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Long-term *in situ* observations on typhoon-triggered turbidity currents in the deep sea

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ABSTRACT

Turbidity currents regulate the transport of terrigenous sediment, abundant in carbon and nutrients, from the shelf to the deep sea. However, triggers of deep-sea turbidity currents are diverse and remain debatable in individual cases due to few direct measurements and unpredictable occurrence. Here we present long-term monitoring of turbidity currents at a water depth of 2104 m on the margin of the Gaoping Submarine Canyon off Taiwan, which has the world's highest erosion rates and wettest typhoons. The unique 3.5 year record of *in situ* observations demonstrates the frequent occurrence of deep-sea turbidity currents (an average of six times per year from May 2013 to October 2016), most of which show enhanced sediment flux, raised temperature, and lowered salinity. They are attributed to elevated discharge of the Gaoping River due to typhoons traversing Taiwan. The total duration of these prolonged turbidity currents amounts to 30% of the entire monitoring period, contributing to ~72% of total sediment transport in the lower canyon. Our study demonstrates for the first time that typhoons are the most important triggers, in the long term, of frequent turbidity currents and enhanced sediment delivery into the deep sea in the typhoon-river-canyon environment.

INTRODUCTION

The large volumes of terrigenous sediment transported by turbidity currents play a significant role in global sediment redistribution and burial (e.g., Meiburg and Kneller, 2010). Turbidity currents develop in a variety of environmental and geological settings, triggered by various mechanisms such as earthquakes, non-seismogenic slope failures, river floods, atmosphere-related hydrodynamic events, and anthropogenic activities (Xu et al., 2004; Talling et al., 2013). Among them, earthquakes have received particular attention because of their acknowledged role in triggering destructive turbidity currents since the famous breakage of submarine cables following the 1929 Grand Banks (Atlantic Ocean) earthquake (Heezen and Ewing, 1952). Other processes, including tropical cyclones and river floods, are regarded as important triggers of frequent turbidity currents, in a context of rivers connected to submarine channels with narrow shelves (e.g., Kudrass et al., 1998).

Typhoons, the severe form of northwest Pacific Ocean tropical cyclones, contribute to turbidity currents in the deep sea, inferred indirectly from the breaking of subsea cables, the largest number of cable breaks being found in the Gaoping Submarine Canyon off Taiwan (Pope et al., 2017). The newly recognized, more-prolonged turbidity currents with slower trailing bodies allows more terrigenous sediment to be delivered to the deep sea (Azpiroz-Zabala et al., 2017). However, the hydrographical structure of typhoon-triggered turbidity currents and their impacts on sediment transport in the deep sea are as yet little known.

The Gaoping Submarine Canyon is located off southwestern Taiwan, and is the largest source of fluvial sediment discharged directly to the northern South China Sea (Fig. 1; Liu et al., 2016b). The head of the canyon directly connects to the Gaoping River catchment, which has an active tectonic setting with the world's highest erosion rates (Liu et al., 2016a). Moreover, Taiwan receives the wettest typhoons originating in the northwest Pacific, where nearly one third of the world's tropical cyclones develop (Elsner and Liu, 2003). The Gaoping River discharge during typhoon-induced floods commonly triggers turbidity currents that propagate over long distances, ventilating the deep sea with the warmer and less-saline water (Kao et al., 2010). Here, we present 3.5 years of *in situ* subsea mooring observations, to establish the direct link between strong atmospheric forcing–induced river floods and consequent sediment transport by prolonged turbidity currents on the levee in the lower reach of the Gaoping Submarine Canyon.

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METHODS

In Situ Observations in the Gaoping Submarine Canyon

A subsea mooring system (TJ-G) was deployed from May 2013 to October 2016 in the lower reach of the Gaoping Submarine Canyon at a water depth of 2104 m (Figs. 1A and 1B). The mooring was located on the levee, ~3.5 km laterally, and 490 m vertically, from the thalweg, 146 km downstream from the head of the canyon. This mooring was equipped with sediment traps, a long-range acoustic doppler current profiler (ADCP), a recording current meter (RCM), and a conductivity-temperature-depth (CTD) to collect sediment particles consecutively with 7 or 18 day intervals, and measure various hydrographic parameters with 2–60 min intervals (Fig. 1C), from which the suspended sediment concentration (SSC) and vertical structure of turbidity currents are inferred. In addition, we analyzed typhoon tracks (Fig. 1D), atmospheric pressure, and water discharge and sediment content of the Gaoping River (Figs. 2A and 2B) to constrain the links between typhoons at the surface and turbidity currents in the deep canyon. We also discuss earthquake data (Fig. 2A). Details of all data sets and associated calculations are provided in the GSA Data Repository[1].

