

## GEOLOGY

# An annually resolved 5700-year storm archive reveals drivers of Caribbean cyclone frequency

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Predictions of tropical cyclone (TC) frequencies are hampered by insufficient knowledge of their natural variability in the past. A 30-m-long sediment core from the Great Blue Hole, a marine sinkhole offshore Belize, provides the longest available, continuous, and annually resolved TC-frequency record. This record expands our understanding, derived from instrumental monitoring (73 years), historical documentations (173 years), and paleotempestological records (2000 years), to the past 5700 years. A total of 694 event layers were identified. They display a distinct regional trend of increasing storminess in the southwestern Caribbean, which follows an orbitally driven shift in the Intertropical Convergence Zone. Superimposed short-term variations match Holocene climate intervals and originate from solar irradiance-controlled sea-surface temperature anomalies and climate phenomena modes. A 21st-century extrapolation suggests an unprecedented increase in TC frequency, attributable to the Industrial Age warming.

## INTRODUCTION

Tropical cyclones (TCs) are among the Earth's most dangerous weather phenomena. Their seasonally recurring landfalls are accompanied by devastating winds, torrential rain, high storm surges, and flooding, which cause massive economic damage to infrastructure in coastal cities and endanger ecosystems and thousands of human lives each year. In the tropical Atlantic, modern TCs form in the Hurricane Main Development Region (MDR) between 9° and 20°N (1, 2). Their major genesis regions are aligned along the northern edge of the Intertropical Convergence Zone (ITCZ; Fig. 1A), a zone of deep convection and high precipitation generated by the convergence of the trade winds. The ITCZ migrates seasonally between 2° and 9°N in response to hemispheric-scaled changes in sea-surface temperatures (SSTs) (3, 4). From June to November, gradually better self-organizing and progressively intensifying storm cells move westward through the tropical western Atlantic, the Caribbean Sea, and/or the Gulf of Mexico, before they deviate toward the northeast at about 30°N.

TC genesis is favored by high SST and low vertical wind-shear stress in the Atlantic MDR (La Niña-like conditions) (5, 6). It is expected that the TC hazard potential becomes more exacerbated in response to ongoing global warming, which may result in constant MDR SSTs above 26°C and an ~1-m global sea-level rise by the end of the 21st century (7–9). Most climatological studies predict a relative increase in the probability of storm cells reaching higher intensities faster and more frequently (10–17). Some studies, in contrast, suggest that the Atlantic TC frequency remains at the current high state, although with a northern shift of the maximum activity zone (18), or even discuss regional decreases (19). Weakness in these forecasts lies in the fact that underlying data originate solely from 73- and 173-year-long instrumental measurements and historical

documentations, respectively, which both suffer from stochastic, observational, and technical biases (20–22). The resultant data are highly valuable to decipher multi-annual and decadal TC-frequency oscillations, but it is already challenging to assess multi-decadal climate forcing with a coverage of only one or two cycles of climate phenomena's modes of action. The understanding of climate boundary conditions that alter TC frequency on centennial to millennial timescales requires longer sedimentary records with a very good temporal resolution and high sensitivity to document TC events in the form of storm deposits (tempestites).

Paleotempestology studies so far have contributed to a 2000-year-long understanding of multi-decadal- to centennial-scale drivers, such as the Atlantic Multidecadal Oscillation (AMO) (23), the North Atlantic Oscillation (NAO) (24), and the El Niño–Southern Oscillation (ENSO) (25). Appropriate TC-frequency archives were recovered in the Atlantic Hurricane Belt from subaerial sinkholes (3, 26–29) and marine blue holes (20, 30–37). In these sediment traps, proximal-passing storms produce distinct coarse-grained overwash deposits (38). Their quantification revealed that alternating periods of storm activity were linked to latitudinal shifts of the ITCZ and SST anomalies in their genesis regions (3, 33, 39–41).

In this study, we present and discuss the variation of TCs in the southwestern Caribbean during the past 5700 years, as documented by event layers ( $n = 694$ ) in a 30-m-long sediment core composite (fig. S1) recently recovered from the Great Blue Hole (GBH), Lighthouse Reef, Belize (Fig. 1, A to C). Our GBH core composite rules out an existing problem of inconsistent regional TC-activity patterns (29) and provides also meaningful explanations for discrepancies between reconstructions from multiple coring efforts in the GBH (30, 31, 34) and a peculiar 340-year age offset between radiocarbon and varve ages (31) (for details, see Materials and Methods). Event layers related to proximal TC passages (Fig. 1, D and E) were identified on the basis of a multi-proxy combination of optical (mandatory), textural, and geochemical (both supportive) criteria (figs. S2 and S3) and counted in binned intervals of 100 and 50 years (fig. S4). Our results shed light on changes in multi-decadal to centennial TC frequencies and their long-term, millennial-scale trends throughout the Middle and Late Holocene.

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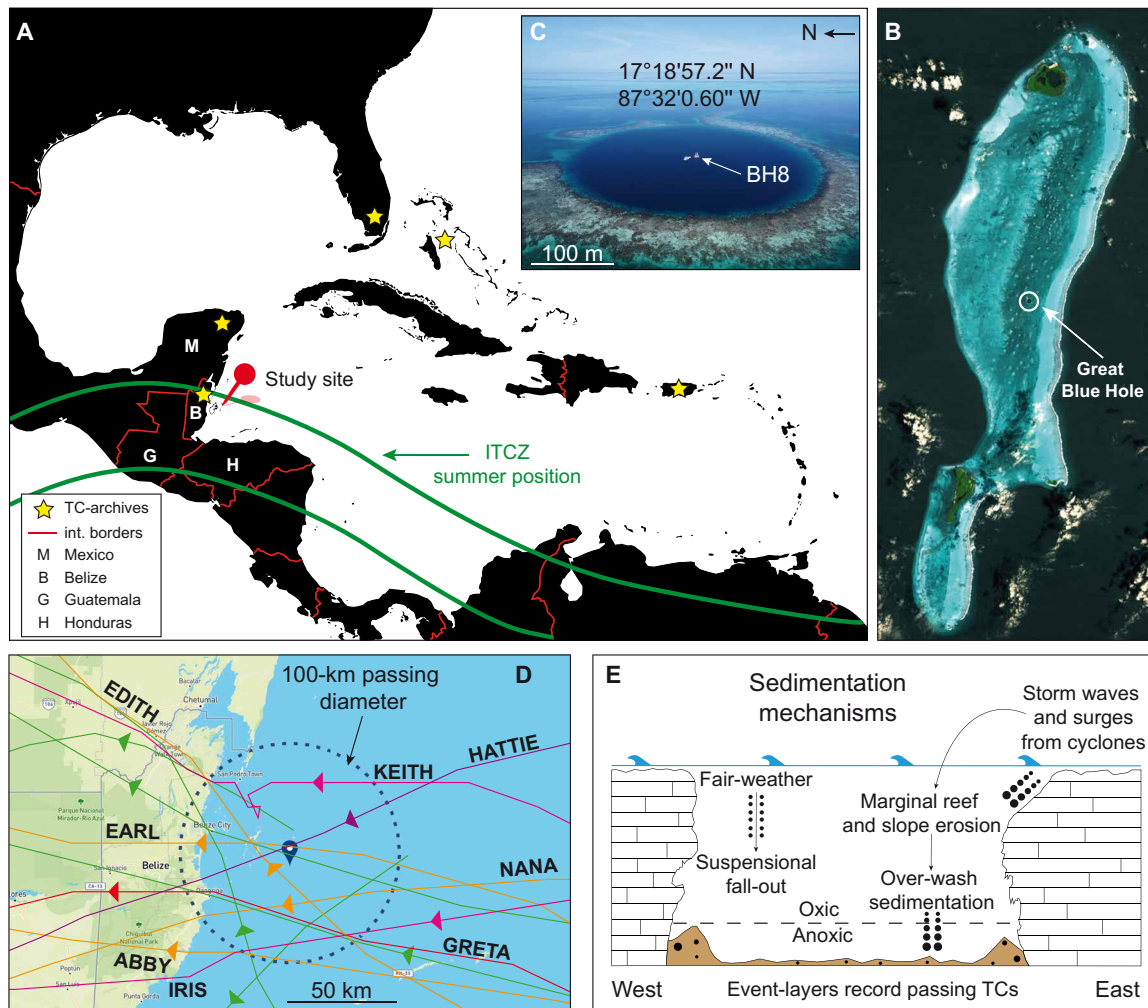


**Fig. 1. Study area, historical storm record, and mechanisms of tempestite sedimentation.** (A) Map of circum-Caribbean region (89) with important TC-frequency archives (yellow stars): Florida (26), Yucatán Peninsula (28, 29), Belize (30, 31, 34, 67, 69), Bahamas (3, 20, 32, 33, 35–37), and Puerto Rico (58) and a conceptual scheme of the ITCZ summer position (105). The red pin points to the study site. (B) The position of the GBH (encircled) on an open access ASTER satellite image of Lighthouse Reef (<https://asterweb.jpl.nasa.gov>) supplied by Japan Space Systems and U.S./Japan ASTER Science TEAM (NASA/METI/AIST/). (C) Aerial view of the GBH taken from an UAV (unmanned aerial vehicle/drone) showing the coring platform at site BH8 (17° 18.572' N, 87° 32.060' W) and a support boat within the sinkhole structure. Photo: E.G. (D) Selected TC pathways from the historical record (2022–1950 CE) passing over the study site within a 100-km diameter circle. Storm track maps were downloaded from <https://coast.noaa.gov/hurricanes/> and compared with the International Best Track Archive for Climate Stewardship-IBTrACS (49). (E) Mechanisms of event-layer (tempestite) formation in the GBH.

