Compounding impact of severe weather events fuels marine heatwave in the coastal ocean

B. Dzwonkowski, J. Coogan, S. Fournier, G. Lockridge, K. Park & T. Lee

Exposure to extreme events is a major concern in coastal regions where growing human populations and stressed natural ecosystems are at significant risk to such phenomena. However, the complex sequence of processes that transform an event from notable to extreme can be challenging to identify and hence, limit forecast abilities. Here, we show an extreme heat content event (i.e., a marine heatwave) in coastal waters of the northern Gulf of Mexico resulted from compounding effects of a tropical storm followed by an atmospheric heatwave. This newly identified process of generating extreme ocean temperatures occurred prior to landfall of Hurricane Michael during October of 2018 and, as critical contributor to storm intensity, likely contributed to the subsequent extreme hurricane. This pattern of compounding processes will also exacerbate other environmental problems in temperature-sensitive ecosystems (e.g., coral bleaching, hypoxia) and is expected to have expanding impacts under global warming predictions.
The resiliency of natural and human systems is often tested by extreme events. Such events alone can be devastating and when coupled with existing environmental stresses and/or low frequency trends, they can serve as critical change points. As a result, advancing the understanding of extreme events is fundamental to risk and vulnerability assessments that support management decision making and policy development. This need for improved understanding is becoming especially important in coastal regions where growing human populations, infrastructure, and stressed natural ecosystems present significant exposure to catastrophic impacts from extreme events.

A primary extreme event of concern for coastal systems throughout lower and mid-latitude regions is tropical cyclones. There are numerous examples of the devastating impacts these storms have had on coastal communities, yet advances in intensity forecasts have been limited. This is particularly problematic for storms making landfall where accurate intensity prediction is critical to human safety.

Forecasting storm intensity, as with other extreme events, is challenging due to contributions from multiple drivers (e.g., storm track, wind shear, dry air entrainment, and air–sea interaction) with their amplification potential dictated by complex causal chains. More specifically, the compounding processes that intensify storms and generate extreme conditions in coastal regions may differ from those in the open ocean due to the presence of shallow shelf bathymetry and coastline. These constraints can influence the way sea surface temperature (SST), the critical thermodynamic interface for ocean–storm interaction, evolves and thus modiﬁes storm intensity. Several studies have shown that the presence of stratiﬁcation prior to storm arrival can signiﬁcantly reduce the intensity of impending storms, via ahead-of-eye SST cooling. Conversely, other studies have suggested or shown that anomalously warm conditions on shelves can contribute to the intensiﬁcation of hurricanes through landfall.

While the previous studies showed connections between the shelf thermal structure and coastal storm intensiﬁcation, the threats associated with the ampliﬁcation of storms making landfall necessitate a broader understanding of processes by which shelf heat content can be pushed to extreme levels. This critical gap in understanding is in large part due to the lack of observational data during extreme events, which by their deﬁnition are rare. Such data could put events in historical context and/or determine the antecedent conditions and processes that generate such events. Despite these challenges, a long-term coastal observing system in the northern Gulf of Mexico provides a unique perspective on shelf thermal conditions before, during, and after Hurricane Michael, an extreme storm event in October 2018. Through the extensive observational records at this mooring site as well as an idealized one-dimensional model, this study demonstrates that the shelf heat content, prior to Hurricane Michael making landfall, was at an extreme state (i.e., experiencing a marine heatwave) set up by a series of compounding atmospheric processes: a shelf mixing event by tropical storm Gordon followed by an atmospheric heatwave. While this study emphasizes the connection between shelf heat content and storm intensiﬁcation, compound events that push the shelf to an extreme state (i.e., a full water column marine heatwave) represent a potentially important means by which other temperature-sensitive coastal issues can be ampliﬁed into extreme states (e.g., coral bleaching, hypoxia), demonstrating the broad importance of this series of compounding processes.

The development and ampliﬁcation of hurricanes in the Gulf of Mexico are a common phenomenon during summer and fall seasons (i.e., the Atlantic hurricane season between June 1 and November 30) due to areas of very high heat content derived from the Loop Current and its associated eddies. Thus, the intensiﬁcation of Hurricane Michael (October 7–10, 2018, Fig. 1) ﬁts a common pattern for this region; however, this event did stand out as an extreme on several metrics. The strength of the storm alone, reaching a rare category 5 designation, demonstrates the extreme nature of the event. More striking is the setup under which this strengthening occurred as the storm developed late in the Atlantic Hurricane Season and intensiﬁed throughout its transit across the continental shelf. Both of these factors are typically associated with weaker or a weakening of storm events. Furthermore, this storm was particularly hazardous because its intensiﬁcation was rapid and was consistently underpredicted by forecasts throughout its life. Consequently, Hurricane Michael, the strongest storm on record to make landfall on the Florida Panhandle, resulted in 16 fatalities and $25 billion in damage in the United States. Initial investigations of this storm highlight several factors that may have contributed to intensiﬁcation including favorable atmospheric and oceanic conditions. However, the ampliﬁcation through landfall suggests the thermal structure and associated heat content on the shelf in the Mississippi Bight may have played a contributing role to the evolution of this extreme storm event.

