1 Geologic Records of Holocene Typhoon Strikes on the Gulf of Thailand Coast.

3 Harry Williams, University of North Texas, HarryF.Williams@unt.edu

4 Montri Choowong, Chulalongkorn University, Thailand.

5 Sumet Phantuwongraj, Chulalongkorn University, Thailand.

6 Peerasit Surakietchai, Chulalongkorn University, Thailand.

7 Thanakrit Thongkhao, Chulalongkorn University, Thailand.

8 Stapana Kongsen, Chulalongkorn University, Thailand.

9 Eric Simon, University of North Texas.

11 Washover sedimentation resulting from modern typhoon strikes on the Gulf of Thailand coast
12 forms anomalous sand layers in low-energy coastal environments including marshes, ponds and
13 swales. The primary diagnostic for recognizing prehistoric typhoon-deposited sand layers in the
14 geologic record are sharp upper and lower contacts between coarser-grained transported sand
15 layers and finer-grained in-situ sediments. In this first paleotempestology study in Thailand,
16 cores from two low-energy settings on the Gulf of Thailand coast – a coastal marsh near Cha-am
17 and beach ridge plain swales near Kui Buri – reveal geologic evidence of up to 19 typhoon
18 strikes within the last 8000 years. The sand layers have sharp upper and lower contacts with
19 enclosing finer sediments. Some sand layers also contain other evidence of a sudden powerful
20 landward-directed surge of ocean water, including gravel-sized clasts, offshore foraminifera,
21 abundant shell fragments, plant debris and mud rip-up clasts. Sand layers record eleven typhoon
22 strikes at Cha-am, ranging in age from AD 1952 to 7575 cal yr BP, and eight typhoon strikes at
23 Kui Buri, ranging in age from 4075 to 7740 cal yr BP. Bayesian age-depth models, derived from

eight AMS radiocarbon dates, suggest that the frequency of typhoon strikes was 2-5 times greater from 3900-7800 cal yr BP compared to 0-3900 cal yr BP. Possible explanations for this variability in the typhoon record are that typhoons were more frequent and/or more intense in Southeast Asia in the mid-Holocene because of climatic changes associated with the Mid-Holocene Warm Period or that the record reflects site sensitivity changes resulting from a mid-Holocene sea-level highstand. The preliminary finding of a possible link between warmer conditions and a greater frequency of intense typhoon strikes could have important societal implications, given possible consequences of ongoing global warming.

Key Words: Tropical cyclone, paleotempestology, washover, storm surge, Gulf of Thailand.

Introduction

The devastating impact of 2013's Typhoon Haiyan in the Philippines highlighted the need for improved understanding of tropical cyclone risk and impacts for vulnerable coastlines throughout Southeast Asia. A major factor in making Haiyan the Philippines' deadliest typhoon, with 6,300 fatalities, was its unusually large storm surge, estimated at 5-7 m near landfall in the Gulf of Leyte (NDRRMC, 2014; Paciente, 2014). There are reports that many local residents may have ignored government warnings and calls for evacuation because they were not aware of the potential danger of a large storm surge, having never experienced a comparable event in their own lifetimes (Mullen, 2013; Paciente, 2014).

Many countries in the region lack long-term records of tropical cyclone strikes which could be used to more reliably estimate landfall recurrence intervals and tropical cyclone risk, and to ascertain if tropical cyclone activity displays centennial to millennium-scale variability, possibly related to climate changes (Elsner and Liu, 2003; Fan and Liu, 2008). This kind of information is valuable because it can be used to better inform public policy, guiding formulation, maintenance and execution of appropriate preparedness plans (Nott, 2007). Linking typhoon activity to climate changes improves prediction of future typhoon activity in response to ongoing global warming. In Thailand, reliable meteorological records of typhoon strikes cover only about the last 70 years – too limited a time span to provide insights into centennial to millennial-scale tropical cyclone variability (Joint Typhoon Warning Center, 2014). In response to these shortcomings in historical data, the new science of paleotempestology (study of ancient storms) has emerged as a way to obtain much longer prehistorical records from chemical, biologic and

geologic proxies of tropical cyclone strikes (Donnelly and Woodruff, 2007; Emery, 1969; Lane et al, 2011; Liu and Fearn, 1993, 2000a, 2000b; Yu et al., 2009).

Paleotempestology studies have focused primarily on identifying and dating washover sand layers in coastal marshes located immediately landward of sandy barriers (Donnelly, 2005; Donnelly and Webb, 2004; Donnelly et al., 2001a, 2001b, 2004; McCloskey and Keller, 2009; Scileppi and Donnelly, 2007; Williams, 2011, 2013). This geologic proxy approach is based on the premise that a tropical cyclone storm surge overtops the barrier and wind-driven waves transport dune, beach, intertidal and sub-tidal sand onto a muddy, organic-rich marsh to form an anomalous sand layer (Williams, 2011). Over time, during which normal marsh aggradation occurs, multiple tropical cyclones are recorded by multiple sand layers separated by muddy, organic-rich marsh sediments (Williams, 2011, 2013). Tropical cyclone storm surge deposits present in the subsurface are typically distinguished by a coarser texture and lower organic content than enclosing marsh sediments, by sharp upper and lower contacts, by marine microfossils and by a wedge-shaped profile that thins and fines landward. Identified storm surge deposits can be readily dated by radiocarbon dating because the buried marsh under the deposit usually contains abundant organic material.

The east coast of Thailand, bordering the Gulf of Thailand, is subject to large damaging typhoon strikes. Most typhoons affecting Thailand originate in the northwestern Pacific Ocean and move in a westerly or northwesterly direction. Many strike the Philippines or China, but some travel west into the South China Sea, making landfall in Vietnam or Thailand. Notable typhoons or tropical storms (powerful cyclonic storms with wind speeds below the threshold for typhoon status) to make landfall on the east coast of Thailand in recent decades include: Tropical Storm Harriet (1962) causing 769 fatalities in southern Thailand; Typhoon Gay (1989), a

Category 3 typhoon at landfall, which caused over 800 fatalities in Thailand; and Tropical Storm Linda (1997) causing 164 fatalities in Thailand (Fig. 1).

There has been relatively little research on storm surge sedimentation in Thailand. Phantu Wongraj et al., (2008), examining shallow coastal sediments near Talat Chaiya, Tha Chana and Laem Talumpuk, describe sand sheets, in otherwise muddy environments, tentatively attributed to Tropical Storm Harriet, Typhoon Gay and Tropical Storm Linda. The sand sheets, found in non-active tidal channels and swales behind beach ridges, vary from four to sixty cm in thickness, generally fine and thin inland and extend up to 90 m from shore. The key distinguishing criteria are sharp top and basal contacts with enclosing muds. Phantu Wongraj et al., (2013) describe washover deposits near Ban Takrop, Laem Talumpuk and Khao Mai Ruak resulting from small-scale, monsoon-driven storm surges occurring along the southern peninsular coast of the Gulf of Thailand in 2007, 2008, 2009, 2010 and 2011. The washover deposits formed washover terraces, perched fans and sheetwash lineations. The deposits vary from fifteen to eighty cm in thickness, extend up to 100 m inland and have sharp basal contacts. Phantu Wongraj et al., (2010) found sand sheets, tentatively attributed to prehistoric typhoons or tropical storms, in paleo-lagoon deposits, 1.2 km inland near Phanang Tak in Chumphon Province (Fig. 1). The sand sheets are typically 2-3 cm thick, but range up to 35 cm in thickness and have sharp contacts with enclosing muds.

This paper reports on a study to identify and date geological evidence of prehistoric typhoon strikes preserved in coastal marshes on the Gulf of Thailand coast. Currently, there are no published long-term records of typhoon strikes on the Gulf of Thailand, even though this coastline is subject to intense tropical cyclone strikes, including 1989's Typhoon Gay (Fig. 1). Typhoon Gay originated in the Gulf of Thailand in November 1989 and intensified rapidly,

resulting in 11-m-high swells and 275 offshore fatalities from capsized vessels. The storm caused high winds and swells along much of the Gulf of Thailand coast. Winds increased to 185 km/hr at landfall, elevating the typhoon to Category 3 status. There was widespread destruction close to landfall in Chumphon Province, where around 450 deaths were directly attributed to the storm. Fatalities totaled more than 800, making Typhoon Gay one of the deadliest tropical cyclones in Thailand's history.

