Variations in the Wave Climate and Sediment Transport Due to Climate Change along the Coast of Vietnam

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Abstract: This study quantifies the climate change (CC)-driven variations in wave characteristics and the resulting variations in potential longshore sediment transport rate along the ~2000 km mainland coast of Vietnam. Wind fields derived from global circulation models (GCM) for current and future (2041–2060 and 2081–2100) climate conditions are used to force a numerical wave model (MIKE21 SW) to derive the deep water wave climate. The offshore wave climate is translated to nearshore wave conditions using another numerical model (Simulating WAves Nearshore—SWAN) and finally, a sediment transport model (GENERAlized model for Simulating Shoreline Change—GENESIS) is used to estimate potential sediment transport for current and future climate conditions. Results indicate that CC effects are substantially different in the northern, central and southern parts of the coast of Vietnam. The 2081–2100 mean significant wave height along the northern coast is estimated to be up to 8 cm lower (relative to 1981–2000), while projections for central and southern coasts of Vietnam indicate slightly higher (increases of up to 5 cm and 7 cm respectively). Wave direction along the northern coast of Vietnam is projected to shift by up to 4° towards the south (clockwise) by 2081–2100 (relative to 1981–2000), up to 6° clockwise along the central coast and by up to 8° anti-clockwise (to the north) along the southern coast. The projected potential longshore sediment transport rates show very substantial and spatially variable future changes in net transport rates along the coast of Vietnam, with increases of up to 0.5 million m³/year at some locations (by 2081–2100 relative to 1981–2000), implying major changes in future coastline position and/or orientation. The vicinity of the highly developed city of Da Nang is likely to be particularly subject to coastline changes, with potentially an additional 875,000 m³ of sand being transported away from the area per year by the turn of the 21st century.

Keywords: climate change; dynamic downscaling; wave modelling; sediment transport; Vietnam coast

1. Introduction

Vietnam has been identified by the International Panel on Climate Change [1,2] as one of the countries that may be most affected by climate change (CC). In particular, the Mekong and the Red
River deltas, featuring extremely high population densities in areas just slightly above present day mean sea level, are severely threatened by CC effects. About 18 million people, almost a quarter of the total population, live in the coastal districts lining the ~2000 km mainland coastline of Vietnam. Early impacts of CC in the coastal zone are already threatening people’s livelihoods as well as the ecological system [3].

Changes in regional wave climate and sediment transport rates, in response to climate change-driven variations of atmospheric circulation, are of particular relevance for coastal zone management and planning. Changes in alongshore gradients in longshore sediment transport (even small gradients) could result in chronic impacts such as coastline recession [4–8], inlet migration and/or intermittent closure [8–10] and ebb/flood delta depletion/accretion [1,11].

At present, there is no clear understanding of projected future wave climate and resulting variations in longshore sediment transport rate along the Vietnam coast. Therefore, this study was undertaken with the specific aim of quantifying and analysing CC-driven variation in wave climate and potential sediment transport rates along the entire mainland coast of Vietnam for the future time spans 2041–2060 and 2081–2100 (relative to 1981–2000).

Using dynamically downscaled global circulation model (GCM)-derived wind fields and numerical wave modelling, here we derive the contemporary and future deep water wave climate from the Red River delta to the Mekong delta (Section 2), and propagate these waves to the nearshore zone. Using this wave information, we subsequently calculate the potential longshore sediment transport rates in different coastal stretches along the coast of Vietnam (Section 3).

2. Offshore Wave Climate

The Vietnam coast is connected to the Pacific Ocean through the South China Sea (referred to as the East Sea in Vietnam). Wave spectra in this region thus not only feature locally wind-generated waves, but also an important swell component.

