Cyclone-driven deep sea injection of freshwater and heat by hyperpycnal flow in the subtropics

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[1] The western tropical Pacific gives birth to 23 tropical cyclones annually, bringing torrential rainfall to mountainous islands across Oceania resulting in a global sediment production hotspot, in which many rivers have great hyperpycnal potential. By using a temperature (T) and salinity (S) profiler, we observed anomalously warm, low salinity turbid water at 3000–3700 m depths in seas ~180 km off southwestern Taiwan immediately after Typhoon Morakot in 2009. This 250m-thick bottom-hugging water occupies ~2400 km^2, and contains 0.15% freshwater, suggesting a remarkably high fraction (6–10%) of event rainfall from southwestern Taiwan. These characteristics indicate the turbid water originated from shallow coastal waters via hyperpycnal flow. Apparently, sediment produced from the land during tropical cyclones open an "express gate" to convey heat and freshwater vertically to the deep ocean basin subsequently warming the deep water from the bottom up. **Citation:** Kao, S. J., M. Dai, K. Selvaraj, W. Zhai, P. Cai, S. N. Chen, J. Y. T. Yang, J. T. Liu, C. C. Liu, and J. P. M. Syvitski (2010), Cyclone-driven deep sea injection of freshwater and heat by hyperpycnal flow in the subtropics, *Geophys. Res. Lett.*, *37*, L21702, doi:10.1029/2010GL044893.

1. Introduction

[2] The Earth's oceans play an important role in regulating climate over a range of timescales owing to their large thermal inertia and deep internal convection. Sea surface temperature and heat content in the world oceans has revealed significant warming trends of the global surface ocean in the 20th century [*Deser et al.*, 2010]. Most significantly, the largest warming signal appears in the northwestern Pacific Ocean [*Deser et al.*, 2010], where tropical cyclones, i.e., typhoons, occur most frequently from July to November, when the sea surface temperature exceeds 26°C. Tropical storms redistribute freshwater on the Earth's surface by transporting moisture from the sea to inland areas. During transport, the winds associated with storms stir up the upper ocean, refueling the oligotrophic warm surface and conveying heat downward in low-latitude oceans [*Korty et al.*, 2008; *Lin et al.*, 2003]; thereby facilitating the ocean's biological pump. Furthermore, such storm-induced diapycnal mixing is responsible for ≈15% of peak poleward ocean heat transport from the tropics to extra-tropics [*Sriver and Huber*, 2007], representing important feedbacks to the climate system, though *Jansen and Ferrari* [2009] modeled much less poleward heat transport than previous estimation. The magnitude and complexity of such feedback processes are however difficult to constrain by field observations. This is particularly so in the context of a warming ocean that will very likely exacerbate the intensity of tropical storms and the attendant rainfall [*Emanuel*, 2005; *Elsner et al.*, 2008; *Liu et al.*, 2009]. Here we provide an undiscovered example in Oceania showing how a typhoon may significantly alter the deep sea's thermal properties.

[3] Typhoons can bring torrential rain to high-standing, tectonically active islands (hereafter HSI) of Oceania in the western tropical Pacific. These islands are characterized by steep landscape morphology and friable meta-sedimentary rocks, and have insufficient space to store eroded sediments and soils. The result is extremely high rates of sediment production. Therefore HSI represent a hotspot of atmospheric driven land-sea export of terrestrial material in the form of both dissolved and particulate organics and inorganics [*Milliman and Syvitski*, 1992; *Milliman et al.*, 1999; *Syvitski et al.*, 2005; *Kao and Milliman*, 2008]. Even though direct observation of such turbid freshwater plumes was never reported in the deep sea, given the importance of sediment plume-associated physical and biogeochemical processes in seas surrounding this region, we believe that deep sea export of a storm-triggered terrestrial signal may have global significance.

[4] In Taiwan, the concentration of river suspended sediments during floods often exceeds the hyperpycnal threshold (>40 g L^{-1}) [*Kao and Milliman*, 2008] that allows fluvial plumes to sink below the halocline, facilitating a direct escape to offshore waters by minimizing normal surface ocean mixing [*Mulder and Syvitski*, 1995; *Mulder et al.*, 2003; *Warrick and Milliman*, 2003]. Hyperpycnal flows are too short-lived (hours to days) to be well studied given the dangerous and difficult task of monitoring such rivers in extreme weather [*Milliman and Kao*, 2005], and the plume behavior in the marine environment during concomitant ocean storm conditions. *Canals et al.* [2006] identified deep ocean export of carbon and nutrients by dense water shelf cascading driven solely by winter cooling. *Johnson et al.* [2001] previously found fresher and warmer water supplied by a small mountain river (Salinas, California) to a depth of <1000 m.