Study Area

Reconnaissance coring, using a gouge corer to probe to ~2 m depth, was conducted at a number of potential sites on the Gulf of Thailand coast. Two sites were selected for this study where gouge coring revealed multiple sand layers at depth with sharp contacts with enclosing predominantly fine-grained sediments: a coastal marsh near Cha-am (site designation HW1) and two beach ridge plain swales near Kui Buri (site designation SRY) (Fig. 1). The coastal marsh occupies about 0.5 km² of undeveloped land 4 km south of the city of Cha-am. The marsh surface is between 2 and 2.5 m above mean sea level (a.m.s.l.), slopes gently seaward and is drained by a branching tidal creek network which flows into the Gulf of Thailand through a breach in a sandy barrier beach. Trees and shrubs line the creek network and low-lying herbaceous plants cover parts of the marsh surface between creek channels. The rest of the marsh surface is unvegetated sand to muddy sand, is slightly lower than vegetated areas and prone to shallow flooding during rain (Fig. 2 a, b, c). The beach ridge plain swales are part of a large beach ridge plain near Kui Buri (Fig. 1). The first swale is about 150 m inland, 50 m wide and is landward of a small beach ridge with a crest about 1.6 m a.m.s.l. The floor of the swale is about

0.6 m a.m.s.l. The second swale is 550 m inland, 40 m wide and has a floor about 0.8 m a.m.s.l. The beach ridge immediately seaward of the swale rises to about 2.4 m a.m.s.l. (Fig. 2 d, e, f). Both swales are floored by fine-grained sediment, were sparsely vegetated when visited and are largely cut off from tidal influence by numerous road beds, which form barriers to tidal inflow. Sediments in the swales seemed relatively undisturbed by human activities, although they are presumably used for growing crops during part of the year. Both swales are also presumably subject to flooding during periods of rain.

A number of studies have documented evidence of a mid-Holocene highstand on the Thai-Malay Peninsula resulting from the Post-Glacial Marine Transgression (Geyh et al., 1979; Hesp et al., 1998; Sinsakul, 1990, 1992; Somboon and Thiramongkol, 1992; Streif, 1979; Tjia, 1996). There is wide agreement amongst these studies of rapid sea level rise in the early Holocene, culminating in a mid-Holocene highstand, followed by a more gradual fall of the sea to its present level. However, more recent studies have emphasized the considerable temporal and spatial variability in both the timing and magnitude of the highstand, driven mainly by hydro-isostasy (Horton et al., 2005; Scheffers et al., 2012). Whereas a maximum highstand of about 5 m has been reported for the Straits of Malacca (Geyh et al., 1979), dating of geologic and biologic sea-level indicators and geophysical modeling suggests the highstand in the study area was probably substantially lower. Choowong (2002) and Choowong et al. (2004), for example, combining new data and a summary of earlier study results, estimated a maximum highstand of about 3.5 m for the Gulf of Thailand (although there are elements of uncertainty and spatial variability in the summarized data). Reinterpretation of two radiocarbon-dated sea-level index points indicate a sea level in the study area of 2 ± 0.7 m a.m.s.l. at 4400-3400 cal yr BP and 1.5 ± 0.7 m a.m.s.l. at 3200-2400 cal yr BP (Horton et al., 2005). These two index points presumably

record the gradual retreat of the sea from its mid-Holocene (ca. 6000 cal yr BP) highstand. Geophysical modeling conducted by Horton et al. (2005) appears to overpredict sea level between ca. 8000-4000 cal yr BP at this site and most other sites around the Thai-Malay Peninsula, suggesting that the highstand in the study area was probably on the order of 2-3 m a.m.s.l. (Fig. 3).

Methods

Topographic profiles

Surveying was conducted by total station, providing spatial coordinates and elevations for all surveyed points. Topographic profiles were referenced to local tide level at the time the surveys were made. Elevations were converted to meters a.m.s.l. using tide tables obtained from tide gauge stations at Hua Hin, about 24 km south of Cha-am, and Ko Lak, about 25 km south of Kui Buri (Thai Royal Navy, 2014). At Cha-am, mean sea level is 1.76 m above the tide datum of mean lowest low water (m.l.l.w.). Mean tidal range is 1.26 m. At Kui Buri, mean sea level is 1.61 m a.m.l.l.w. and mean tidal range is 1.03 m.

Marsh stratigraphy

Spade pits, ~40 cm deep, were used to examine shallow sediments at all sites. Coring was used to reveal and sample the deeper stratigraphy. Vibracores were obtained by driving thin-walled 7.5-cm-diameter aluminum tubes into marshes until coring was stopped by resistance. At Cha-am, a series of eight cores was obtained along a transect approximately perpendicular to the coastline, extending about 800 m inland from the beach (Fig. 2 a, b; cores V1 – V8). At Kui

Buri, three cores were obtained from the swale closest to the coastline, all within ~10 meters of each other - cores 2 and 3 were attempts to penetrate deeper into the swale deposits (Fig. 2 d, e; cores SRY 1, 2, & 3). Another core was obtained from the second swale, farther inland (Fig. 2 d, e; core SRY 4). All cores were checked for compaction by measuring the distance between the top of the core inside the coring tube and the ground surface. Compaction was found to be negligible, presumably because the sediments were not readily compactible, consisting mostly of dense mixtures of mud and clay or mud and sand, with relatively low organic contents. Most cores were in the range of 1-2 m in length. Core tubes were sealed upon extraction and transported to a lab at Chulalongkorn University where the tubes were cut lengthwise and the sediment cores within were split into two halves longitudinally. Cores were logged in the lab, photographed and sampled at selected depths for textural analysis, foraminiferal analysis, and radiocarbon age determinations. Sediment samples were also collected from the beach and shallow offshore (~ 1 m depth at the time of collection) at both study areas, because these locations represent potential sediment sources of washover deposits.

Textural analysis

Sediment samples were collected from selected cores from within, below and above suspected typhoon-deposited sand layers for textural and microfossil analyses to help document contrasts in lithology and microfossil content between the sand layers and the enclosing sediments. All samples were divided into two subsamples for analysis. One subsample was weighed and then oven-dried at 105 °C for the determination of moisture content (% wet weight). The other subsample was weighed and then wet-sieved through a 63- μ m sieve to retain the sand fraction. The sand fraction was air-dried and weighed. The measured moisture content was used to calculate the dry weight of the sieved sample, and the weight of the sand fraction was then used

to calculate sand content (% dry weight).

Particle size analysis was conducted on sand fractions from sand layers of suspected typhoon origin using sieves at 0.25 phi unit intervals from -1 phi (2 mm) to 4 phi (63 μ m). A few samples contained fine-gravel-sized clasts in the 2 mm sieve. The sieve data was analyzed using the GRADISTAT program (Blott and Pye, 2001), which provided particle size parameters using graphical procedures proposed by Folk and Ward (1957).

Microfossil analysis

Sand fractions derived from wet sieving were examined under a dissecting microscope to identify and count foraminifers. If the sand fraction was small (<1 g), the entire sample was examined for foraminifers; if the sand fraction was large (>1 g), a subsample (typically 0.2–0.5 g) was examined and foraminiferal counts were multiplied accordingly to estimate the number of specimens in the entire sample. The total number of foraminifers in the sample was used to calculate the number of foraminifers per gram of dry sediment.

Radiocarbon dating

None of the twelve cores collected for the study contained large amounts of organic material; for example, no peat layers were encountered. Modern roots and rhizomes, penetrating down into the sediment, were found in parts of some cores, but this material was not abundant. Small shell fragments were common in some cores and wood/plant fragments were rare, but present, in some cores. Wood and plant fragments were selected for AMS radiocarbon dating on the assumption that these relatively delicate materials were less likely to survive extensive reworking and would more closely date the age of enclosing sediments than the generally more robust shell fragments.

Samples were obtained from within some suspected typhoon-deposited sand layers and from within enclosing finer-grained sediments. Eight samples were submitted for radiocarbon age determinations – five samples from the coastal marsh at Cha-am and three samples from the swales at Kui Buri. Samples were submitted to the NSF AMS radiocarbon dating lab at the University of Arizona.

Results

Marsh stratigraphy, texture and microfossils

Cha-am coastal marsh: all eight cores from the Cha-am marsh site contained at least one, and up to seven, anomalous sand layers, with sharp upper and lower contacts with enclosing finer-grained, more organic-rich, deposits. The sand layers contain between 58% and 98% sand (> 63 μ m fraction); the intervening deposits range from 1% to 53% sand content. Texturally, the sand layers vary from well sorted to poorly sorted and very fine sand to sandy very fine gravel (Table 1).

In addition to sharp upper and lower contacts, there are other indications of a high-energy storm-surge origin for the sand layers. Five sand layers in core V5 contain gravel-sized clasts (> 2000 μ m). Two of these layers have a textural classification of sandy very fine gravel (Table 1). A coarse sand layer in core V5 at a depth of 1.1 m contains abundant large plant fragments; another sand layer in the same core at a depth of 1.58 m contains a large wood fragment at the top of the layer. The presence of organic detritus within or on top of sand layers suggests the sand and organic debris were both transported by the same mechanism, presumably a large storm surge. Sand layers in cores V3 and V5 contain large mud rip-up clasts (~1-2 cm), apparently

derived from erosion of underlying deposits (Figs.4, 5).