**Results**

**Shelf heat content evolution.** The temperature data at site CP provide a unique view of shelf heat content and its potential to have contributed to the intensiﬁcation of Hurricane Michael (Fig. 2). Prior to landfall, the thermal conditions on the shelf were exceptionally warm with the depth-average temperatures, a proxy for heat content, generally above 29 °C during the latter half of September into October. The heat content only dropped by ~0.5 °C over the 3–4 days when Michael transited across the shelf, leaving the conditions well above the 26 °C threshold typically considered conducive for storm intensiﬁcation. The pre-storm period is particularly striking when put in context with historical data at site CP. The long-term (2005–2018) mean in late September is around 27 °C (standard deviation of ~1 °C), much closer to the lower temperature limit associated with...
intensification (~26 °C). By comparison, the 2018 depth-average temperature was well above these conditions (at or above the 90th percentile), making it the warmest year observed in the in situ time series at site CP and exceeding any other year by 0.5–1 °C for this late September/early October time period.

To arrive at this high level of thermal energy (i.e., a full water column marine heatwave), the evolution of the depth-average temperature experienced two critical periods of increasing heat content. The first increase from ~26.5 to ~29 °C (August 25–September 2) was driven by a downwelling event caused by southeast winds in late August (Fig. 2b–d), associated with the approach and arrival of TS Gordon. The onshore Ekman transport driven by the easterly component of the southeast winds brought warm surface waters across the shelf which are then forced down at the coast, thereby initiating the warming in the subsurface. The subsequent increase of wind speed enhanced the vertical mixing of the warmer surface and cooler subsurface waters, which further homogenized the temperature in the water column. The event resulted in a dramatic change in the temperature structure with the highly stratified shelf becoming vertically uniform (Fig. 2e). As the storm passed over the region, site CP lost ~0.75 °C in the depth-average temperature consistent with some thermal dynamic heat loss expected from tropical storms, i.e., heat transferred from the ocean to the atmosphere9. Despite the heat loss, the vertical mixing of surface water increased the bottom temperature by ~4 °C relative to pre-storm conditions.

The well-mixed conditions lasted several days, at which point the second warming period began (September 6–22) and was associated with relatively mild wind conditions (wind magnitudes <~5 m s⁻¹) and excessively warm atmospheric conditions (air temperature ~28 °C) (Fig. 2b, f). For context, most of the mid to late September 2018 air temperatures were consistently above the 90th percentile threshold from climatological September air temperatures at marine stations throughout the region (Fig. 2f and Supplementary Fig. 1). This atmospheric heatwave produced a warming event of longer duration (relative to TS Gordon), reheating the upper water column resulting in depth-average temperatures >29 °C and restratifying the thermal structure with the SSTs exceeding 32 °C at times (Fig. 2e, g). Interestingly, there was a mid-water column warming in late September (~28th–29th, Fig. 2e). From the available data it is difficult to determine the cause of this event, however, the warming may have been generated by advection or density compensation. The overall effect of these processes resulted in a water column that maintained extreme heat content well into early October when coastal waters usually begin to experience rapid cooling. Given the thermal conditions at site CP, two natural questions arise in relation to Hurricane Michael. First, is the coupling of events (i.e., a storm mixing event followed by an atmospheric heatwave) critical to the observed excessively high heat content on the shelf in early October? Second, are the conditions at this shelf site (i.e., site CP) representative of the broader Mississippi Bight where Hurricane Michael intensified (Fig. 1)?

Compounding impacts on heat content. To address these questions, a relatively simple one-dimensional (vertical) model, similar to the one in ref. 22, was used to provide a first-order
understanding of the processes impacting the thermal structure on the shelf as well as the relative importance of the coupled events. The one-dimensional model simulates the time evolution of the vertical profile of the temperature by applying surface heat fluxes as well as mixing energy determined from bulk formulas for wind and tidal currents at the surface and bottom, respectively. The design of different model runs is summarized in Table 1 with details in the “Methods” section. In short, three simple model scenarios were conducted to determine (1) the best available surface heat flux parameterization; (2) the impact of storm mixing; and (3) the effects of varying shelf depths.