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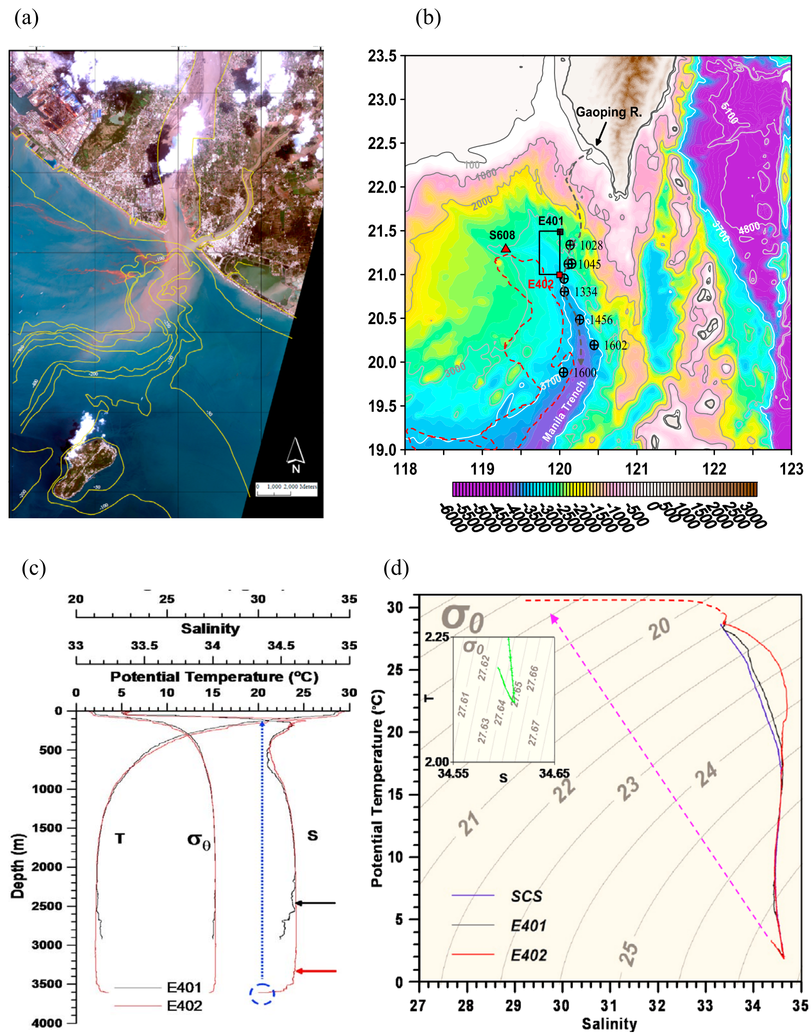

Figure 1. (a) Satellite image acquired on 13 August by FORMOSAT II with bathymetric contours superimposed. (b) Map showing southern Taiwan, the Gaoping River, the Gaoping Canyon (black dotted arrow), Manila Trench and three CTD stations of this study: E401 (black square), E402 (red square) and S608 (red triangle). A rectangular area is assumed for freshwater volume estimates (see text for details). Undersea cables had broken in sequence as marked by time on 12 August. (c) Depth profiles of salinity (S), temperature (T) and density (σ_θ) at stations E401 (black) and E402 (red). Black and red arrows define the upper boundaries of turbidity water mass used for average salinity estimation. (d) The T-S diagram from this study combined with the statistical mean T-S profile of the South China Sea (SCS, purple). Note that the observed T-S profiles merge with the SCS curve when σ_0 is greater than 25.0; however, in the deep sea they are inverted. Inset diagram is an enlarged view of inverted portion of the T-S profile (T = 2.00–2.25°C and S = 34.55–34.65 at ~2900 m water depth) collected at station S608 located around 100 km away from the main axis of Gaoping Canyon.

To date, to our knowledge there are no qualitative and quantitative observations in Oceania regarding the impact of tropical storms on deep sea characteristics. Here we present for the first time a rapid injection of cyclone-induced freshwater into the deep sea basin (3000–3700 m depths) in a subtropical region.

