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Mud budget imbalance in the Taiwan Strait receiving high input of fluvial sediments from mountainous rivers

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Abstract

The Taiwan Strait between Taiwan and China receives abundant sediments (~70 Mt/y) from turbid mountainous rivers draining through Taiwan, where has the highest sediment yield on the global surface. However, the western coast of Taiwan is primarily eroding evidencing the importance of the sediment budget study in the Taiwan Strait. In this study mud (<64 um) and sand (>64 um) concentrations were measured during flashing floods. Observation indicated fluvial materials in Taiwanese rivers are chiefly composed of mud (70% or higher). By contrast, sand fraction dominates (> 85% for most stations) sea surface sediments in the Taiwan Strait, where receives sediments discharged from the largest river, Choshuei, in Taiwan. No significant mud deposited at the Choshuei River mouth 6 months latter the Super Typhoon Herb, during which 130 Mt sediments (supposedly 100 Mt mud) were delivered into this area. Wave, tide and current apparently prevent fine grained sediment deposition. Budget estimate shows the burial output of sand (12 Mt/y) is comparable to the sand input (16-21 Mt/y) from major western Taiwanese rivers. However, the mud burial (6 Mt/y) is far below the mud input (37-49 Mt/y) resulting in a significant shortfall, which suggested >80% of the fluvial mud had gone somewhere out of the strait. Hydrodynamic condition explains the limited mud patch at the central strait and reveals potential pathways of fine-grain sediment transportation in seas surrounding Taiwan.

Keywords: mud, river, sediment, sedimentation rate, Taiwan Strait

1. Introduction

Fine-grained particles are important carrier for organics and particle-reactive elements according to its high mobility and surface to volume ratios (Mayer, 1994; Keil et al., 1994; Hedges and Keil, 1995). Strong positive correlations between heavy metals or organics contents and fine-grained fractions (<64 um) in surface sediments had been reported from the East China Sea (Hung et al., 1999; Lin et al., 2002; Kao et al., 2003) and elsewhere. Seas surrounding Taiwan receive huge amount of sediments from its mountainous rivers due to high uplift rate (5-7 mm/yr; Liu, 1982), vulnerable rocks, steep slopes and natural driving forces such as active earthquakes and frequent typhoon-induced torrential rainfalls (Li, 1976; Milliman and Syvitski, 1992; Dadson et al., 2003). The annual total suspended sediment discharge from 21 primary rivers in Taiwan is ~175 to 380 MT/y (value is method dependent; Dadson et al., 2003; Kao et al., 2005), which is around the same magnitude of the sediment flux from the largest river, Changjiang, in China (500 Mt/y; Milliman et al., 1985). Recent study further suggested that the island-wide high erosion has continued over million years (Dadson et al., 2003). Tremendous suspended sediments inputs over a long time from land might have significant impacts on biogeochemical cycles of carbon (Kao et al., 1996; Lyons et al., 2002) and other elements in the oceans. Yet the most fundamental information, the grain size distribution, flux and the fate of fluvial sediments in seas surrounding Taiwan are not clear.

The Taiwan Strait (TS), bounded by the China continent to the west and the island of Taiwan to the east (Fig. 1a), is a relatively shallow channel (180 km wide, 350 km long and 60 m in average depth) connecting the East and South China Seas. The shallow Taiwan Strait receives sediment inputs from western Taiwan rivers including the largest river, Choshuei River, in Taiwan. Choshuei sediment discharge in recent years has been particularly high (Dadson et al., 2004; Milliman and Kao, 2005) in response to several major typhoons (Herb in 1996 and Toraji and Nari in 2001) together with earthquake Chichi (1999). During the six-year period between 1996 and 2001, it is calculated that the Choshuei discharged about 500 Mt of sediment, equivalent to about 1/3 the volume of the Great Wall. However, the western coast of Taiwan is primarily eroding, it is clear that fluvial sediments do not remain in coastal waters, but rather are transported away from Taiwan. Previous study indicated that sand covered most areas in the strait (Boggs et al., 1979). Thus, the fate and budget of tremendous amount of fluvial sediments, particularly the fine fraction, delivered by Taiwan rivers needs to be examined.

Three topographic features: the Penghu Channel (PHC), Changyun Rise (CYR) and Taiwan Bank (TB) characterize the shallow Taiwan Strait (Fig. 1b). The CYR shallow locates at the middle east of the strait. The TB with depths ranging from 20 to 40 m and relatively deep PHC locate, respectively, at the southwest and southeast opening of the TS. Topographic features, monsoon driven seasonal circulation and tidal current within the strait, coupled with the temporal discharge rate of fluvial sediments and grain size composition in fluvial material are main factors governing the spatial distribution, range of transportation and budget of sediments in the TS.

Sediment discharge rate is highly variable in small rivers that one typhoon event may account for over 75% of total sediment outputs on annual basis (Kao and Liu, 1996; Kao et al., 2005). Unlike large rivers such as the Changjiang and Huanghe, the eroded sediments from small mountainous rivers are quickly washed to the sea by flashing floods (2-3 days) with minor deposition in the estuary (Liu et al., 2000; Hong et al., 2004). Thus, to quantify the flood-related fluxes and size fraction is critical in calculating sediment inputs and understanding the sediment transportation in the Taiwan Strait. Despite the importance of flood events in flux estimation, rare time-series data for sediment concentrations and no grain size distribution data for suspended sediments were documented since typhoon floods often accompany with extreme weather condition preventing operators to conduct field sampling. Our field observations during flood periods offered the first document of grain-size spectrum for flood sediments from mountainous rivers in Taiwan. The field data allows to estimate coarse- and fine-grained sediment delivery and thus to evaluate the budget of the two fractions in the strait sediments.