In this part of the study, a MIKE21 SW model [12] (see Supplementary Materials for summary model description) is set up to derive contemporary (here: 1981–2000) and future offshore wave climates with bathymetry input from the General Bathymetric Chart of the Oceans (GEBCO) [13]. The model was first forced by a global hindcasted wind field (NCEP/CFSR, Saha et al., 2010) for the period 1981–2000, representing baseline contemporary (i.e., reference) conditions. The wind fields derived from the downscaled ECHAM5 [14] and The Geophysical Fluid Dynamics Laboratory Climate Model (GFDL CM2.1) [15] GCMs were then used to force the model for the period 1981–2000 and two future time spans: 2041–2060 and 2081–2100. A high-end future scenario of greenhouse gas emissions, A2 from the IPCC Special Report on Emission Scenarios (SRES), [16] was selected as the forcing scenario in the GCMs. This scenario describes a very heterogeneous world with high population growth, slow economic development and slow technological change, thus representing a situation close to the “worst-case” scenario that is more suited for risk-averse decision making.

ECHAM5 is the fifth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology (MPIM). It uses 1.875° longitude × 1.875° latitude (T63) horizontal resolution with 31 layers in the atmospheric part of the model and 1.5° longitude × 1.5° latitude resolution with 40 layers in the oceanic model. Climate change simulations using ECHAM5 are carried out by adding observed atmospheric greenhouse gas and aerosol concentrations since the middle of the 19th century. The model simulations correspond to a mean global warming between 2.5 °C and 4.1 °C towards the end of this century, depending on how much greenhouse gas is emitted into the atmosphere [14].

GFDL CM 2.1 is based on a prior model version (GFDL CM 2.0, [17]) where significant changes were made to all parts of the model (atmosphere, land surface, ocean, and sea ice) with the aim of reducing errors and climate drift observed in the CM 2.0 model outcomes [15].

The downscaling Conformal Cubic Atmospheric Model (CCAM) [18] (see Supplementary Materials for summary model description) used in this study is developed and maintained at CSIRO
Australia. The model features a conformal-cubic grid that is numerically appealing because of its quasi-uniformity, orthogonality and isotropy. All variables are located at the centre of the grid cells (please see Supplementary Materials for more model details). Here, CCAM was used to dynamically downscale ECHAM5 and GFDL CM 2.0 output in the study area. The monthly sea surface temperature (SST) biases have been corrected in the GFDL CM 2.1 GCM output to first order, and then the atmosphere has been rerun for consistency with the new SSTs. In the present study, the six hourly wind speeds ($u$ and $v$ components) at 10 m elevation from ground were obtained from the CCAM. Wind data was extracted for three 20-year periods (1981–2000, 2041–2060 and 2081–2100) used for the analysis of contemporary and future climate scenarios.

In order to validate the GCM-derived wave fields, we forced the same spectral wave model (MIKE21 SW) with the NOAA National Centre for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) analytical global wind fields (hereon: reference model). The NCEP/CFSR dataset is a combination of atmosphere, ocean, sea ice hindcasts, and satellite data run in a coupled mode with a state-of-the-art data assimilation system [19]. NCEP/CFSR data was extracted at a spatial resolution of $0.5^\circ \times 0.5^\circ$ for six-hourly time steps of $u$- and $v$-wind components at 10 m height at 600 h, 1200 h, 1800 h, 0 h covering the “contemporary” period 1981–2000.

2.1. Wave Model Calibration and Validation

Wave data from ship observations and the European Centre for Medium-Range Weather Forecasts (ECMWF ERA-40) hindcast [20] were used to calibrate the reference South China Sea (or East Sea) spectral wave model forced with the NCEP/CFSR wind fields (Figure 1). Calibration was performed by systematically varying bottom friction, wave breaking and white-capping parameters.

![Figure 1](image-url)  
*Figure 1*. Locations of wave data used for model calibration. The extent of the figure corresponds to the wave model domain.

Table 1 shows a summary of the error statistics of the NCEP/CFSR-forced reference modelling results at two ship observation points (Hon Dau and Hon Ngu), and three ERA-40 wave locations (Points B, E and K, Figure 1). The time series comparison between the CFSR-forced model output
and the ERA-40 data at station E is shown in Figure 2. Model validation at Hon Dau and Hon Ngu using ship observation data shows moderate model performance. Overall, the correlation coefficient ($r$) values show good linear correlation of computed significant wave height and direction with the ship observation wave data. Model validation at Station B, E and K using ERA-40 wave data also shows good model performance with a small root mean square error (RMSE).

