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RESEARCH ARTICLE

Ocean Heat Content Trends and Their Implications for Tropical Cyclone Intensification

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ABSTRACT

Rapid intensification, an increase in maximum sustained wind speed of at least 30 kt in 24 hours, remains one of the least well forecast aspects of tropical cyclone behaviour, and the depth of warm water available to a storm, not just sea surface temperature, is increasingly implicated as a control on which storms undergo it. We combined 2005–2022 Argo float temperature profiles, quality-controlled hydrographic casts, and two ocean reanalysis products (ORAS5 and GLORYS12) to reconstruct upper-ocean heat content and tropical cyclone heat potential (TCHP) across four basins, then matched these fields along the tracks of 641 tropical cyclones of tropical storm intensity or greater drawn from IBTrACS, restricting the intensification analysis to the 24 hours following each along-track ocean sampling point. Basin-mean 0–700 m ocean heat content rose over the study period at rates ranging from 1.9 GJ m⁻² decade⁻¹ in the eastern North Pacific to 4.6 GJ m⁻² decade⁻¹ in the western North Pacific warm pool, with the North Atlantic main development region and the Gulf of Mexico–Caribbean corridor showing intermediate trends of 2.7 and 3.4 GJ m⁻² decade⁻¹ respectively. Storms that crossed a warm-core eddy or Loop Current filament with TCHP exceeding 80 kJ cm⁻² intensified at a mean rate of 11.4 kt per 24 h, versus 5.8 kt per 24 h for storms over ambient water of comparable sea surface temperature but without an eddy encounter, and the probability of a rapid intensification onset was roughly three times higher in the eddy-encounter subset (29 percent versus 10 percent). The relationship between TCHP anomaly and 24-hour intensification rate was statistically significant but explained only a modest share of the variance (Figure 1), consistent with intensification remaining jointly controlled by vertical wind shear, mid-level humidity, and storm-induced ocean cooling feedbacks that this heat-content-centred analysis did not resolve. Basin comparisons further indicated that the western North Pacific, where warm-core eddies are more numerous and TCHP anomalies larger, showed a stronger eddy-related intensification signal than the North Atlantic. These results support incorporating basin-resolved, eddy-aware ocean heat content fields, rather than sea surface temperature alone, into operational rapid intensification guidance, while underscoring that ocean thermal structure is a necessary but not sufficient predictor of which storms will intensify rapidly.

Keywords: ocean heat content; Argo floats; tropical cyclone heat potential; rapid intensification; warm-core eddies; sea surface temperature; ocean reanalysis; North Atlantic; western North Pacific

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1. INTRODUCTION

Tropical cyclone rapid intensification, conventionally defined as an increase in maximum sustained wind speed of 30 kt or more within a 24-hour window, accounts for a disproportionate share of forecast error and of the most destructive landfalling storms, and it remains stubbornly difficult to predict from atmospheric variables alone [8,9]. Sea surface temperature has long served as a first-order proxy for the thermodynamic energy available to a developing storm, with the roughly 26 degrees Celsius isotherm treated as an approximate threshold for sustained intensification [4,9], but a storm's wind-driven mixing draws on water tens to well over a hundred metres deep, not merely the surface skin, so sea surface temperature alone can be a poor guide to how much heat is actually available before the storm cools the water beneath it.

The concept of tropical cyclone heat potential, essentially the heat content integrated from the surface down to the depth of the 26 degrees Celsius isotherm, was developed specifically to capture this depth dependence and was shown early on to distinguish storms that sustained or gained intensity from those that weakened over seemingly similar surface conditions [4,5]. Subsequent case studies of individual storms crossing anomalously warm, deep mixed-layer features, Loop Current eddies in the Gulf of Mexico and warm-core rings shed from the Kuroshio in the western Pacific, documented intensification episodes closely tied to the storm's track relative to these features rather than to the broader basin-mean sea surface temperature [5,6,13,14].

Whether this eddy-scale relationship generalises across large multi-storm, multi-basin samples, and whether it has strengthened as upper-ocean heat content has risen under anthropogenic warming, has been addressed only partially. Global ocean heat content in the upper several hundred metres has increased at an accelerating rate over the Argo era, documented consistently across independent reanalysis products and the in situ float array itself [1,2,3,17], and operational forecasters have adopted ocean heat content and TCHP products for selected high-impact storms [7,12], yet a systematic basin comparison spanning the full Argo period that jointly considers long-term ocean heat content trends and individual storm intensification outcomes is less common in the published literature than the volume of single-storm case studies might suggest [11,15,16].