## RESULTS

### Development of the GBH

The core composite BH8 from the GBH (fig. S1) was investigated for sedimentology (fig. S2) and palynology (fig. S5; for details, see Materials and Methods). Its chronology (Fig. 2) is based on varve-counting confirmed by radiocarbon–accelerator mass spectrometry (AMS) dating (fig. S6) and in the uppermost part by palynological and tephrochronological data. The record reflects the depositional history since  $12,091 \pm 605$  years (a) before the present (B.P.) and can be separated into three major sedimentary units (Fig. 2).

The basal unit A [30.0 to 28.6 m below sea floor = mbsf; 12.5 to 7.2 thousand years (ka) B.P.] consists of finely laminated organic-rich carbonates of gray to brown color with intercalated white or reddish event layers (fig. S7). Deposition most likely took place in a partially inundated subaerial terrestrial sinkhole, locally known as

cenote, which developed after the roof collapse of a cave in a limestone island (Fig. 2) during glacial and postglacial times, when sea level was up to 120 m below modern level (42). This inference is supported by the occurrence of freshwater gastropods (*Pyrgophorus coronatus*, *Pyrgophorus parvulus*) characteristic for local cenotes (43) and by a sedimentation rate of  $0.20 \pm 0.00$  mm/a (Fig. 2), which is similar to the sedimentation rate of the subaerial Blackwood Sink-hole on the terrestrial environment of Abaco Island, Bahamas (20). According to palynological data (fig. S5), the steep limestone island was covered by a diverse neotropical forest (*Myrtaceae*). Organic-rich deposits and fine lamination evidence a stratified water column with anoxic bottom waters (probably saline water intrusions overlain by a freshwater lens). Taking the early Holocene sea-level rise with a rate of  $4.0 \pm 0.4$  m/ka (44) into account, the water level of the cenote successively increased from about 60 m (12.5 ka B.P.) to 5 m

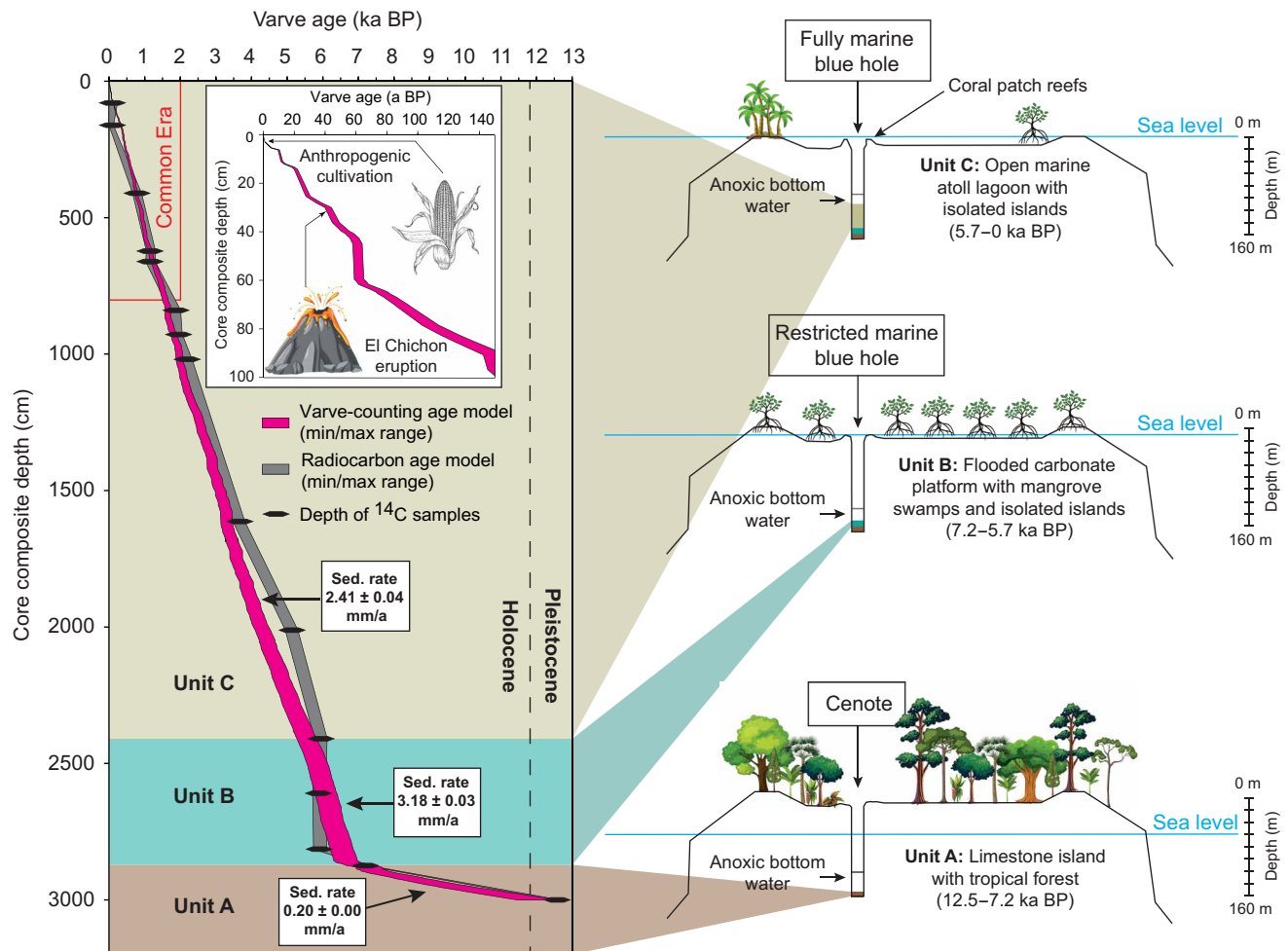


**Fig. 2. Age-depth framework of the core composite BH8.** The age model is based on varve-counting confirmed by radiocarbon-AMS dating and by the documentation of anthropogenic plantings in corn (*Zea mays*), pine (*Pinus*), and palm (*Arecaceae*) pollen from 2.5-cm depth and volcanic glass shards from the 1982 CE eruption of El Chichón (Mexico) in 30-cm depth. The GBH sediment succession is separated into three major units (A, B, and C), which are characterized by different composition and sedimentation rates and which reflect three depositional and environmental settings. On the basis of a meteoric stalactite recovered from the GBH (106) and the sedimentation rate of 0.2 mm/a, additional 1.85 m of the basal unit A could be present above a karst breccia of Pleistocene bedrock.

(7.2 ka B.P.) below modern level (Fig. 3C), albeit this did not affect the general sedimentation processes. The rising sea reached the former rim of the sinkhole approximately around the end of deposition of unit A. The event layers in unit A (fig. S7) contain high abundances of organic materials and rare fragments of common aquatic organisms (bivalves, gastropods, foraminifera, and ostracods). These deposits do not mandatorily originate from cyclone over-wash since the environmental setting in the cenote phase was detrimental for tempestite formation. They rather originate from other processes such as heavy rainfalls, landslides, or earthquakes. This interpretation is supported by the absence of tempestites in the sediment records of the subaerial Great Cistern (45) and No Man's Land sinkholes (3, 20), Bahamas, which are also located several tens of meters away from shore and probably were governed by similar environmental conditions as the GBH during its cenote phase.

Unit B (28.6 to 24.6 mbsf; 7.2 to 5.7 ka B.P.) consists of varved fair-weather carbonates of grayish-green color with intercalated white to pale brown or almost black event layers (fig. S7). Deposition of this unit commenced, when a continued, but decelerated

mid-Holocene sea-level rise of  $0.5 \pm 0.2$  m/ka (44) from 5 to 3 m below the modern level provoked an almost complete marine inundation of the limestone island (Figs. 2 and 3C). As a consequence, the cenote became fully submerged between 7.2 and 6.8 ka B.P. and a blue hole formed in an environment dominated by widespread mangrove swamps (*Rhizophora*) and restricted marine conditions with brackish waters. During the late unit B phase, keep-up reefs surrounding the GBH likely initiated on top of the sinkhole rim (46). This scenario is supported by coincident ages of peat deposits and coral fragments cored in the Lighthouse Reef lagoon and surrounding marginal reefs (47), as well as by a substantially increased sedimentation rate of  $3.18 \pm 0.03$  mm/a and the fair-weather sediments of unit B lacking coral skeletons and largely consisting of ostracod, bivalve, and gastropod shells. The lack of bioturbation, on the other hand, reflects persistence of the stratified water column with anoxic bottom waters (Fig. 2). The event layers in unit B clearly stand out from the varved fair-weather deposits by their color and thickness (fig. S7). Their different composition evidences formation by storms. The tempestites contain a combination of skeletal reef