Table 1. Summary error statistics of modeling results at Hon Dau, Hon Ngu, Point B, E and K-Root Mean Squared Error (RMSE); Mean Absolute Error (MAE); Root Mean Square Error Mean (RMSEM); Root Mean Square Error over Standard Deviation (RMSES); $r$ (linear regression slope); $R^2$ (coefficient of determination).

| Index          | Hon Dau | Hon Ngu | Point B | Point E | Point K |
|----------------|---------|---------|---------|---------|---------|
| $H_m$ (m)      | 0.29    | 0.22    | 0.24    | 0.20    | 0.25    |
| $\theta_m$ (deg) | 47.10  | 47.37   | 53.90   | 8.09    | 0.96    |
| MAE (m, deg)   | 0.21    | 0.10    | 0.16    | 0.16    | 0.19    |
| RMSEM          | 0.11    | 0.26    | 0.36    | 0.12    | 0.15    |
| RMSES          | 0.55    | 0.58    | 0.74    | 0.36    | 0.66    |
| $r$            | 0.71    | 0.63    | 0.58    | 0.97    | 0.95    |
| $R^2$          | 0.43    | 0.43    | 0.45    | 0.94    | 0.90    |

Overall reference model performance gives moderate to good values of $r$ and $R^2$ for the comparison between computed values and ship observations/ERA-40 wave characteristics. The best model performance is at Station E and the worst is at Hon Ngu. The reference model underestimates the higher values of the wave heights and shows a bias in the simulated direction for wave heights lower than 1.0 m.

To gain confidence in the outcomes of the model runs forced by downscaled GCM wind fields for future time periods, we validated the wave model results forced by CCAM-downscaled GFDL CM2.1

Figure 2. Comparison between wave characteristics from European Centre for Medium-Range Weather Forecasts (ECMWF ERA-40) and National Centre for Environmental Prediction Climate Forecast System Reanalysis (NCEP/CFSR)-forced model output at point E: (a) significant wave height; (b) mean wave direction.
and ECHAM5 wind fields for the 1981–2000 period using the calibrated NCEP/CFSR time series via an inter-comparison of the monthly mean values of the significant wave height, peak period and mean wave direction (e.g., for point E, Figure 3). Overall, the differences in mean wave heights between the GCM outcomes and the reference run are small, except for the southern stations K, L and O. Here, the GCM wind field-forced models underpredict the wave heights. As for the other two parameters, the GCM-forced models underpredict the wave period, and overpredict the wave direction in station Hon Ngu. In the other stations, the differences are negligible for the purposes of this study.

![Figure 2](image_url)

**Figure 2.** Comparison between wave characteristics from European Centre for Medium-Range Weather Forecasts (ECMWF ERA-40) and National Centre for Environmental Prediction Climate Forecast System Reanalysis (NCEP/CFSR)–forced model output at point E: (a) significant wave height; (b) mean wave direction.

![Figure 3](image_url)

**Figure 3.** Validation of downscaled global circulation model (GCM) wind field-forced wave climate at point E, by comparison with the NCEP/CFSR model results for the period 1981–2000: (a) monthly mean significant wave height; (b) monthly mean peak period; (c) monthly mean wave direction.

### 2.2. Modelling the Future Wave Climate

The calibrated and validated spectral wave model was then forced by downscaled ECHAM5 and GFDL CM2.1 winds for the future time spans 2041–2060 and 2081–2100. Subsequently, the temporal changes were assessed for 14 locations along the Vietnam coast (Hon Dau, Hon Ngu, A, B, C, E, G, K, L and O, and four additional nearshore wave locations C1, E1, G1 and L1 (Figure 1)). Again, we choose to compare the average (of the two GCMs) wave characteristics and look into the monthly variations.