RESULTS AND DISCUSSIONS

Frequent Turbidity Currents in the Gaoping Submarine Canyon

Turbidity currents were identified by dramatic increases in near-bottom SSC recorded by the turbidity probe, and by sediment particle flux collected by the lower sediment trap at ~30

[1]GSA Data Repository item 2018228, supplementary information for calculation of suspended sediment concentration and sediment transport, and Figures DR1–DR3 and Table DR1, is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org.

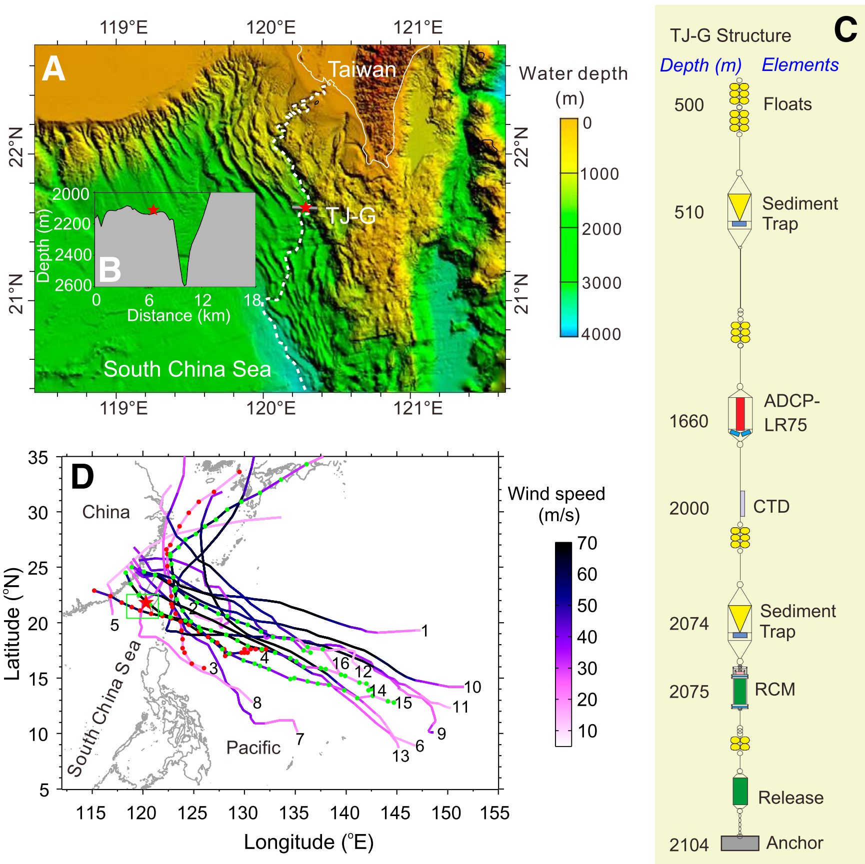

Figure 1. Mooring system in the Gaoping Submarine Canyon, offshore Taiwan. A: Bathymetry of study area. Dashed white line shows canyon thalweg, gray line shows cross section in B; red star is mooring position. B: Cross-canyon profile showing mooring (red star) located on the levee. C: Vertical structure of the TJ-G mooring. D: Tracks of 16 typhoons that influenced the study area between 2013 and 2016. Green dotted lines show three super-typhoons in September 2016 (marked as numbers 14, 15, and 16). Green box shows the area in A; red star is mooring.