In the past 30 years, growing studies and investigations on sediment transportation, clay minerals, heavy metals, and sedimentation rate, etc. had been reported. Unfortunately, no data compilation and contour maps have been made for sediments. In this paper we compiled reported grain size and sedimentation rate data in sediments surrounding Taiwan. Basing on the compiled data sets, we map the spatial distribution of mud and further calculate sediment output through burial. Flow field and hydrodynamic modeling reported previously was draw for discussion and linked qualitatively to spatial distribution of surface sediments and their potential transportation pathways in and out of the Taiwan Strait.

2. Materials and Methods

Three types of material are presented in this section: 1) new field observations for fluvial suspended sediments, 2) new grain size data from the river mouth of the Choshuei and, 3) reported data regarding grain size and sedimentation rates in seas surrounding Taiwan. Methodology for sediment burial estimation is illustrated also.

2.1 Field observations

2.1.1 Riverine sediments in flood monitoring

Suspended sediment samples were taken from 10 rivers (Fig. 1b). Nine of them locate at western Taiwan and one locates at the northeastern Taiwan. All river samples reported in this study were collected at watershed outlets during typhoon period, which are representative of the major exports. During the typhoon Tim (July 9-11, 1994), Billis (21-23 Aug., 2000) and Mindulle (1-3 July, 2004) we conducted intensive sediment samplings (3-4 hours interval) through the event hydrograph for the Lanyang (River 10), Danshuei (River 1) and Choshuei (River 7) rivers, respectively. Beside the three flood event monitoring cases, we collect samples from 9 western rivers during flood recession period of the typhoon Doug (6-8 Aug., 1994) and Nari (6-19 Sept., 2001). The turbid water samples were taken to lab waiting for grain size and concentration analyses.

2.1.2 Near-shore sediments off the Choshuei River

Marine sediments were taken from the shallow coastal zones off the Choshuei River mouth (River 6 in Fig.1b ; shoreline to 35 m in Fig. 4). Two cruises were conducted (one is in July 1996 and the other is in March 1997). Total 260 samples (20 offshore transects and 13 samples for each transect) were collected by using dredges on fish boat. Wet samples were taken to lab waiting for grain size analysis. Between the two cruises, the Super-Typhoon Herb (July 31-August 1, 1996) invaded Taiwan resulting in a 130 MT suspended sediment output from the Choshuei River (details can be seen in Milliman and Kao, 2005). This case allows us to examine the grain size distribution pattern of sediments in the coastal zone before and after a significant sediment discharge event.

2.3 Grain size and mass accumulation data compilation

For grain size data compilation, one database and 9 previous studies (area and code shown in Fig. 2a) with available data (collectively 854 data points) were listed in Table 1. Published data cover most of the areas surrounding Taiwan including the Kaoping Canyon at the southwest off Taiwan and the southern Okinawa Trough off northeastern Taiwan (Fig. 2a). Reported data were compiled and combined with the data we collected at the river mouth of the Choshuei for mapping the spatial distribution of mud around Taiwan.

Since most of the areas in the Taiwan Strait are covered by sand, none researches regarding mass accumulation rates (MAR) were done by using ^{210}Pb and ^{137}Cs. Fortunately, the MARs were measured at 19 sites by dating ^{14}C age (Chen and Covey, 1983; Xu et al., 1989, 1990) in shell layers (see Fig. 2b) and determined at 26 sites by using ^{10}Be (Lee at al., 1993). Lee et al. (1993) indicated ^{10}Be method is suitable for areas undergoing rapid deposition and the MARs in the Taiwan Strait derived by ^{10}Be method compared favorably with those from ^{14}C dating. The MARs in modern basin are even comparable to the rates in the paleo-basin at western Taiwan. Thus, all 45 data points are used in contour mapping for MAR distribution. The spatial coverage of sedimentation rate data is sufficient for burial estimation within the strait. However, this compilation must still be treated with some caution due to differences in methodology.

2.3 Estimate the sediment burial out

The sediment burial estimation is bounded to the eastern Taiwan Strait (23300 km^2; box shown in gray solid line in Fig. 2b) since the reported grain size data is only distributed in the east part of the strait, where is mainly influenced by western Taiwan rivers.

Total mass accumulation was separated into two fractions, namely, mud burial and sand burial. To obtain the burial rates, we firstly grid bulk MAR (in $g/cm^2/y$) data at equal pixel space ($1/10^o$) by using the Kriging method in the Surfer (PC software). The grid process generated the contour map and gave us interpolations for unmeasured pixels. Secondly, we grid mud (%) data at the same space interval to make exactly matching grid pixels as those in MAR calculation. The mud burial thus can be obtained by multiplying the MAR by mud fraction in each respective pixel. Summarize the mud burial rates in all pixels within the selected area we derive the total mud burial. Similarly, we can obtain the total sand burial for the boxed area.

3. Results and Discussion

3.1 Concentration and grain size composition of flooding sediment

The three floods were monitored over a wide range of water discharge (Fig. 3). During those periods, sediment concentrations vary over 3 orders of magnitude from <0.1 g/L at low flows to ~200 g/L at high flows. The hydrological response with respect to rainfall is very fast (as three cases shown in this study, Fig. 3). The water discharge rate increases from several cms to 2-3 orders of magnitude high in several hours and flow rate peaks at 2-3 hours after the peak of precipitation. Suspended sediment concentration varies concomitantly with the water discharge rate.