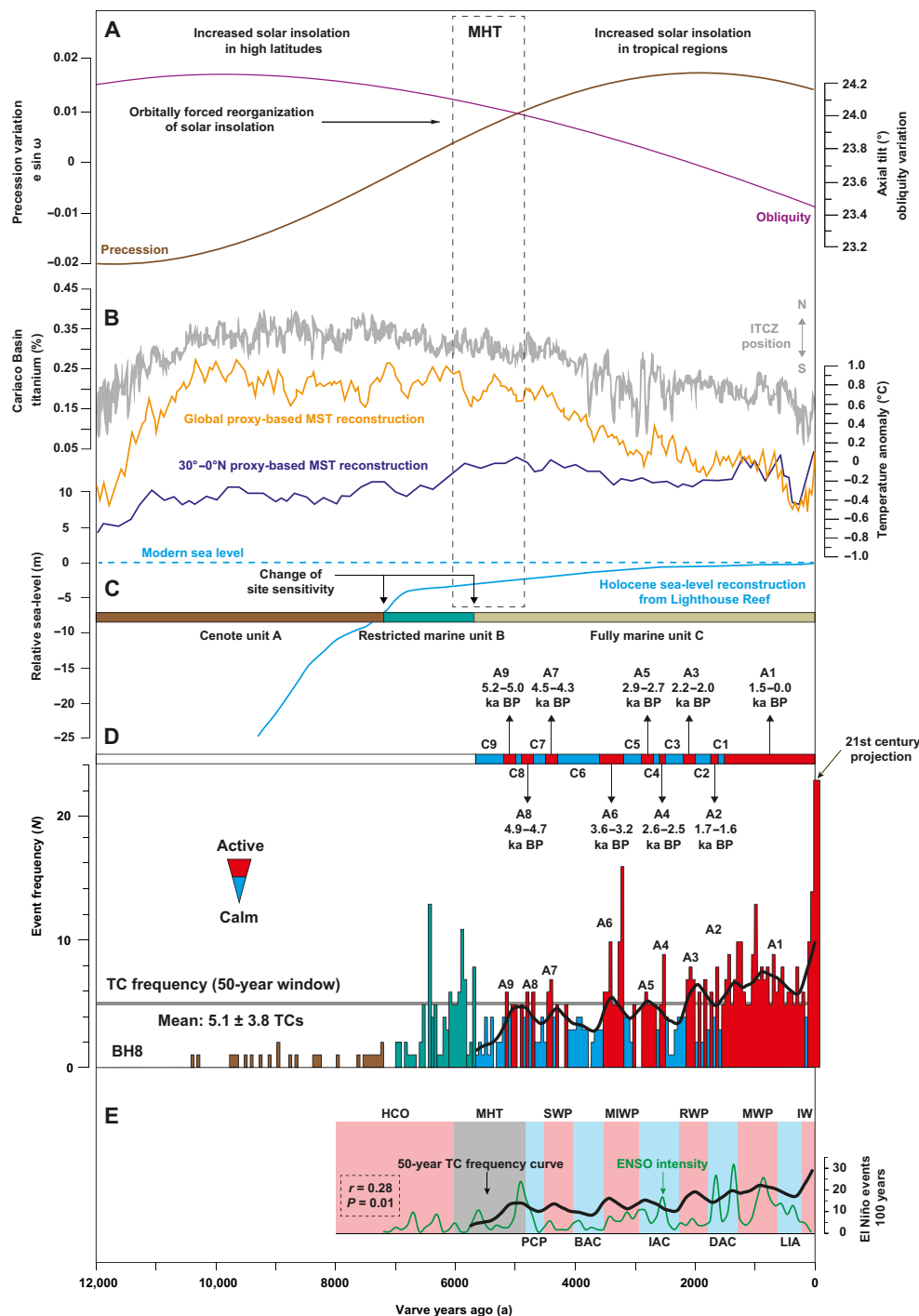


**Fig. 3. 5700-year-long reconstruction of southwestern Caribbean TC frequency.** (A) Obliquity and precession changes, which lead to a gradual modification of solar insolation in high latitudes and tropical regions, respectively (107). (B) Southward ITCZ migration during the Holocene, reconstructed from titanium contents of Cariaco Basin sediments (53) along with proxy-based global and 30° to 0° N mean surface temperatures (MST) (108). (C) Sedimentary units in core composite BH8 with their paleoenvironmental interpretation combined with a modeled relative sea-level curve (RSL) of Lighthouse Reef (47) that explains two stages of a varying site sensitivity starting at 7.2 ka B.P. (boundary unit A/B) and 5.7 ka B.P. (boundary unit B/C), respectively. (D) 5700-year-long TC-frequency reconstruction in a 50-year counting window, with the TC frequency for the 21st century based on an extrapolation of nine event-layer counts from 2000 to 2022 CE, showing a long-term trend of increase and short-term fluctuations. Increased and decreased cyclone activities, with  $>5.1$  and  $<5.1$  TCs per 50 years, are indicated by red and blue coloring of the bars, respectively, and the smoothed 50-year TC-frequency reconstruction is shown by the bold black curve. (E) Comparison of our smoothed 50-year TC reconstruction with the ENSO intensity (57) and prominent Holocene cold (light blue) and warm (light red) phases: HCO, Holocene Climate Optimum; MHT, mid-Holocene transition; PCP, Piora Cold Period; SWP, Summerian Warm Period; BAC, Bronze Age Cold; MIWP, Minoan Warm Period; IAC, Iron Age Cold; RWP, Roman Warm Period; DAC, Dark Ages Cold; MWP, Medieval Warm Period; LIA, Little Ice Age; and IW, Industrial Warmth. For coloring, please consider the online version of the manuscript.

detritus (*Halimeda*, corals, bivalves, gastropods, and foraminifera) and organic particles (wood pieces and leaf material), which became likely over-washed and/or mobilized by cyclones from the developing marginal reef of the Lighthouse Reef platform and adjacent mangrove forests, respectively. The tempestites have white to pale brown colors, when dominated by skeletal detritus, or dark brown to almost black colors, when consisting almost exclusively of organic material (fig. S7).

Unit C (24.6 to 0 mbsf; since 5.7 ka B.P.) has all the sedimentological characteristics that were described in detail for the uppermost 8.55 m of the GBH sediment succession (30, 34). It consists of a lighter sequence of grayish green and annually laminated fair-weather carbonates with intercalated white to pale brown event layers (fig. S7), which have been deposited in fully marine conditions and anoxic bottom waters. The sedimentation of unit C was associated with a further decelerated sea-level rise from 3 m below to the modern level. Accreting keep-up coral patch reefs (46) that surround the GBH in present days in a circular surface-breaking ring (Fig. 1C) have continuously compensated the 3-m sea-level rise since 5.7 ka B.P. so that constant conditions for the formation and preservation of tempestites have prevailed. The constant sedimentation rate of  $2.41 \pm 0.04$  mm/a well resembles that of  $2.55 \pm 0.05$  mm/a determined in the GBH for the past 2000 years (34) and is also similar to that of other blue hole sequences from the Bahamas (33, 36). The tempestites in unit C predominantly contain over-washed reef detritus (*Halimeda*, corals, bivalves, gastropods, and foraminifera) due to recurring cyclone passages that cause storm-wave erosion at windward marginal reef sites of the Lighthouse Reef platform and induce hydrodynamic currents toward the lagoon. They are formed by density currents and a gradual settling out of suspension during and after storm passages (Fig. 1E).

### Site sensitivity

As evident from the development of the GBH, our counting of event layers (Fig. 3D and fig. S4) reflects a remarkable trichotomy, which is an expression of an evolving site sensitivity (fig. S4) as indicated by two significant changes in mean sedimentation rates at the boundaries (Fig. 3C) of units A/B (7.2 ka B.P.) and B/C (5.7 ka B.P.). The 35 event layers (bars are highlighted with brown coloration; Fig. 3D and fig. S4) that have been found during the cenote phase A (12.5 to 7.2 ka B.P.) may not be safely associated with TCs. The 85 event layers (bars are highlighted with dark green coloration; Fig. 3D and fig. S4) formed during the restricted marine phase B (7.2 to 5.7 ka B.P.) are entirely traced back to TCs; however, the strong increase in their numbers coincides with a rapid sea-level rise that may have biased the sensitivity of the record. Five hundred and seventy-four event layers have been precisely identified as tempestites in the fully marine unit C (<5.7 ka B.P.). The event-layer counts in unit C [bars are highlighted with red (active) and blue (calm) colorations; Fig. 3D] provide robust information concerning climatic-driven variabilities of Mid- and Late-Holocene TC frequency at the GBH site (fig. S4) under the reasonable assumption that the site sensitivity and the physical and sedimentary processes promoting tempestite deposition remained virtually constant when the brackish blue hole passed into the fully marine blue hole (onset of unit C) and a decelerated sea-level rise was compensated by the surrounding keep-up coral patch reefs (46). A comparison of 16 event layers in the upper 61.8 cm of the GBH core composite (1950 to 2022 CE) to 19 historically documented TCs revealed an tempestite preservation potential of 84% for storm systems that formed in the Caribbean Sea

and east of the Lesser Antilles (see Materials and Methods, fig. S8, and table S1) (48, 49), which is most likely representative for the deposition of the entire unit C.

## DISCUSSION

### Long-term TC increase

During the deposition of unit C, i.e., since 5.7 ka B.P., the TC frequency shows distinct short-term decadal to centennial-scale variability albeit with a prolonged long-term increase usually from 1 to 2 to almost 10 TCs/50 years (Fig. 3D). The long-term rise in TC frequency follows hemispheric-scale modifications of oceanic and atmospheric boundary conditions, set in motion from 6.0 to 4.8 ka B.P. by orbital forcing and solar variability (50–52). Periodic variations in the 21-ka precession and 41-ka obliquity cycles caused a reorganization of global solar insolation, i.e., an increase of solar radiation in the tropics, which finally resulted in the onset of the Mid-Holocene transition (MHT; Fig. 3A). During the early Holocene, a time when solar insolation was in contrast increased in high latitudes (Fig. 3A), the ITCZ was reconstructed to have seasonally migrated at a more northerly position (4, 53), with an expected latitude of 10° to 20° in the Caribbean region. A tropical Atlantic SST band (MDR) was predicted to have been located equally further poleward (25° to 30°N) in the northwestern Atlantic adjacent to the east coast of North America (51). A southward displacement of the Atlantic ITCZ (Fig. 3B), a repositioning of the North Atlantic Subtropical High (NASH) and a concomitant relocation of the MDR commenced since the onset of the MHT (2, 4, 53, 54).

The reorganization of global solar irradiation also notably increased the ENSO intensity in the Pacific Ocean (55–57). A previous study (58) demonstrated that an intensified ENSO should, in general, hamper TC frequency through an increase of vertical wind shear stress in the MDR (Fig. 3E). This inverse correlation and the ENSO record itself were, however, recently questioned by two other studies (59, 60), and instead a positive long-term covariation between an intensifying ENSO and Atlantic TC frequency was postulated (59). This important finding is only weakly confirmed by our data (correlation test: 50-year TC counts and the Laguna Pallcacocha ENSO intensity data;  $r = 0.276$ ;  $P = 0.01$ ; Fig. 3E), so we do not pursue the ENSO intensification as a major controlling factor.