m above the seafloor (Fig. 2). We identified 23 major turbidity currents by the average SSC exceeding 0.5 mg/L during the 3.5 yr of continuous monitoring (Fig. 2E). The average SSC during turbidity currents was enhanced almost sixfold compared to the background value at the mooring site. Correspondingly, the sediment flux calculated from the lower-trap sediment analysis synchronously increased (Figs. 2C and 2D). Monitoring on the levee within the upper part of the turbidity current, rather than the main body of the current in the thalweg, was intended to avoid damage to the instruments. This slower-moving, more-dilute part of the turbidity currents, with a velocity magnitude of 15 cm/s monitored here (Fig. 2F), is in marked contrast to the fast-moving main body of 5–8 m/s inferred from the coincidence of 6 cable breaks associated with the turbidity current in August 2015 in the lower canyon (Gavey et al., 2017) (event number 15 in Fig. 2E).

In contrast to the enhanced sediment fluxes observed by the lower sediment trap (with a mean value of 7.78 × 10³ mg/m²/d), approximately

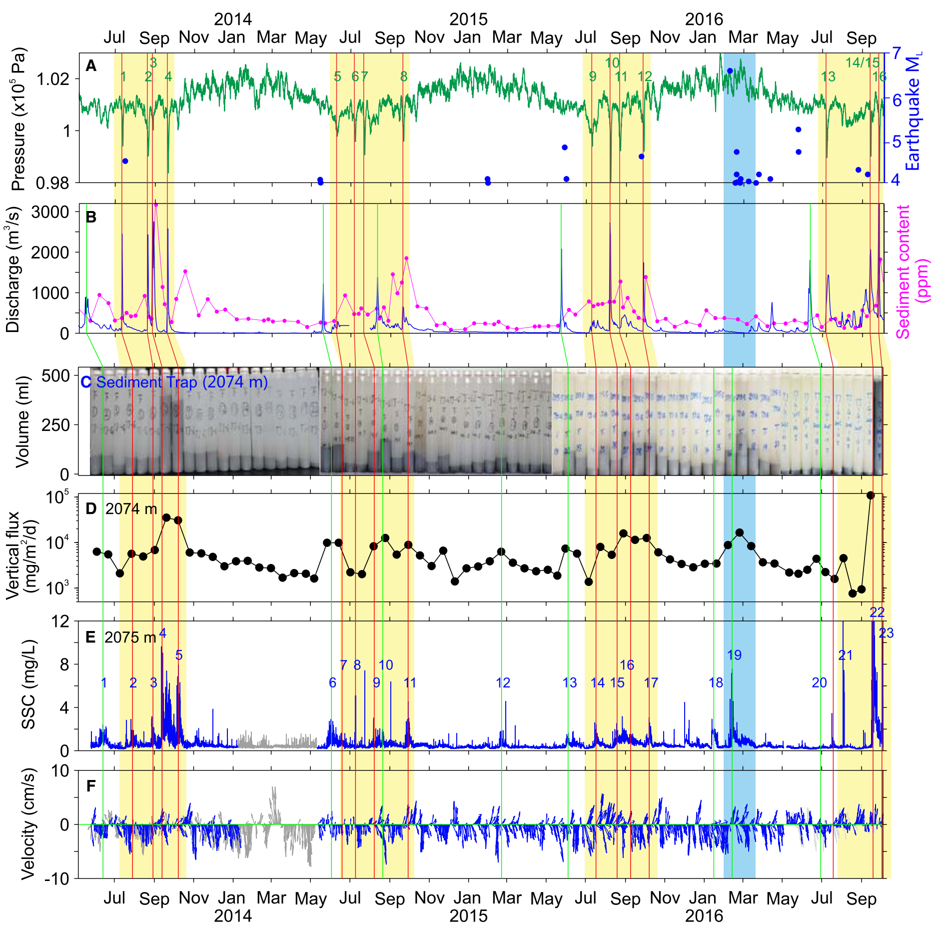

Figure 2. Timing and triggers of turbidity currents. A: Sixteen typhoons (labeled with green numbers) accompanied by low atmospheric pressure, with earthquakes of $M_L > 4$ shown as blue dots. B: Daily river discharge (blue line) at Gaoping River mouth (Taiwan), with sediment content (pink line). C: Bottled sediment samples collected by the lower trap ~30 m above seafloor. D: Vertical sediment flux calculated from sediment samples shown in C. E: Suspended sediment concentration (SSC, blue line) inferred from a recording current meter (RCM) at 2075 m (~29 m above seafloor). Due to a RCM malfunction, data for January and May 2014 (gray line) are calculated from acoustic Doppler current profiler (ADCP) echo intensity at ~2000 m. Labeled numbers show turbidity currents with SSC > 0.5 mg/L. F: Same as E, but for current velocity with tides removed at 2075 m. Red lines from top to bottom in A–F connect typhoons (accompanied with peak river discharge) and associated deep-sea turbidity currents. Green lines in B–F connect peak river discharge and related turbidity currents in the absence of typhoons. Yellow shaded regions indicate typhoon seasons. Blue shaded region shows $M_L = 6.5$ Kaohsiung earthquake followed by a swarm of $M_L = 4$–5 aftershocks.

two orders of magnitude less particles were collected by the upper sediment trap positioned at a depth of 510 m (with a mean value of 78.4 mg/m^2/d), and there is only a negligible increase in particles during turbidity currents (Fig. DR1 in the GSA Data Repository). The contrast in sediment flux with water depth is suggestive of turbidity current–driven sedimentation, rather than particle settling from the surface.

