Ocean mixing during Hurricane Ida (2021): The impact of a freshwater barrier layer

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Abstract

Tropical cyclones are one of the costliest and deadliest natural disasters globally, and impacts are currently expected to worsen with a changing climate. Hurricane Ida (2021) made landfall as a category 4 storm on the US gulf coast after intensifying over a Loop Current eddy and a freshwater barrier layer that extended from the coast to the open ocean waters off the continental shelf. An autonomous underwater glider sampled this ocean feature ahead of Ida. We use this data with 1-D shear driven mixed layer models to investigate the sensitivity of the upper ocean mixing to a barrier layer during Ida’s intensification period. We show that the freshwater barrier layer inhibited cooling by as much as 56% and resulted in increased enthalpy flux to the atmosphere by >20% as the storm made landfall. This highlights the utility of sustained observations to support coupled ocean and atmosphere hurricane forecasts.

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Key Points:

- Hurricane Ida (2021) intensified over an open ocean freshwater barrier layer in the final 12 hours before landfall.
- Upper ocean mixed layer models were initialized with in-situ glider data to evaluate the barrier layer impact on sea surface cooling.
- The barrier layer reduced modeled sea surface cooling by up to 56% and enthalpy flux to Hurricane Ida by more than 20%
Abstract

Tropical cyclones are one of the costliest and deadliest natural disasters globally, and impacts are currently expected to worsen with a changing climate. Hurricane Ida (2021) made landfall as a category 4 storm on the US gulf coast after intensifying over a Loop Current eddy and a freshwater barrier layer that extended from the coast to the open ocean waters off the continental shelf. An autonomous underwater glider sampled this ocean feature ahead of Ida. We use this data with 1-D shear driven mixed layer models to investigate the sensitivity of the upper ocean mixing to a barrier layer during Ida’s intensification period. We show that the freshwater barrier layer inhibited cooling by as much as 56% and resulted in increased enthalpy flux to the atmosphere by >20% as the storm made landfall. This highlights the utility of sustained observations to support coupled ocean and atmosphere hurricane forecasts.

Plain Language Summary

This study investigates the sensitivity of upper ocean cooling in Hurricane Ida (2021) to a freshwater Mississippi river plume over the open ocean off the continental shelf. A combination of underwater robots and ocean mixed layer models show that ocean cooling was significantly reduced due to the freshwater plume. Heat flux to the atmosphere, which contributes to storm intensification, remained high relative to model simulations with the freshwater plume removed.

1 Introduction

Tropical cyclones (TCs) are one of the costliest and deadliest natural disasters on the planet (Smith, 2020). The ability to forecast TC intensity has improved recently (Cangialosi et al., 2020), however intensity forecast errors remain large (~12 kts at 72 hours). The primary controls of the intensity of mature TCs are vertical wind shear, dry air intrusion, and the fluxes of enthalpy and momentum between the surface ocean and atmosphere (Emanuel, 1986). Recent studies have shown that the upper ocean can evolve rapidly beneath TCs (Dzwonkowski et al., 2021; Glenn et al., 2016; Gramer et al., 2022; Miles et al., 2017; Seroka et al., 2016, 2017) and feedback on storm intensity.

The magnitude of upper ocean cooling is dependent on water column stability and upper ocean mixing processes. Stratification inhibits vertical mixing and limits entrainment of cool subsurface waters into the mixed layer. In regions with large freshwater input, upper ocean barrier layers can occur (Foltz & McPhaden, 2009; Lukas & Lindstrom, 1991; Sprintall & Tomczak, 1992). These ocean features are found on continental shelves, near river outflows (Sengupta et al., 2008), and over the open ocean with offshore transport of freshwater (Pailler et al., 1999). Barrier layers reduce vertical mixing efficiency, inhibit sea surface temperature (SST) cooling, and support enhanced enthalpy fluxes into the atmosphere during hurricanes (Balaguru et al., 2012, 2020; Rudzin et al., 2018, 2019, 2020; Wang et al., 2011). Only a few observations and studies have focused on the interactions of TCs passing over the Mississippi river-induced salinity barrier layer (Le Hénaff et al., 2021), the largest river outflow in the US, in a region where strong hurricanes make landfall.