If one excludes ENSO, then either the orbital-forced increase in tropical Atlantic SSTs or the steady shift of major storm trajectories from once higher (25° to 30°) to then lower latitudes (9° to 20°N) may be responsible for explaining the prolonged long-term increase in tempestite deposition at the GBH (61–63). As a consequence, the frequency of storm genesis either generally increased synchronously in the Atlantic Basin, in response to rising tropical Atlantic SSTs (hypothesis 1), or the storm climate changes provoked on a regional scale a higher number of cyclone landfalls along the coast of Central America and around the Gulf of Mexico (hypothesis 2). A more southerly position of the NASH, which is known to result in more storm systems moving straight without a stronger northeastern deflection since 4.0 ka B.P., could have contributed to the latter (2, 33, 63–65).

An event-based TC-frequency reconstruction from a single location may, however, not necessarily reflect long-term changes of the Atlantic storm climate, as the stochastic nature of cyclone strikes is responsible for a certain proportion of the site-specific variability through time (66). A comparison to available multi-millennial TC-frequency records from

the circum-Caribbean region is required (Fig. 4) to support one of both hypotheses. A general increase in TC frequency over the past 5700 years, as shown in the GBH record, has been recorded by the Laguna Playa Grande record, Vieques Island, Puerto Rico (58), which is located on almost the same latitude. The archives from Mullet Pond, Florida (26) and Andros Islands, Bahamas (3), located in higher latitudes, in contrast, show almost constant or even decreasing trends, although there is a sufficiently coherent alternation traceable between active and calm phases during the past 2200 years (Fig. 4). For the past millennium, such a spatial north-south heterogeneity is well known from instrumental data and proxy-based TC-frequency reconstructions across the Atlantic Basin (36). Our data from the GBH supply evidence that this antiphase north-south variability can be traced further back in time through the entire Late Holocene.

We consider the lack of a basin-wide concurrency to be evidence that the long-term increasing trend, detected in the GBH and Puerto Rico records, is a regional manifestation in lower latitudes, caused by persistent southward ITCZ, NASH, and MDR migrations, which affected sites in higher latitudes in a different (antiphase) way. Our data support this coupled ITCZ and NASH forcing (45, 65), as the southwestern Caribbean TC-frequency fluctuates around a relatively low average value of seven events per century from 5.7 to 4.0 ka B.P. (fig. S4), when a more northern ITCZ/NASH prevailed (26, 53). From 4.0 to 1.0 ka B.P., mean cyclone activity, in contrast, increased from around 9 to 14 events per century, following an ongoing southerly migrating ITCZ/NASH. Therefore, we can exclude that the long-term trend is a basin-wide phenomenon in response to a general Late Holocene SST increase in the tropics. This view is supported by a recently published study (67) from the Pelican Cays, southern Belize, which demonstrates likewise a gradually increasing southwestern Caribbean TC frequency since 1.2 ka B.P., albeit over a much shorter time frame than the GBH record.

### Short-term TC fluctuations

This apparently regional long-term trend is superimposed by several multi-decadal and multi-centennial periods of enhanced or hampered TC frequency, which are differentiated by a calculated site-specific threshold of 5.1 TCs per 50-year counting interval. The GBH was exposed to an almost continuous interval of exceptionally high TC frequency (Fig. 3D) for most of the Common Era (A1 and A2). From 5.7 to 2.0 ka B.P., a pronounced quasi-periodical oscillation between active (A3–A9) and quiescent (C1–C9) stages occurred in phase with Holocene warm and cold climate variations (Fig. 3, D and E). A comparison (Fig. 4) with the TC-frequency reconstruction from Mullet Pond, Florida (26) demonstrates a general antiphase behavior to the GBH record from 4.2 to 1.7 ka B.P., followed by a coherent activity phase from 1.7 to 1.6 ka B.P. (A2) and two commonly pronounced activity peaks from 1.1 to 0.6 ka B.P. (A1). Some coinciding phases of elevated TC frequency are also visible in the reconstruction from Andros Islands, Bahamas (3). There are partial matches with the GBH activity intervals A4 and the beginning of A1, and a satisfactory coherence with the GBH activity intervals A3 and A2 are also visible. The alternations of TC frequency are less pronounced between the GBH and Puerto Rico (58) records, but three activity intervals in Belize (A9–A7 and A3–A1) coincide with two hyperactive phases in Puerto Rico (5.0 to 3.5 ka B.P. and 2.5 to 1.0 ka B.P.), respectively. In analogy to the modern pattern of storm clustering (48), the event-layer records from these four sites were possibly generated in parts by different storm populations with different trajectories

and landfall sites. Given the described long-term antiphase behavior between northern and southern sites, it is expected that they do not show a perfect agreement in timing and length of active/calm phases and differ crucially at some points (Fig. 4). The coincidence of several multi-centennial active and calm phases across the Atlantic Basin, however, strongly supports the argument that certain climate drivers are involved at synchronously influencing TC-frequency patterns from different study sites on shorter timescales.

An Atlantic Basin-wide compilation (68) verified the importance of endogenous climate variability for short-term TC-frequency fluctuations during the past millennium. In this synthesis, solar insolation-controlled MDR SST anomalies and phase changes of climate phenomena, such as the Interdecadal Pacific Oscillation (IPO), the AMO, the ENSO, and/or the NAO, were identified as the main climate drivers of synchronous TC-frequency variations on multi-decadal and multi-centennial scales. We focus on the interpretation of short-term fluctuations in the GBH record of the past 1200 years (Fig. 5A) as comparable reanalyses of sediment-based TC-frequency reconstructions have so far not been performed for times before 800 CE. As demonstrated by our core composite (fig. S1), the GBH TC-frequency curve (Fig. 3D) accurately resembles the Atlantic Basin-wide activity patterns (Fig. 5A), and it is also highly equivalent to another regional reconstruction from Cenote Muyil, Northern Yucatán Peninsula ( $r = 0.44$ ;  $P = 0.03$ ) (29). Some deviations from the basin-wide compilation (68) may be explained by the fact that the BZE-BH-SVC4 record (31) was included in this Common Era reanalysis. We recommend excluding this core and the BH6/7 (34) record in future comparisons as both obviously lack the core tops, i.e., the modern period (fig. S1). Both regional records of the GBH and Cenote Muyil (Fig. 5B) display three concurrent intervals of enhanced southwestern Caribbean TC frequency (600 to 800 CE, 900 to 1400 CE, and 1800 CE-modern) and exhibit also a shared calm phase with below-average activity from 1400 to 1800 CE. We have not taken into account another regional record from the Belizean coastal wetland site (69), mainly due to unresolved age dating uncertainties, a lower site sensitivity, and differences in temporal resolution and proxy methods. The pronounced phase in the southwestern Caribbean with above-average TC frequency from 900 to 1400 CE matches three centuries of basin-wide homogeneously increased storminess (900 to 1200 CE), attributable to the Medieval Warm Period. Such a basin-wide increased TC frequency was likely the consequence of elevated MDR SSTs due to high, near-equatorial insolation, and reinforcing effects of strong La Niña-like conditions, a cooler IPO phase and reduced tropical and high latitude volcanic activity (25, 70, 71). The subsequent decline in southwestern Caribbean storm activity from 1400 to 1800 CE (Fig. 5B) mirrors a basin-wide hampered TC frequency during the Little Ice Age (25). Lower rates of solar irradiance resulted in a negative MDR SST anomaly (70) not conducive for frequent storm genesis. A strongly negative NAO (24), two phases of intense volcanism (71), a particularly active African Easterly Jet (72), and latitudinal shifts of the NASH (73) are suggested as additional hampering factors. The sharp rise in TC frequency subsequent to 1800 CE, which was detected in both regional records and also in nearly all other circum-Caribbean records, is attributable to the Industrial Warmth and explainable by anthropogenic interventions leading to exceptionally high MDR SSTs.

The GBH consequently is suggested to host an excellent archive for TC-frequency changes on annual to millennial timescales for