Correlation between Typhoons and Turbidity Currents in the Deep Sea

Sixteen typhoons with wind speeds exceeding 33 m/s traversed Taiwan during our mooring observation period (Fig. 1C; Table DR1). All these typhoons induced an abrupt increase in river discharge, up to 2–3 orders of magnitude more than the amount during the dry season (Fig. 2B). Four powerful typhoons crossed Taiwan each year, resulting in 15 events with peak river discharge (twin typhoons 14 and 15 [Fig. 1C] in 2016 produced one combined discharge peak). These peak river discharge events, usually with elevated sediment content (Fig. 2B), were followed by 15 turbidity currents (thin red lines in Fig. 2). This correlation suggests a link between typhoon-induced river discharge and turbidity currents in the deep sea, even if the timing of the turbidity currents suggests that they were not triggered directly by river plunging (Table DR1). We therefore conclude that these frequent turbidity currents in the deep sea were triggered as a result of typhoons passing over Taiwan, consistent with the findings of other studies over shorter time scales (Kao et al., 2010; Liu et al., 2016a).

Five additional peak river discharge events, mostly prior to the typhoon season, are also associated with turbidity currents (thin green lines in Fig. 2). Thus, among the 23 observed turbidity currents, 20 are directly attributed to peak river discharge during flood periods. Only three turbidity currents occurring in boreal winter are potentially attributed to the seasonal variability of deep-sea circulation (Liu et al., 2016b) or to the M_L 6.5 Kaohsiung (southern Taiwan) earthquake followed by a swarm of M_L 4–5 aftershocks in February 2016 (Fig. 2A). Although there is no direct correlation between other earthquakes of $M_L > 4$ and timing of the turbidity currents, the frequent earthquakes occurring within 150 km of the canyon head are potentially conducive to slope failure and consequent turbidity currents.

Unique Features of Typhoon-Triggered Turbidity Currents

The duration of these flows in the Gaoping Submarine Canyon ranges from a week to a month (Table DR1), mostly far more prolonged than the longest previously documented turbidity current (10 days) in the Congo Canyon, offshore West Africa (Khripounoff et al., 2003; Azpiroz-Zabala et al., 2017). The total duration of all turbidity currents at the mooring is up to 368 days, amounting to 30% of the entire monitoring period (1228 days). These sustained turbidity currents in the deep canyon commonly lagged the peak river discharge by a few days; ranging from 2 to 7 days due to the weak velocity of the discharge (Table DR1, Fig. DR2).

