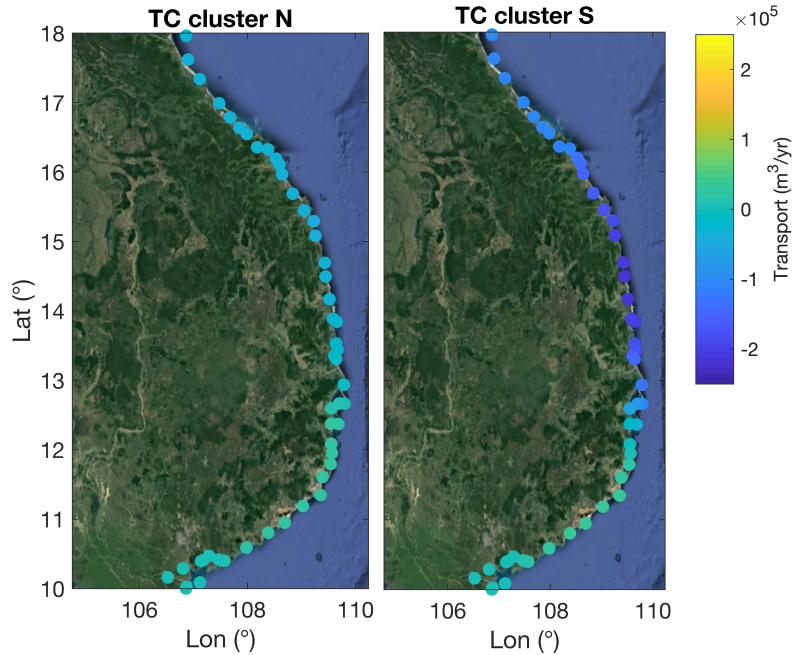


Figure 11: Map of longshore sediment transport due to TCs along the Vietnam coast calculated from ERA-I wave fields and Kaczmarek formulation. Southward transport is negative.

320 in sediment transport of about 10% associated with increased wave energy in the SCS. The  
 321 years 1999 and 2011, which experienced particularly strong La Niña events, stand out (40%  
 322 increase) but other years are also above average from the previous two decades. Coastal  
 323 erosion results from the divergence of longshore transport (Exner equation), which can vary  
 324 at the scale of bays according to local geology or man-made coastal developments. Therefore,  
 325 a natural increase of transport is expected to reflect on coastal erosion and may have played  
 326 a significant contribution in erosion alerts of this decade such as that of Hoi-An beaches  
 327 (Nagasawa et al., 2018).

328 The role of typhoons (and more generally tropical cyclones) in the SCS is also of inter-  
 329 est, but their relation to climate modes is more complex. We confirm here for the SCS a  
 330 reduction of TCs during the last cold PDO phase by 20%. However, contrarily to monsoon  
 331 modulation, the same phases of ENSO and PDO (cold or warm) have opposite effects on  
 332 typhoon frequency in the SCS – while they have similar effects in the whole NWP region.  
 333 The reason appears essentially linked to competing processes affecting TC tracks and cy-

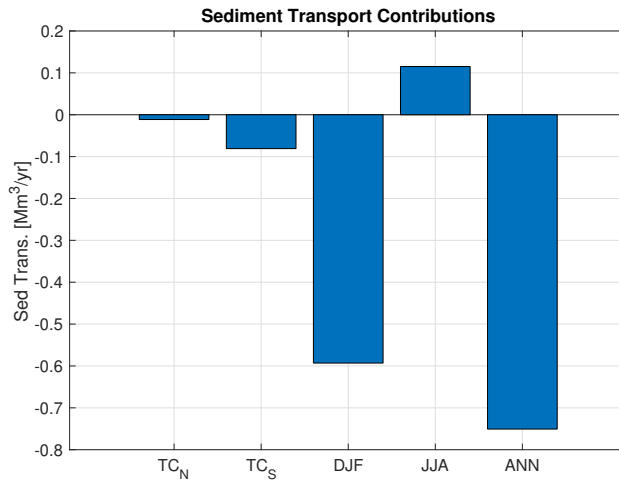


Figure 12: Longshore sediment transport due to TCs along the central Vietnam coast (around Hoi An), comparing annual, seasonal (December-February/DJF and June-August/JJA months for winter and summer respectively) and TC contributions ( $TC_N$  and  $TC_S$  are for Cluster North and South respectively). Note that the annual transport (ANN) is larger than the net result of DJF and JJA contributions because part of the transport occurs during other months but at lower rates.

334 clogogenesis, as well as local and remote environmental factors. In addition, TC activity in  
 335 the northern and southern SCS (in summer and winter respectively) are modulated by dif-  
 336 ferent ENSO phases (La Niña events favor northern TCs in summer, while CP Niños favor  
 337 southern TCs in early winter), which makes it even more convoluted.

338 Nevertheless, it appears that in the last cold PDO phase, a large increase of vertical  
 339 wind shear in the Central Pacific may have been responsible for the observed decrease in TC  
 340 activity (20% in the SCS). This decrease is not as clear for stronger typhoons but statistics  
 341 are less reliable in this case. Interestingly, the PDO cold phase marked both an increase  
 342 in winter monsoon wave energy and a decrease in TC frequency in the SCS. Therefore,  
 343 negative impacts that may occur from the former could be compensated by positive impacts  
 344 of the latter. However, there is no compensation at ENSO time scales, as La Niña events  
 345 can increase both wave energy (through a reinforcement of winter monsoon) and typhoon  
 346 occurrence in the SCS.

347 Interestingly, TCs contribute about 15% of the net annual sediment transport to the  
 348 south. The main contribution is by southern TC tracks during early winter monsoon (from

349 October to December), which adds up to the already large winter monsoon southward trans-  
350 port. If TCs and monsoons work together on average, we expect that their sediment trans-  
351 port variability are opposite, both at interannual scale (at least during CP Niños) and at  
352 decadal scale, as a cold PDO phase is favorable to strong winter monsoon waves but detri-  
353 mental to SCS TC numbers.

354 This study only accounts for climate-modulated wave effects on erosion, dismissing other  
355 potentially important processes such as coastal sea level variations, and precipitation affect-  
356 ing both coastal flood events and erosion (e.g., Clift et al. 2015, for paleoclimate effects  
357 in the SCS). At seasonal, interannual and decadal scales, wave and wind-driven effects are  
358 major drivers of coastal morphology and sea level. Our result may provide predicting infor-  
359 mation at these scales. For example, if it is confirmed that the strong El Niño of 2015-2016  
360 marked a new regime shift from a cold to a warm PDO phase, we should expect weaker  
361 winter monsoons but more frequent TCs. Because monsoon events appear to dominate the  
362 coastal response, we may expect a reduction in the general erosion along the Vietnam coast,  
363 but possibly an increase in damages caused by winds, waves and precipitation caused by  
364 typhoons.

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