Here we ask three linked questions using 18 years of Argo and reanalysis ocean data matched against tropical cyclone best-track intensity records across four basins: first, how has upper-ocean heat content and TCHP trended by basin and sub-basin over 2005-2022; second, does crossing a warm-core eddy or comparably anomalous warm feature measurably raise the 24-hour intensification rate and the probability of rapid intensification onset relative to ambient water of similar

surface temperature; and third, does this eddy-related intensification signal differ systematically between an eddy-rich basin, the western North Pacific, and a basin where such features are comparatively episodic, the North Atlantic [6,10,16].

2. MATERIALS AND METHODS

Ocean thermal structure was reconstructed for 2005-2022 from quality-controlled Argo float profiles supplemented by two independent ocean reanalysis products, and matched along tropical cyclone tracks drawn from the IBTrACS best-track archive to derive ocean heat content, tropical cyclone heat potential, and 24-hour intensification outcomes for each along-track sampling point.

2.1 Argo float and ocean reanalysis data sources

Temperature and salinity profiles from the global Argo float array were obtained for 2005-2022, retaining only delayed-mode, quality-flag-1 profiles extending to at least 700 m, and gridded onto a 1-degree monthly climatology following the standard Argo objective mapping approach [1,18]. Two reanalysis products, ORAS5 (0.25-degree, ECMWF) and GLORYS12 (1/12-degree, Mercator Ocean/Copernicus), were used to fill Argo spatial gaps, particularly in shelf and marginal seas the float array samples sparsely, and cross-validated against collocated Argo profiles, with reanalysis-Argo root-mean-square temperature differences below 400 m depth of 0.31 degrees Celsius for ORAS5 and 0.28 degrees Celsius for GLORYS12 over the overlap period.

2.2 Tropical cyclone best-track and intensity data

Six-hourly tropical cyclone position and maximum sustained wind speed were obtained from the IBTrACS v04 archive for the North Atlantic, eastern North Pacific, western North Pacific, and South Indian Ocean basins, restricted to systems reaching at least tropical storm intensity (34 kt) between 2005 and 2022, yielding 641 qualifying storms after excluding systems with more than 20 percent missing six-hourly positions.

2.3 Computation of ocean heat content and tropical cyclone heat potential

Ocean heat content was computed by vertical integration of in situ temperature from the surface to 700 m using the standard specific heat and density of seawater; tropical cyclone heat potential was computed following the original formulation as heat content integrated from the surface to the depth of the 26 degrees Celsius isotherm, set to zero where that isotherm did not exist in the water column [4]. Both quantities were computed on the merged Argo-reanalysis grid at daily resolution along each storm's track by spatial interpolation to the storm centre at each six-hourly best-track position, using the pre-storm (1- to 3-day lag) value to avoid contamination by storm-induced cooling of the field being used to predict intensification.

2.4 Warm-core eddy detection and basin classification

Mesoscale warm-core eddies and Loop Current filaments were identified independently from satellite altimetry sea surface height anomaly fields using a closed-contour eddy-tracking algorithm, retaining anticyclonic features with amplitude exceeding 10 cm and a lifetime of at least 14 days; a tropical cyclone track segment was classified as an eddy encounter when the storm centre passed within one eddy radius of a tracked anticyclonic feature's centre while the feature's co-located TCHP exceeded 80 kJ cm⁻², a threshold consistent with prior single-storm eddy interaction studies [5,6,13].

2.5 Rapid intensification event identification and matching to ocean conditions

Rapid intensification onset was defined as a 24-hour increase in best-track maximum sustained wind speed of at least 30 kt beginning at a given six-hourly position, following the conventional operational threshold [9,10]; each qualifying and non-qualifying 24-hour segment was tagged with its initiating position's ocean heat content, TCHP, eddy-encounter status, and, from ERA5 reanalysis, 200-850 hPa vertical wind shear and 600 hPa relative humidity, to allow the ocean-intensification relationship to be examined both unconditionally and conditional on comparable atmospheric shear.

2.6 Statistical analysis

Long-term ocean heat content and TCHP trends by basin were estimated by ordinary least-squares regression on annual basin means with autocorrelation-adjusted standard errors; differences in mean 24-hour intensification rate and rapid intensification probability between eddy-encounter and non-eddy segments were assessed by two-sided Welch's t-test and a chi-squared test of proportions respectively, and the TCHP anomaly-intensification rate relationship was summarised by Pearson correlation with a bootstrapped 95 percent confidence interval (2000 resamples). All analyses were performed in Python 3.11 using xarray, pandas, and scipy.