This coupling is most apparent for the turbidity currents that occurred during typhoon seasons in 2013 and 2016 (Fig. 2). Here we show turbidity current number 22 (Figs. 2E and 3), triggered by super typhoons numbers 14 and 15 (Fig. 1C), which brought the heaviest rainfall to the Gaoping River drainage on 14 September 2016. Our observations of deep-water flow properties show a marked increase in temperature and SSC at 2075 m (~29 m above seafloor) on 16 September, and then an increase in temperature and a decrease in salinity at 2000 m on 17 September. This indicates that the warmer, more-turbid and fresher water from the river mouth reached the TJ-G mooring site ~2 days after the typhoon-induced maximum water discharge at the Gaoping River. Combined with the elevated sediment content of the Gaoping

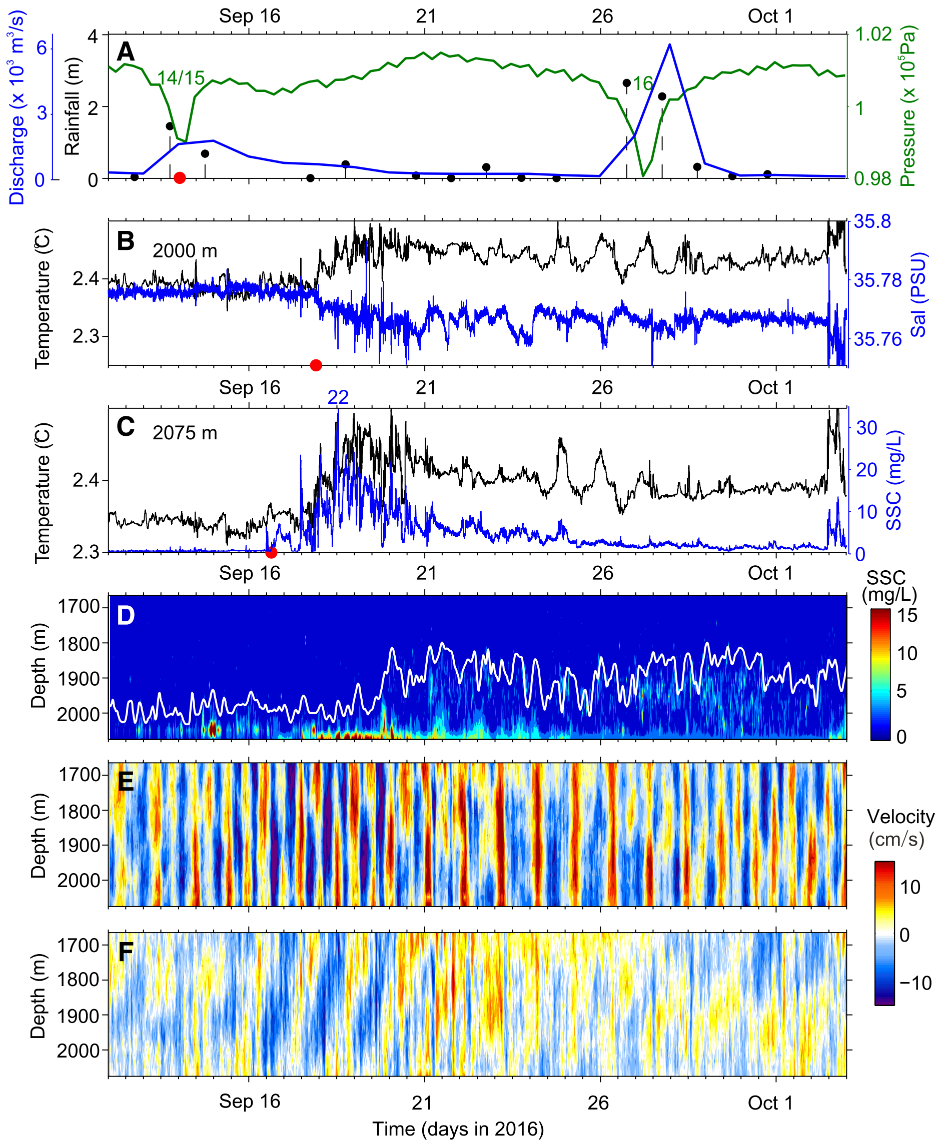

Figure 3. Structure of a representative typhoon-triggered turbidity current. A: Atmospheric pressure (green), rainfall (black dots), and river discharge (blue) at Gaoping River mouth (Taiwan) during three super typhoons (numbers 14, 15, and 16) in September 2016. Bottom red dot shows time (~12:00 on 14 September) of maximal river discharge. B: Temperature and salinity (Sal) recorded by the conductivity, temperature, depth sensor. Red dot shows time (~21:00 on 17 September) of appearance of turbidity current at 2000 m. C: Temperature and suspended sediment concentration (SSC) recorded by the recording current meter (RCM). Red dot shows time (~12:00 on 16 September) of appearance of turbidity current at 2075 m. D: Merged SSC calculated from RCM turbidity and acoustic Doppler current profiler (ADCP) echo intensity. White line indicates boundary of SSC exceeding 0.5 mg/L. E: Full velocity of current along the canyon. F: Same as E, but with tidal velocities removed.

River during the typhoon season (Fig. 2B), this higher temperature and lower salinity therefore demonstrates that the typhoon-triggered deep-sea turbidity activity originated directly from the river-discharge–fueled hyperpycnal flow.

The extended thick layer of high SSC lasted for at least 16 days until the occurrence of another turbidity current in October 2016 (Fig. 3D), triggered by another typhoon (number 16). Distinctly elevated temperatures were also first identified at 2075 m and subsequently appeared at 2000 m ~31 h later (Figs. 3B and 3C). The isoline of significant SSC (= 0.5 mg/L), characteristic of the turbidity current with more suspended particles, is elevated from 100 to 300 m above the sea bottom (Fig. 3D). The difference in appearance time in the two horizons indicates that the turbidity current was initially confined to a relatively thin layer near the bed, and gradually thickened with time (Azpiroz-Zabala et al., 2017).