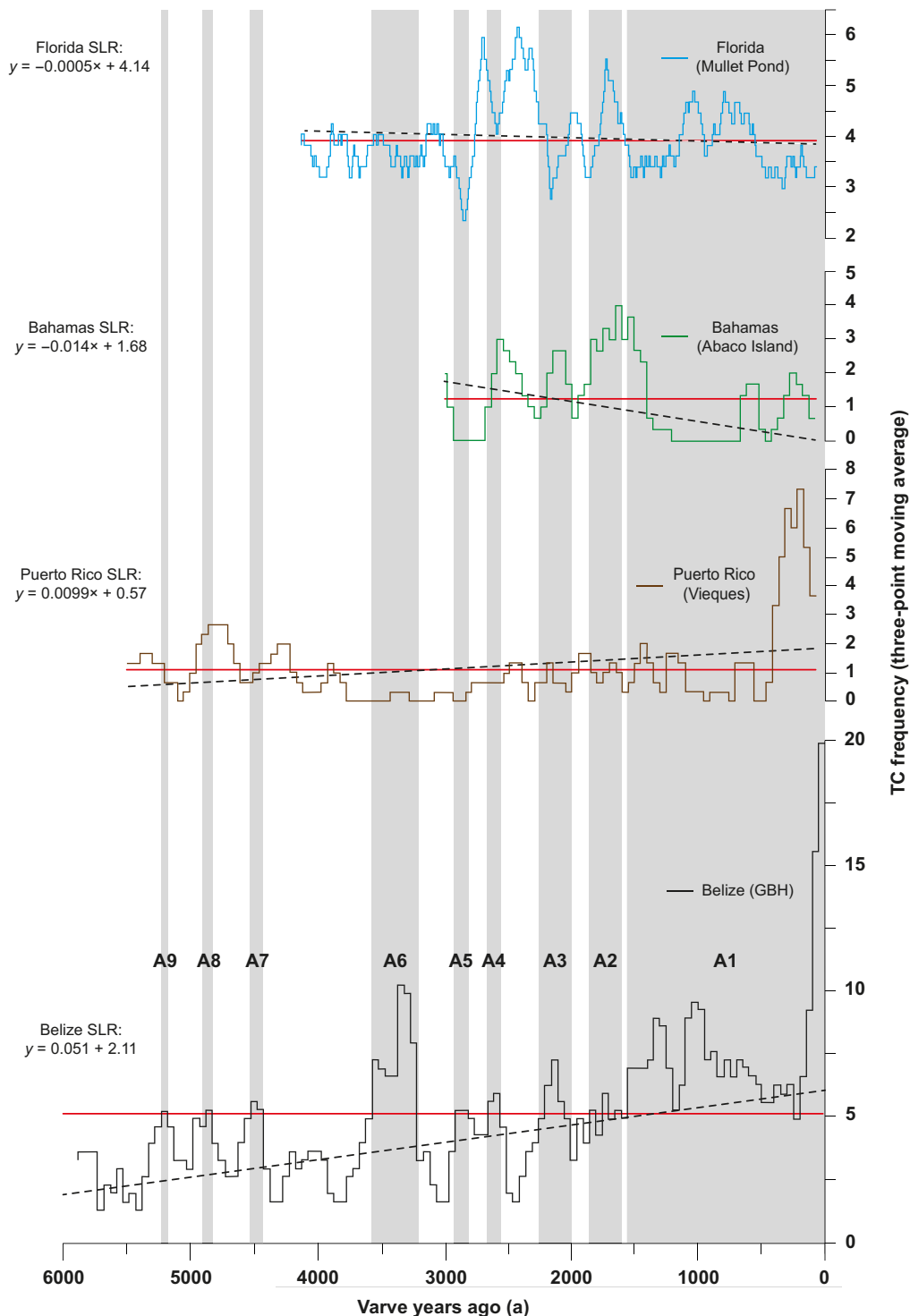


**Fig. 4. Comparison of multi-millennial TC-frequency records.** Multi-millennial TC-frequency records from the GBH, Puerto Rico (58), the Bahamas (3), and Florida (26), covering up to the past 5700 years. Active and calm phases are separated by site-specific thresholds (red lines) and highlighted for the GBH record in gray (for coloring, please refer to the online version of the manuscript). The black dashed lines are linear regressions (SLR), demonstrating long-term trends in the data. All the raw data for the reanalysis of the Puerto Rico, Bahamas, and Florida records originate from the NOAA paleoclimate database. It was taken into account that their age models have a different reference point (calibrated years B.P. 1950). The TC-frequency plots were generated processing a three-point moving average step plot using the software package PAST.v.4.08.

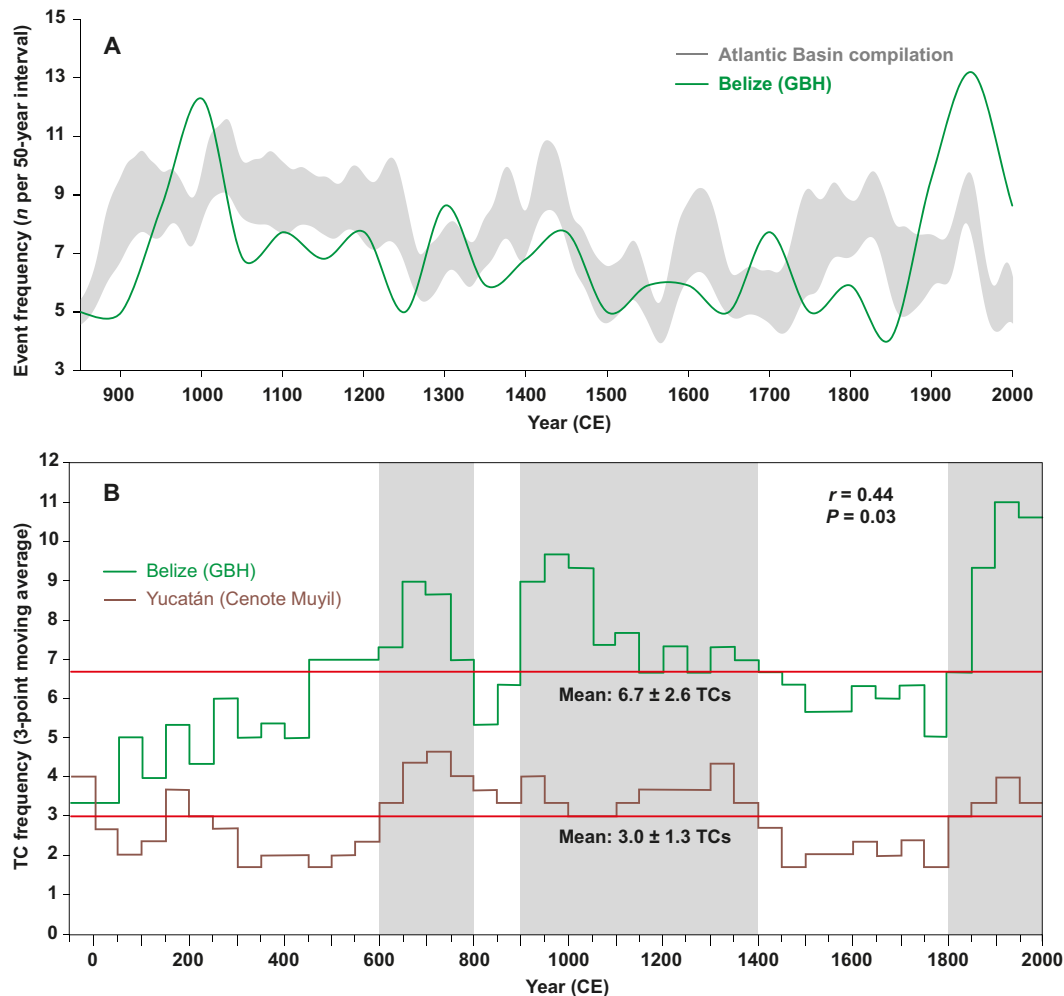


**Fig. 5. Reconstruction of Atlantic TC frequency from 850 to 2000 CE and regional comparison.** (A) A multisite sedimentary-based Atlantic Basin compilation (gray shading) (68) is provided besides the TC-frequency curve from this study (green). (B) Regional comparison between our TC-frequency reconstruction from the GBH (green) and the adjacent Cenote Muyil record (29) over Common Era times. TC-frequency plots were generated processing a three-point moving average step plot using the software package PAST.v.4.08. Active and calm phases have been defined by calculating site-specific thresholds (red lines) for storm activity:  $6.7 \pm 2.6$  TCs (GBH) and  $3.0 \pm 1.3$  TCs (Cenote Muyil) per 50-year counting window. Both records show overlapping intervals (gray) of enhanced south-western TC frequency (600 to 800 CE, 900 to 1400 CE, and 1800 CE–modern) and a mutual calm phase from 1400 to 1800 CE.

5700 years. We deciphered a regional long-term TC-frequency trend interpreted to be predominantly driven by ITCZ and NASH migrations, whereas short-term fluctuations synchronously followed prominent Holocene climate variations across the Atlantic Basin (Fig. 3E) and were, as demonstrated for the past 1200 years, strongly controlled by MDR SST anomalies and climate phenomena modes. The outstanding high numbers (nine TCs during the past two decades) of modern TC strikes in the southwestern Caribbean suggest an overriding control by modern global warming (Fig. 3D). An extrapolation (nine TC per 20-year window  $\times 5 = 45$  TCs per 100-year window) until the end of the 21st century, assuming the same or even more favorable climatic and oceanographic boundary conditions, displays a century of unprecedentedly high TC frequency that lies far above the natural variability of the Holocene interglacial ( $10.0 \pm 5.7$  TCs per 100-year window). Predictions of a continued tropical Atlantic SST increase and more frequently occurring La Niña events (from one every 20 years to one every 10 years; NOAA Report) are in harmony with our projected worst-case scenario of 45 TC strikes in the southwestern Caribbean

region from 2000 to 2100 CE. In response to a warming climate, multiple studies, however, predict a change in future TC behavior (74, 75). If the northern Atlantic experiences, for example, a disproportionate warming (18), either the present TC-strike latitudes may expand further northward (74) or a poleward migrated major trajectory and maximum intensity zone (75) could be established in higher latitudes. The latter could possibly lead to a TC-frequency decrease in the southwestern Caribbean as best-case scenario but at the same time cause an increase in northern Atlantic regions.

## MATERIALS AND METHODS

Deep blue holes with anoxic bottom water conditions have some noteworthy advantages as paleoenvironmental archives compared to coastal lakes (54), back barrier lagoons (58, 76), coastal wetlands (52, 69, 77), and salt marsh ponds (78–81). They are largely independent from minor sea-level changes, not affected by bioturbation and permanent wave action, and marked by a constantly high sediment supply, as well as an ample accommodation space (38).

## Coring the anoxic GBH

The coring equipment operated on the GBH was shipped in a 20-foot shipping container from Cologne (Germany) to Belize City (Belize). It consisted of an UWITEC Hybrid Platform, equipped with UWITEC gravity and percussion piston corers. The coring platform was assembled in Belize City and towed to Lighthouse Reef by a 9-m-long charter boat with outboard engines. The Belize Fisheries Department and the Belize Audubon Society helped to organize the use of existing mooring buoys and finding arrangements with dive boats that visit the GBH on a daily basis, as the anchored platform was a potential obstacle for other boats. The coring platform was moored in the sinkhole center (17° 18.572' N, 87° 32.060' W; Fig. 1C) at four fixed positions during a 6-day-long coring operation in June 2022, using ropes attached to two mooring buoys at the NE and NW margins of the GBH and two special marine reef anchors that were temporarily added at the SE and SW margins.