The initial model runs (cases A1–A3 in Table 1) were designed to determine how well a one-dimensional model may capture the main features of the observed thermal structure with three different heat flux parameterization methods (see “Methods” section). For these runs, a subset of the data between August 25 and October 7 (horizontal black line in Fig. 2e) was selected to examine the model performance over the period around the two main events hypothesized to contribute to the late October extreme heat content. The results of cases A1–A3 captured several important aspects of the observed thermal structure (Fig. 3) despite the inherently three-dimensional nature of coastal heat

| ID | Initial conditions | Surface heat flux | Comments |
|----|-------------------|-------------------|----------|
| Three runs to test the model (August 25–October 7) |
| Case A1 | 8/25 condition | NARR and S&B<sup>a</sup> | Salinity specified with data |
| Case A2 | 8/25 condition | NARR and TOGA (with observed SST)<sup>b</sup> | Salinity specified with data |
| Case A3 | 8/25 condition | NARR and TOGA (with modeled SST)<sup>c</sup> | Salinity specified with data |
| Three runs to examine the importance of the storm mixing event (September 7–October 7) |
| Case B1 | 8/25 condition | NARR and S&B | |
| Case B2 | 8/25 condition (mixed)<sup>a</sup> | NARR and S&B | |
| Case B3 | 8/25 condition (mixed) | NARR and S&B | With a generic storm heat loss<sup>d</sup> |
| Eight runs to examine the depth dependency of the compound impact<sup>e</sup> (September 7–October 7) |
| Case C1a, C2a, C3a, C4a | Stratified NARR and S&B | |
| Case C1b, C2b, C3b, C4b | Vertically mixed NARR and S&B | |

<sup>a</sup>The observed thermal profile at 23:00 on August 25, 2018 and its vertical average (black solid and black dashed lines in Fig. 4, respectively): The initial depth-average temperatures are 27.3 °C for cases A’s and B’s, and 28.8, 27.5, 26.1, and 23.4 °C for C1, C2, C3, and C4, respectively.

<sup>b</sup>Net outward radiation estimated using the bulk formulations in ref. 22.

<sup>c</sup>Latent and sensible heat flux estimated using the TOGA-COARE algorithms in ref. 35 forced with observed or modeled SST.

<sup>d</sup>With a generic storm heat loss based on an open ocean category 3 storm following ref. 9.

<sup>e</sup>Idealized thermal profiles with water depths of 20, 30, 40, and 60 m (cases C1–C4: see Fig. 4) with vertically uniform salinity.

![Fig. 3 Times series of the model results for cases A1-A3.](https://example.com/fig3.png)

The modeled temperature structure from cases a A1, b A2, and c A3 as well as d the comparison between the observed (Obs) and modeled depth-average temperature, with the filled triangles indicating the landfall time of TS Gordon (9/4/2018). The three model cases differ in the parameterization of the heat flux terms and their use of observed or modeled SST with details provided in the “Methods” section and Table 1. Accounting for the cold bias associated with response to TS Gordon, case A1 in (d) best captured the depth-average temperature response after the impact of TS Gordon with $r = 0.89$. The case A1 parameterization was used in the subsequent model experiments (cases B’s and C’s in Table 1) with the black vertical dashed line in (a) marking the post TS Gordon period (9/7/2018) when the subsequent model runs began.
budgets. All three forcing approaches demonstrated: (1) the complete mixing of the water column by TS Gordon resulting in the warming of the lower portion of the water column, and (2) the post-Gordon thermal re-stratification associated with the reheating of the upper ocean.

It is clear that this one-dimensional approach fails to reproduce the initial warming in late August and the timing of the homogenization of the water column associated with TS Gordon (Figs. 2e and 3a). These features in the temperature structure are characteristics of downwelling events, which highlights the established importance of three-dimensional processes associated with hurricane responses in the coastal ocean. This model limitation imparts a cold bias in temperature outputs at the start of the post TS Gordon period with the depth-average temperatures in the different A cases being between -1 and 3 °C cooler than the observations (~September 7, Fig. 3d). While case A2 had SST and depth-average temperature closer to the observed conditions, the heat flux parameterizations used in case A1 was selected for the subsequent model experiments for two reasons. First, the latent and sensible heat fluxes in case A2 were derived with the observed SST which represents a dependency on a priori information nudging the model outputs toward the observations that they are being compared to. Furthermore, this same parameterization of the heat flux when using the modeled SST (case A3), i.e., without the observationally derived heat fluxes, did much worse relative to case A1 (Fig. 3c, d). Second and more importantly, of the three modeled cases, case A1 showed the best representation of the observed post-Gordon depth-average temperature variations, after accounting for the cold bias associated with the passage of TS Gordon (Fig. 3d). The relatively high correlation between case A1 and observations ($r = 0.89$) indicates that the post-storm thermal structure of the water column was primarily a one-dimensional balance driven by surface heat fluxes and vertical mixing. Thus, this simple one-dimensional model (case A1) was used in the subsequent model experiments to further examine the thermal structure with and without compounding processes.