As representative examples, we consider stations Hon Dau and G. The monthly mean wave climate at Hon Dau (Figure 4) in 2041–2060 shows a slight decrease of the mean significant wave height compared to the 1981–2000 reference period. It has a maximum change of 0.16 m (21%) in October and a minimum change of 0.04 m (7%) in April. The average monthly mean significant wave height in the timeframe 2081–2100 is less than the average mean significant wave height in 2040–2061. The monthly mean wave period is slightly increased by 0–0.28 s with a maximum difference of 0.28 s (5%) in November and a minimum difference of 0.02 s (0.4%) in February and October (in 2081–2100 relative to 1981–2000). The variation of the monthly mean wave direction is 0°–15°. On average, the monthly mean wave direction turns clockwise throughout the year, with a maximum difference in clockwise direction by 15° in September (in 2081–2100 relative to 1981–2000). At Station G, the monthly mean...
significant wave height varies between 0 m and 0.30 m. The average mean significant wave height in 2041–2060 decreases throughout the year, relative to 1981–2000. On the other hand, in 2081–2100 (relative to 1981–2000), the average mean significant wave height is reduced during May to October by 0–0.10 m (less than 10%) and significantly increased during November to January by 0.30 m (17%). The average of the monthly mean wave period has a similar trend as the average of the monthly mean significant wave height. The maximum difference is 0.43 s (9%) in September and November and the minimum difference is 0.02 s (0.5%) in March. The variation of the monthly mean wave direction lies between 0° and 13°. In April and May, the monthly mean wave direction has slightly changed by 9° in counter-clockwise direction and in September, the wave direction is shifted 13° in clockwise direction (Figure 5).

Figure 4. Changes in monthly mean wave height, direction and period at Hon Dau for periods 2041–2060 and 2081–2100 relative to the period 1981–2000.
Figure 5. Changes in monthly mean wave height, direction and period at point G for periods 2041–2060 and 2081–2100 relative to the period 1981–2000.

Differences between the average contemporary and future wave climates (between 2041–2060 and 1981–2000, and between 2081–2100 and 1981–2000) are shown in Figure 6 for the 14 locations shown in Figure 1. Their spatial variability allows for a subdivision in three major areas: 1. northern coast (i.e., stations Hon Dau, Hon Ngu, A and B), 2. central coast (i.e., stations C, C1, E and E1), and 3. southern coast (i.e., stations G, G1, K, L, L1 and O) of Vietnam.
In northern Vietnam (stations Hon Dau, Hon Ngu, A and B), future significant wave heights slightly decrease along the coast by 1–5 cm (1%–7%) in 2041–2060 and by 3–8 cm (3%–12%) in 2081–2100. One exception is station B, where we see an increase by 5 cm (4%). For changes of the future wave period distribution, the results show a slightly increasing trend at all stations by 0.03–0.08 s (1%–2%) in
2041–2060 and 0.12–0.19 s (2%–4%) in 2081–2100. The future wave direction turns in the clockwise direction (towards the south) by 1°–3° (1%–2%) in 2041–2060 and slightly more, by 3°–4° (2%–3%) in 2081–2100 from the mean southeasterly wave direction under contemporary conditions.

In central Vietnam (stations C, C1, E and E1), the future significant wave heights along the coast tend to decrease by around 4–6 cm (3%–7%) in the period 2041–2060, and increase by 4–5 cm (1%–5%) in 2081–2100. The wave period at each station tends to decrease slightly by 0.02–0.07 s (1%) from 2041 to 2060, and increase by 0.07–0.10 s (1%–2%) in 2081–2100, except at station C1, where the average wave period reduces by 0.02 s by 2100. The future wave direction turns in the clockwise direction (toward the south) by 1° to 5° (1%–4%) in the period 2041–2060 and by 1° to 6° (1%–5%) in 2081–2100 relative to 1981–2000.

In southern Vietnam (stations G, G1, K, L, L1 and O), future monthly mean significant wave height decreases slightly by 3–6 cm (1%–8%) in 2041–2060 and increases by 2–7 cm (1%–5%) in 2081–2100. The future monthly mean wave period decreases slightly by 0.03–0.11 s (1%–2%) in the period 2041 to 2060 but, in contrast, increases by 0.02–0.16 s (1%–3%) in 2081–2100. The future monthly wave direction turns in the counter-clockwise direction (towards the north) by 2° to 5° (1%–4%) in 2041–2060 and 3° to 8° (2%–6%) in 2081–2100.