Hurricane Ida (2021) underwent rapid intensification (RI) over the warm waters of the Gulf of Mexico (GoM), Loop Current (LC), and Loop Current Eddy (LCE) with an increase in maximum wind speed of 60 kts (~30 m/s) in 24 hours (Beven II et al., 2022). Ida continued to
intensify as it passed over the Mississippi River plume and continental shelf before making landfall as a category 4 hurricane in Louisiana on August 29th (Figure 1) as the second costliest storm to make landfall in the region after Hurricane Katrina (2005) (Smith, 2020). A recent study (Zhu et al., 2022) identified that nearshore SSTs ahead of Ida were >30°C, above the mean SSTs (28.7°C) that other major hurricanes crossed over in the region. They also indicated that slow translation speeds kept the backside of the storm over these warm waters for an extended duration, contributing to Ida’s slow weakening after landfall.

Figure 1. Maps of a) SSS, b) SST, and c) upper ocean heat content from the Navy Global Ocean Forecast System (GOFS) 3.1 on 8/27 at 18z. In all three panels Hurricane Ida’s track is plotted from the International Best Track Archive for Climate Stewardship (Knapp et al., 2010, 2018) in black with colored circles denoting storm category. NG645s glider track is in gray with the white section denoting the glider track 10 days ahead of Ida (8/17 to 8/27 18z). The cyan triangle indicates the location closest to Ida’s track that identified a barrier layer, while the dark blue triangle is NG645’s position during storm passage. The red star indicates buoy 42040.

An autonomous underwater glider operated by the US Navy (NG645) as part of the 2021 hurricane glider field program (Miles et al., 2021) captured a thin freshwater layer (<10 m) between the a LCE and the continental shelf one week prior to Ida’s track passing over the region (Figure 1). Model output from the Navy Global Ocean Forecast System showed a broad area of fresh (<33) surface waters extending from the coast beyond the shelf-break that persisted through Ida’s eye-passage (Figure 1a). These nearshore waters had warm SSTs, yet low ocean heat content (Figure 1c) relative to deeper offshore waters.

In this study we investigate the sensitivity of SST cooling to the strong vertical salinity stratification Hurricane Ida (2021) passed over just before landfall. Using pre-storm in-situ data from glider NG645 as initial conditions, we carry out 1-D mixed layer model sensitivity experiments to barrier layer presence and absence with the Price-Weller-Pinkel (PWP) model (Price et al., 1986).

2 Methods and Data
We use a combination of ocean observing networks, atmospheric model output, and 1-D PWP to investigate the role of salinity stratification in shear-driven upper ocean mixing as Hurricane Ida (2021) approached and made landfall on the Louisiana coastline.

Ocean observations ahead of Hurricane Ida were obtained from Slocum glider (Schofield et al., 2007) NG645, operated by the Naval Oceanographic Office. Slocum gliders are buoyancy driven uncrewed underwater vehicles that can profile vertically (up to 1000 m at ~20 cm s⁻¹) and horizontally (~20 km/day) that have been used over the past decade to study upper ocean processes during TCs (Domingues et al., 2015; Glenn et al., 2016; Lim et al., 2020; Miles et al., 2017; Seroka et al., 2016, 2017) and to provide near real-time data for assimilation into operational hurricane forecast models (Miles et al., 2021).

NG645 was deployed on June 13th, 2021 offshore of the continental shelf at 27.6°N and 94.6°W. The glider was navigated eastward between the northern escarpment of the GoM and a LCE to the south (Figure 1). NG645 crossed ahead of Ida’s track at 89.23°W and 28.12°N on August 19th (Figure 2) and was equipped with a standard Seabird Scientific pumped conductivity, temperature, and depth sensor. Pre-storm temperature and salinity profile data from NG645 were used to initialize twin 1-D PWP model experiments.