Given the reasonable results produced by the one-dimensional model after TS Gordon, we conducted experiments focused on the specific time period between September 7 and October 7 to assess the impact of the mixing on the evolution of the thermal structure, particularly in terms of the depth-average temperature, prior to the atmospheric heatwave. The first set of numerical experiments (cases B1–B3 in Table 1) were conducted using the thermal structure just prior to TS Gordon (either stratified as observed or artificially mixed: black lines in Fig. 4) as initial conditions and allowing them to evolve based on forcing conditions during the model run. The results were notably different with the stratified water column remaining stratified while the mixed case restratified beginning in early September but remained much more weakly stratified due to the warm thermal conditions at depth (Fig. 5a, b). This difference in stratification had an impact on the uptake/loss of heat across the air–sea interface with the mixed cases (cases B2 and B3) having ~1 °C higher depth-average temperature than the stratified case (Fig. 5c). Given that the observed depth-average temperature was nearly 2 °C above the long-term mean in early October, this ~1 °C increase from the mixing event coupled with a subsequent atmospheric heatwave accounts for nearly 50% of the observed deviation from the long-term mean state (Fig. 2a) and represents a temperature change large enough to significantly impact storm intensity. Importantly, removing this added 1 °C effect from the observed depth-average temperature in early October would place the depth-average temperature well below the 90th percentile threshold associated with marine heatwaves (Fig. 2a). Thus, the compounding processes observed in September of 2018, adding 1 °C depth-average temperature to the water column, made what would have been an otherwise above average event into an extreme event (above the 90th percentile threshold, Fig. 2a).

Additional numerical experiments using idealized thermal profiles more typical of the northern Gulf of Mexico over a range of depths (cases C1–C4 in Table 1 and Fig. 4) indicate a depth-dependent pattern with the relative impact increasing with increasing depth (Fig. 5d). In these model experiments, the focus was on the differences in the evolution of the depth-average temperatures between the initially stratified and mixed conditions at a given water column depth. The idealized 20-m water column (case C1) had less thermal stratification than the observation-based case and hence a smaller difference in the upper ocean temperatures between the mixed and stratified cases (Fig. 4). As a result, the stratified and mixed initial conditions (cases C1a and C1b, respectively) showed very little effect on the overall heat content of the water column, i.e., very little differences in the depth-average temperatures (Fig. 5d). This changed as deeper profiles allowed for larger differences in the upper ocean temperatures between the mixed and stratified cases. In the two deepest cases (i.e., 40 and 60 m), the event coupling provided differences >0.8 °C in the depth-average temperatures between

---

**Fig. 4 Initial temperature structure for the different model cases.** The observed profile (black solid line) and its vertical average (black dashed line) are from site CP at 23:00 on August 25, 2018, and used as the initial thermal structure for the model runs with ‘8/25 condition’ and ‘8/25 condition (mixed)’ in Table 1, respectively (cases A1–A3 and B1–B3). The colored solid and dashed lines indicate the idealized stratified (Cases C1a, C2a, C3a, and C4a) and mixed (Cases C1b, C2b, C3b, and C4b) initial temperature conditions, respectively, for the four additional model scenarios with different depths (Table 1). Note that the vertical dash line indicates the depth-average temperature associated with a given stratified case, projected over the full water column to represent ‘mixed’ temperature structure for that scenario (e.g., Cases C1a and C1b).
the mixed and stratified cases (Fig. 4d). In addition, these modeling scenarios suggest that the increasing heat content difference with water depth will eventually be mitigated by the depth-average temperature dropping to or below 26 °C (e.g., gray dashed line in Fig. 4), leading to conditions that would not be expected to favor hurricane intensification. While additional observational and modeling work is needed to fully understand relationships between mixing and reheating events on continental shelves, our findings do indicate that changes in depth and hydrographic structure will, not surprisingly, affect the extent to which compounding processes intensify the warming of the water column. Overall, the coupling of a mixing event followed by an atmospheric heatwave does enhance heat content of the water column relative to an atmospheric heatwave without a mixing event.

Fig. 5 Results of model experiments that compare the temperature characteristics of the water column with and without a mixing event. The water column temperature structures with the stratified and mixed initial conditions, i.e., without and with the storm mixing (cases B1 and B2 in Table 1, respectively); the black contours in (a) and (b) indicate isotherms (26, 28, and 30 °C). c The depth-average temperature from cases B1 (red, stratified), B2 (blue, mixed), and B3 (cyan, mixed with initial heat loss from a storm event); note that the mixed cases (B2 and B3) end nearly 1 °C warmer than the stratified case (B1). d The depth-average temperature difference between the mixed (cases C1b-C4b) and stratified (cases C1a-C4a) model experiments with idealized temperature profiles with water depths of 20 (magenta), 30 (orange), 40 (yellow), and 60 m (gray); see Table 1 for a summary description of different cases and Fig. 4 for the initial temperature profiles used. For all model experiments, the net outward radiation was estimated using the bulk formulations in ref. 22.