2.3. Spatial Distribution of Changes in Wave Climate

Time-averaged mean significant wave heights, wave periods and wave directions from downscaled GCM-derived wind fields for the contemporary period 1981–2000, projection periods 2041–2060 and 2081–2100, and their average long-term changes are used to represent spatial variations of future wave climate in Figures 6–9. Positive changes in wave direction indicate clockwise rotation (toward the south) and negative changes indicate counter-clockwise rotation (toward the north) of future wave directions.
Figure 7. Spatial distribution of time-averaged ECHAM and GFDL mean significant wave height in 1981–2000, 2041–2060, 2081–2100 and the difference plot between 2081–2100 and 1981–2000.
Figure 8. Spatial distribution of average ECHAM and GFDL mean wave period in 1981–2000, 2041–2060, 2081–2100 and the difference plot between 2081–2100 and 1981–2000.
Figure 9. Spatial distribution of average ECHAM and GFDL mean wave direction in 1981–2000, 2041–2060, 2081–2100 and the difference plot between 2081–2100 and 1981–2000.
3. Potential Longshore Sediment Transport

Next, we used the 1981–2000 and 2081–2100 offshore wave climate derived in Section 2 to determine the nearshore wave climate for both time spans for 22 different coastline sections along the coast of Vietnam (Figure 10). This was done by using the spectral wave model Simulating WAves Nearshore (SWAN) [21] (see Supplementary Materials for summary model description). The nearshore wave climate was subsequently used as the input to the GENEralized model for Simulating Shoreline Change (GENESIS) model [22] (see Supplementary Materials for summary model description) to estimate the annual average of potential longshore sediment transport (LST) at these 22 coastline sections.

![Figure 10. Locations of 22 selected coastal sections along the Vietnam coastline and model validation locations.](image)

3.1. Model Verification

The GENESIS-estimated LST rates were compared with reported LST rates from literature. There are a number of studies of LST along the coast of Vietnam, but most of them focus on the central coast, especially at the coast of Thua Thien-Hue province. Estimations of LST rates at some areas along the
coast of Vietnam from previous research studies (shown by red triangles in Figure 10) were selected for model verification. The results of these previous studies are summarized as follows:

(a) Northern coast of Vietnam at Hai Hau Beach (Nam Dinh province)

Hung and Dien [23] compute the LST at Hai Hau beach using the program SEDTRAN with input wave conditions for the period spanning 2001 and 2005. The estimated net sediment transport is 63,000 m$^3$/year in a southwesterly direction, while the gross transport is 490,000 m$^3$/year.

(b) Central coast of Vietnam at Thua Thien Hue province and Quang Binh province

Tien [24] calculated the LST in central Vietnam using the Bijker method, the CERC method and an improved method based on the Meyer-Peter Müller formula with a wave hindcast of 2002. The computed results at Thuan An area (Thua Thien Hue province) were found to be in the range of 600,000–1,100,000 m$^3$/year for the total gross transport and 400,000–700,000 m$^3$/year for the net transport, which was directed to the northwest. The net transport at Hai Duong (Thua Thien Hue province) and Ngu Thuy (Quang Binh province) was about 1,500,000 m$^3$/year and 900,000 m$^3$/year respectively, both in the northwesterly direction.

Lam [25] evaluated different measurements and calculations of the LST for the coast of Thua Thien-Hue province reported by different authors throughout the period 1970–2004. The most reasonable results (which agreed with the observed development rate of sand spits and dredge records) were found to be in the range of 600,000–1,600,000 m$^3$/year for the gross transport and 300,000–700,000 m$^3$/year for the net transport, which is directed to the northwest.

(c) Southern coast of Vietnam at the Tat canal, in the Mekong delta

Doan et al. [26] calculated the LST at Tat canal (Phu Long province) using the LITDRIFT model with input wave conditions covering the period 1999 to 2008. The estimated net sediment transport was found to be in the range of 150,000–170,000 m$^3$/year in a southwesterly direction.