The maximum sediment concentration is ~6, 25 and 200 g/L, respectively, for the Danshuei, Lanyang and Choshuei stations. The relatively lower maximum concentration observed in the Danshuei is consistent to the long-term observations reported by the Water Resources Agency in Taiwan (see Figure 1 in Milliman and Kao, 2005). The lower concentrations are attributed to limited sediment supply since the watershed is well protected and two water reservoirs located at middle to upper reaches may block significant portion of suspended sediments sourced from upstream. By contrast, the moderately high concentrations observed in the Lanyang are caused by intensive agricultural activities at the upstream and on the middle-reach floodplain (Kao and Liu, 2001; Kao, 2002). The extremely high concentration found at the Choshuei River was attributable to its vulnerable basement rocks and augmented by the 1999 Chi-Chi earthquake (Dadson et al., 2004).

In the Choshuei case, mud fractions decreased as the increasing of flow rate and sediment discharge (Fig. 3c). During the peak flow mud fraction dropped down to ~50%, which is the lowest fraction found in all flood observations. Higher concentrations and fractions of sand during high flow reflect the elevated sediment carrying capacity due to the increasing of flow velocity and stream power. The flux-weighted mean fractions of mud over those event periods are 92, 87 and 70 percent, respectively, for the Danshuei, Lanyang and Choshuei rivers. And the sediment transport caused by the single event of Mindulle is 72 Mt, in which mud accounts for 50 Mt.

Suspended sediment concentrations observed at the other nine western rivers during invasions of Typhoon Doug and Nari are listed in Table 2. The sediment concentrations observed during the two typhoons range from 0.5 to 12.9 g/L. Regardless of the large spatial variability in concentrations, observed mud fractions are always higher than 79% and the highest percent is 98%. Apparently, mud dominates the fluvial discharges for all those western rivers. In the following calculation for mud budget, we assume 70% to be the mean fractional contribution of mud to fluvial sediment inputs.

3.2 Mud patches off the Choshuei river mouth before and after a typhoon

Between the two cruises, the Super-Typhoon Herb contributed 130 Mt, which equals to ~10^8 m^3 of sediment. Assuming half is mud ($5*10^7$ m^3) a 10-cm thick mud deposition should be found covering an area of 500 km^2. However, results from the 260 samples collected off the Choshuei River coast exhibited near-shore surface sediments are dominated by sand with most areas having sand fractions > 80% (Fig. 4), not mention the 10-cm mud deposits. This result is consistent to that reported at the coastal zone off the Tsengwen River that sand fraction dominated surface sediments (Liu et al., 2000; Fang and Hong, 1999). Mud patches within a limited area at the north off the river mouth reflecting a northward transport. The maximum mud fraction in surface sediments is around 20%, which is much lower than mud fractions (70%) observed in suspended sediments during the typhoon Mindulle periods. Deficit in mud percentage and sparely patched mud indicates that most of the fluvial sediment sourced from Choshuei was dispersed out of the near-shore region.

Interestingly, no significant differences appear in contour maps between the two cruises. The second cruise was conducted 6 month after the Typhoon Herb. In between the two cruises the northeast monsoon wind prevailed. Therefore, very possibly the fluvial muds might deposit temporally after typhoon events and be re-suspended by waves driven by the prevailing monsoon wind and transported out of the coastal area. On the other hand, the fluvial mud might never deposit and be transported far away instead during the storm period since the high fluvial discharge rate always accompanies with the turbulent marine condition caused by strong wind brought by typhoon.

3.3 Mud distribution pattern surrounding Taiwan

Contour map shows that values higher than 75% in mud fraction mainly located at three regions: central north strait connecting to 26-27 ^{o}N near the coast of mainland China, the southern Okinawa Trough (SOT) and the continental slope southwestern off Taiwan (Fig. 5a). The circulation pattern likely dominated the fine-grained sediment deposition and transportation. Along the coast of mainland China, the mud belt was reported to extend from the Changjiang River mouth to the northern Taiwan Strait (Hu et al., 1998; Zhao and Yan, 1994). The Changjiang sediments were transported southward by the China Coast Current (CCC, Fig. 1a and 1b) during the northeast monsoon in winter (Milliman et al., 1985; Liu et al., 2003). Besides the coastal mud belt, most areas of the East China Sea (mid to outer shelf) are covered by relic sands (Boggs, 1979) with low organic contents (Kao et al., 2003) revealing that fine-grained sediments can hardly deposit on the middle to outer shelf. As for the SOT, it is suggested to be a depocenter receiving sediments from the China coastal mud belt and from Taiwanese rivers (Hung et al., 1999; Kao et al., 2003; Lee et al., 2004). Another mud depocenter patches at the southwest seas off Taiwan, where the narrow shelf and canyon systems allow fast transportation of fluvial fine-grained sediments to deep slope.

Within the Taiwan Strait, mud patches at the central area that agrees with the first report of grain size distribution in surface sediments in the TS by Boggs et al. (1979). Mud distribution pattern is approximately coincident with the bottom topography of the strait that muddy sediments (>75 % of mud) mostly deposit in the deep Guanyin Depression (Fig. 1b), and coarser sediments (<25% of mud) reside over the shallow CYR, deep PHC and in the eastern part of the strait. The distribution pattern is attributable to the variation of tidal dissipation and the seasonal circulations over the complicated topography.

The tidally induced bottom friction, which is the major factor affecting the deposition, is small in the middle-west coast of Taiwan. The situation is favorable for sediments deposing in that region. The major tidal current ellipses (M2 tide) calculated from model results of Jan et al. (2004) show that tidal currents are weak in the middle sections with deep water depth (the Guanyin Depression) and strong over shallow shoals (the Taiwan Banks) and coastal regions adjacent to northwest and southwest of Taiwan island (Tidal ellipses were shown in Fig. 5a). The spatial variations of muddy and sandy sediments essentially match the relative weak and strong tidally induced bottom friction regions, respectively.