Potential extent of the compound event. While the model results indicate that the compounding impact of the sequential atmospheric events (i.e., TS Gordon and then the atmospheric heatwave) did contribute to the extreme state of heat content at site CP, its location is notably distant away from the track of Hurricane Michael (Fig. 1). There is some evidence suggesting that the processes observed in the western Mississippi Bight were similar to those in the eastern part of the basin where Hurricane Michael crossed the continental shelf. First, the shelf mixing associated with TS Gordon likely impacted the broader Mississippi Bight region as the structure of the system had a significant wind field. This is supported by satellite data that showed notable decreases in SST (ΔT of 1–2 °C) and increases in sea surface salinity (ΔS of 1.0–1.5), indicative of mixing across the shelf throughout the region (Fig. 6). The response to the atmospheric heatwave was also regional in nature as indicated by the exceptionally warm satellite-derived SST anomalies across the region, consistent with a marine heatwave (Fig. 1). The only in situ data on the shelf in the eastern Mississippi Bight was SST data at site PCB. Similar to site CP, the water temperature was anomalously high relative to historical values, and more importantly the in situ SST data between site CP and PCB for 2018 followed very similar patterns including the warming prior to TS Gordon and the slower, longer duration of warming associated with the regional atmospheric heatwave (Fig. 2g). Thus, the extreme heat content observed at site CP was indicative of a regional marine heatwave in the Mississippi Bight that would have resulted in the intensification of Hurricane Michael.

Discussion

Regardless of the exact contribution of shelf heat content on the intensification of Hurricane Michael, this study has identified a new pattern of compounding processes that can lead to extreme conditions in coastal oceans (Fig. 7). The observed extreme thermal conditions were set up by an initial mixing event during the passage of TS Gordon and intensified by a subsequent regional atmospheric heatwave. While the downwelling effect associated with TS Gordon was clearly important in influencing the heat content at this specific site, the storm generated mixing that impacted the broader shelf region (Fig. 6) and proved critical in two ways. First, the direct mixing of shelf water resulted in a mixed initial conditions, i.e., without and with the storm mixing (cases B1 and B2 in Table 1, respectively); the black contours in (a) and (b) indicate isotherms (26, 28, and 30 °C). c The depth-average temperature from cases B1 (red, stratified), B2 (blue, mixed), and B3 (cyan, mixed with initial heat loss from a storm event); note that the mixed cases (B2 and B3) end nearly 1 °C warmer than the stratified case (B1). d The depth-average temperature difference between the mixed (cases C1b-C4b) and stratified (cases C1a-C4a) model experiments with idealized temperature profiles with water depths of 20 (magenta), 30 (orange), 40 (yellow), and 60 m (gray); see Table 1 for a summary description of different cases and Fig. 4 for the initial temperature profiles used. For all model experiments, the net outward radiation was estimated using the bulk formulations in ref. 22.

Potential extent of the compound event. While the model results indicate that the compounding impact of the sequential atmospheric events (i.e., TS Gordon and then the atmospheric heatwave) did contribute to the extreme state of heat content at site CP, its location is notably distant away from the track of Hurricane Michael (Fig. 1). There is some evidence suggesting that the processes observed in the western Mississippi Bight were similar to those in the eastern part of the basin where Hurricane Michael crossed the continental shelf. First, the shelf mixing associated with TS Gordon likely impacted the broader Mississippi Bight region as the structure of the system had a significant wind field. This is supported by satellite data that showed notable decreases in SST (ΔT of 1–2 °C) and increases in sea surface salinity (ΔS of 1.0–1.5), indicative of mixing across the shelf throughout the region (Fig. 6). The response to the atmospheric heatwave was also regional in nature as indicated by the

the mixed and stratified cases (Fig. 4d). In addition, these modeling scenarios suggest that the increasing heat content difference with water depth will eventually be mitigated by the depth-average temperature dropping to or below 26 °C (e.g., gray dashed line in Fig. 4), leading to conditions that would not be expected to favor hurricane intensification. While additional observational and modeling work is needed to fully understand relationships between mixing and reheating events on continental shelves, our findings do indicate that changes in depth and hydrographic structure will, not surprisingly, affect the extent to which compounding processes intensify the warming of the water column. Overall, the coupling of a mixing event followed by an atmospheric heatwave does enhance heat content of the water column relative to an atmospheric heatwave without a mixing event.