The sediment transports in the period 1981–2000 at or near the above-mentioned verification locations, which are coastal Sections S1, S19, S20 and S22 (Figure 10), were computed by the GENESIS model. First, the calibration factors of GENESIS model $k_1$ and $k_2$ were set equal to the values of previous studies (refer to Supplementary Materials for description of these calibration factors), and gross and net transports were calculated for the selected coastal sections. Subsequently, the calibration factors were adjusted until the computed results of net and gross longshore sediment transport rates between this study and previous studies matched. The optimal values of the calibration parameters $k_1$ and $k_2$ thus obtained are shown in Table 2.

| Coastal Section | $k_1$ | $k_2$ |
|-----------------|-------|-------|
| S1              | 0.95  | 0.50  |
| S19             | 0.65  | 0.50  |
| S20             | 0.75  | 0.50  |
| S22             | 0.80  | 0.40  |

The computed results of net and gross LST rates from the GENESIS model at these coastal sections and corresponding values reported in literature are summarized in Tables 3 and 4.
Table 3. Comparison of computed and reported net longshore sediment transport rates at coastal Sections S1, S19, S20 and S22 (Positive transport direction is southward).

| Study Area | Estimates of $Q_{\text{net}}$ (m$^3$/Year) | Previous Study |
|------------|---------------------------------|----------------|
| Section    | Nearby Area | This Study | ECHAM Wave | GFDL Wave | |
| S1         | Tat channel | 33,000 to 102,000 | 9000 to 77,000 | 150,000 to 170,000 | |
| S19        | Thuan An beach | −786,000 to −1,772,000 | −721,000 to −1,703,000 | −300,000 to −700,000 | |
| S19        | Hai Duong   | −786,000 to −1,772,000 | −721,000 to −1,703,000 | −1,500,000 | |
| S20        | Ngu Thuy   | −768,000 to −1,725,000 | −684,000 to −1,579,000 | −900,000 | |
| S22        | Hai Hau beach | −21,000 to 71,000 | 5000 to 111,000 | 63,000 | |

Table 4. Comparison of computed and reported gross longshore sediment transport rates at coastal Sections S1, S19, S20 and S22.

| Study Area | Estimates of $Q_{\text{gross}}$ (m$^3$/Year) | Previous Study |
|------------|---------------------------------------------|----------------|
| Section    | Nearby Area | This Study | ECHAM Wave | GFDL Wave | |
| S1         | Tat channel | 96,380 to 168,000 | 73,892 to 151,000 | N/A | |
| S19        | Thuan An beach | 787,000 to 1,772,000 | 721,000 to 1,705,000 | 600,000 to 1,600,000 | |
| S19        | Hai Duong   | 787,000 to 1,772,000 | 721,000 to 1,705,000 | N/A | |
| S20        | Ngu Thuy   | 769,000 to 1,727,000 | 686,000 to 1,580,000 | N/A | |
| S22        | Hai Hau beach | 77,000 to 136,000 | 53,000 to 152,000 | 490,000 | |

The computed results of LST rates vary annually and depend on the GCM used to force the wave model (ECHAM5 or GFDL CM2.1), as well as on the coastline orientation. Nevertheless, there is reasonable agreement between the computed results and the reported values. Differences in methods and periods of computation, accuracy of adopted coastline orientation, bathymetry and wave climate are the most likely reasons for the inconsistencies between previously reported LST rates and those computed in the present study.

3.2. Modelling the Future Potential Sediment Transport

Finally, GENESIS was applied with the above $k_1$ and $k_2$ values, with the wave climates obtained from forcing the spectral wave model with the ECHAM5 and GFDL CM2.1 wind fields to calculate annual LST at the 18 remaining coastal sections for 1981–2000 and 2081–2100 time spans.

The GENESIS results for the future period are compared with the potential sediment transport rate for the 1981–2000 wave climate. The results are summarized in Table 5.