The gravity corer was used twice to sample the sediment-water interface and the uppermost 14 cm of the sediment succession. Deeper sediments were recovered with successive deployments of the piston corer, which was guided into the borehole by a metal funnel (connected to the drill platform by two steel cables) that was placed on the sinkhole floor. The piston corer consists of a 2-m-long steel barrel with an inner polyvinyl chloride (PVC) liner and a core catcher at the bottom. The liners were cut into 1-m-long core segments, and the core catchers (in average 13 cm) were stored in zip-lock bags. An unmanned aerial vehicle/drone was used to take aerial photos from both the location and the operational coring setup (Fig. 1C). The sediment samples were transported in thermo boxes by air cargo from Belize City to Cologne (Germany). Following initial processing in Cologne, the cores were transported further to Frankfurt (Germany) for subsequent analyses.

## Core opening, photo documentation, and sampling

The PVC tubes were cut lengthwise into two halves, one for subsampling and one for archive, with a semiautomatic core opening system with cranks and blades. Before subsampling, the surface area of the core halves was smoothed with an ultrathin copper sheet (0.7 mm). Subsequently, a photo documentation of the archive halves was carried out using a line-scan camera attached to a nondestructive x-ray fluorescence core scanner (XRF; COX-ITRAX). Subsamples taken with ultrathin metal cut-out plates (34) for radiocarbon dating ( $n = 9$ ), pollen investigation ( $n = 38$ ) (82), and textural analysis ( $n = 819$ ) originate from 2.5-mm-thick slabs (~5-g bulk material), which approximately equal the annual sediment deposition.

## GBH core composite

A GBH core composite has been intentionally created to close some of the core catcher gaps of the 30-m-long sediment core BH8. In the first step, the BH8 core segments, which were recovered at coring sites a few meters from each other during the 2022 CE drilling campaign, were stratigraphically and chronologically matched (fig. S1). Down to a depth of 4 mbsf, this involved two piston core segments from the main hole (BH8-4/1 and BH8-4/2) but also two short gravity cores (BH8-CO412-1 and BH8-CO412-2) and two short piston cores (BH8-18/1 and BH8-18/2; BH8-19/1 and BH8-19/2) from holes close by. In the second step, the 8.55-m-long spliced core (BH6 and BH7) and the 2.38-m-long core BH1, which had been recovered in the 2017 survey in the GBH (34), were stratigraphically and chronologically correlated to core BH8. As a result, the

core catcher gaps CC8-4, CC8-5, and CC-8-6 were closed to a depth of 8.2 mbsf.

It became apparent that there is an exceptional high degree of visual and sedimentological compliance of sediment anomalies (event layers) by complementary displaying the images from cores BH8 and BH6/7 side by side (fig. S1, B and C), using the open-source application Corelyzer (version 2.2.1). In the overlapping depth interval (upper 8.2 m), 195 of 212 event layers (92%) were replicated (table S2). The lack of 17 coherent event layers probably originates from the different coring technique that was used to recover the cores BH6 and BH7: Rossfelder P3 electrical vibrocore system without liner. During the extraction of the 9-m-long pipes of BH6 and BH7, degassing and minor material slides took place in deeper core sections. These processes caused minor stratigraphic disturbances in some areas of their successions. Therefore, it was not possible to retrace some of the sediment anomalies found in core BH8 in the corresponding sections of the spliced core BH6/7. An alternative explanation for some missing event layers might be a spatially limited density-surge deposition in the GBH. Some event layers, in particular, from weaker or more distantly passing storm systems, do probably not cover the entire bottom of the 320-m-wide sinkhole.

Our GBH core composite provides also a meaningful explanation for open questions about inconsistent regional TC-activity patterns, which have been raised by a recent study (29), that compared a Common Era frequency reconstruction from Cenote Muylil (northeastern Yucatán Peninsula) with two previous records from the GBH. The frequency curve reconstructed from the spliced sediment core BH6/7 (34) differs somewhat from that of Cenote Muylil (29) and another 1200-year reconstruction from the GBH (31). The chronological and stratigraphical correlation to the core BH8 reveals that the uppermost sections of cores BH6 (160 cm) and BH7 (67 cm) were not retrieved during the 2017 drilling campaign. This was likely due to sediment liquefaction during the core recovery process. The core BH1 (90 cm) and other short vibrocores (BH2 to BH5), the latter not shown in fig. S1, experienced the same issue. This significant material loss (minimum age offset of 78 years) explains why the TC-frequency curve of BH6/7 is not reproducible, without a recounting and redating of all identified event layers (table S2), using the BH8 composite as the master chronology.

We also compared the BH8 composite with the sediment core BZE-BH-SVC4, which was recovered in June 2009 from the GBH (31). A particularly conspicuous succession of pronounced event layers in 140 to 250 cm bsf in the BH8 composite also appears in core BZE-BH-SVC4 (yellow dashed lines in fig. S1). This suggests that the latter core also has a not yet expected core-top hiatus, in the order of ~80 cm, since it was recovered using the same error-prone Rossfelder technique as for BH6 and BH7. Images of the additionally existing gravity core (BZE-BH-GC2) were not accessible. However, from the ~80-cm hiatus, it becomes evident that this 65-cm-long surface core does not correlate with core BZE-BH-SVC4, as originally expected (31). The ~80-cm hiatus would also explain a constant age offset of ~339 years determined between radiometric measurements and varve counting in the BZE-BH-SVC4 record (31). This offset was explained by an unidentified older carbon source, which was, however, not evidenced again in previous (30) and the current radiocarbon dating approaches of the GBH sediments. Hence, we recommend being cautious with the BZE-BH-SVC4 record (31) and suggest to exclude the uncorrected BH6/7 TC-frequency curve (34) from regional

comparisons. Instead, the composite-based TC-frequency curve presented here (Fig. 3) shall be used, which reliably mirrors a basin-wide compilation of TC-frequency records from the tropical Atlantic over the past 1200 years (68).

### Varve-counting and radiocarbon age models

To gain an age model for event-layer timing at annual resolution, individual varves were counted directly on the core halve surfaces and cross-checked with counting on the high-resolution linescan images using optical color differences (open source image processing software ImageJ v.1.53 t). Complementary laminae thickness measurements provide annual information on sedimentation rates. We excluded geologically instantaneous event sedimentation and determined event-free sedimentation rates downcore by considering only laminae thickness measurements of fair-weather deposits. A previous study on the GBH sediments determined a maximum 5% error using a similar varve-counting approach (30). The core catcher gaps below 8.2 mbsf, which were not covered and filled by the core composite (see above), were texturally analyzed and identified either as an undisturbed fair-weather deposition without an event layer, or a section, that includes a single event layer, by means of their textural signatures in relation to that of the two different types of sediments. The time contained in these core catcher gaps was estimated following the calculated event-free sedimentation rates of the respective sedimentary unit ( $C = 2.41 \pm 0.04$  mm/a,  $B = 3.18 \pm 0.03$  mm/a, and  $A = 0.20 \pm 0.00$  mm/a), to which the core catcher section belongs. The results are somewhat inaccurate in the interval 16 to 24 mbsf, where the varve counting is more difficult to apply as in younger and older core sections. A few core catcher segments within this interval comprise up to 40-cm thickness and some fair-weather sections obviously lack intact varves. In these core parts, we had to take the mean fair-weather sedimentation rate of  $2.41 \pm 0.04$  mm/a, calculated for the sedimentary unit C (24.6 – 0 m), as the basis for varve counting and dating. This proceeding yielded a varve age of  $12,091 \pm 605$  years (a) B.P. (2022) at the core composite base.

The varve-counting age model is confirmed by a radiocarbon-based age model, which shows very similar progressions, with a noteworthy age offset appearing only in the middle core part (Fig. 2). We used a total of 15 radiocarbon dates as age-control points (table S3). Nine of those samples were extracted from the 30-m-long sediment core BH8. We considered six additional radiocarbon dates from the uppermost 8.55 m of the spliced sediment core BH6/7 (33), which were depth- and age-corrected on the basis of the stratigraphical correlation with the core composite BH8. The radiocarbon-based age model with 95% confidence intervals (fig. S6) was developed with Bayesian statistical approaches using the R library package BACON v 2.2 (83). The  $^{14}\text{C}$ -radiocarbon dating has been undertaken by Beta Analytic Inc., Miami, Florida with AMS. There, the organic material was separated from the bulk sediment samples by dissolving the carbonate material with HCl, washing the sample with NaOH, and repeating this process until no more carbonate remained. For the samples down to a depth of 2814.0 cm, Beta Analytic Inc. provided average  $\delta^{13}\text{C}$  values of  $-16.8$  ‰. Such a  $\delta^{13}\text{C}$  value is typically associated with a marine carbon origin, attributable to aquatic macrophytes and algae (84). Two samples at 2874.0 and 3000.6 cm bsf have more negative  $\delta^{13}\text{C}$  values ranging from  $-17.7$  to  $-27.2$ ‰. This is indicative of a different organic matter source, such as terrestrial C3 plants ( $-20$  to  $-30$ ‰) (85). For reservoir correction, the global marine reservoir effect of 405 years (residence time of carbon cycled in

the ocean before bio-assimilation) was considered for all samples indicating marine carbon origin and applied by Beta Analytic Inc. The conventional radiocarbon ages from both the marine and terrestrial organic residues were converted to calibrated years B.P. using either the BetaCal4.20 MARINE20 (86) or INTCAL20 (87) calibration curves (High Probability Density Range Method) (88). All calibrated ages are presented with a  $2\text{-}\sigma$  error in a 95% confidence interval. Radiocarbon dating revealed an overlapping age of  $12,583 \pm 101$  cal. years (a) B.P. (1950) at the core composite base (table S3).

Additional confirmation for the varve-counting age model in its uppermost part (Fig. 2) and confirmation for the enclosure of the sediment surface in the core composite (fig. S1) come from two chronological markers. First, increased pollen abundances of corn (*Zea mays*), pine (*Pinus*), and palm (*Arecaceae*) at 2.5-cm depth, which do not appear elsewhere in the core, provide evidence of known anthropogenic cultivation in the past decade (fig. S5). Second, higher abundances of volcanic glass shards, likely from the 1982 CE El Chichón eruption, occurred at 32.4-cm depth, which is dated to  $1979 \pm 2$  CE (fig. S8).