A sample from the beach at the Cha-am site contained 100% sand and was classified as moderately sorted medium sand. A sample from offshore (~1 m water depth at the time of collection) contained 98% sand and was classified as moderately sorted fine sand. Neither sample contained gravel-sized clasts. Shell fragments were common in both samples. Texturally, the samples from the beach and shallow offshore are similar to many of the sand layers found at this site, with the exception of the five sand layers containing gravel-sized clasts in core V5. The source of this gravel is uncertain, but it may be that the beach and shallow offshore zones contained coarser sediment in the past, which is reflected in these washover sand layers. Another possibility is that storm surges eroded gravel-sized clasts from older coarser-textured sediments underlying the marsh deposits, perhaps exposed in the floors of tidal channels.

With the exception of the sample from the shallow offshore zone, all samples at the Cha-am site were barren of foraminifera (Table 1). The modern marsh surface is frequently flooded by freshwater from rain runoff; if similar conditions prevailed at times in the past, this could explain the lack of foraminifera in some of the marsh deposits (i.e. they are primarily freshwater deposits). It is not uncommon for beaches, particularly if coarse-grained, to lack foraminifera. The shallow offshore sample contained 22 specimens of foraminifera per gram of sediment, all common calcareous marine species. This is a low concentration of foraminiferal tests. If conditions were similar in the past and the sand layers in the marsh consist of beach and shallow offshore sediments transported inland by a storm surge, this could explain the lack of foraminifera in these deposits. It is also possible that foraminiferal tests were initially present, but not preserved in the marsh deposits because of dissolution of calcareous tests, bacterial degradation of agglutinated tests, or metazoan ingestion (Williams, 2010).

Kui Buri swale sites: the four cores from the Kui Buri swale sites all contained anomalous sand layers with sharp upper and lower contacts with enclosing finer-grained swale deposits. The number of sand layers varied from two (in core SRY 2) to eight (in core SRY 3). All sand layers were found in the deeper parts of the cores, between 0.79 and 2.06 m depth; there were no sand layers in the fairly uniform fine-grained swale deposits above this interval. The sand layers contain between 63% and 98% sand; the intervening swale deposits range from 2% to 68% sand content. Texturally, the sand layers at Kui Buri are more uniform than those found at Cha-am; all layers fall into the classifications of well sorted or very well sorted fine sand (Table 2).

Other indications of a high energy storm surge origin include abundant fine shell fragments in a sand layer in core SRY 1 and sand layers containing multiple mud rip-up clasts in cores SRY 1 and SRY 3 (Fig. 4). A sample from the beach at the Kui Buri site contained 99% sand and was classified as very well sorted very fine sand. A sample from offshore (~1 m water depth at the time of collection) contained 96% sand and was also classified as very well sorted very fine sand. Texturally, the samples from the beach and shallow offshore are similar to all the sand layers found at this site. Assuming the beach and shallow offshore zones had similar sediment characteristics in the past when the sand layers were deposited, the beach and/or offshore zone may have been the source of these sand layers; the slight increase in mean grain size in the sand layers compared to the beach and offshore zone, could have resulted from sorting of the sand during transport and deposition. In contrast to the Cha-am site, none of the sediment samples from the Kui Buri site contained gravel-sized clasts.

All sediment samples from the Kui Buri site contained foraminifera (Table 2). Concentrations range from very low (2 specimens per gram) to abundant (1034 specimens per gram). Generally, the sand layers have higher foraminiferal concentrations, but there are exceptions – the sand

layer at a depth of 1.28 m in core SRY 4 contained only 16 specimens per gram, while the swale deposit at a depth of 1.11 m in the same core contained 400 specimens per gram (Table 2).

The ubiquitous presence of foraminifera throughout the swale deposits indicates a constant marine influence on the swales as they filled with sediment, at least in the lower part of the swale deposits covered by sampling. Foraminifera found in the samples are entirely common marine calcareous forms. No agglutinated marsh forms were encountered. *Ammonia* spp., *Elphidium* spp. and *Quinqueloculina* spp. are prominent in the foraminiferal assemblages. These taxa are all common in intertidal and shallow offshore zones in the Gulf of Thailand (Melis and Violanti, 2006). *Ammonia* spp. and *Elphidium* spp. are known to be tolerant of harsh environments, for example, they can thrive in brackish water conditions caused by significant freshwater inputs. *Ammonia* spp., *Elphidium* spp. and *Quinqueloculina* spp. are also dominant in the offshore sample from the Cha-am site, but in much lower numbers.

Stratigraphy at the Cha-am marsh site was based on the assumption that the sand layers represent washover sediments transported by a storm surge and deposited into the study area. Correlation of sand layers between cores was based primarily on depth and the assumption that relief of former surfaces was similar in the past to that of the present day (~0.3-0.4 m; Fig. 2). Other criteria used in correlation were textural character of the sand layers and the presence of mud rip-up clasts. Resulting correlations suggest there are eleven washover sand layers recorded in the Cha-am marsh (Fig. 6). Layer 1, at the surface of the marsh, is found in cores V1, V2, V3, V4 and V8, and is presumably of recent origin (Fig. 5). The occurrence of this sand layer in five out of eight cores indicates that washover deposits may not be continuous over the entire marsh surface. Williams (2013) found a similar “patchy” distribution of washover sand deposited by Hurricane Rita in a Louisiana coastal marsh. Layer 2 is found in cores V1, V2, V3 and V4, at

depths ranging from 0.24 to 0.56 m. Layer 3 is found only in cores V2 and V3, at depths of 0.39 to 0.51 m. Layer 4, which appears stratigraphically below layer 3, is found only in cores V6 and V7, at depths from 0.7 to 0.8 m. Layer 5 is found in cores V4, V5, V6 and V7, at depths ranging from 0.83 to 1.05 m. This layer is relatively thick, ranging from 5-15 cm, which contributed to its correlation. The remaining six layers were found only in core V5, the longest core at 1.83 m. Layers 6 through 11 are found in core V5 at depths ranging from 1.17 to 1.68 m.

Stratigraphy at the Kui Buri swales site was based primarily on stratigraphic position; the first sand layer encountered in each core was correlated and assumed to represent a washover deposit which formed a sand layer on the floor of both swales. Other sand layers at increasing depths within the cores were similarly correlated (Fig. 6). The resulting correlations indicate that eight washover sand layers are recorded in the four cores taken at this site. Layers 1 through 5 are found in core SRY 1, layers 1 and 2 are present in core SRY 2, all eight layers are recorded in core SRY 3, and layers 1 through 4 are found in core SRY 4. No sand layers were found in the upper parts of the four cores, from the surface to depths ranging from 0.8 m to 1.21 m (Fig. 6).

Radiocarbon Dating

The results of AMS radiocarbon dating are shown in Table 3. Ages indicated on Fig. 6 are mean values of 2-sigma calibrated age ranges. The two radiocarbon ages from core SRY 4 at Kui Buri are clearly inverted (an older date above a younger date in the same core). This has presumably resulted from reworking and re-deposition of older organic detritus (resulting in the shallower older date) or from contamination by a root penetrating down through the sediment column from a higher level within the core (resulting in the deeper younger date). Radiocarbon dates were calibrated to calendar years using the CALIB 7.0.2 calibration program and the Reimer et al.

(2013) dataset intcal13.

Discussion

The main diagnostic criterion for proposing a high-energy storm-surge origin for the sand layers found at Cha-am and Kui Buri are the sharp upper and lower contacts with enclosing finer-grained deposits. The sharp contacts imply abrupt transport of much coarser-grained sediment into these sites, followed by an equally abrupt return to finer-grained sedimentation. It is unlikely that any other mechanism could have deposited the sand layers. A fluvial flood origin can be ruled out for sand layers at the Cha-am site because there are no significant fluvial sources in this area. The swale sites at Kui Buri are close to the Kui Buri River and there may well have been an open connection between the river and swales in the past, but the presence of large concentrations of marine foraminifera in the sand layers at this site argues against a fluvial origin for the sand. Slope wash or mass wasting processes from slopes surrounding the swale sites can also be ruled out because of the presence of foraminifera in the sand layers. The Cha-am site is surrounded by essentially flat terrain, making a mass wasting origin for the sand layers at this site unlikely. The migration of tidal channels at the Cha-am site could create a sharp erosional contact with underlying marsh deposits, but the transition back to marsh deposits as the channel migrated away would presumably record a more gradual return to finer-grained sedimentation, rather than the abrupt sharp upper contact recorded in all of the sand layers.

