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News & Views

Storms dominate the erosion of the Yangtze Delta and southward sediment transport

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Densely populated coasts are vulnerable to storm damage. Episodic storm-induced redistribution of coastal sediment is known to have major geological and ecological implications [1,2], but little is known about storm-driven delta erosion and longshore sediment transport. The Yangtze (Changjiang) Delta and Zhejiang–Fujian coasts (Fig. S1 online) are among the world's largest coastal depositional systems, and play an important role in supporting China's socioeconomic development [3,4]. Previous studies have suggested that East Asian winter monsoon wind is the key factor driving southward sediment transport from the Yangtze Delta, creating a 1000-km-long mud wedge on the inner shelf of the East China Sea. Summer (flood season) wind waves are relatively weak and sediments from the Yangtze River are deposited in the delta area, while in winter the northerly monsoon winds drive strong waves and longshore currents, leading to sediment resuspension and removal from the delta [5–7]. However, the role of storms in Yangtze Delta erosion and southward sediment transport has received little attention. Here, we find that episodic storms occurring not only in winter but also in other seasons contribute most to the delta erosion and southward sediment transport.

We defined a fair weather as wind speed $\leq$ 5.4 m/s, storm weather as a wind speed $\geq$ 10.8 m/s, a storm event as a storm wind period $\geq$ 6 h, and a major storm event as a storm period $\geq$ 2 d (see Methods in the Supplementary materials online). On the Yangtze Delta, longshore wind is dominated by southward winds, particular for storm winds of which 86% are southward (Table S1 online). In the Northern Hemisphere, storm winds derived from polar outbreaks are southward. Likewise, typhoon-driven storm winds are usually southward, with typhoons commonly being formed over the ocean southeast of the Yangtze Delta and rotating counterclockwise as they approach and commonly move northward on the east side of the Yangtze Delta (e.g., Malakas track in Fig. S1a online). Storm winds contribute >30% of the total net southward wind component, although storm winds occur on only ~5% of days per year (Tables S1 and S2 online).

Our observations indicate that wind speed and wave height during storm events were respectively 2–4 and 3–5 times higher than during fair weather (Fig. 1a, b, Figs. S2–S4, and Table S3 online). Wave energy is proportional to the square of wave height [8], so wave energy during storm events is an order of magnitude higher than during fair weather. Storm surges enhance sediment resuspension in shallow waters and initiate sediment resuspension in deeper waters where the seabed is not disturbed during fair weather.

For example, during Typhoon Malakas in 2016, the daily average surficial suspended sediment concentration (SSC) at Station A (7 m depth; Fig. S1b online) reached a maximum of 1.45 kg/m^3 on 19 September, 34 times that during fair weather one week earlier (0.043 kg/m^3 on 11–12 September) (Fig. S3f online). Under the assumption of no storm impact, and based on the power-law relationship between daily average SSC and tidal range in fair weather (Fig. S5d online), the maximum SSC increase on 19 September due to increased tidal effect alone would have been 0.676 kg/m^3 (Fig. S3f online). Therefore, ~45% of the increased SSC from 11–12 to 19 September was due to the increased tidal range, while ~55% was attributable to storm impact. Thus, storm impact alone increased the SSC by 18 times. At Station B (20 m depth; Fig. S1b online), the mean SSC on 19 September (0.432 kg/m^3) was 55 times that on 11–12 September (0.0078 kg/m^3) (Fig. S4g, h online). Thus, ~30% of the SSC increase (16 times) from 11–12 to 19 September resulted from the increased tidal range, while ~70% (38 times) resulted from storm-induced sediment resuspension.

To better understand sediment resuspension during Typhoon Malakas, we compared the SSC among phases. During Phase 1 (four tidal cycles), when both waves and currents were weak, the SSC was low. During Phase 2 (eight tidal cycles), the SSC increased with wave height and current velocity due to the approaching typhoon and the transition from neap to spring tide. During Phase 3 (five tidal cycles), the SSC further increased as both the wave height and current velocity reached their maxima (Table S3 online). From Phase 1 to Phase 3, the SSC at stations A and B increased by 22 and 35 times, respectively. Based on the relationship between SSC and