### Stratigraphic description and optical event-layer identification

A stratigraphic core log was created using both the optical descriptions and the high-resolution linescan images of the archive core halves (fig. S2). Major sedimentary structures and macrofossils were recorded, and all the different unconsolidated lithologies were described in terms of sedimentology. We identified 694 event layers, which clearly differ from the fair-weather sediments in the GBH (fig. S7). In the full marine unit C, light grayish (Munsell soil color: 5GY 6/2) to grayish green (5GY 5/2) fair-weather deposits are clearly distinguishable from white (2.5Y 8/1) to pale brown (2.5Y 8/2) colored event beds. In the restricted marine unit B, similarly colored, however slightly darker, grayish green (5GY 5/2) to grayish brown (2.5Y 5/2) fair-weather deposits appear, interrupted by clearly visible white (2.5Y 8/1) or very dark brown (10YR 2/2) up to almost black (10YR 2/1) event layers. In the cenote unit A, the fair-weather sedimentation is first characterized by a fine lamination of gray brown (2.5Y 3/2) deposits, followed by a structureless black (2.5Y 2.5/1) section at the core composite base. Event layers in this core part are white (2.5Y 8/1) colored and slightly faded.

The occurrence of optically pronounced event layers makes the study site stand out from other well-investigated blue holes (33, 35, 36). There, the sedimentary sequences completely lack conspicuous optical event layers, thereby requesting continuous quantitative textural analyses to be applied to differentiate between storm- and fair-weather sedimentation. In addition to the conspicuous differences in color, there are some more visual sedimentary characteristics that allow an optical separation of the GBH event layers from the fair-weather deposits: (i) sharp sedimentary contacts, (ii) presence of coarse sand and gravel-sized grains (e.g., mollusk shells, coral fragments, and/or *Halimeda*-platelets), (iii) lack of internal lamination, (iv) signs of coarsening/fining upward, and (v) increased content of organic material. Another helpful parameter to support the optical identification is the thickness of the event layers, as the sedimentation rate should be substantially increased during an instantaneous high-energy event. Varve thickness was determined to average values of 2.4 mm (unit C), 3.2 mm (unit B), and 0.2 mm (unit A) in the laminated sections (years without a cyclone landfall). The thickness of all visible event layers, in contrast, ranges from 2.5 to 376 mm, with a mean thickness of 17 mm.

## Textural analysis of event layers

We confirmed the optical identification of event layers by discrete quantitative coarse fraction data (%) and measured/calculated mean grain size values (micrometer). Classic textural analyses of 694 event layers and 125 fair-weather samples were carried out, the latter taken in different sampling intervals with a maximum spacing of 50 cm over the entire record (table S4). On their basis, we were able to confirm the textural thresholds for event-layer identification in the upper 24.6 m of the core composite, which was already determined in a previous project (34, 89), using continuous downcore textural analyses of 2914 samples at 2.5-mm steps from a 8.55-m-long section in the fully marine unit C. All these textural data of the spliced core BH6/7 were juxtaposed with laminated sections of fair-weather sediments and intercalating event layers. In the laminated fair-weather sediments, virtually no coarse fraction anomalies were observed above the textural thresholds.

For textural analysis, the samples were wet sieved through a 63- $\mu\text{m}$  standard grain-size sieve to separate the coarse fraction ( $>63\ \mu\text{m}$ ) from the fine fraction ( $<63\ \mu\text{m}$ ). The coarse fraction was dried at 50°C for 12 hours with a Thermo Fisher Scientific HERATHERMA-OVEN OMS-180; sieved through standard grain-size sieves of 2 mm, 1 mm, 500  $\mu\text{m}$ , 250  $\mu\text{m}$ , and 125  $\mu\text{m}$  (full  $\Phi$ ); and then weighed to determine dry masses, respectively. The fine fraction was left to rest for 48 hours in a sedimentation vessel (settling out of suspension), subsequently decanted, dried at 50°C for 24 hours, and dry-weighed to equally define the amount of fine material. From these data, a grain-size distribution was created with absolute (g) and relative (%) values for each grain-size class.

For mean grain-size determination, a more detailed analysis of the fine fraction is needed, including a further separation of the fine fraction into 63-, 50-, 40-, 20-, 10-, 2-, 1-, and 0.05- $\mu\text{m}$  intervals. Fine material analyses were performed by a laser-optical particle analyzer (HORIBA Laser Particle Analyser-950), with 1-g fine material, suspended in 0.4 N  $\text{Na}_4\text{P}_2\text{O}_7$  and demineralized water. All event layers from the historical record ( $n = 32$ ) were analyzed down to a depth of 103 cm (table S5). In addition, the fine materials of 32 more samples ( $n = 28$  fair weather and  $n = 4$  event layers) were measured for fine material abundances across the core composite at ~1-m intervals (table S5). A linear calibration was made between mean grain-size values, obtained from the laser-optical particle analyzer measurements and the amounts of coarse fraction ( $>63\ \mu\text{m}$ ) received from the initial sieving test (table S6). The correlation between both parameters is statistically significant ( $r = 0.81$ ;  $P < 0.05$ ). This calibration step allows the calculation of mean grain-size values for all the other textural samples in a sufficiently accurate approximation without extensive laser measurements by using the following linear equation:  $y = 2.6664 \times \text{amount of coarse fraction (\%)}$ . All textural samples were finally categorized by determination of classical grain-size parameters (mean grain size, sorting, skewness, and kurtosis), following the “Geometric and Logarithmic Folk & Ward method” using the software package gradistat v. 9.1 (90).

The 125 fair-weather samples of core BH8 depict a very low average coarse fraction content ( $>63\ \mu\text{m}$ ) of 4.3% (unit C), 2.3% (unit B), and 4.5% (unit A). For the 694 event layers, coarse-fraction abundances were calculated on average at 20.8%, with a range appearing from 2.1 to 96.5%. The mean grain size of the investigated fair-weather sediments amounts to 16.4  $\mu\text{m}$  (coarse silt) in unit C, 8.4  $\mu\text{m}$  (medium silt) in unit B, and 15.9  $\mu\text{m}$  (medium silt) in unit A. The average grain size of the 694 event layers is 54.9  $\mu\text{m}$  (very

coarse silt) but encompasses a range from 5.7  $\mu\text{m}$  (fine silt) to 625.9  $\mu\text{m}$  (coarse sand). For unit C, we determined a textural threshold for event-layer assignment to a mean grain size  $>24.9\ \mu\text{m}$  and a coarse fraction content  $>6.6\%$ , which satisfactorily resembles the continuous downcore textural analyses of fair-weather sediments in the spliced core BH6/7 ( $>24\ \mu\text{m}$  and  $>10.5\%$ ). We also introduced textural thresholds for the core composite units B ( $>14.5\ \mu\text{m}$  and  $>3.8\%$ ) and A ( $>21.0\ \mu\text{m}$  and  $>6.5\%$ ), respectively. Depending on the sedimentary unit, 91 to 96% of the optically identified event layers were confirmed by corresponding peaks above the core composite textural thresholds, using exclusively the coarse fraction ( $>63\ \mu\text{m}$ ) data. The grade of agreement with mean grain-size values is notably lower at 74 to 80%, which is probably the result of the linear approximation approach and the sufficient, but not perfect, correlation between mean grain size and coarse fraction data ( $r = 0.81$ ;  $P < 0.05$ ).

Textural data of 32 event layers from an observational record back to 1850 CE (table S1) were additionally compared with instrumental TC data, such as wind speed at the location (kilometer per hour), storm duration (days/hours), and the distance between storm tracks and study site (kilometer). All textural parameters were found to correlate best ( $P < 0.05$ ) with the wind speed at the study site (TC intensity). The statistical correlations ( $r = 0.53$ ;  $r = 0.40$ ;  $r = 0.45$ ) are, however, only moderate, and there are not enough data available to create and calibrate a valid proxy for reconstructing past TC intensity based on sediment texture (table S1). In the modern part of the record, only two event layers can be correlated with TC category H2 and just one event layer with category H3. We therefore discuss in the article only the variability of TC frequency.

## XRF and grayscale analyses

To determine the element composition of the sediment (in counts per second), the archive-halves were scanned at 2-mm resolution (~13,400 measurements) with an ITRAX-XRF scanner that was equipped with a Cr-anode x-ray tube set to 30 kV and 55 mA with 60-s integration time. Special attention was given to the strontium content and its ratio over calcium. For the GBH sediments, the Sr/Ca ratio seems to be a sensitive geochemical tool (fig. S3) for event-layer identification, supporting the identification on the basis of optical markers and textural data, since it differs between over-washed event layers (mean  $0.0329 \pm 0.0222$ ) and fair-weather sediments (mean  $0.0289 \pm 0.0083$ ). The higher ratio in the event layers is explained by higher amounts of carbonate materials from marginal reef sites (e.g., aragonitic coral skeletons and *Halimeda* chips), which are found to be generally enriched in strontium (91). The laminated fair-weather sediments, in contrast, mainly consist of lagoonal particles (e.g., mollusk shells and foraminiferal tests), that are relatively depleted in strontium. We first calculated a mean fair-weather Sr/Ca ratio for units C ( $0.0293 \pm 0.081$ ), B ( $0.0254 \pm 0.061$ ), and A ( $0.0334 \pm 0.0122$ ) and implemented specific thresholds for each core segment (table S7; sheet c columns F/G and L/M). In the two upper units C and B, 70.7 and 71.8% of 694 event layers can be confirmed by significant Sr/Ca peaks above the respective core segments threshold. The Sr/Ca application works particularly well to record event layers of fine- to coarse-sand size (e.g., EL39, EL43, EL46, and EL48), enriched in *Halimeda* chips and fragments of broken corals, whereas in event layers of silt size, in which these components are largely absent (e.g., EL37, EL41, EL41, and EL47), the Sr/Ca application reaches its limits (fig. S3). In the basal unit A, the accuracy of

the Sr/Ca proxy decreases sharply (48.6%), which is very likely the result of an increasing terrestrial influence during the cenote phase and an almost complete lack of coral skeletons and *Halimeda* chips as important sources of strontium.