However, sources of the mud patched in the Guanyin Depression are not known. It might be sourced from the western Taiwan rivers through flood discharge in summer typhoon season. However, the strong northeast monsoon in winter drives the CCC originating in the Changjiang (Yangtze) river mouth moving southward to emerge into the northern TS. The intruded CCC makes a U-turn (Jan et al., 2002, 2004; Lee and Chao, 2003) due to the topographic blocking of CYR and thus forms a cyclonic cold eddy over the deep Guanyin Depression shown in Fig. 1b. The Changjiang sediments carried by the CCC might temporally deposit at the central TS (Boggs et al., 1979; Chen et al., 1988) and/or move eastward across the shelf at the northern TS (Liu et al., 2003; Kao and Liu, 2003). The wintertime circulation pattern likely suggests that patched sediments in the Guanyin Depression are presumably sourced from the coast zone of China. More studies of mineralogy and chemical composition are needed to validate the sediment source.

Another important feature in the mud contour plot is the mud tongue off the north TS (Fig. 5a). The mud tongue extended from the China coastal mud belt to the SOT area being consistent to the spatial distribution of total organic carbon content and organic carbon isotopic composition in surface sediments reported by Kao et al. (2003) and consistent to the drifter study on surface currents (see below).

3.4 Input-output budget of sediments in the strait

For the area we focused in the strait, the mean of the mass accumulation rate is 76 mg/cm^2/y with most areas <100 mg/cm^2/y. Rates higher than 300 mg/cm^2/y were restricted at the eastern strait (Fig. 5b). A seaward decreasing in MAR with increasing water depth was indicated by Lee et al. (1993). The increasing distance away from the sediment sources from the western rivers explains such a decreasing trend. According to our estimator, we obtain an annual total sediment burial output of 18 Mt/y, which comprises 12 Mt sand and 6 Mt mud in the boxed area.

The input term is obtained by summarizing the mean annual discharge of suspended sediment from western rivers (from River 1 to 7). Based on Kao et al (2005) the annual total sediment load from the seven rivers during 1980-2001 ranges from ~6 Mt/y to 270 Mt/y showing variability by factor of 4. The cumulative sediment flux is 1160 Mt with an average of 53 Mt/y, which is slightly lower than that (71 Mt/y, 15 % bed load is removed; details in Kao and Liu, 2001) reported by the Water Resources Agency in Taiwan. Here we take the two number as upper and lower values for the input term. Basing on our typhoon monitoring data (30% sand and 70% mud), we obtain the sand and mud inputs, respectively, to be 16-21 Mt/y and 37-49 Mt/y.

Compared to the sand burial outputs, the sand input is slightly higher but comparable with the estimated sand output (12 Mt/y). The uncertainty of input and output values can be both from the input and output estimations. However, the mud input (37-49 Mt/y) is much higher than the estimated mud burial output (6 Mt/y). The offset is far beyond the acceptable range. The significant shortfall in the mud burial term suggests that abundant fluvial mud had gone somewhere out of the strait. Additionally, if those muds patched in the central strait is sourced from the China coastal mud belt, there will be ignorable amount of Taiwan mud deposited in the studied area.

3.5 The fate of the missing mud and future studies

Drifter study done by Tseng et al. (2003) shed lights on potential pathways of sediment transportation. In their November observation, water parcel trajectory (Fig. 5a, green curve) leaved the strait moving northward to the China coastal mud belt around 26^{o} (Fig. 5a) and then turned southeastern moving toward the SOT. In their May observation (purple curve in Fig. 5a), the drifter went from the central TS to northeastern TS and then turned clockwise directly passing through the Mian-Hwa Canyon to the southern Okinawa Trough. This drifter observation confirms three-dimensional numerical models simulations in the ECS (Lee and Chao, 2003) and in the Taiwan Strait (Jan et al, 2004).

The numerical model and drifter experiment both demonstrated the possibility of across-shelf path of particle transport (Liu et al., 2003). Their results are also consistent with chemical tracer studies (Hung et al., 1999; Kao et al., 2003) around the region off the northern Taiwan Strait. As the main stream of the Kuroshio encounters the shelf break of the ECS, a cyclonic eddy forms off northeastern Taiwan (Fig. 1a), while the Kuroshio turns northeastward. The cyclonic eddy may suck the sediments offshore to the SOT. Similar cross-shelf transport has also been observed near the depocenter off Cape Hatteras on the east coast of the US (DeMaster et al., 1994), where the circulation pattern known as the

"Hatteras funnel" is responsible for the seaward export of particulate matter (Rhoads & Hecker, 1994). All evidences suggested possibilities that both Taiwan mud and the China coastal mud may have contributions to the sediment burial in the SOT, where has high sedimentation rates ranging 100-1400 mg/cm^2/y (Chung and Chang, 1995; Lee et al., 2004), which are more than ten times higher than those observed in the northern and central trough (<10 to 80 mg/cm2/y; Ikehara, 1995; Iseki et al., 2003).

The subtidal currents in the Taiwan Strait flow northward essentially along the west coast of Taiwan peaking in summer (Jan and Chao, 2003). The northward flow might transport fine grain sediments sourced from rivers in the west coast of Taiwan into the East China Sea, meanwhile, the strong and persistently northward flow through the PHC (Fig. 1b) eliminated the possibility of the southward movement of fine-grained suspended sediments delivered by summer floods.