2. Typhoon Morakot and Data Acquisition

[5] Typhoon Morakot, a category 2 tropical storm with a maximum wind speed of 40 m s^{-1}, invaded Taiwan August 7–9, 2009. The 3-day accumulated rainfall during the event exceeded 2000 mm at many river monitoring stations in southwestern Taiwan. The total rainfall even surpassed the previous record of 1736 mm set by Typhoon Herb in 1996. Typhoon Morakot resulted in a number of deadly mudslides in the mountains, leading to 618 deaths, 67 missing and a property loss of roughly $3.3 billion US dollars, which was the most severe natural disaster in Southern Taiwan caused by a typhoon during the last 50 years. *Hong et al.* [2010] attributed such unexpectedly high rainfall to the topographic lifting effect, a typical meteorological feature of the HSI in Oceania.

[6] Satellite imagery reveals that Morakot activated a total rainfall-triggered landslide area of 152 km^2 in Gaoping watershed (3250 km^2, erstwhile Kaoping). After 4 days of the peak river discharge (August 8 midnight) in Gaoping River (Figure 1a), FORMOSAT II satellite with a 10 m pixel resolution captured a clear image of a suspended sediment plume

~10 km along the Gaoping Canyon off southwestern Taiwan (Figure 1a). The downstream freeway bridge was washed away during the flood and the gauging station did not record the peak values of river discharge. To track the transport pathway of typhoon Morakot-sourced turbid water mass in the deep sea, the oceanographic research vessel, *R/V Dongfanghong II*, visited three stations (E401, E402 and S608 (Figure 1b)) on 14th–15th August. We used a conductivity-temperature-depth (CTD) probe and rosette sampling system to profile water properties (Seabird CTD-rosette SBE-911). We retrieved high resolution (0.5-m interval) CTD profiles to water depths approaching 50 m above the sea floor at stations E401 and E402. Figure 1c shows the temperature (T), density (σ_θ) and salinity profiles of stations E401 and E402. In contrast to almost all previous deep sea CTD profiles, our T and S profiles show a distinct T increase with concomitant S decrease at their bottom depths (Figure 1c). The measured suspended solid concentrations at station E401 at 2500 m and 2950 m depths were 28.8 mg L^{-1} and 201.5 mg L^{-1}, respectively, which are large enough to compensate the T-S derived density deficit (0.028 and 0.201 mg cm^{-3}) at these stations to keep the water mass stable.

[7] Since the stations E401 and E402 are located 80 km apart (Figure 1b), the T-S reversals observed between them provide evidence that the unusual bottom-hugging plume may occupy a wide geographical area. The greater salinity decrease appeared at the furthest offshore station E402. This might reflect either the time history of the hyperpycnal plume or that the plume might have moved farther south. At station S608, the CTD rosette were lowered to 151 m above the sea floor (bottom depth: 3071 m) and T-S reversal was still remarkably identifiable at the deepest part of the profile (small panel in Figure 1d). The T-S inversions observed at all three stations help us to constrain the minimum volume of the turbid water mass transported into the deep sea during typhoon Morakot.

3. Hyperpycnal Plume Source

[8] Theory on the development of a hyperpycnal plume [*Mulder and Syvitski*, 1995; *Mulder et al.*, 2003] reveals that the ambient seawater would be entrained into the flow to increase S and reduce T. Accordingly, the T-S feature of plume water should be skewed toward the typical T-S characteristics of the South China Sea (SCS) (Figure 1d) water mass during travel. Interestingly, the T-S features of turbid water mass at stations E401 and E402 are identical and can be differentiated from that of the deep SCS water. The salinity value at the bottom of E402 (blue circle in Figure 1c) is significantly lower than the observed salinity throughout the water column, except shallow depth of <100 m confirming a shallow source for the hyperpycnal flow plunging. The δ^{13}C of total organic carbon on two suspended particle samples give values of −25.2 and −25.7‰, which are identical to those of the suspended sediments collected from Gaoping and nearby rivers during floods (−25.0 ± 0.2‰; n = 3), but significantly different from the δ^{13}C values (−22.9 ± 0.8‰, n = 30) reported for shelf and slope surface sediments off Gaoping [*Kao et al.*, 2006]. This implies that organics on mineral particles are mainly sourced from the watershed with less contribution from entrained seafloor sedimentary organics into the flow, suggesting that Gaoping Canyon may act as a conduit for rapidly channeling freshwater, terrestrial organics and potentially nutrients and pollutants to the deep sea basin.