The event-layer identification is further supported by radiographic images taken by a separate high-energetic XRF-scanning run along the central part of the archive core half. Their grayscale characteristics reflect minor density variations in the sediment cores (92). Grayscale values were automatically recorded at 0.20- to 0.40-mm intervals and processed in a linear profile by using the open-source image processing software ImageJ v1.53 t. In radiographic images, event layers have lighter colors (lower density) than varved core sections (higher density). Some pronounced peaks are exemplarily visible in the 40-cm-long core section of BH8-18/2 (fig. S3). Over the entire core length, tempestites have on average higher grayscale values of  $394.31 \pm 94.66$ , while the varved sections tend to lie around a lower mean value of  $383.53 \pm 88.59$  (table S8; sheets b/c columns F/G). We calculated average grayscale thresholds for the fair-weather sediment of units C ( $395.92 \pm 93.84$ ), B ( $355.71 \pm 66.08$ ), and A ( $347.75 \pm 62.59$ ) and implemented specific thresholds for each individual core segment (table S8; sheet c columns F/G and LM). In units C, B, and A, 62.9, 75.3, and 64.7% of 694 event layers are recorded by positive gray-value excursions above the respective core section threshold. Similar to the Sr/Ca method, grayscale values are highly dependent on the sediment properties (density and composition). Peaks in the record only satisfactorily reflect event layers of fine- to coarse-sand size, which are clearly separated from the fair-weather sediments in terms of a lower density, due to higher abundances of *Halimeda* chips. After completing both XRF runs in Cologne, the archive halves were packed in vacuum, transported to Frankfurt, and stored in a cold room at 4°C for archive purpose.

### Computing TC frequency

The findings on the event-layer characteristics presented above support the results of two other studies (93, 94), which indicate that the amount of the grain-size fraction ( $>63 \mu\text{m}$ ) is a sufficient proxy for identifying event layers in reef lagoon sediments or blue hole environments. However, for the anoxic GBH, we provided strong evidence by using a multi-proxy identification approach, primarily based on optical markers (fig. S7), supported by textural analyses, varve and event-layer thickness measurements, Sr/Ca ratios, and grayscale variations (fig. S3). For a successful identification of a potential event layer, the targeted deposit mandatorily requires a match with the primary criteria: (i) color (fair-weather sediments, gray or green; event layer, white to pale brown) and (ii) the lack of internal sedimentary structures such as varves or seasonal laminae. In addition, we considered several secondary criteria (textural and geochemical) to most precisely recognize event layers: (iii) deposit thickness ( $>2.41 \pm 0.04 \text{ mm}$ ,  $>3.18 \pm 0.03 \text{ mm}$ , and  $>0.20 \pm 0.00 \text{ mm}$  for units A, B, and C, respectively), (iv) amount of coarse fraction ( $>4.3$ ,  $>2.3$ , and  $>4.5\%$  for units A, B, and C, respectively), (v) mean grain size ( $>16.4$ ,  $>8.4$ , and  $>15.9 \mu\text{m}$  for units A, B, and C, respectively), (vi) Sr/Ca ratio ( $>0.0334 \pm 0.0122$ ,  $>0.0254 \pm 0.061$ , and  $>0.0289 \pm 0.0083$  for units A, B, and C, respectively), and (vii) grayscale variation ( $>347.75 \pm 62.59$ ,  $>355.71 \pm 66.08$ , and  $>395.92 \pm 93.84$  for units A, B, and C, respectively). After all the event layers had been reliably identified, we computed TC-frequency changes by simply counting the number of event layers in the working core halves (26) and added event layers found in core catcher samples after the BH8 core composite was created in the upper 8.2 m.

We summed up the event layers in 100-year observational windows (fig. S4A) to picture centennial-scaled shifts of storm frequency but also to facilitate basin-wide comparisons with other records using the same time window (35). In addition, a 50-year observational window was used to map multi-decadal shifts of TC frequency in the record (Fig. 3 and fig. S4B). In these 100- and 50-year windows, active and quiescent phases of storm activity were identified by calculating regionally derived thresholds (20) of  $10.0 \pm 5.7 \text{ TCs/100 a}$  and  $5.1 \pm 3.2 \text{ TCs/50 a}$ , respectively. The 100- and 50-year frequency data were smoothed (fig. S4 and table S9) using the software package PAST.v.4.08 and the LOWESS (LOcally WEighted Scatterplot Smoothing) algorithm with recommended default parameters (95, 96) and user-specified smoothing parameters (q). With a bootstrap option, a 95% confidence band is displayable for the smoothed curve fit, based on 999 random replicates.

### Historical record calibration

In the uppermost 100 cm of the BH8 core composite, 36 event layers were detected and compared with the historical record of TCs (International Best Track Archive for Climate Stewardship, IBTrACS) (49, 97) passing the study site within a 100-km radius to assess the sensitivity of the record for event-layer formation. In the past two centuries, 32 storms of different strengths left their traces in the unconsolidated sediments of the GBH (table S1). Their strength ranged from tropical depressions (rare) to tropical storms (moderate) and hurricanes (frequent) up to occasionally passing major hurricanes of categories 4 and 5 (Saffir-Simpson scale). Sixteen of these storms are reflected by event layers in the core composite, attributable to times younger than 1950 CE. From this point on, airplane reconnaissance (98) and satellite monitoring (99) supplied very reliable data for storm track distance, maximum wind speed/intensity, and residence time. We confine our instrumental record calibration thus only to historically documented TCs (intensity: tropical storms, major hurricanes), that migrated over the study site between 2022 and 1950 CE ( $n = 19$ ).

We were able to assign 16 recent event layers to passing storm systems ( $>\text{TS}$ ) with very small age offsets to the recorded strike year (fig. S8). Among these are tropical storms such as HARVEY (2011 CE), ALEX (2010 CE), ARTHUR (2008 CE), KYLE (1996 CE), and GERT (1993 CE), and stronger hurricanes, such as H1 NANA (2020 CE), H1 EARL (2016 CE), H4 IRIS (2001), H4 KEITH (2000 CE), H3 GRETA (1978 CE), H1 EDITH (1971 CE), and H1 ABBY (1960 CE). A particular outstanding 14.4-cm-thick event layer (EL20) at 45.0- to 59.4-cm core depth is attributable to H5 HATTIE (1961 CE), one of the region's most powerful storms ever (100). Besides these, three more distal distal crossing storm systems likely left event layers in the sedimentary record. Although H5 DEAN (2005 CE; 176 km), H5 MITCH (1998 CE; 217 km), and H2 FRANCELIA (1969 CE; 122 km) passed outside of a commonly used 100-km observational radius, they were due to their high intensity still in range to produce event layers (48). With a matching rate of 84.2%, the GBH site has, like all other proxy-based TC-frequency archives, a bias for underrating past storm activity (here, 15.8%).

Among the missing event layers from the instrumental era are the remnants of the cyclones HERMINE (1980 CE), LAURA (1971 CE), and GILDA (1954 CE), which could not be found in the core composite at or near the expected depth and age. These tropical storms have been probably too weak to generate storm waves and surges at the study site that induce an event sedimentation. However, the evaluation of the instrumental data and event layers in the BH8 record

suggests that the documentation of a storm in the GBH also depends, whether a storm system passes to the north, on the south or straight over the hole. With a success rate of 91%, nearly all southerly traversing storm systems were recovered in the sedimentary record. The centrally or northerly crossing storms were recovered much less often with only 75%. We assume that this is related to the morphology of the sinkhole, with eastern and northern channels in the surrounding coral reef and the rotational direction of storm systems on the northern hemisphere. For south-trending storm systems with counter-clockwise rotation, it is much easier to produce an event layer at the sinkhole floor. In such a case, the storms' strongest northeasterly winds and the attributed storm waves are oriented straight in direction to the channel openings of the sinkhole. With a northerly migration path, the strongest winds and highest waves tend to be directed away from the channels into the GBH. Both HERMINE (1980 CE) and LAURA (1971 CE) passed Lighthouse Reef at or from a northern position. Tropical storm GILDA (1954 CE), however crossed the region, unlike the two other storms, further south. This storm probably was too weak and distant to leave a visible event layer despite its generally favorable pathway.

On the other hand, we identified two event layers (EL17: 1965 CE and EL19: 1962 CE), which do not match any known historical TC events. Such coarse-grained anomalies may have been caused by rare winter storms or strong seismic activity, which can occur at the active strike-slip zone along the Caribbean and North American plate boundary, leading to tsunami wave-controlled redepositions of allochthonous particles and/or sinkhole slope destabilization. EL19 was probably the result of higher waves originating from a strong nearby earthquake with a magnitude of 6.1 (US Geological Survey), located 55 km south of Bodden Town, Cayman Islands. Far-field tsunamis were completely absent in the historical record and occurred in the Caribbean realm only very rarely in prehistoric times (101, 102). Only two major tsunami events were identified in the Caribbean realm during the past 1600 years (103, 104) however with only very small wave runups compared to the storm waves of intensive storms. Given the large number of 694 event layers in the core composite, recurring passages of TCs are by far the most likely origin for all the coarse-grained event layers in the GBH, considering the low number of tsunami events and the excellent historical record match of TCs and sedimentary anomalies.

## Supplementary Materials

### The PDF file includes:

Figs. S1 to S8  
Legends for tables S1 to S9  
References

### Other Supplementary Material for this manuscript includes the following:

Tables S1 to S9

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