Is that possible most of the Taiwan muds spread northward onto the huge mid-outer shelf of the East China Sea and deposited homogeneously as a minor portion in relic sediments? Or most of the fine grains were carried out of the strait and dispersed into the Kuroshio Current (as indicated by drifter trajectory) flowing far away not deposited in the East China Sea or in the Okinawa Trough. Since the major portion of suspended sediments from western Taiwan rivers does not deposit on the Taiwan Strait, more investigations are required to unravel the fate, transport and final sinks over a different time and spatial scale. Applications of sediment profiling system such as the high-resolution multi-channel seismic system, side-scan sonar and chirp sonar on regional scale survey are strongly suggested. These high-resolution geophysical tools may help us to understand the large scale sediment distribution, deposition, sediment structure and hopefully to reveal the paths of sediment transportation and burial in seas around Taiwan.

5. Conclusions

Mud and sand concentrations monitored during flashing floods indicated fluvial materials in Taiwanese rivers are chiefly composed of mud (~70%), which is contrast to sea surface sediments in the Taiwan Strait dominated by sand (> 85% for most stations). Pre- and post-typhoon sediment investigation apparently indicated wave, tide and current conditions prevent fine grained sediment deposition. The significant shortfall in mud burial suggested >80% of the fluvial mud, which is good carrier for pollutants, had gone somewhere out of the strait. Hydrodynamic condition reveals that the missing mud sourced from western Taiwan rivers very possibly 1) diffused northward spreading into the large East China Sea Shelf or 2) were sucked by the year-round cyclonic eddy and then deposited on the southern Okinawa Trough or dispersed into the Kuroshio Current been carried away.

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Table 1. Refereed studies with grain size data or plots.

Area code	Data Source	Data available
1	National Center for Ocean Research, Taiwan	74
2	Lin et al. (2000)	15
3	Chen et al. (1988)	25
4	Chen et al. (1997a)	52
5	Chen et al. (1997b)	38
6	This study	260
7	Fang and Hong (1999); Hong et al. (2004)	150
8	Liu et al. (2000)	194
9	Chen, I. C. (1998); Liu et al. (2002)	46
10	Chen and Lin (1997c)	314
Total		854

Table 2

Typhoon River	Doug (1994) TSM (g/L); (Mud %)	Nari (2001)	Typhoon monitoring Event; (Mud %)
1. Danshuei	3.5 (95 %)	2.0 (95 %)	Billis (92 %)
2. Tochian	1.5 (97 %)	1.1 (98 %)	
3. Holung	0.5 (97 %)	0.5 (98 %)	
4. Daan	4.3 (92 %)	5.1 (87 %)	
5. Dajia	4.6 (85 %)	3.1 (79 %)	
6. Wu	3.9 (92 %)	5.8 (94 %)	
7. Choshui	6.5 (81 %)	9.5 (98 %)	Mindulle (70 %)
8. Tsengwen	12.9 (81 %)	3.5 (91 %)	
9. Kaoping	3.6 (92 %)	4.0 (92 %)	
10. Lanyang			Tim (87 %)