Discussion

Regardless of the exact contribution of shelf heat content on the intensification of Hurricane Michael, this study has identified a new pattern of compounding processes that can lead to extreme conditions in coastal oceans (Fig. 7). The observed extreme thermal conditions were set up by an initial mixing event during the passage of TS Gordon and intensified by a subsequent regional atmospheric heatwave. While the downwelling effect associated with TS Gordon was clearly important in influencing the heat content at this specific site, the storm generated mixing that impacted the broader shelf region (Fig. 6) and proved critical in two ways. First, the direct mixing of shelf water resulted in a mixed
was caused by the reduced SST post-mixing event which lowered the effectiveness of the primary heat loss terms (i.e., sensible and latent heat fluxes). The reheating of the upper ocean was further facilitated by initially weak stratification levels due to storm mixing which were conducive to a rapid redistribution of incoming solar radiation to deeper waters. Since solar irradiation is primarily absorbed by the very near surface of the water column, low levels of stratification would allow this incoming heat to be more easily mixed to depth, limiting the rate of temperature increase at the sea surface and thus slowing the heat loss out of the upper ocean. Consequently, the compounding impacts of a mixing event followed by an atmospheric heatwave resulted in the highest late September/early October heat content on the shelf in the Mississippi Bight over a 13-year record.

An unclear aspect of the newly identified sequence of events is the duration of the bottom warming associated with the downward transfer of heat after a mixing event (Fig. 7b). This question directly relates to the residence time of bottom waters which, being dependent on shelf geometry and circulation, is likely to be highly variable among different shelf regions. The Mississippi Bight is generally a wide (~200 km) and gently sloping (depth to width ratio of ~0.001) shelf (with the exception of the centrally located Desoto Canyon region), which would favor long residence times. Furthermore, current velocity data from site CP after TS Gordon showed a series of upwelling and downwelling events producing limited net transport between September 7 and October 7 with a depth-average mean of ~3.3 cm s$^{-1}$ which translates to a transport length scale of ~85 km. While this information is from only a single location, it suggests the broader regional circulation was likely weak, favoring a longer retention of the warm bottom water.

The importance of heat content and thermal structure on hurricane intensity is well-established and much of the recent work on continental shelves has focused on intensity reduction through stratification breakdown and the resulting injection of colder bottom water into the upper water column as storms pass over these regions. Our findings highlight that this same de-stratification process, given the right conditions, can be a precursor for extreme heat content, and hence intensification of subsequent storms. The shelf-wide extent of the processes observed at the mooring site was consistent with the regional marine heatwave occurring across the Mississippi Bight and would have contributed to the observed intensification of Hurricane Michael as it transited the continental shelf. With near-real-time availability of many coastal in situ and satellite observations and an understanding of this type of compound event, prediction of potential storm intensification of landfall events could be enhanced. Thus, this study reinforces the urgent need to better represent coastal hydrographic conditions in hurricane prediction efforts.

Unfortunately, the understanding of extreme events is complicated by climate change, and current long-term climatic trends suggest a growing positive feedback between the processes involved in this compound event that could expand the impact of such extreme conditions. For example, tropical storms are expected to increase in strength and there is some evidence of a poleward expansion of their activity$^{29}$. In addition, there is abundant evidence that terrestrial heatwaves will increase in frequency, duration, and intensity$^{29}$. As a result of these shifts in the event characteristics, mixing events are likely to impact wider swaths of shelf areas and the subsequent reheating is likely to be more intense. Thus, the cumulative effect should amplify the impacts of this compound event pattern on shelf heat content under the current forecasts for a warmer climate.

While the statistical likelihood of this compound event is unclear now as well as in the future, the importance of

Fig. 6 Surface temperature and salinity differences. Surface ocean property differences in a temperature and b salinity before and after the passage of TS Gordon, with the circles showing the storm track of Gordon as tropical storm (TS) and depression (TD). Dictated by data availability, the temperature difference was determined using the conditions on August 28 and September 7, 2018, and the salinity difference using September 2 and September 9, 2018. The gray and black contours are 20- and 100-m isobaths.

Fig. 7 Conceptual diagram of the compound event. Conceptual diagram of the compound event that resulted in extreme shelf heat content including the a initial stratified shelf, b mixing event response, and c atmospheric heatwave response, showing the water column temperature profile (black thick line), the water column heat content ($H_c$: thick black bar on the bottom), the incoming solar radiance ($Q_i$: yellow arrow), and the net heat loss ($Q_o$: red arrow). The dashed black line in (b) and (c) indicates the temperature structure from a previous phase of the sequence of events. The magenta dashed line in (c) indicates changing upper-layer stratification during the atmospheric heatwave. The changing arrows for $Q_o$ reflect the dependence of this term on SST.
understanding extreme conditions lies in their disproportionately large impact on human and natural systems. As suggested by this study, extreme hurricanes, being linked to SST, are clearly one class of coastal hazard that will be influenced by such extreme heat content. However, this compounding amplification of heat content may be devastating to ecosystems as well, which are typically of significant societal and economic value. For example, temperature-sensitive benthic communities and habitats (e.g., coral reefs and hypoxia-prone shelves) already stressed by long-term warming trends and terrestrial inputs may be pushed beyond their resilience capacity by such extreme heat events.\(^3^0\)\(^3^9\).