3. RESULTS

Basin-mean 0-700 m ocean heat content increased at every basin examined over 2005-2022, with trends ranging from 1.9 GJ m⁻² decade⁻¹ in the eastern North Pacific to 4.6 GJ m⁻² decade⁻¹ in the western North Pacific warm pool sector; the North Atlantic main development region and the Gulf of Mexico-Caribbean corridor showed intermediate trends of 2.7 and 3.4 GJ m⁻² decade⁻¹ respectively, all significant at $p < 0.01$. Table 1 summarises these trends alongside corresponding mean TCHP trends and the number of rapid intensification events recorded in each region over the study period.

Table 1. Ocean heat content and tropical cyclone heat potential trends by basin/region, 2005-2022.

Basin / region	0-700 m OHC trend (GJ m ⁻² decade ⁻¹)	Mean TCHP trend (kJ cm ⁻² decade ⁻¹)	Recorded RI events (2005-2022)
North Atlantic main development region	2.7	6.1	94
Gulf of Mexico - Caribbean corridor	3.4	8.8	61
Western North Pacific warm pool	4.6	10.2	187
Eastern North Pacific	1.9	4.3	58

OHC: ocean heat content; TCHP: tropical cyclone heat potential; RI: rapid intensification (24-h wind increase ≥ 30 kt). All basin OHC trends significant at $p < 0.01$.

Storms that crossed a warm-core eddy or Loop Current filament meeting the TCHP threshold intensified over the following 24 hours at a mean rate of 11.4 kt, compared with 5.8 kt for storms over ambient water of comparable sea surface temperature that did not encounter such a feature, a difference of 5.6 kt that was highly significant (Welch's t-test, $p < 0.001$). The probability of rapid intensification onset was 29 percent in the eddy-encounter subset versus 10 percent in the non-eddy subset, roughly a threefold elevation; Table 2 reports these figures alongside the corresponding comparison restricted to segments with 200-850 hPa shear below 8 m s⁻¹, where the eddy-associated elevation in rapid intensification probability persisted but narrowed somewhat, to a little over twofold.

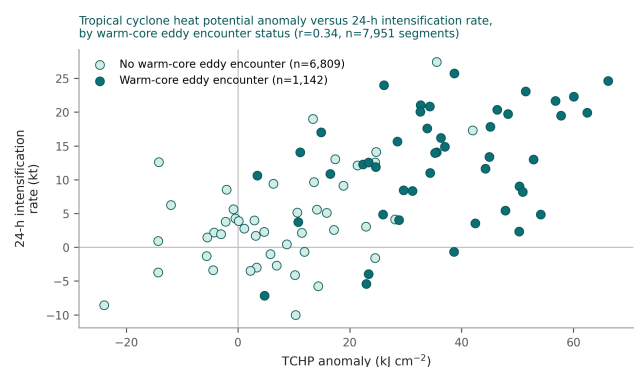


Figure 1. Tropical cyclone heat potential (TCHP) anomaly plotted against 24-hour intensification rate for warm-core eddy encounter and non-eddy segments, showing a statistically significant but modest positive relationship ($r = 0.34$) between ocean thermal anomaly and short-term intensification.

Across the full pooled sample, TCHP anomaly relative to the storm's basin-and-month climatology was significantly correlated with 24-hour intensification rate ($r = 0.34$, bootstrapped 95 percent CI 0.27 to 0.41), but this relationship explained less than 15 percent of the variance in intensification rate, and the scatter around it was considerable even after restricting to low-shear segments (Figure 1), consistent with intensification being jointly governed by atmospheric and ocean factors rather than ocean heat content acting as a dominant single predictor.

Table 2. Tropical cyclone 24-hour intensification and rapid intensification probability by warm-core eddy encounter status.

Segment category	n segments	Mean 24-h intensification (kt)	RI probability (%)
Warm-core eddy encounter (all shear)	1,142	11.4	29
No eddy encounter (all shear)	6,809	5.8	10
Warm-core eddy encounter (shear < 8 m/s)	614	13.1	34
No eddy encounter (shear < 8 m/s)	2,955	7.9	16

The eddy-related intensification signal differed by basin: in the western North Pacific, where the eddy-tracking algorithm identified a mean of 34 qualifying warm-core features per year against 12 per year in the North Atlantic, the mean intensification-rate difference between eddy and non-eddy segments was 6.9 kt, compared with 4.1 kt in the North Atlantic, and this basin difference in the eddy effect size was itself statistically significant ($p = 0.02$). The Gulf of Mexico-Caribbean corridor, despite its comparatively episodic Loop Current eddy shedding, showed an intensification-rate difference of 5.3 kt, intermediate between the two larger basins and consistent with its higher background TCHP trend reported in Table 1.