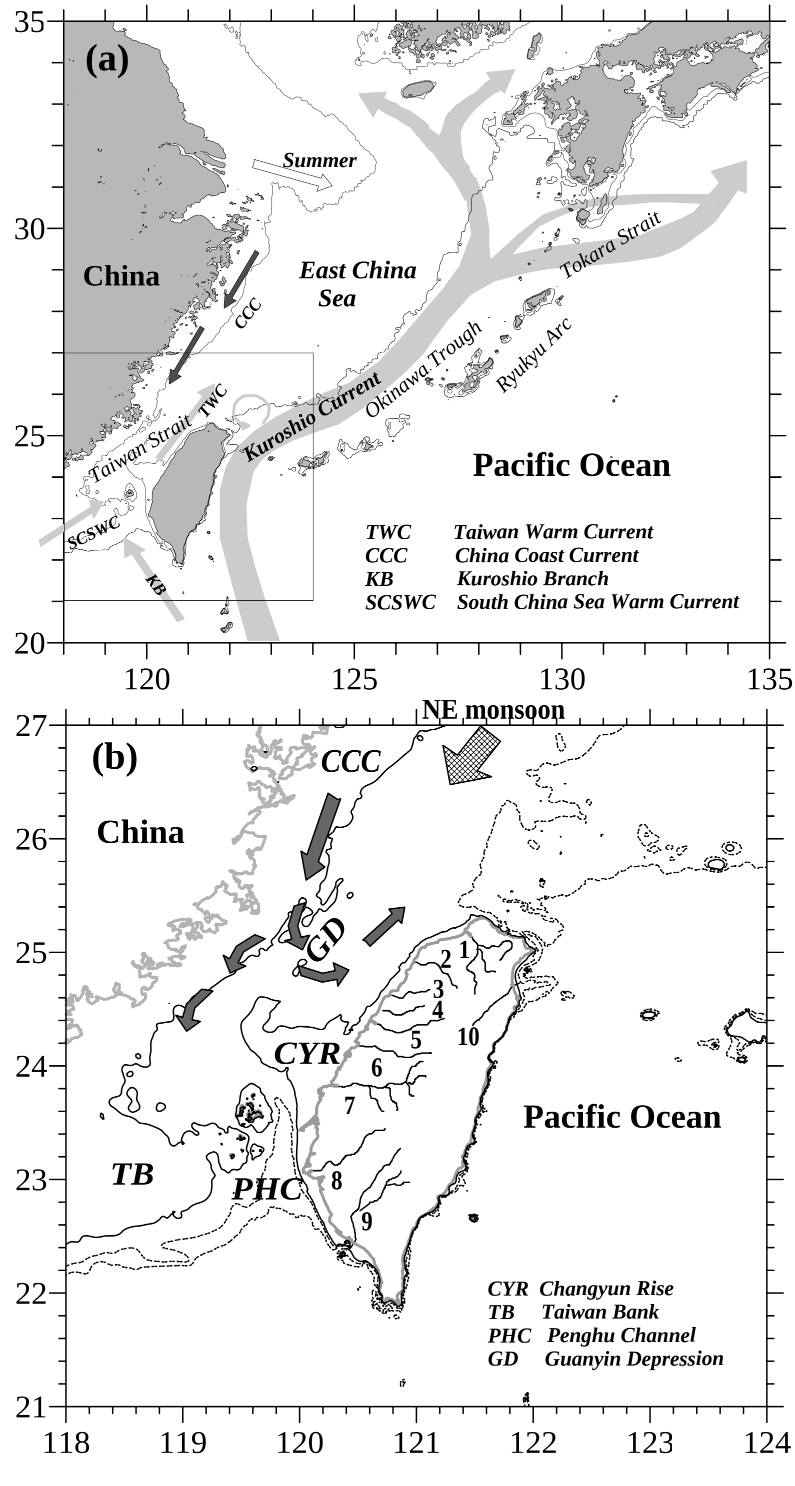

Figure 1. (a) Location map of the Taiwan Strait and oceans surrounding Taiwan. (b) Topographic features in the Taiwan Strait, and locations of 10 primary rivers. Abbreviations for currents (see text) and topographic feature are shown in the lower right corner.

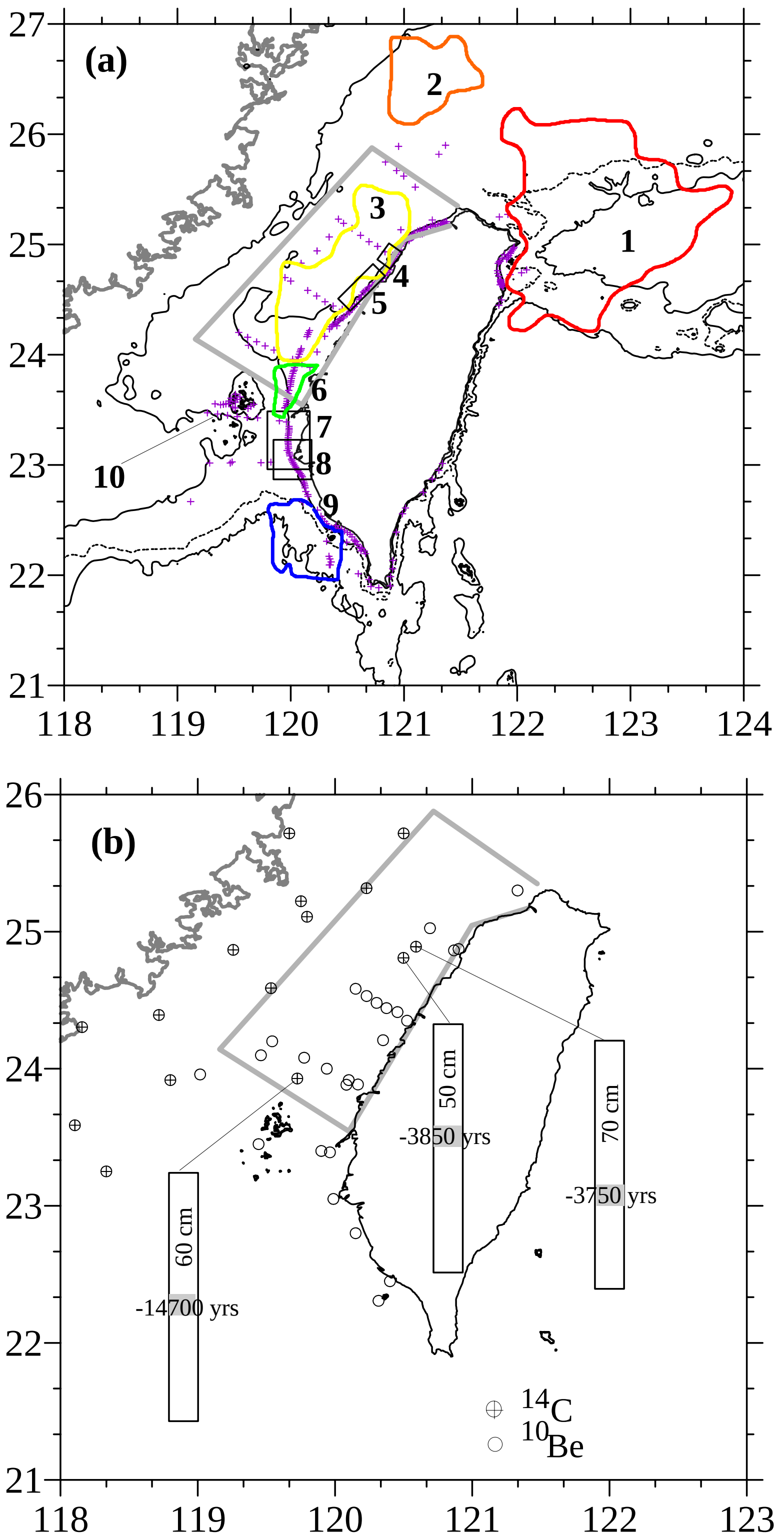

Figure 2. (a) Spatial coverage of studies (labeled with code numbers) with grain size data reported. Purple crosses are data points from Chen and Lin (1997c; Reference 10 in Table 1). (b) Location map for reported mass accumulation rates. Gray box represents the budgeting area in this study.