Other evidence that supports a high-energy storm-surge origin includes the presence of gravel clasts and organic debris in sand layers at the Cha-am site and the inclusion of mud rip-up clasts in several sand layers at both sites, implying erosion of the local surface coincident with emplacement of the sand layers. The AMS radiocarbon dates suggest a recurrence interval for

the emplacement of the sand layers on the order of centuries; this rarity of the events that deposited the sand layers also argues in favor of an infrequent, high-energy storm-surge origin. Typhoons are the rarest form of tropical cyclone to strike Thailand; for example, in the 60-year period 1951-2010, out of 185 tropical cyclones to make landfall, 171 were tropical depressions, 13 were tropical storms and only one was a typhoon (Thai Meteorological Department, 2015). A tsunami origin for the sand layers is unlikely. There is no historical evidence for tsunami overwash on the east coast of Thailand (in contrast to the west coast, where large, destructive tsunamis do occur). Modeling of tsunamis generated at the Manila Trench, approximately 2,500 km to the east, indicates a maximum wave amplitude at the coast of the Gulf of Thailand of about 0.65 m, in response to a Mw 9.0 earthquake. Attenuation of tsunami waves in the Gulf of Thailand is caused by diffraction of waves around the coast of Vietnam (Ruangrassamee and Saelem, 2009; NGI and NORSAR, 2009).

On the assumption that all 19 sand layers record typhoon strikes, age-depth models can be used to estimate the ages of typhoon strikes for each study area. The R software package BACON (Bayesian accumulation histories; Blaauw and Christen, 2011) was used to create an age-depth model for each site, using uncalibrated AMS radiocarbon dates and an age of -2 cal yr BP for the surface at Cha-am (AD1952 - landfall of Typhoon Vae – see discussion below) and an age of -63 cal yr BP for the surface at Kui Buri (AD2013 – the year the cores were collected) (Fig. 7). BACON utilizes Bayesian techniques for calibration and age modeling simultaneously. Prior information, such as stratigraphic order, is incorporated into the calibration approach ensuring that age models are consistent with sample order and that modeled ages increase with increasing depth. This approach has been shown to produce reliable age-depth models, with effective handling of outliers and with more realistic estimates of age model uncertainties (Shanahan, et

al., 2012).

Because the typhoon-deposited sand layers represent “instantaneous events”, thicknesses of these deposits were excluded from core depths for the purposes of age estimation. The depth of sand layers used to estimate ages was the average depth to the basal contact of each layer. These depths were used to obtain 95% probability age ranges and mean age for each typhoon strike from the age-depth models. The resulting estimated ages of typhoon strikes have large uncertainties because of the low number of radiocarbon dates used to construct the age models (Table 4).

The age and origin of sand layer 1 at Cha-am is uncertain, but its position on the surface of the marsh suggests it is a recent washover deposit. The oldest air photo available of the study area, from 1967, shows a bright, largely unvegetated marsh surface with what appear to be lobes of sand extending out from the marsh margins (Fig. 8). These features are consistent with a recent washover deposit and suggest deposition occurred sometime prior to 1967. A likely candidate for the storm that formed this washover deposit is Typhoon Vae, which crossed the northern Gulf of Thailand in 1952 (Fig. 1). Typhoon Vae made landfall in Vietnam with typhoon-strength winds, but then, crossing land, it degraded to tropical storm status as it entered the northern Gulf of Thailand. Nevertheless, the storm caused extensive damage in Thailand due to strong winds, a storm surge of 1.2 m and waves up to 2.5 m high (Vongvisessomjai, 2007). The combination of storm surge and waves would have been sufficient to overtop the marsh, particularly if the storm occurred during high tide conditions in the study area.

The age model results raise the possibility that many sand beds at the two sites may be coeval, presumably recording washover at both sites caused by the same typhoon strikes. All eight typhoon deposits at Kui Buri overlap in age with one or more of sand beds 4-11 at Cha-am

(Table 4). Williams (2012) found that Hurricane Ike deposited relatively thick sand layers into marshes along about 150 km of the Gulf of Mexico coastline and so the possibility that on up to eight occasions the same typhoon formed washover deposits at Cha-am and Kui Buri, which are about 80 km apart, is plausible. However, given the large uncertainties in age ranges, the number of coeval deposits, if any, cannot be precisely determined.

Despite the large uncertainties in ages, the frequency of typhoon strikes over the ca. 8000 year period covered by coring is clearly uneven: three or four typhoon strikes are recorded in the period 0-3900 cal yr BP (depending on whether sand layer 4 at Cha-am was deposited before or after 3900 cal yr BP), whereas as many as 16 typhoon strikes or as few as 8 typhoon strikes are recorded in the period 3900-7800 cal yr BP (depending on whether none, some or all of the typhoon strikes prior to 3900 cal yr BP are coeval between the two sites). At a minimum, there were twice as many typhoon strikes prior to 3900 cal yr BP compared to after 3900 cal yr BP (8 typhoons before 3900 cal yr BP, 4 typhoons after 3900 cal yr BP); at a maximum, there were approximately five times as many typhoons before 3900 cal yr BP, compared to after 3900 cal yr BP (three typhoons from 0 to 3900 cal yr BP; 16 typhoons from 3900 to 7800 cal yr BP) (Table 4, Fig. 9).

A possible reason for this uneven frequency of typhoon strikes is heightened site sensitivity in the mid-Holocene, increasing the chances of a nearby typhoon strike being recorded by a washover sand layer. Another possibility is that a change in climatic conditions in the mid Holocene increased the frequency and/or intensity of typhoons making landfall in the Gulf of Thailand. Higher intensity typhoons are more likely to cause overwash of coastal barriers and form a relatively thick, laterally extensive and preservable washover deposit.

Many factors influence the formation, magnitude and preservation of washover deposits at a

given site, including proximity to landfall, position relative to cyclonic wind field, storm surge height, wave height, wind speed, barrier height, thickness and lithology of washover sediments and post-storm sedimentation and bioturbation (Williams, 2011, 2012; Williams and Flanagan, 2009). The mid-Holocene sea-level highstand in the Gulf of Thailand presumably increased sensitivity to typhoon strikes at both sites because their relative elevations were lower, increasing the likelihood of storm surge overwash. Geomorphology at the two sites during the mid-Holocene is uncertain, but it is probable that both sites were below sea-level at the peak of the highstand around 6000 cal yr BP and became elevated above sea-level in the last three to four thousand years (Fig. 3, 6).

It is possible that both sites were lagoons at the peak of the highstand and the deeper parts of cores at both sites contain fine-grained lagoonal sediments; this is consistent with the sediment record at both sites – predominantly low-energy, fine-grained sedimentation, generally low organic content, but close enough to shore to receive wood and plant fragments from land nearby, punctuated by rare high-energy inputs of sand presumably transported from sandy barriers and/or offshore deposits by typhoon storm surges. The foraminiferal record at Kui Buri is consistent with this interpretation because it shows persistent marine influence throughout the sampled part of the cores, from ca. 4075 to 7740 cal yr BP (Table 2). The reason for the lack of foraminifers at Cha-am is uncertain: it may be that the site had strong freshwater inputs or foraminiferal tests were poorly preserved. As sea-level fell from its highstand, both sites must have transitioned from sub-tidal to supra-tidal conditions; however, there are no apparent lithologic changes within the cores to mark this transition.

Falling sea-level in the late-Holocene presumably decreased sensitivity to typhoon strikes at both sites. The 2-3 m drop in sea-level increased relative elevation of the sites and increased their

distance from the coastline. Other factors, such as depositional progradation of the coastline, vertical growth of barrier crests and closure of tidal inlets, may also have contributed to lower sensitivity at these sites. However, it seems unlikely that decreased sensitivity alone explains the reduction in the number of typhoon-deposited sand layers post-3900 cal yr BP. Despite falling sea-level, both sites remain at a relatively low elevation (below ~2 m a.m.s.l.) and are within a few hundred meters of the coastline. At Cha-am, Typhoon Vae, which was only tropical storm strength at landfall, was presumably able to transport sand over 800 m into the marsh. A higher-intensity storm, such as Typhoon Gay, which reportedly had 11-m-high swells and 185 km/hr winds at landfall, would very likely be capable of transporting sediment into both sites and forming preserved geologic records.