While the effects of marine heatwaves on ecosystems have been demonstrated\(^3^1\)\(^3^2\), the impacts of the observed extreme heat content events are difficult to quantify using conventional SST-based identification algorithms because of the significance of the water column temperature structure at depth. As such, this sequence of compounding processes and the resulting extreme conditions represent a ‘black swan’ event that a range of coastal interests should be considering in management and disaster response decisions.

**Methods**

**In situ data and associated analysis.** To understand the atmospheric and oceanic conditions on the shelf before, during, and after Hurricane Michael, field and analysis data from various sources were used. Standard meteorological data, including air temperature, relative humidity/dew point temperature, and wind speed and direction from two NOAA National Data Buoy Center (NDBC) stations were used: 42012 offshore of Orange Beach, AL (ORB) and D91A1 on Dauphin Island, AL (Fig. 1). These stations were the closest measurements available to the main mooring site (CP), and both were typically similar in nature and have relatively long records (10 and 32 years at ORB and D9, respectively). Other key atmospheric variables, including incoming solar radiation and outgoing long-wave radiation, were obtained from the National Centers for Environmental Prediction (NCEP) North American Region Reanalysis (NARR) for the grid cell closest to site CP\((https://www.esrl.noaa.gov/psd/data/gridded/data.narr.html)\). The NARR outputs are on 1/3° grid \((~32-km\) resolution\) and were interpolated from the 3-h outputs to hourly to match the NDBC data.

The hydrographic data were primarily derived from a long-term mooring station (site CP) on an isobath to the south-southwest of Mobile Bay (Fig. 1). The site provides a relatively long-term (13 years in 2005–2018) perspective of shelf thermal structure from a suite of instruments throughout the water column. The instrument suite has changed over time, but typically consists of bottom \((~0.4 m\) above bottom, mab) and near-surface \((~15.5 mab\) CTD instruments, and 4–9 thermistors. Details of the mooring configurations and aspects of the processing can be found in various studies\(^3^3\)\(^3^4\). Importantly, the summer of 2018 featured an additional data stream from a CTD on a surface buoy \((~100 m\) apart from site CP), which had relatively minor gaps in the times series and resulted in ensemble properties (i.e., means, standard deviations, and max/min values) that are more robust and sensibly comparable to the CP record. One exception was PCB, which had minor gaps in the times series and resulted in ensemble properties determined using 5–9 years of data as availability allowed. These ensemble properties for in situ SST and air temperature were consistent with an overlapping 11-year time series from an inshore station in St. Andrews Bay (2008–2018), ~20 km east-southeast of PCR.

The heat content/flux calculations were carried out following the typical procedures. For heat content, the depth-average temperature was used given the significance of the water column temperature structure at depth. The resulting time series were filled using either linear interpolation or through substitution of data from a nearby station. The resulting time series were readily comparable to recent marine heatwave studies\(^4^1\) making this work readable and consistent with previous studies.

**Modeling setup and scenarios.** A simple one-dimensional (vertical) model, similar to the one in ref.\(^2^2\), was used to explore the primary processes impacting the thermal structure of the water column at site CP. The model requires surface heat flux and mixing energy to simulate the evolving hydrographic structure of the water column. The mixing energies at the surface and bottom boundaries were determined using bulk formulas as functions of wind speed and tidal current, respectively\(^7^2\). The wind energy for mixing was determined from wind data at ORB, the closest oceanic wind measurement source to site CP. Since the Mississippi Bight is a microtidal environment, the tidal mixing was determined using bulk formulas. The energy for mixing was determined using a small fixed current value \((12 cm\) s\(^-1\)) for the strait up at the TOGA-COARE, but the salinity data were very limited (only three vertical depths). With linearly interpolated salinity specified at each time step, only the temperature structure evolution was
modeled. The model was run for three cases: net outward radiation estimated using the bulk formulations in ref. 25 (case A1), and sensible and latent heat estimated using the TOGA-COARE algorithms in ref. 26 forced with observed (case A2) or modeled (case A3) SST. From the comparison between the modeled thermal structure and depth-average temperature time series to data (see the “Results” section), the heat flux parameterization in case A1 was selected as most appropriate and used for the subsequent model experiments.