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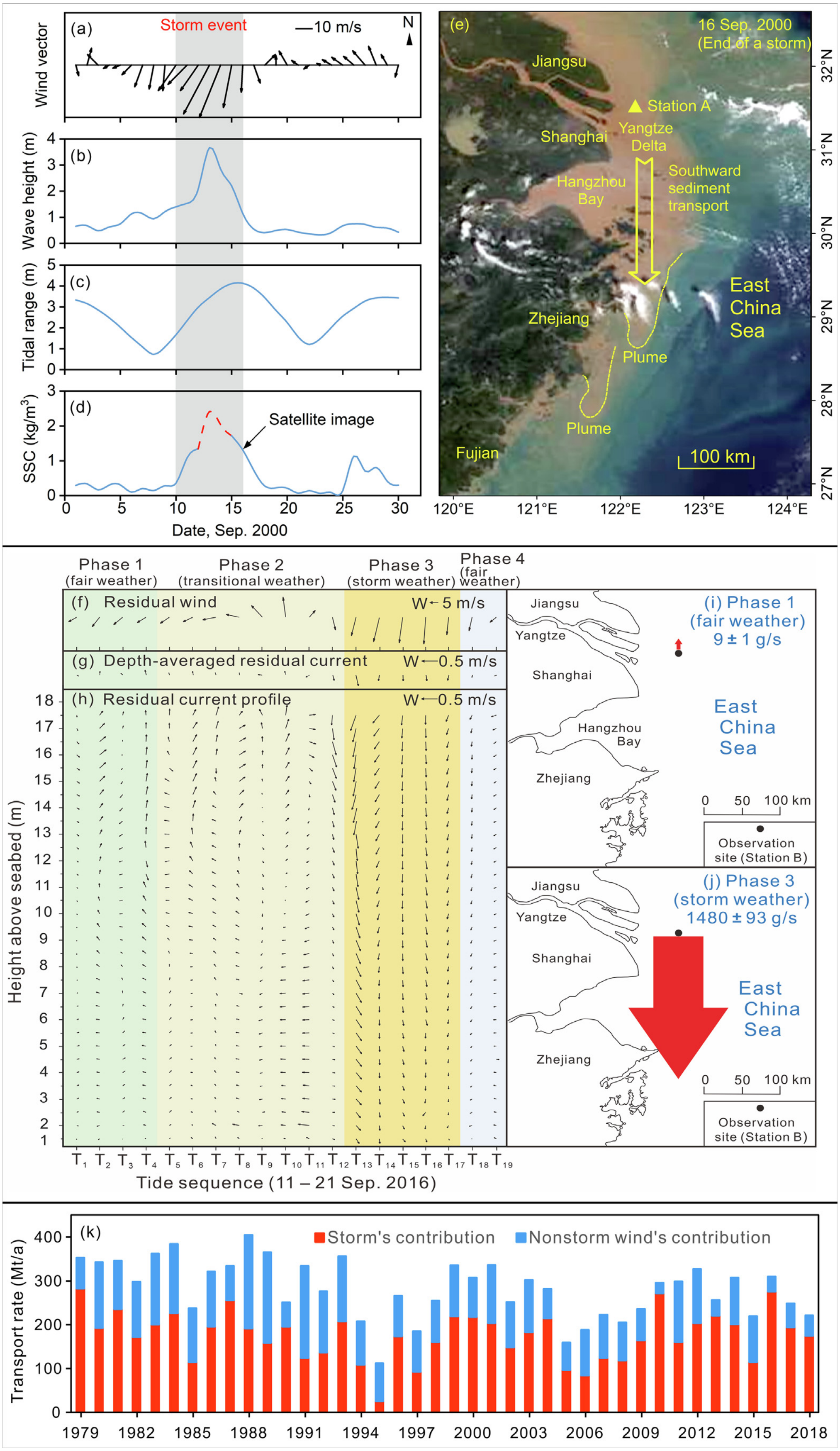
(a) Storm event 10 m/s N
Wind vector
(b) Wave height (m)
(c) Tidal range (m)
(d) Satellite image
SSC (kg/m³)
Date, Sep. 2000
(e) 16 Sep. 2000 (End of a storm)
Jiangsu
Station A
Shanghai
Yangtze Delta
Hangzhou Bay
Southward sediment transport
East China Sea
Zhejiang
Plume
Plume
Fujian
100 km
32°N
31°N
30°N
29°N
28°N
27°N
120°E
121°E
122°E
123°E
124°E
Phase 1 (fair weather)
Phase 2 (transitional weather)
Phase 3 (storm weather)
Phase 4 (fair weather)
(f) Residual wind W 5 m/s
(g) Depth-averaged residual current W 0.5 m/s
(h) Residual current profile W 0.5 m/s
Height above seabed (m)
Tide sequence (11 – 21 Sep. 2016)
(i) Phase 1 (fair weather) 9 ± 1 g/s
Jiangsu
Yangtze
Shanghai
Hangzhou Bay
Zhejiang
East China Sea
0 50 100 km
Observation site (Station B)
(j) Phase 3 (storm weather) 1480 ± 93 g/s
(k) Storm's contribution Nonstorm wind's contribution
Transport rate (Mt/a)