Over the last few decades tropical cyclone climatology research has focused on linking evidence of millennial-scale tropical cyclone variability to climatic changes within the Holocene. The underlying premise of these studies is that changing climatic conditions, such as sea surface temperatures or the position of high and low pressure centers, can change the location and frequency of tropical cyclogenesis, increase the intensity of tropical cyclones, or affect atmospheric steering mechanisms, preferentially guiding more tropical cyclones into a particular region (Bove et al., 1998; Donnelly, 2005; Donnelly and Woodruff, 2007; Elsner and Liu, 2003; Elsner et al., 2004, 2008; Emanuel, 2005; Emanuel and Nolan, 2004; Emanuel et al., 2004; Fan and Liu, 2008; Frappier et al., 2007; Liu, 2004; Knutson et al., 2010; Liu and Fearn, 2000; McCloskey, et al., 2013; Nott, 2003; Nott and Hayne, 2001; Nott et al., 2007; Pielke et al., 2005; Toomey et al., 2013; Trenberth, 2005; Webster et al., 2005; Walsh, 2004; Woodruff et al., 2009, 2015; Wu and Wang, 2004).

In the western North Pacific, increased Northern Hemisphere solar forcing in the early- to mid-Holocene resulted in the Mid Holocene Warm Period, characterized by warmer and wetter conditions (Braconnot et al., 2007; Kerwin et al., 1999; Wanner et al., 2008, 2014). ENSO activity was reduced during this period, creating La Nina-like conditions. Increased Northern Hemisphere summer insolation also created higher summer temperatures and a stronger summer monsoon. These climatic changes may have resulted in more frequent and/or more intense tropical cyclones in Southeast Asia, including the Gulf of Thailand – a similar mechanism (depressed ENSO activity and a stronger West Africa monsoon) has been invoked to explain a 5000-year record of intense hurricane variability from Puerto Rico (Donnelly and Woodruff, 2007).

Paleotempestological studies conducted in Japan and southern China have provided insights into possible linkages between climate change and basin-wide patterns of tropical cyclone variability. Woodruff, et al., (2009) used sediment coarseness and strontium (Sr) content in lagoonal sediments at Kamikoshiki, Japan, to identify periods of increased tropical cyclone activity over the last 6400 years. Their results suggest a correlation between periods of increased El Nino (ENSO) occurrence and periods of more typhoon-induced deposition (Figure 10 a, b). Although in the western North Atlantic there is a general suppression of cyclogenesis during ENSO years (Bove et al., 1998; Gray, 1984; Fig. 10 c), the frequency of tropical cyclones is less affected by ENSO variability in the western North Pacific. There is, however, an eastward shift in tropical cyclone genesis location during enhanced ENSO periods. As a result, tropical cyclones are more likely to follow northward recurving trajectories, leading to greater likelihood of tropical cyclone strikes on Japan (Elsner and Liu, 2003). A ca. 1000-year record of typhoon landfalls from southern China, shows increased typhoon activity during reduced ENSO activity

over the last ca. 400 years, reflecting a westward shift in tropical cyclone genesis location and more southerly storm trajectories (Liu, et al., 2001). Historical observations also support an ENSO-driven seesaw pattern in typhoon activity in the western North Pacific (Chan, 1985).

Preliminary study results from Thailand appear to support this model of an oscillating pattern in tropical cyclone activity between the northern and southern western North Pacific (Fig. 10 d). Between two and five times as many typhoons are recorded on the Gulf of Thailand coast in the mid-Holocene compared to the late-Holocene; this higher-activity period corresponds to an apparently long period of generally suppressed ENSO activity in the mid-Holocene (to at least 6400 cal yr BP – the end of the ENSO record of Moy et al., 2002). A maximum of three out of 11-19 typhoons recorded in Thailand occurred during periods of enhanced ENSO activity ca. 2500-3600 cal yr BP and ca. 300-1000 cal yr BP (the vertical shaded bars in Fig. 10). This is an intriguing finding and supports the need for additional work on the typhoon record from Thailand to improve record chronology and better control for site sensitivity effects.

Conclusions

Anomalous sand layers in low-energy, fine-grained coastal environments form a record of Holocene typhoon strikes on a section of the Gulf of Thailand coast. The record has pronounced variability; typhoons are two to five times more frequently recorded in the mid-Holocene, compared to the late-Holocene. Although this variability may in part reflect greater site sensitivity resulting from the mid-Holocene sea-level highstand on the Thai-Malay Peninsula, it is unlikely that site sensitivity changes alone explain this record. It is also possible that the record reflects climatic changes associated with the Mid-Holocene Warm Period that favored the development of more frequent and/or intense typhoons in Southeast Asia. The apparent

millennial-scale variability in typhoon activity from Thailand supports an emerging model of an ENSO-driven oscillation in tropical cyclone activity between the northern and southern western North Pacific. This preliminary finding of a link between climatic controls and typhoon activity in Southeast Asia warrants further investigation. Long-term typhoon records should be obtained from other sites to confirm a mid-Holocene tropical cyclone hyper-active period within the region. If confirmed, this finding could have important implications for future typhoon activity in Southeast Asia, given projected consequences of ongoing global warming.

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References

- Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age depth models using an autoregressive gamma process. *Bayesian Analysis* 6, 457-474.
- Blott, S.J., Pye, K., 2001. Technical communication Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26, 1237–1248.
- Bove, M.C., Elsner, J.B., Landsea, C.W., Niu, X.F., O'Brien, J.J., 1998. Effect of El Nino on US landfalling hurricanes, revisited. *Bulletin of the American Meteorological Society* 79, 2477–

552 2482.

553 Choowong, M., 2002. The geomorphology and assessment of indicators of sea-level changes to
554 study coastal evolution from the Gulf of Thailand. Proceedings of International Symposium on
555 “Geology of Thailand”, Department of Mineral Resources, Thailand, August, 2002, 207-220.

556 Choowong, M., Ugai, H., Charoentitirat, T., Charusiri, P., Daorerk, V., Songmuang, R.,
557 Ladachart, R., 2004. Holocene Biostratigraphical Records in Coastal Deposits from Sam Roi
558 Yod National Park, Prachuap Khiri Khan, Western Thailand. The Natural History Journal of
559 Chulalongkorn University 4(2):1-18, October 2004.

560 Donnelly, J.P., 2005. Evidence of past intense tropical cyclones from backbarrier salt pond
561 sediments: a case study from Isla de Culebrita, Puerto Rico, USA. Journal of Coastal Research
562 42, 201–210.

563 Donnelly, J.P., Bryant, S.S., Butler, J., Dowling, J., Fan, L., Hausmann, N., Newby, P., Shuman,
564 B., Stern, J., Westover, K., Webb III, T., 2001a. 700 yr sedimentary record of intense hurricane
565 landfalls in Southern New England. Geological Society of Bulletin 113, 714–727.

566 Donnelly, J.P., Roll, S., Wengren, M., Butler, J., Lederer, R., Webb III, T., 2001b. Sedimentary
567 evidence of intense hurricane strikes from New Jersey. Geology 29, 615–618.

568 Donnelly, J.P., Butler, J., Roll, S., Wengren, M., Webb III, T., 2004. A backbarrier overwash
569 record of intense storms from Brigantine, New Jersey. Marine Geology 210, 107–121.

570 Donnelly, J.P., Woodruff, J.D., 2007. Intense hurricane activity over the past 5,000 years
571 controlled by El Niño and the West African monsoon. Nature 447, 465–468.

572 Elsner, J.B., Liu, K.-b., 2003. Examining the ENSO-typhoon hypothesis. Climate Research
573 25, 43–54.

574 Elsner, J.B., Niu, X.F., Jagger, T.H., 2004. Detecting shifts in hurricane rates using a Markov

575 chain Monte Carlo approach. *Journal of Climate* 17, 2652–2666.

576 Elsner, J.B., Jagger, T.H., Liu, K.-b., 2008. Comparison of hurricane return levels using
577 historical and geological records. *Journal of Applied Meteorology and Climatology* 47, 368–374.

578 Emery, K.O., 1969. A coastal pond studied by oceanographic methods. Oyster Pond
579 Environmental Trust Inc., Woods Hole, Mass. (111 pp.).

580 Emanuel, K., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*
581 436, 686–688.

582 Emanuel, K.A., Nolan, D.S., 2004. Tropical cyclone activity and global climate. *Bulletin of*
583 *the American Meteorological Society* 85, 666–667.

584 Emanuel, K., DesAutels, C., Holloway, C., Korty, R., 2004. Environmental control of tropical
585 cyclone intensity. *Journal of Atmospheric Science* 61, 843–858.

586 Fan, D., Liu, K.-b., 2008. Perspectives on the linkage between typhoon activity and global
587 warming from recent research advances in paleotempestology. *Chinese Science Bulletin* 53,
588 2907–2922.

589 Frappier, A., Knutson, T., Liu, K.-b., Emanuel, K., 2007. Perspective: coordinating
590 paleoclimate research on tropical cyclones with hurricane–climate theory and modeling. *Tellus*
591 A. <http://dx.doi.org/10.1111/j.1600-0870.2007.00250.x>.