Table 5. Changes in net longshore sediment transport due to climate change at 22 coastal sections along the Vietnam coastline (2081–2100 compared to 1981–2000).

| Region | Coastal Section | Change in Direction of Net LST | Change in Magnitude of Net LST Percentage and Order of Change |
|--------|-----------------|-------------------------------|-------------------------------------------------------------|
| S1     | No/Remains towards the south | +62% (30,000 m$^3$/year) | |
| S2     | Yes/No dominant direction/change towards the south | −7% (1000 m$^3$/year) | |
| S3     | No/Remains towards the south | +34% (125,000 m$^3$/year) | |
| S4     | Yes/No dominant direction/change towards the south | −28% (2000 m$^3$/year) | |
| S5     | No/Remains towards the south | +50% (122,000 m$^3$/year) | |
| S6     | No/Remains towards the south | +37% (113,000 m$^3$/year) | |
| S7     | No/Remains towards the south | +40% (78,000 m$^3$/year) | |
Table 5. Cont.

| Region     | Coastal Section | Change in Direction of Net LST | Change in Magnitude of Net LST Percentage and Order of Change |
|------------|----------------|--------------------------------|-------------------------------------------------------------|
| Central Coast |                |                                |                                                             |
| S8         | No/Remains towards the south | −30% (145,000 m³/year)       |                                                             |
| S9         | Yes/No dominant direction/change towards the north | +240% (162,000 m³/year)     |                                                             |
| S10        | No/Remains towards the south | −7% (80,000 m³/year)         |                                                             |
| S11        | No/Remains towards the south | −22% (155,000 m³/year)       |                                                             |
| S12        | No/Remains towards the south | −30% (176,000 m³/year)       |                                                             |
| S13        | No/Remains towards the south | +16% (434,000 m³/year)       |                                                             |
| S14        | No/Remains towards the south | −23% (131,000 m³/year)       |                                                             |
| S15        | No/Remains towards the south | +9% (170,000 m³/year)        |                                                             |
| S16        | No/Remains towards the south | −15% (105,000 m³/year)       |                                                             |
| S17        | No/Remains towards the south | +23% (460,000 m³/year)       |                                                             |
| S18        | No/Remains towards the north | +45% (290,000 m³/year)       |                                                             |
| S19        | No/Remains towards the north | +10% (124,000 m³/year)       |                                                             |
| North Coast |                |                                |                                                             |
| S20        | No/Remains towards the north | +15% (170,000 m³/year)       |                                                             |
| S21        | No/Remains towards the north | +20% (113,000 m³/year)       |                                                             |
| S22        | Yes/No dominant direction/change towards the north | +60% (5000 m³/year)         |                                                             |

4. Discussion

Only a few wave-downscaling studies have been undertaken at similar spatial scales as the present study (i.e., ~1000 km). While the greenhouse gas emission scenarios, GCMs, RCMs, wave models and spatial resolutions therein differ among the studies (and the present study), all of them indicate changes in mean significant wave heights (by 2100, relative to the end of the 20th century) between 0.1 m–0.5 m (Table 6), which is somewhat larger than those projected for the same period for Vietnam in this study. The studies at the Bay of Biscay [27] and New South Wales, Australia [28] also indicate a rotation of up to 5° in mean wave direction for the same period, which is consistent with the projected variations in mean wave direction obtained for the Vietnam coast in the present study.

Table 6. Summary of previous regional scale wave-downscaling studies.

| Study Area                        | Wave Model Resolution | Projected Variation in Mean Wave Conditions by 2100 (Relative to End of 20th Century) | Source |
|-----------------------------------|-----------------------|--------------------------------------------------------------------------------------|--------|
| Western North Pacific             | ~100 km               | Hs decrease/increase by <0.5 m                                                      | [29]   |
| United Kingdom                    | ~12 km                | Hs slight increase/decrease <0.5 m                                                  | [30]   |
| North Sea                         | ~5.5 km               | Hs slight increase/decrease <0.2 m                                                  | [31]   |
| US West Coast                     | ~25 km                | Hs decrease by <0.5 m                                                                | [32]   |
| NW Mediterranean Sea               | ~50 km                | Hs decrease/increase by <0.1 m                                                       | [33]   |
| New South Wales, Australia        | ~10 km                | Hs decrease <0.1 m and rotation of 5°                                                | [28]   |
| Bay of Biscay                     | ~10 km                | Hs decrease <10% and rotation of 5°                                                  | [27]   |