4. Hyperpycnal Flow Potential

[9] A necessary criterion for self-maintained hyperpycnal flow is that the seafloor slope must be steep enough so that the bottom stress generated by gravity-driven downslope flow can keep sediment in suspension. Following *Wright et al.* [2001], the force balance for sediment gravity flow can be written as

$$\left(gs\int_0^h cdz\right)\sin\theta = C_D u_g^2, \quad (1)$$

where u_g is the downslope velocity of the hyperpycnal flow, g is the gravitational acceleration, s is the submerged weight of sediment, c is the volumetric sediment concentration in the hyperpycnal layer, h is the layer thickness, and C_D is the drag coefficient (range: 3–6 × 10^{-3}) [*van Kessel and Kranenburg*, 1996]. To derive the necessary condition for hyperpycnal flow, the bottom stress is solely attributed to the velocity of hyperpycnal flow itself (u_g), as opposed to ambient wave-current velocities (e.g., wave-supported turbidity current on the Eel river shelf noted by *Traykovski et al.* [2000]). *Wright and Friedrichs* [2006] assumed that the sediment-induced stratification and vertical shear of u_g maintain a critical gradient Richardson number (Ri_c) of 0.25 at the interface between the turbid layer and the clear overlying water. As a consequence, equation (1) can be further simplified to

$$\sin\theta = \frac{C_D}{Ri_c}. \quad (2)$$

Given the above range in the drag coefficient, the offshore bathymetry must have a slope of >0.012–0.4 to support a self-sustained hyperpycnal flow, conditions that are met for hyperpycnal flow along the Gaoping Canyon [*Liu et al.*, 2002].

[11] Serial undersea cable breaks (Figure 1b) were recorded along the Gaoping Canyon on 12th August. Eight damaged sites (6 recorded the timings) along the canyon axis are related to transport emanating from the Gaoping River. Given the inverse density along with highly turbid waters observed after breaking events, we hypothesize that the damage of undersea cable was related to the momentum impact of seafloor erosion by hyperpycnal flows. Though the triggering mechanism differs from previous event in the same area caused by turbidity current associated with submarine landslide induced by earthquake Hengchun (21.9°N, 120.6° E, M = 7.2 on 26 December 2006) [*Hsu et al.*, 2008], the hyperpycnal plume shows a similar moving velocity in the lower canyon (~30 km/hr).

5. Quantification of the Freshwater Volume

[12] As mentioned earlier, when the turbid freshwater encountered coastal seawater, significant seawater entrainment happened as the flow plunged and moved offshore in a form of hypepycnal underflow [e.g., *Mulder et al.*, 1998]. Extrapolation of the T-S diagram (pink dashed arrow in Figure 1d) gives a high source water salinity of around 29 psu. Since the river mouth gauging station in Gaoping had been washed away during the flood, we don't have the critical

parameters such as river flow velocity and sediment concentration data to give better estimation or uncertainty of fluid entrainment at the initial stage in the coastal zone. However, based on modeling work by *Mulder et al.* [1998], entrainment process is most active within a few kilometer of the plunging point where the flow attains a supercritical condition (i.e., entrainment coefficient increases with Froude number, according to *Parker et al.* [1986]). The high temperature and salinity of source water is likely a result of high entrainment rate near the river mouth, in combination with active wind-/wave-induced mixing due to rough sea state during the event.

[13] By the difference in salinity between ambient seawater (S_{ASW}) and the turbid water mass (S_{TWM}), we estimate the freshwater fraction (V_f) in the total volume of the turbid water mass (V) as

$$V_f = V(S_{ASW} - S_{TWM})/S_{ASW},$$
$$V_f = V(34.602 - 34.549)/34.602. \quad (3)$$

The average salinity of the turbid water mass was obtained by averaging salinity values between depths of 2470 and 2922 m (452-m thick) at station E401 and between 3350 and 3610 m (260-m thick) at station E402. We obtained average salinities of 34.545 and 34.557 respectively for the turbidity water columns at station E401 and E402. The thickness-weighted average salinity for these two columns (34.549) is also used as the average salinity for the turbid water mass. This is a conservative estimate since a sharper and larger salinity decrease might exist while approaching the bottom, as observed at offshore station E402. The salinity of ambient seawater of 34.602 was derived from typical South China Sea (SCS) water at depths of 3000 to 3700 m. The resulting freshwater fraction was thus 0.15%. The uncertainty of this value depends on the representativeness of two observed salinity profiles for the plume water. Riskier and more difficult *in-situ* observations and full-scale modeling effort are needed to obtain in-depth understanding about the behavior and magnitude of hyperpycnal plumes.