592 Folk, R.L., Ward, W.C., 1957. Brazos River Bar: a study in the significance of grain size
593 parameters. *Journal of Sedimentary Petrology* 27, 3–26.

594 Geyh, M.A., Kudrass, H-R., Streif, H., 1979: Sea-level changes during the late Pleistocene and
595 Holocene in the Straits of Malacca. *Nature* 278, 441–443.

596 Hesp, P.A., Hung, C.C., Hilton, M., Ming, C.L., Turner, I.M., 1998. A first tentative Holocene
597 sea-level curve for Singapore. *Journal of Coastal Research* 14, 308–314.

598 Horton, B.P., Gibbard, P.L., Milne, G.M., Morley, R.J., Purin Tavaragul, C., Stargardt, J.M.,
 599 2005. Holocene sea levels and palaeoenvironments, Malay-Thai Peninsula, Southeast Asia. *The*
 600 *Holocene* 15, 1199-1213.

601 Joint Typhoon Warning Center, 2014. Western North Pacific Best Track Data.
 602 http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.php

603 Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin,
 604 J.P., Srivastava, A.K., Sugi, M., 2010. Tropical cyclones and climate change. *Nature Geoscience*
 605 3,157–163.

606 Lane, P., Donnelly, J.P., Woodruff, J.D., Hawkes, A.D., 2011. A decadal-resolved
 607 paleohurricane record archived in the late Holocene sediments of a Florida sinkhole. *Marine*
 608 *Geology* 287, 14–30.

609 Liu, K.-b., 2004. Paleotempestology: principles, methods, and examples from Gulf coast
 610 lake-sediments. In: Murnane, R.J., Liu, K.-b. (Eds.), *Hurricanes and Typhoons: Past,*
 611 *Present, and Future.* Columbia University Press, New York, pp. 13–57.

612 Liu, K.-b., Fearn, M.L., 1993. Lake-sediment record of late Holocene hurricane activities
 613 from coastal Alabama. *Geology* 21, 793–796.

614 Liu, K.-b., Fearn, M.L., 2000a. Reconstruction of prehistoric landfall frequencies of catastrophic
 615 hurricanes in northwestern Florida from lake sediment records. *Quaternary Research* 54, 238–
 616 245.

617 Liu, K.-b., Fearn, M.L., 2000b. Holocene history of catastrophic hurricane landfalls along
 618 the Gulf of Mexico coast reconstructed from coastal lake and marsh sediments. In: Ning, Z.H.,
 619 Abdollahi, K.K. (Eds.), *Current Stresses and Potential Vulnerabilities: Implications of Global*

620 Change for the Gulf Coast Region of the United States. Franklin Press, Baton Rouge LA, pp. 38–
 621 47.

622 McCloskey, T.A., Keller, G., 2009. 5000 year sedimentary record of hurricane strikes on the
 623 central coast of Belize. *Quaternary International* 195, 53–68.

624 McCloskey, T.A., Bianchette, T.A., Liu, K-b. 2013. Track patterns of landfalling and coastal
 625 tropical cyclones in the Atlantic Basin, their relationship with the North Atlantic Oscillation
 626 (NAO), and the potential effect of global warming, *American Journal of Climate Change* 2, 12–
 627 22.

628 Melis, R., Violanti, D. 2006. Foraminiferal biodiversity and Holocene evolution of the
 629 Phetchaburi coastal area (Thailand Gulf). *Marine Micropaleontology* 61, 94-115.

630 Mullen, J., 2013. In Tacloban's history, little compares with terror of Typhoon Haiyan. CNN,
 631 <http://www.cnn.com/2013/11/21/world/asia/philippines-typhoon-history/>

632 NDRRMC, 2014. National Disaster Risk Reduction and Management Council (Philippines).
 633 *Update on Effects of Typhoon YOLANDA (HAIYAN)*, 17APR2014.pdf.
 634 [http://ndrrmc.gov.ph/attachments/article/1329/Update_on_Effects_Typhoon_YOLANDA_%28H](http://ndrrmc.gov.ph/attachments/article/1329/Update_on_Effects_Typhoon_YOLANDA_%28Haiyan%29_17APR2014.pdf)
 635 [aiyan%29_17APR2014.pdf](http://ndrrmc.gov.ph/attachments/article/1329/Update_on_Effects_Typhoon_YOLANDA_%28Haiyan%29_17APR2014.pdf)

636 NGI and NORSAR. 2009. Evaluation tsunami hazard in Vietnam and Gulf of Thailand. Project
 637 on Tsunami Risk Reduction Measures phase 2. NGI Report 20061179-00-225-R, 17 pp.

638 Nott, J., 2003. Intensity of prehistoric tropical cyclones. *Journal of Geophysical Research*
 639 108, 4212. <http://dx.doi.org/10.1029/2002JD002726>.

640 Nott, J., 2007. The importance of Quaternary records in reducing risk from tropical cyclones.
 641 *Palaeogeography, Palaeoclimatology, Palaeoecology* 251, 137–149.

642 Nott, J., Hayne, M., 2001. High frequency of ‘super-cyclones’ along the Great Barrier

643 Reef over the past 5,000 years. *Nature* 413, 508–512.

644 Nott, J., Haig, J., Neil, H., Gillieson, D., 2007. Greater frequency variability of landfalling
645 tropical cyclones at centennial compared to seasonal and decadal scales. *Earth and Planetary
646 Science Letters* 255, 367–372.

647 Paciente, R.B., 2014. Response and Lessons Learned from Typhoon “HAIYAN” (YOLANDA).
648 *JMA/WMO workshop on effective tropical cyclone warning in Southeast Asia*. Tokyo, Japan
649 March 11-14, 2014.

650 Pielke Jr., R.A., Landsea, C., Mayfield, M., Laver, J., Pasch, R., 2005. Hurricanes and global
651 warming. *Bulletin of the American Meteorological Society* 86, 1571–1575.

652 Phantu Wongraj, S., Choowong, M., Chutakositkanon, V., 2008. Possible Storm Deposits
653 from Surat Thani and Nakhon Si Thammarat Provinces, the Southern Peninsular
654 Thailand. In M. Choowong and T. Thitimakorn (eds.), *Proceedings of the International
655 Symposium on Geoscience Resources and Environments of Asian Terranes*, Bangkok,
656 Thailand, p. 395-399.

657 Phantu Wongraj S., Choowong M., Silapanth P. 2010: Geological evidence of sea-level change: a
658 preliminary investigation at Panang Tak area, Chumphon Province, Thailand. *The 117th Annual
659 Meeting of the Geological Society of Japan*. Toyama, Japan, p 185.

660 Phantu Wongraj, S., Choowong, M., Nanayama, F., Hisada, K. I., Charusiri, P., Chutakositkanon,
661 V., Chabangbon, A. 2013. Coastal geomorphic conditions and styles of storm surge washover
662 deposits from Southern Thailand. *Geomorphology* 192, 43–58.

663 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E.,
664 Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hafflidason, H.,
665 Hajdas, I., Hatté, C., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B.,

666 Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney,
 667 C.S.M., van der Plicht, J. 2013. IntCal13 and MARINE13 radiocarbon age calibration curves 0-
 668 50000 years cal BP. Radiocarbon 55(4). DOI: 10.2458/azu_js_rc.55.16947
 669 Ruangrassamee, A., Saelem, N. 2009. Effect of tsunamis generated in the Manila Trench on the
 670 Gulf of Thailand. Journal of Asian Earth Sciences 36, 56–66.
 671 Scheffers A., Brill D., Scheffers S., Kelletat D., Fox K. 2012. Holocene sea levels along the
 672 Andaman Sea coast of Thailand. The Holocene 22, 1169-1180.
 673 Scileppi, E., Donnelly, J.P. 2007. Sedimentary evidence of hurricane strikes in western Long
 674 Island, New York. Geochemistry, Geophysics, Geosystems 8, Q06011.
 675 <http://dx.doi.org/10.1029/2006GC001463>.
 676 Shanahan, T.M., Beck, J.W., Overpeck, J.T., McKay, N.P., Pigati, J.S., Peck, J.A., Scholz,
 677 C.A., Heil Jr., C.W., King, J., 2012. Late Quaternary sedimentological and climate changes at
 678 Lake Bosumtwi Ghana: new constraints from laminae analysis and radiocarbon age modeling
 679 Palaeogeography, Palaeoclimatology, Palaeoecology 361–362, 49–60.
 680 Sinsakul, S., 1990. Evidence of sea level changes in the coastal areas of Thailand: a review.
 681 Workshop on global environmental change, Chiang Mai, Thailand. Economic and Social
 682 Commission for Asia and the Pacific-Coordination of Joint Prospecting of Mineral Resources in
 683 Offshore Areas of Asia (ESCAP-CCOP).
 684 Sinsakul, S., 1992. Evidence of quaternary sea level changes in the coastal areas of Thailand: a
 685 review. Journal of Southeast Asian Earth Science 7, 23-37.
 686 Somboon, J.R.P., Thiramongkol, N. 1992. Holocene highstand shoreline of the Chao Phraya
 687 delta, Thailand. Journal of Southeast Asian Earth Science 7, 53-60.