The very few reported studies of potential climate change-driven variations in LST have been done at much smaller spatial scales than the present study (~2000 km). Furthermore, the methods adopted in these studies are highly variable, ranging from assumed future wave conditions and simple analytical LST equations to downscaled wave conditions and physics-based empirical LST formulations. Nevertheless, summary details of such reported studies are shown in Table 7, indicating that climate change-driven variations in LST can indeed be significant, which is broadly consistent with the findings of the present study.
Table 7. Summary of previous studies investigating climate change-driven variations in longshore sediment transport rates.

| Study Area            | Length and Time Scale of Study | Projected Future Variations in LST                                                                 | Source |
|-----------------------|--------------------------------|---------------------------------------------------------------------------------------------------|--------|
| NW Portugal           | 35 km; 25 years.               | CC-driven variations in wave conditions could result in a shoreline retreat rate double or triple that due to SLR | [34]   |
| Po River Delta, Italy | 100 km; 100 years.             | CC-driven variations in wave conditions could lead to 10%–20% decrease in LST                     | [35]   |
| Catalan coast, Spain  | 300 km; 50 years.              | CC-driven variations in wave conditions could lead to 50%–100% decrease in LST rates, and at some locations changes in net LST directions | [36]   |

5. Conclusions

This study has quantified climate change-driven variations in mean wave characteristics and resulting variations in potential longshore sediment transport rate along the ~2000 km mainland coast of Vietnam using dynamically downscaled wind fields derived from two global climate models, two spectral wave models (MIKE21 SW and SWAN), and a longshore sediment transport model (GENESIS). Results show that the 2081–2100 averaged significant wave height along the northern coast of Vietnam could be up to 8 cm lower (compared to 1981–2000), have slightly longer wave periods (increase of 0.20 s), and shift towards the south (clockwise) by up to 4°. Along the central coast, the 2081–2100 averaged significant wave height is projected to slightly increase by 5 cm (relative to 1981–2000), with an average wave period increase of up to 0.08 s and a directional shift to the south (clockwise) up to 6°. For the same time period, averaged significant wave height is projected to slightly increase by 7 cm, combined with a longer wave period (increase of 0.16 s) and a shift towards the north (counter-clockwise) by up to 8° along the southern coast of Vietnam. The most significant future potential change in the mean wave climate along the Vietnamese coastline is therefore the projected change in wave directions, leading to a zone of wave direction divergence in the vicinity of Da Nang.

The computed results indicate that the volume and direction of longshore sediment transport along the coast of Vietnam is rather variable. For 1981–2000 conditions, the annual averages from ECHAM5 and GFDL CM2.1-forced models at 22 contiguous coastal sections were found to be in the range of 11,000–2,748,000 m³/year for the total gross transport. Net longshore sediment transport estimates ranged between 1400–1,426,000 m³/year in a northerly direction in coastal Sections S2, S4 and S18–S21. In Sections S1, S3, S5–S17 and S22, the net transport ranged between 35,000–2,740,000 m³/year in a southerly direction. For the future time span 2081–2100, the annual average results along the 22 coastal sections are in the range of 10,000–3,403,000 m³/year for the total gross transport. The net longshore transport ranges between 2000–1,569,000 m³/year in a northerly direction at coastal Sections S4, S9, S18–S21. In coastal Sections S1–S3, S5–S8, S10–S17 and S22 the net sediment transport is estimated at 500–3,174,000 m³/year in a southerly direction.

The above projections indicate that climate change (CC)-induced future variations in longshore sediment transport rates are very substantial along the coast of Vietnam, with up to 0.5 million m³/year increase in the net transport rate at some locations. Such large changes in net longshore sediment transport rates can have major implications on the position and orientation of some sections of the Vietnamese coastline, emphasizing the urgent need for detailed coastal morphological studies and quantitative risk assessments at vulnerable coastal areas along the coast of Vietnam. This appears to be particularly the case in the vicinity of the highly developed Da Nang city (coastal Sections S17–S19) due to the large projected future change in longshore sediment transport direction and magnitude therein, with potentially an additional 875,000 m³ of sand being transported away from the area per year by the turn of the 21st century.
Supplementary Materials: The following are available online at www.mdpi.com/2077-1312/4/4/86/s1.
Description of Models: CCAM, MIKE21, SWAN, GENESIS.

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