[14] For mass volume, we assumed a 30-km width (Figure 1b) for the turbid water mass and a minimum thickness of 250 m, which is smaller than the column thickness used for average salinity estimate. Taking into account the 80 km distance between stations E401 and E402, we calculated that the total volume (V = 80 km × 30 km × 250 m) of the turbid water mass was 600 km^3, yielding an estimate for V_f of 0.9 km^3 (freshwater amount), which represents ~10% of total rainfall (2777 mm) precipitated in the Gaoping watershed (3250 km^2) during typhoon Morakot (9.0 km^3). If we take nearby rivers into consideration, the total watershed area will be ~5700 km^2. This conservative estimate still occupies a fraction of ~6% of event rainfall. Such a high proportion of freshwater entrainment into the deep sea via hyperpycnal plume is previously unknown. The sediment particles in this deep water mass would settle out eventually, thus leaving a buoyantly unstable water mass, altering convective mixing in the quiescent deep sea.

[15] It is interesting to point out that the heat carried by the hyperpycnal plume derived mostly from the warm shallow coastal waters (as indicated in Figure 1d) rather than the freshwater itself during plunging. Thus, by extrapolating the mixing line to the freshwater end with salinity of 0, we will obtain an unreasonably high temperature (180°C) for freshwater. This indicates that Hyperpycnal Rivers in the tropics and subtropics may carry extra heat from the surface thermocline to the deep basin.

[16] Based on 3.5-kHz echogram profiles, *Damuth* [1979] reported a 25,000 km^2 field of migrating sediment waves in this study area extending as far as 450 km away to 17°N (area enclosed by red dashed line in Figure 1b). He noted that the sediment wave developed adjacent to the Manila Trench, the major turbidity current pathway and depocenter, suggesting the waves were created by the upper part of the turbidity flows that were thick enough to escape the confines of the trench and thus spread laterally outward (westward) across the left trench wall with gentle slope. This sediment wave is supportive of frequent occurrence of gravity-induced downslope flows to regional extent, though the trigger may be both earthquake and cyclone.

[17] Based on our recent integrated project conducted in Taiwan (FATES: Fate of Terrestrial Substances), downslope transport of warm water with ~2°C anomaly to 600 m was commonly observed during the cyclone invasion period (2–7 days) either due to high turbidity freshwater discharge (unpublished data) or due to strong wave resuspension in shallow coastal zones as reported by *Johnson et al.* [2001]. How deep/far those warm waters may reach is still not known, yet a 2°C anomaly is believed to be adequate to alter the thermocline. Since the frequency of cyclone occurrence is much higher than that of earthquake-induced submarine landslides, we suggest that the large area of sand waves in the northern South China Sea proposed by *Damuth* [1979] was more likely triggered by cyclones.

6. Implication and Conclusion

[18] Our study off southwestern Taiwan shows that storm-induced hyperpycnal plumes can penetrate into the deep sea to depths >3700 m. Given the geographic location and geomorphic river-shelf-slope continuum, we argue that high-standing islands may transport event rainfall, heat and terrestrial material rapidly into the deep West Pacific Ocean. It is difficult to extrapolate the effect of a single event (Morakot) to Oceania, due to insufficient systematic observation. However, *Parsons et al.* [2001] demonstrated that even a low sediment concentration of 5 g L^{-1} can create a hyperpycnal plume. Their results allow us to conceptually generalize our case to Oceania where the small mountain rivers mostly go hyperpycnally during typhoons. In contrast to well-known top-down mixing in surface ocean, the turbid water mass physically intrudes into the bottom and might enhance deepwater ventilation by pushing up the deep water column, thereby facilitating large-scale bottom-up advection. Due to frequent typhoon events in this area, this mixing will certainly have a regional impact although the penetration depth is dependent on sediment concentration driven by rainfall intensity. An increase in the frequency of stronger cyclones in the general context of climate change might thus result in the injection of ever larger volumes of fresh warm water directly into the deep ocean along with heat, inorganic particles and terrestrial organic carbon. Thus, such atmospherically-driven deep sea injection may represent an important but hitherto unexplored process in global ocean dynamics and climate feedbacks. Since the typhoon disturbance on the deep sea characteristics in the Oceania region

was poorly studied, we recommend more observational and theoretical research on this under-observed phenomenon.

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