Contrary to the SSC, temperature, and salinity footprints of turbidity currents, the flow speed does not intensify much during the event (Figs. 3E and 3F). We obtained a residual speed of only 15 cm/s by removing the tidal components. Although such weak flow speed is comparable to deep-sea turbidity currents on levees adjacent to channels (e.g., Khripounoff et al., 2003), it is almost one order of magnitude slower than those previously measured in the main body of submarine turbidity currents from locations in the axis of canyons such as the Congo Canyon (Azpiroz-Zabala et al., 2017) and the Monterey Canyon (offshore California, USA; Xu et al., 2004).

Fluvial Sediment Delivered into the Deep Sea by Typhoon Triggered Turbidity Currents

The sustained turbidity currents consequently led to pronounced increases in near-bottom sediment flux, with a peak value of 1.1×10^5 mg/m^2/d in September 2016 (Fig. 2D), >49× the normal condition. By integrating the cross-canyon profile (Fig. 1B) over the duration of turbidity currents in the 3.5 yr monitoring period, the net downward-canyon sediment transport is estimated at up to 89.2 Mt, accounting for ~72% of the total time-integrated sediment transfer through the lower canyon (see the Data Repository). Accordingly, the annual mean sediment transport (25.5 Mt) associated with such frequent deep-sea turbidity currents represents 13.6% of the 187.5 Mt total sediment discharge of major southwestern Taiwanese rivers flowing into the South China Sea, and 52% of the 49 Mt input from the Gaoping River (Liu et al., 2016b). Thus, typhoon-triggered turbidity currents act as the most important process for redistributing river-derived terrigenous sediment from the shelf to the deep sea along the Gaoping Submarine Canyon.

CONCLUSIONS

Our long-term *in situ* observations emphasize the importance of typhoons as a triggering mechanism for far-sourced turbidity currents in the deep sea, as compared to other mechanisms. The extended thick layer of high SSC and the prolonged duration of such typhoon-triggered turbidity currents make them major agents of sediment transport through the river-canyon dispersal system. These observations strongly suggest that hyperpycal flow conditions associated with the river floods during the typhoon season are the dominant driver of sediment redistribution in tectonically active and climatically disturbed areas such as Taiwan and its connected submarine canyons, and support the link between upstream hyperpycnal flows and sustained turbidity currents in the deep sea. While at present, hyperpycnal flows are largely limited to exceptional settings such as Taiwan, this is probably not the case during lowstands of sea level (Mulder et al., 2003). This sediment-routing process constitutes a major part of the riverine contribution to the global sediment transfer from land to deep sea (Milliman et al., 2007).

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