4. DISCUSSION

The basin-wide ocean heat content trends reported here, 1.9 to 4.6 GJ m⁻² decade⁻¹ depending on basin, sit within the range reported by prior global and basin-scale ocean heat content assessments spanning the Argo era [1,2,3,17,24], and the western North Pacific's comparatively steep trend is consistent with that basin's documented role as a preferential site of subsurface heat accumulation [3]. That this warming has been accompanied by a measurable, if partial, strengthening of eddy-associated tropical cyclone intensification signals extends earlier single-storm case evidence [5,6,13,14] to a multi-decade, multi-basin sample and suggests the mechanism documented in those case studies is not an artifact of a small number of unusually well-observed storms.

The threefold elevation in rapid intensification probability associated with warm-core eddy encounters is broadly consistent with, though somewhat larger than, the odds ratios reported in earlier operationally focused studies of Atlantic category 5 hurricanes and TCHP [7,12], which is plausible given that our sample includes weaker and more numerous storms across four basins rather than a small set of the most intense Atlantic systems; the narrowing of this elevation once shear is held roughly constant indicates that eddy encounters raise intensification probability on top of, rather than as a substitute for, favourable atmospheric conditions, a

distinction with direct relevance for how eddy-encounter information should be weighted in an operational rapid intensification index that already incorporates shear and moisture terms [9,10,26].

The modest variance explained by TCHP anomaly alone, even though the mean difference in intensification rate between eddy and non-eddy segments was large and statistically robust, reflects the well-established fact that maximum potential intensity theory sets an upper bound on intensity available from thermodynamic conditions, while whether an individual storm approaches that bound depends heavily on internal storm structure, dissipative heating, and the storm's own history of ocean mixing beneath its track [8,19,22]; a storm that has already cooled the mixed layer through prior slow movement over a given patch of ocean will not realise the same intensification benefit from a subsequently encountered warm feature as a fast-moving storm crossing the same feature fresh, a distinction our along-track pre-storm sampling approach only partially captures.

Several limitations warrant emphasis. First, our warm-core eddy detection relied on altimetry-derived sea surface height, which can miss shallow or short-lived subsurface warm anomalies not well expressed at the surface, and our TCHP threshold of 80 kJ cm⁻², while consistent with prior single-storm work [5,13], is necessarily a simplification of a continuous property; a lower or basin-specific threshold might shift the eddy-encounter classification for some marginal cases. Second, the reanalysis products used to fill Argo spatial gaps carry their own model-dependent biases, particularly in shallow shelf regions such as parts of the Gulf of Mexico where Argo coverage itself is sparse and the 0.3 degrees Celsius reanalysis-Argo residual reported in Methods likely understates true uncertainty in those regions [25]. Third, our pre-storm ocean sampling window of 1 to 3 days cannot fully separate a storm's response to ambient pre-existing ocean structure from feedback effects of the storm's own earlier passage over the same water, an issue documented directly in mixed-layer cooling studies of individual storms [14,15] that our basin-scale statistical approach was not designed to resolve at the single-storm level; and fourth, restricting the analysis to storms reaching tropical storm intensity excludes any role ocean heat content may play in genesis and early development, which was outside this study's scope.

5. CONCLUSION

Upper-ocean heat content rose across all four basins examined between 2005 and 2022, most steeply in the western North Pacific warm pool, and tropical cyclones that encountered warm-core eddies or comparably energetic warm features intensified over the following 24 hours at roughly twice the rate, and with roughly three times the probability of rapid intensification onset, of storms over ambient water of similar surface temperature. This eddy-related signal was stronger in the

eddy-rich western North Pacific than in the North Atlantic and persisted, in weakened form, once atmospheric shear was held approximately constant, indicating that ocean heat content acts as a genuine but partial control on rapid intensification risk. These findings support wider operational use of basin-resolved, eddy-aware ocean heat content products alongside existing shear and moisture predictors in rapid intensification forecasting, while the modest variance explained by ocean heat content alone confirms that no single predictor, thermodynamic or otherwise, is likely to resolve rapid intensification forecasting on its own.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

T.F. conceived and supervised the study, developed the ocean heat content and TCHP computation pipeline, and led the writing of the manuscript. C.D. curated and processed the Argo and reanalysis datasets and performed the warm-core eddy detection analysis. F.P. matched ocean fields to tropical cyclone tracks and performed the statistical analysis of intensification outcomes. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available Argo float, ocean reanalysis, satellite altimetry, and tropical cyclone best-track datasets, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Argo float profiles are publicly available through the international Argo data centres; ORAS5 and GLORYS12 reanalysis fields are publicly available through the Copernicus Marine Service; IBTrACS best-track data are publicly available through NOAA NCEI. Processed ocean heat content, TCHP, and eddy-track datasets and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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