688 Streif, H., 1979. Holocene sea-level changes in the Straits of Malacca. Proceedings of the 1978
 689 International symposium on coastal evolution in the Quaternary. Sao Paolo: IGCP Project 61
 690 552-572.

691 Thai Royal Navy, 2014. Tide Tables, Thai Waters, Gulf of Thailand and Andaman Sea. 2014.
 692 Thiramongkol, N., 1984. Geomorphology of the lower Central Plain, Thailand: Proceedings of
 693 the 3rd meeting of the working group on geomorphology of rivers and coastal plain. Bangkok.
 694 Department of Geology, Chulalongkorn University, Bangkok, 103-117.

695 Tjia, H.D., 1996. Sea-level changes in the tectonically stable Malay-Thai Peninsula. Quaternary
 696 International 31, 95-101.

697 Thai Meteorological Department, 2015. Tropical Cyclones in Thailand, Historical data 1951-
 698 2010. [http://www.ptc-](http://www.ptc-wmoescap.org/AdhocGroupAttachments/26_TROPICAL%20CYCLONES%20IN%20THAILAND.pdf)
 699 [wmoescap.org/AdhocGroupAttachments/26_TROPICAL%20CYCLONES%20IN%20THAILA](http://www.ptc-wmoescap.org/AdhocGroupAttachments/26_TROPICAL%20CYCLONES%20IN%20THAILAND.pdf)
 700 [ND.pdf](http://www.ptc-wmoescap.org/AdhocGroupAttachments/26_TROPICAL%20CYCLONES%20IN%20THAILAND.pdf)

701 Toomey, M.R., Donnelly, J.P., Woodruff, J.D., 2013. Reconstructing mid-late Holocene cyclone
 702 variability in the Central Pacific using sedimentary records from Tahaa, French Polynesia.
 703 Quaternary Science Reviews 77, 181-189.

704 Trenberth, K., 2005. Uncertainty in hurricanes and global warming. Science 308, 1753–1754.

705 Vongvisessomjai, S. 2007. Impacts of Typhoon Vae and Linda on wind waves in the upper gulf
 706 of Thailand and east coast. Songklanakarin Journal of Science and Technology 29, 1199–1216.

707 Walsh, K., 2004. Tropical cyclones and climate change: unresolved issues. Climate Research
 708 27, 77–83.

709 Wanner, H., Beer, J., Butikofer, J., Crowley, T.J., Cubasch, U., Fluckiger, J., Goosse, H.,
 710 Grosjean, M., Joos, F., Kaplan, J.O., Kuttel, M., Muller, S.A., Prentice, I.C., Solomina, O.,

Stocker, T.F., Tarasov, P., Wagner, M., Widmann, M., 2008. Mid- to Late Holocene climate change: an overview. *Quaternary Science Reviews* 27, 1791–1828.

Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309, 1844–1846.

Williams, H.F.L. 2011. Stratigraphic record of hurricanes Audrey, Rita and Ike in the Chenier Plain of Southwest Louisiana. *Journal of Coastal Research Special Issue* 64, 1921–1926.

Williams, H.F.L. 2012. Magnitude of Hurricane Ike storm surge sedimentation: implications for coastal marsh aggradation. *Earth Surface Processes and Landforms* 37, 901–906.

Williams, H.F.L. 2013. 600-year sedimentary archive of hurricane strikes in a prograding beach ridge plain, southwestern Louisiana. *Marine Geology* 336, 170–183.

Woodruff, J.D., Donnelly, J.P., Emanuel, K.A., Lane, P., 2008. Assessing sedimentary records of paleohurricane activity using modeled hurricane climatology. *Geochemistry, Geophysics, Geosystems* 9. <http://dx.doi.org/10.1029/2008GC002043>.

Woodruff, J.D., Donnelly, J.P., Okusu, A., 2009. Exploring typhoon variability over the mid-to-late Holocene: evidence of extreme coastal flooding from Kamikoshiki, Japan. *Quaternary Science Reviews* 28, 1774–1785.

Woodruff, J.D., Kanamaru, K., Kundu, S., Cook, T.L., 2015. Depositional evidence for the Kamikaze typhoons and links to changes in typhoon climatology. *Geology* 43, 91–94.

Wu, L.G., Wang, B., 2004. Assessing impacts of global warming on tropical cyclone tracks. *Journal of Climate* 17, 1686–1698.

FIGURE CAPTIONS

Figure 1. Location map showing study areas at Cha-am and Kui Buri, sites of documented washover sedimentation and tracks of recent notable tropical cyclones in the Gulf of Thailand (TS: Tropical storm, T: Typhoon).

Figure 2 a. coastal marsh at Cha-am showing topographic survey points (yellow circles) and vibracore sites (white squares) (Google Earth image, 2014); b. topographic profile across Cha-am marsh; c. view of marsh showing tidal creek (foreground), vegetated and unvegetated marsh surface (view from building shown in Fig. 2a); d. beach ridge plain at Kui Buri showing topographic survey points (blue circles) and the two swales where vibracores were collected (yellow squares) (Google Earth image, 2014); e. topographic profile across Kui Buri beach ridge plain; f. view of the swale at vibracore site SRY4, looking northeast.

Figure 3. Geophysical model prediction of Holocene sea-level behavior and radiocarbon-dated sea-level index points for Kui Buri region, Gulf of Thailand (modified from Horton et al., 2005; error bars on sea-level index points represent temporal and sea-level uncertainty).

Figure 4 a. Fine sand layer, with sharp upper and lower contacts, in core HW1 V1, depth 0.25 m; b. Coarse sand layer, with gravel-sized clasts and sharp upper and lower contacts, in core HW1 V5, depth 1.25 – 1.29 m; c. Two coarse sand layers in core HW1 V5, depth 1.6 – 1.72 m. Both layers have sharp contacts and gravel-sized clasts. The deeper layer contains a large mud rip-up clast (MRC); d. Layer of sand and large plant fragments in core HW1 V5, depth 1.1 m. The layer has sharp contacts with enclosing fine sediments; e. Large wood fragment (WF) on top of a

coarse sand layer (CS) in core HW1 V5, depth 1.58 m; f. Sand layer with abundant fine shell fragments in core SRY V1, depth 0.8 m. The layer has sharp contacts with enclosing swale deposits; g. Multiple mud rip-up clasts (MRC) in a sand layer in core SRY V1, depth 0.95 m; h. Multiple mud rip-up clasts (MRC) in a sand layer in core SRY V3, depth 1.48 m. Ruler has cm and inch markings.

Figure 5. Upper part of core V3 from the Cha-am coastal marsh site (see Fig. 2a for location; top of core is to the left). Sixteen centimeters of oxidized fine sand overlies clay with a sharp contact. A mud rip-up clast is enclosed within the sand layer. Ruler has inch and cm scales.

Figure 6. Stratigraphy showing suspected storm-surge-deposited sand layers and intervening marsh deposits*, proposed correlations and radiocarbon dates, at a. Cha-am coastal marsh and b. Kui Buri swales. Radiocarbon dates are averages of 2-sigma calibrated age ranges. * Because of the mid-Holocene sea-level high stand, “marsh” deposits in deeper, older parts of cores are probably intertidal/subtidal deposits (see discussion section).

Figure. 7. Bayesian age-depth models for site HW1 near Cha-am and site SRY near Kui Buri. Blue markers represent calibrated radiocarbon dates, grey stippled lines show 95% confidence intervals; red curve shows single 'best' model based on the weighted mean age for each depth.

Figure 8 a. Study area near Cha-am in 1967. The surface of the marsh appears to be largely unvegetated sand. What appear to be recent depositional lobes (circled) extend from the margins

of the marsh (Royal Thai Survey image); b. The study area in 2014; the marsh is largely vegetated (Google Earth image 2014).

Figure 9. Bayesian age-depth model derived 95% probability ranges of ages of typhoon strikes recorded at Cha-am and Kui Buri. Some of sand beds 4-11 at Cha-am may be coeval (result of the same typhoon strike) with sand beds at Kui Buri, but the precise number cannot be determined because of the large uncertainties in ages.