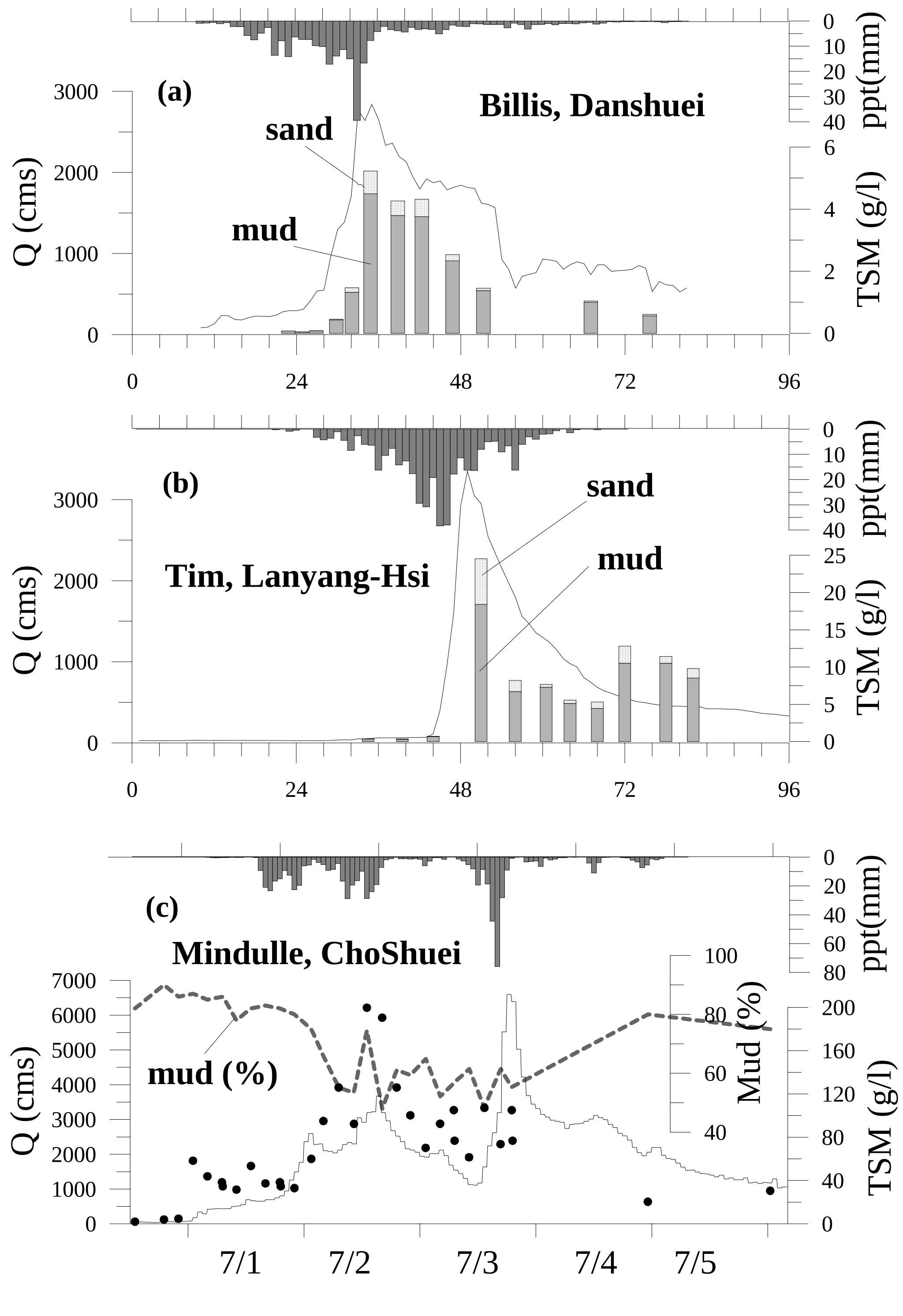

Figure 3. Typhoon monitoring for (a) Danshuei River during Billis typhoon; (b) Lanyang-Hsi River during Tim typhoon, and (c) Choshuei River during Mindulle. Rainfall (inverse black columns), flow rate (curves) and total suspended matters concentration (stacked columns and dots in (c)) are shown in time series. Gray dashed curve in (c) represents mud fraction.