A second set of model experiments (cases B1–B3 in Table 1) were designed to examine the compounding impacts of the storm mixing event and atmospheric heatwave. To exclude the three-dimensional nature of storm impacts by TS Gordon, this set of experiments was conducted from September 7 (after landfall of TS Gordon on September 4) until October 7. However, the initial conditions were based on the observed stratified temperature and salinity profiles on August 25 prior to TS Gordon so the evolution of the thermal structure of the water column just prior to TS Gordon could be evaluated with and without the impacts of a mixing event. As such, three scenarios were tested, differing only in the structure of the initial conditions. In case B1 the observed thermal (black solid line in Fig. 4) and salinity profiles were used as initial conditions. Because the temperature structure on August 25 had a very distinct bottom mixed layer (15–20 m depth, defined using a temperature change threshold of $\Delta T < 0.01 ^\circ C$), the salinity profile was constructed to have uniform salinity at this depth interval based on the bottom measurements and through linear interpolation for the remainder of the water column. In case B2, the depth-average of the interpreted temperature (black dashed line in Fig. 4) and salinity were used as initial conditions to generate a uniform water column (i.e., mixed initial profile). Note that case B2 does not include the full effects of storm mixing and the initial total heat content in the water column was the same between cases B1 and B2. As such, another experiment (case B3) was conducted with the same conditions as case B2 except with a generic storm heat loss based on an open ocean category 3 storm following ref. 9, so the water column was the same between cases B1 and B2. As such, another experiment include the full effects of storm mixing and the initial total heat content in the uniform water column (i.e., mixed initial pro...
34. Coogan, J., Dzvonkowski, B. & Lehrter, J. Effects of coastal upwelling and downwelling on hydrographic variability and dissolved oxygen in Mobile Bay. *J. Geophys. Res.* 124, 791–806 (2019).

35. Fairall, C., Bradley, E., Rogers, D., Edson, J. & Young, G. Bulk parameterization of air-sea fluxes for Tropical Global Atmosphere Coupled-Ocean Atmosphere Response Experiment. *J. Geophys. Res.* 101, 3747–3764 (1996).

36. Balaguru, K. et al. Dynamic potential intensity: an improved representation of the ocean’s impact on tropical cyclones. *Geophys. Res. Lett.* 42, 6739–6746 (2015).

37. Balaguru, K., Foltz, G., Leung, L., Hagos, S. & Judi, D. On the use of ocean dynamic temperature for hurricane intensity forecasting. *Weather Forecast* 33, 411–418 (2018).

38. Alduchov, O. & Eskridge, R. Improved Magnus form approximation of saturation vapor pressure. *J. Appl. Meteor.* 35, 601–609 (1996).

39. August, E. F. Ueber die Berechnung der Expansivkraft des Wasserdunstes. *Ann. Phys.* 137, 225–247 (1844).

40. Hobday, A. et al. A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.* 141, 227–238 (2016).

41. Dzvonkowski, B., Park, K., Lee, J., Webb, B. M. & Valle-Levinson, A. Spatial variability of flow over a river-influenced inner shelf in coastal Alabama during spring. *Cont. Shelf Res.* 74, 25–34 (2014).

42. Balaguru, K. et al. Pronounced impact of salinity on rapidly intensifying tropical cyclones. *Bull. Amer. Meteor. Soc.* https://doi.org/10.1175/BAMS-D-19-0303.1 (2020).

43. Oliver, E. et al. The unprecedented 2015/16 Tasman Sea marine heatwave. *Nat. Commun.* 8, 16101 (2017).

44. Schlegel, R. W., Oliver, E. C., Wernberg, T. & Smit, A. J. Nearshore and offshore co-occurrence of marine heatwaves and cold spells. *Prog. Oceanogr.* 151, 189–205 (2017).

45. Oliver, E. C. et al. Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* 9, 1324 (2018).

46. Dzvonkowski, B. et al. Hydrographic variability on a coastal shelf directly influenced by estuarine outflow. *Cont. Shelf Res.* 31, 939–950 (2011).

**Acknowledgements**

This work would not have been possible without the help of the Tech Support Group at the Dauphin Island Sea Lab. A portion of this work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. This research was made possible by the NOAA RESTORE Science Program (NA17NOS4510194) and NOAA NGI NMFS Regional Collaboration Network (18-NGI3-61).

**Author contributions**

R.D. contributed to conceptualization, investigation, formal analysis, and writing (original draft). J.C. contributed to data curation and formal analysis. S.F. contributed to investigation and formal analysis. G.L. and K.P. contributed to data curation and investigation. T.L. and the other authors contributed to the writing (review and editing).

**Competing interests**

The authors declare no competing interests.

**Additional information**

Supplementary information is available for this paper at https://doi.org/10.1038/s41467-020-18339-2.

**Correspondence** and requests for materials should be addressed to B.D.

**Peer review information** *Nature Communications* thanks the anonymous reviewers for their contribution to the peer review of this work. Peer reviewer reports are available.

**Reprints and permission information** is available at http://www.nature.com/reprints

**Publisher’s note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s) 2020