Figure 10 a. Sr time-series for inferred typhoon-induced deposition at Kamikoshiki, Japan; b. ENSO reconstructions from Laguna Pallcocha, Ecuador (Moy et al., 2002); c. hurricane-induced sedimentation from the western North Atlantic (Donnelly and Woodruff, 2007); d. Estimated age ranges of typhoon strikes on the Gulf of Thailand coast. Vertical shaded bars in plots represent periods of increased ENSO activity (modified from Woodruff et al., 2009).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Table 1. Cha-am Tidal Marsh: Textural Characteristics and Foraminiferal Contents.

Core Number and Depth (cm)	Sedimentary Unit	Sand %	Mean Grain Size (um)	Folk and Ward (1957) Textural Description	Foraminiferal content (Number/gram)
V1 3	Sand layer	78	151	Moderately Well Sorted Fine Sand	0
V1 7	Marsh*	32	N/A	N/A	0
V1 24	Sand layer	96	159	Well Sorted Fine Sand	0
V1 26	Marsh	17	N/A	N/A	0
V2 1	Sand layer	69	128	Moderately Well Sorted Very Fine Sand	0
V2 3	Marsh	53	N/A	N/A	0
V2 37	Marsh	48	N/A	N/A	0
V2 41	Sand layer	83	459	Moderately Sorted Medium Sand	0
V2 47	Marsh	3	N/A	N/A	0
V2 53	Sand layer	87	405	Moderately Sorted Medium Sand	0
V2 55	Marsh	32	N/A	N/A	0
V3 15	Sand layer	73	242	Moderately Well Sorted Fine Sand	0
V3 18	Marsh	36	N/A	N/A	0
V3 39	Sand layer	84	186	Well Sorted Fine Sand	0
V3 43	Marsh	30	N/A	N/A	0
V4 50	Marsh	41	N/A	N/A	0
V4 56	Sand layer	75	446	Poorly Sorted Coarse Sand	0
V4 67	Marsh	16	N/A	N/A	0
V4 99	Sand layer	80	242	Moderately Sorted Fine Sand	0
V5 102	Marsh	10	N/A	N/A	0
V5 107	Sand layer	58	344	Poorly Sorted Coarse Sand	0
V5 110	Marsh	3	N/A	N/A	0
V5 117	Sand layer	79	727	Very Fine Gravelly Coarse Sand	0
V5 119	Marsh	1	N/A	N/A	0
V5 128	Sand layer	95	1041	Very Fine Gravelly Coarse Sand	0
V5 131	Marsh	8	N/A	N/A	0
V5 136	Sand layer	91	520	Slightly Very Fine Gravelly Coarse Sand	0
V5 157	Marsh	16	N/A	N/A	0
V5 162	Sand layer	90	1127	Sandy Very Fine Gravel	0
V5 166	Marsh	31	N/A	N/A	0
V5 168	Sand layer	90	954	Sandy Very Fine Gravel	0
V5 170	Marsh	2	N/A	N/A	0
V6 79	Marsh	27	N/A	N/A	0
V6 84	Sand layer	94	360	Moderately Sorted Medium Sand	0
V7 74	Marsh	51	N/A	N/A	0
V7 89	Sand layer	98	462	Moderately Well Sorted Medium Sand	0
Cha-am beach	Beach	100	438	Moderately Sorted Medium Sand	0
Cha-am offshore	Shallow marine	98	236	Moderately Sorted Fine Sand	22

* Because of the mid-Holocene sea-level highstand, “marsh” deposits in deeper, older parts of cores are probably intertidal/subtidal deposits (see discussion section).

Table 2

Table 2. Kui Buri Swales: Textural Characteristics and Foraminiferal Contents.

Core Number and Depth (cm)	Sedimentary Unit	Sand %	Mean Grain Size (um)	Folk and Ward (1957) Textural Description	Foraminiferal content (Number/gram)
V1 79	Marsh*	60	N/A	N/A	188
V1 80	Sand layer	98	151	Very Well Sorted Fine Sand	443
V1 83	Marsh	2	N/A	N/A	72
V1 95	Sand layer	84	169	Well Sorted Fine Sand	57
V1 98	Marsh	17	N/A	N/A	16
V1 121	Sand layer	97	156	Very Well Sorted Fine Sand	325
V1 124	Marsh	43	N/A	N/A	193
V1 126	Sand layer	97	143	Very Well Sorted Fine Sand	448
V1 128	Marsh	7	N/A	N/A	21
V2 101	Marsh	41	N/A	N/A	2
V2 104	Sand layer	96	183	Well Sorted Fine Sand	100
V2 106	Marsh	6	N/A	N/A	9
V3 120	Marsh	25	N/A	N/A	6
V3 121	Sand layer	98	174	Well Sorted Fine Sand	88
V3 123	Marsh	7	N/A	N/A	5
V3 143	Marsh	43	N/A	N/A	60
V3 147	Sand layer	97	201	Well Sorted Fine Sand	20
V3 151	Marsh	6	N/A	N/A	2
V3 190	Marsh	8	N/A	N/A	12
V3 192	Sand layer	97	137	Well Sorted Fine Sand	1034
V3 198	Sand layer	96	142	Well Sorted Fine Sand	476
V3 200	Sand layer	63	142	Well Sorted Fine Sand	760
V3 206	Sand layer	94	145	Well Sorted Fine Sand	750
V3 208	Marsh	11	N/A	N/A	335
V4 111	Marsh	68	N/A	N/A	400
V4 114	Sand layer	96	140	Very Well Sorted Fine Sand	115
V4 117	Marsh	32	N/A	N/A	35
V4 118	Sand layer	98	157	Very Well Sorted Fine Sand	81
V4 127	Marsh	28	N/A	N/A	8
V4 128	Sand layer	98	143	Very Well Sorted Fine Sand	16
V4 131	Marsh	3	N/A	N/A	8
V4 140	Sand layer	98	144	Very Well Sorted Fine Sand	51
V4 142	Marsh	43	N/A	N/A	82
Kui Buri beach	Beach	99	114	Very Well Sorted Very Fine Sand	394
Kui Buri offshore	Shallow marine	96	107	Very Well Sorted Very Fine Sand	133

* Because of the mid-Holocene sea-level highstand, “marsh” deposits in deeper, older parts of cores are probably intertidal/subtidal deposits (see discussion section).

Table 3. Radiocarbon Ages and Calibrated Age Ranges & Mean.

Core Number	Depth (m)	Material	^{14}C Age BP & Error	2-Sigma Calibrated Age Range & Mean
HW1 V1	1.50	Wood	6,192 + 47	6,971 – 7,244, 7,108 cal. yr BP
HW1 V2	0.72	Wood	6,623 + 48	7,436 – 7,574, 7,505 cal. yr BP
HW1 V5	1.10	Wood/Plants	4,815 + 45	5,336 – 5,645, 5,491 cal. yr BP
HW1 V5	1.58	Wood	6,564 + 49	7,419 – 7,568, 7,494 cal. yr BP
HW1 V7	1.05	Wood	6,769 + 49	7,523 – 7,688, 7,606 cal. yr BP
SRV V3	2.09	Wood/Plants	6,269 + 96	6,982 – 7,421, 7,202 cal. yr BP
SRV V4	1.10	Wood	6,083 + 47	6,797 – 7,156, 6,977 cal. yr BP
SRV V4	1.44	Wood	5,174 + 45	5,754 – 6,169, 5,962 cal. yr BP

Table 4

Table 4. Estimated Ages of Assumed Typhoon Strikes for the Cha-am and Kui Buri Sites.

Study Area	Sand Layer	Average Depth ¹ (m)	Estimated Age (cal. yr BP)	
			95% Probability Range	Mean Age
Cha-am	1	0	-	1952 AD ²
Cha-am	2	0.308	908-2759	1789
Cha-am	3	0.32	982-2829	1863
Cha-am	4	0.75	3341-4893	4197
Cha-am	5	0.865	3990-5234	4709
Cha-am	6	1.11	5398-5821	5611
Cha-am	7	1.15	5550-6158	5804
Cha-am	8	1.21	5755-6630	6141
Cha-am	9	1.23	5831-6736	6254
Cha-am	10	1.40	6875-7526	7220
Cha-am	11	1.42	7045-7575	7294
Kui Buri	1	1.04	4075-5531	4870
Kui Buri	2	1.10	4448-5734	5151
Kui Buri	3	1.27	5245-6066	5717
Kui Buri	4	1.36	5807-6244	6004
Kui Buri	5	1.42	5910-6479	6166
Kui Buri	6	1.72	6620-7351	6990
Kui Buri	7	1.82	6949-7585	7264
Kui Buri	8	1.87	7126-7740	7427

¹Depths exclude sand layer thicknesses; depth is to basal contact of sand layer.

²Assumed to be storm surge deposit of Typhoon Vae 1952.