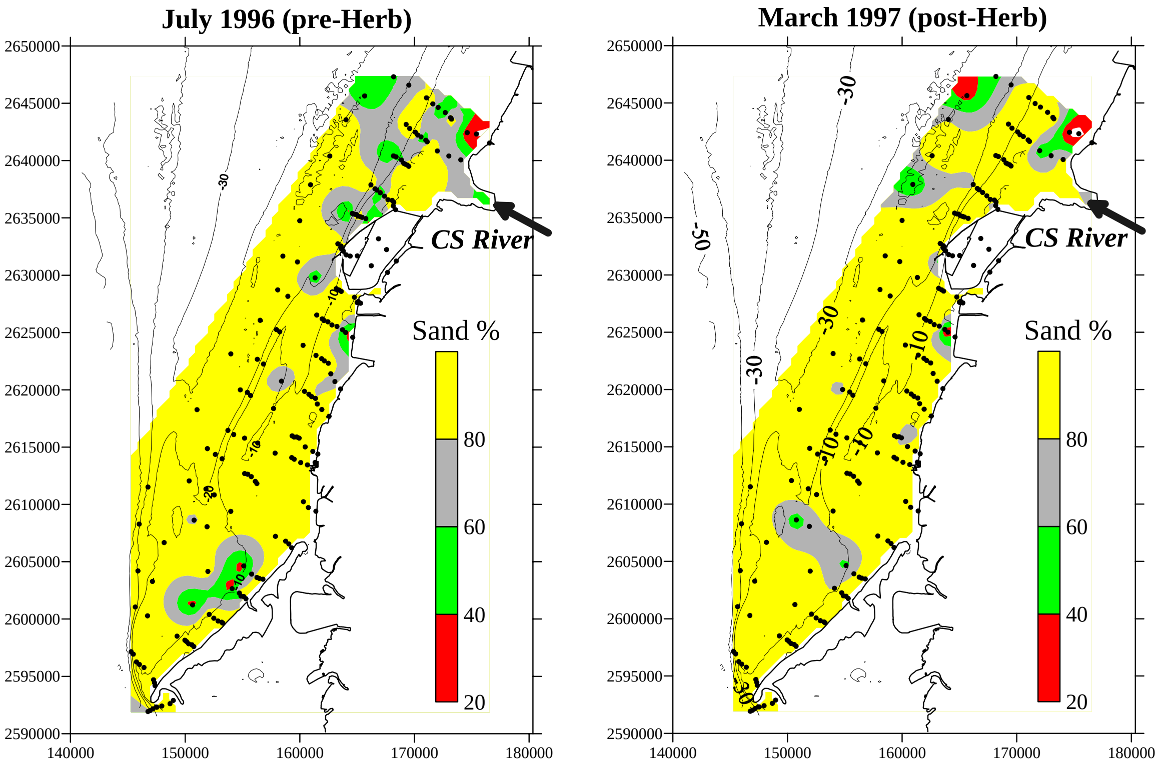

Figure 4. The contour map of sand off the Choshuei (CS) River coast in July 1996 (before Typhoon Herb) and in March 1997 (after Typhoon Herb). Isopleths are shown in curves. Solid dots represent sampling locations.

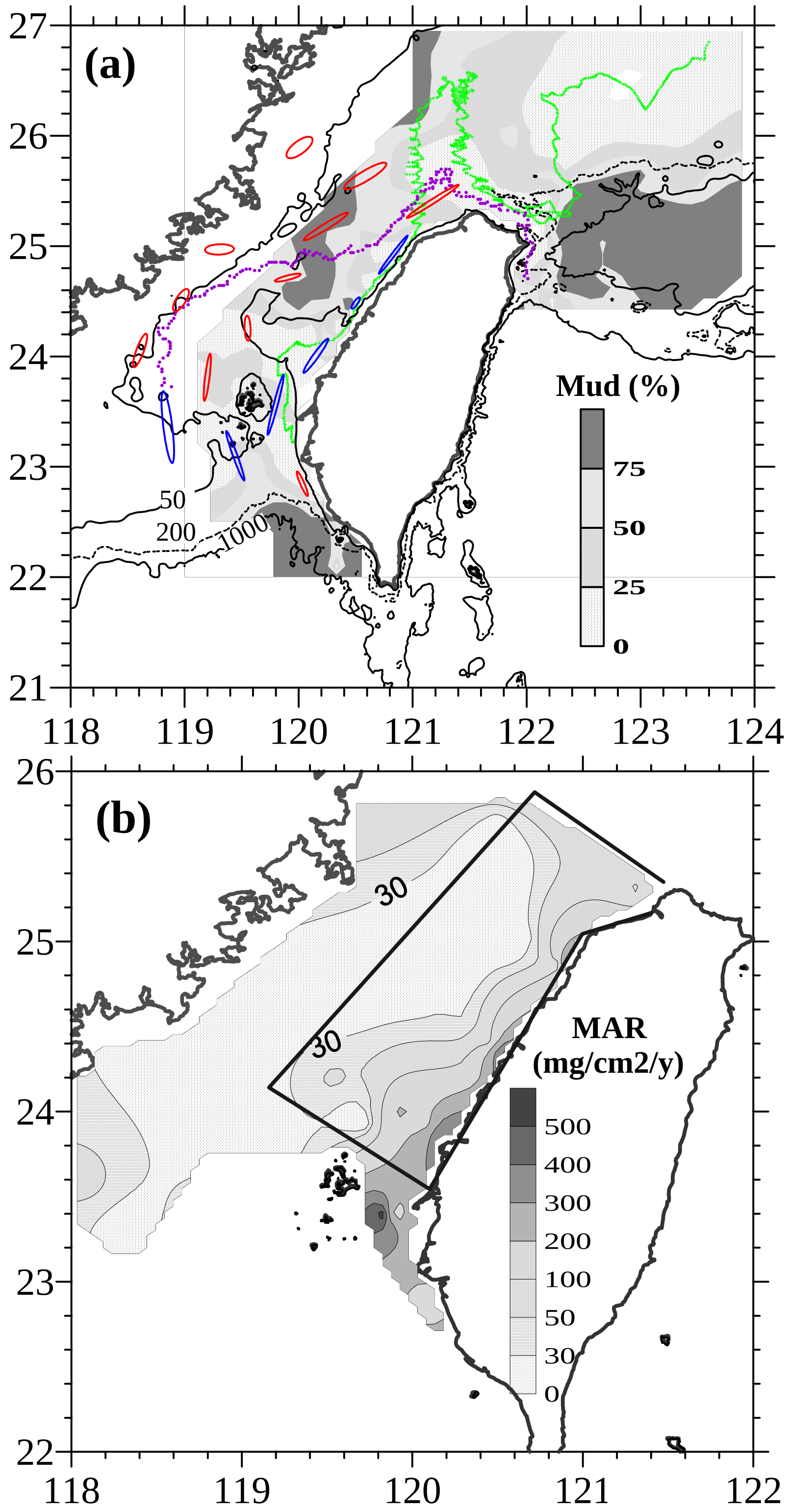

Figure 5. (a) Contour map of mud fraction. Water depths of 50, 200 and 1000 m are in curves. Tidal ellipses (see text) and the drifter trajectories observed in May (in purple) and in Nov. (in green) are overlaid for comparison. (b) Contour map of mass accumulation rate. Budgeting area is marked in black bold line.