tidal range in fair weather (Fig. S5d online), 68% of the SSC increase at Station A and 46% at Station B from Phase 1 to Phase 3 is attributed to the increased tidal effect. It follows that 32% of the SSC increase at Station A and 54% at Station B can be attributed to storm impact.

Storm-induced sediment resuspension results in an expansion of the turbid zone toward deeper waters. A satellite image taken near the end of a storm event associated with Typhoon Sonamu shows an ~80-km-wide turbid zone in the offshore subaqueous Yangtze Delta (Fig. 1e), which is ~40 km wide under normal weather conditions [9]. Considering that wind speed, wave height, and SSC during the strongest period of the storm (2–3 d before the time when the satellite image was obtained) were much higher than when the image was taken (Fig. 1a, b, d), the turbid zone in the offshore subaqueous Yangtze Delta during the strongest period of the storm would have been wider than that shown in the image.

Southward storm winds drive southward residual currents in the offshore subaqueous Yangtze Delta. Under fair-weather conditions prior to Typhoon Malakas, residual currents of individual tidal cycles had low velocities and varied directions that were inconsistent with residual wind directions. However, during the typhoon event, the residual current velocities were increased markedly, and their directions were consistent with the residual wind direction in both vertical profiles and time series (Fig. 1f–h and Table S4 online). During fair weather, when the residual wind speed and direction were 5.3 m/s and 59°, the depth-averaged residual current velocity and direction were 0.07 m/s and 354° (the flow direction is the direction of on-going flow), respectively. During the storm event, the residual wind speed and direction were 10.1 m/s and 12°, and the depth-averaged residual current velocity and direction were 0.32 m/s and 180°, respectively (Table S5 online).

We estimated the residual sediment transport rate per unit width of cross-section as the product of water depth, depth-averaged residual current velocity, and depth-averaged SSC. The residual sediment transport rate per meter width of the water column at Station B during Typhoon Malakas was 1480 ± 93 g/s (see Methods in the Supplementary materials online for uncertainties) (direction of 180°), far exceeding the fair-weather value of 9 ± 0.7 g/s (direction of 354°) (Fig. 1i, j and Table S5 online). We also found increased median sizes of suspended and bottom sediments during and immediately after the typhoon event, suggesting storm-induced southward transport of coarser-grained sediments. To estimate the residual sediment transport rate through the cross-shore profile, we first quantified the cross-shore changes in SSC (Fig. S6 online). The depth-averaged residual current velocity at Station B was then used to represent the mean residual velocity in the cross-shore profile, considering that (1) the offshore subaqueous delta is open (Fig. S1a online) and cross-shore changes in wind speed and direction during the storm were negligible (Fig. S7 online), (2) the coastal slope is very gentle (gradient < 0.03%) and smooth (Fig. S1c online), and (3) Station B is located centrally in the offshore subaqueous delta (Fig. S1b online). The water depth for each unit width was then calculated from Fig. S1c (online). Finally, the total longshore sediment transport flux during the storm event was estimated as the product of the residual sediment transport rate through the cross-shore profile and the duration of the storm.

We found that ~63 ± 4.1 Mt of sediment was transported southward from the offshore subaqueous delta during the Malakas event (Table S6 online). This is 126 times the sediment supplied by the Yangtze River during the event (0.5 Mt) and indicates that 99% of the southward sediment transport was derived from delta erosion. Considering that the offshore subaqueous Yangtze Delta covers an area of ~10,000 km^2 (Fig. S1b online) and the mean dry bulk density of Yangtze River sediment is 1.3 g/cm^3 [4], the mean erosion depth during the Malakas event was ~5 ± 0.3 mm. Our optimal estimate of the storm-induced southward sediment transport from the Yangtze Delta during 2016 was 275 ± 54 Mt, or 89% of the total sediment transport. Optimal estimates of storm-induced annual fluxes of southward sediment transport from the delta over the past 40 years have varied between 25 ± 4.5 Mt in 1995 and 282 ± 55 Mt in 1979, with an average of 175 ± 69 Mt/a. The marked interannual changes in storm-induced southward sediment transport from the Yangtze Delta (Table S7 online) reflect the impact of climatic variability. On average, 52% of the storm-induced annual net southward sediment transport has occurred in winter, 39% has occurred in autumn, and 9% has occurred in spring (Table S8 online). The storm contribution to total sediment transport ranges from 23% in 1995 to 92% in 2010, with an average of 62% (Fig. 1k and Table S7 online).

Prior to the closure of the Three Gorges Dam (TGD) (1979–2002), Yangtze sediment discharge to the sea was 379 ± 79 Mt/a, while our estimate of southward sediment transport from the Yangtze Delta was 300 ± 90 Mt/a with 176 ± 69 Mt/a being contributed by storms. After the TGD closure (2003–2018), the Yangtze sediment discharge rate was 133 ± 42 Mt/a, while our estimate of sediment transport from the Yangtze Delta was 254 ± 67 Mt/a with 175 ± 69 Mt/a being contributed by storms (Table S7 online). Thus, the Yangtze Delta underwent a transition from pre-TGD accretion to post-TGD erosion, which is in agreement with measured bathymetric changes [10]. The annual storm-driven transport exceeded the post-TGD discharge and was less than the pre-TGD discharge, thus causing the Yangtze Delta transition.

We developed a conceptual model of the fate of Yangtze-derived sediments. In fair weather, when waves are low and residual longshore currents are weak, fluvial sediments from the Yangtze tend to be deposited on the offshore subaqueous delta. However, in stormy weather, when wave energy and bottom perturbation are greatly increased and southward longshore currents are stronger, previously deposited sediments are resuspended and transported southward (Fig. S8 online). The southward transport distance during a storm event is typically <100 km. For example, the distance of southward sediment transport during the Malakas event was ~70 km, based on the duration (2.6 d) and mean residual flow velocity during the storm period (0.32 m/s) (Table S5 online).

Our optimal estimate of the mean rate of southward sediment transport from the Yangtze Delta over the past four decades (280 ± 85 Mt/a) is consistent with results of previous studies based on observations and sediment budgets [7,11]. The sediment transport is generally dominated by storm-induced resuspension and

Fig. 1. Storm-induced changes in hydrodynamics and sediment transport. (a–d) Daily average wind vector, significant wave height, tidal range, and suspended sediment concentration (SSC) at Station A. (e) Satellite image at the end of a storm showing turbid zone and southward sediment plums. (f–h) Tidal-cycle residual wind vector, depth-averaged current, and current profile at Station B. (i, j) Residual sediment transport rates and direction per meter width of the water column at Station B in fair weather and storm event. (k) Storm's and nonstorm wind's contributions to annual net southward sediment transport from the Yangtze Delta. Note: the broken line in (d) is an estimate of missing SSCs for 12–15 September, when sediment-sampling efforts failed because of dangerous storm winds and surges. The estimate was based on a binary regression between SSC and wave height and tidal range in the other 26 d in September (R^2 = 0.65, P < 0.001).

longshore currents, even though transport driven by southward nonstorm winds of the winter monsoon may exceed storm-induced transport in some individual years when storm events are rare. Storm-induced southward sediment transport is not limited to winter or the winter monsoon period but may occur in most seasons. Marked increases in SSC and surficial sediment grain size found immediately after typhoons in the mud wedge also suggest storm-induced sediment resuspension and redistribution [12,13]. Our results differ from those of previous studies that attributed southward sediment transport to longshore currents driven by the winter monsoon [5,7]. Our findings highlight the importance of storms in delta erosion and longshore sediment delivery, which is of particular significance considering the projected increase in storm intensity with global warming [14] and the dam-induced decrease in river sediment discharge to the world's coastal seas [15].

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary materials

Supplementary materials to this news & views can be found online at https://doi.org/10.1016/j.scib.2023.03.005.

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