PWP has been used extensively to study ocean mixing during hurricane conditions (Rudzin et al., 2018; Wang et al., 2011; Yang et al., 2019; Zedler et al., 2002). The PWP model is initialized from profiles of temperature and salinity and forced with observed or idealized wind stress, freshwater surface flux, and heat flux. The bulk and gradient Richardson numbers determine mixed layer and shear stability, respectively. PWP primarily includes processes and parameterizations that represent shear-induced mixing and buoyancy forcing processes, as well as rotational effects due to Coriolis.

External model forcing was limited to surface wind stress as in previous PWP studies (Balaguru et al., 2020) to evaluate the isolated impact of salinity stratification on upper ocean shear-driven mixing processes. The surface wind stress was extracted in real-time from the publicly available High Resolution Rapid Refresh (HRRR) model operated by NOAA via their Operational Model Archive and Distribution System. HRRR is a 3km horizontal resolution implementation of the Weather Research and Forecasting model (Skamarock et al., 2019) updated hourly. We evaluate HRRR with the nearest National Data Buoy Center (NDBC) buoy 42040 to the northeast of Ida’s track (Figure 1). Evaluation of the HRRR model 10m wind speeds showed that the wind speed magnitudes mean bias for the model forcing duration (08/25 to 08/31) was 0.13 m s⁻¹ with a correlation coefficient of 0.91.

Initial temperature and salinity profiles for the model experiments were extracted from NG645 based on proximity to the storm track, and evidence of a barrier layer. Each glider profile was evaluated for the presence of a barrier layer with a thickness of ≥10m (Balaguru et al., 2012). Barrier layer thickness was calculated using the isothermal layer depth (ILD) and the mixed layer depth (MLD) of each profile, with the MLD defined following de Boyer Montégut et al., (2007) using the potential density:

\[
\Delta \sigma_\theta = \sigma_\theta(T_o - \Delta T, S_o) - \sigma_\theta(T_o, S_o)
\]

where \(T_o\) and \(S_o\) are the 2m temperature and salinity, respectively. \(\Delta T\) is 0.5°C as in (Rudzin et al., 2017). We calculated the ILD as the shallowest depth where the temperature is 0.5°C less.
than the SST, and the barrier layer thickness (BLT) is the distance between the ILD and the MLD. The 0.5°C criteria is larger than that used by de Boyer Montégut et al., (2007) however it is aligned with Rudzin et al., (2017), which adapted the criteria for salinity barrier layers. Pre-storm temperature and salinity data from the glider and calculated ILD and MLDs are presented in Figure 2. The largest BLT within a single radius of maximum winds of Ida’s track and the glider track was located at 28.12°N and 89.37°W (Figure 1) on 8/19 at ~2:00 GMT (Figure 2). This sampling location was ~19km to the west of the storms future track, referred to as the “study-site” hereafter.

**Figure 2.** Glider NG645 cross-sections of a) temperature and c) salinity pre-storm (corresponding with the white line track in Figure 1). MLD and ILD estimates are represented by x’s and triangles, respectively. Panels b) and d) are profiles of temperature and salinity, respectively, extracted from NG645 at 08/19 ~2:00 GMT. Solid lines are f observations used in case 1 PWP simulations, while dashed salinity line is used in case 2 with the removal of the barrier layer. The horizontal (red) dashed line is the ILD and (black) MLD. The case 2 salinity profile is extrapolated to the surface from the MLD.

Hurricane Ida was declared a hurricane on 08/27 at 18 GMT (Figure 3b), rapidly intensified to a maximum of over 66 m s⁻¹ on 08/29 making landfall at peak winds at 1655 GMT (Figure 1). It weakened following landfall but remained a hurricane for ~12 hours as it moved inland. PWP simulations were initialized on 08/25, 2021 at 00 GMT, ~5 days ahead of Ida’s landfall and were run through 08/31. This time-period accounts for the gradual increase in wind speeds between 08/25 and 08/28 (Figure 3) ahead of Ida’s arrival, peak wind forcing on 08/29, and weakening following landfall.
Figure 3. a) wind speed magnitude from NOAA NDBC buoy 42040 (blue) HRRR extracted at 42040 (green) and extracted at the study-site (yellow). Buoy winds were extrapolated from 4.1m to 10m following a power law b) The NHC best track maximum wind speeds following Ida, with color denoting storm category. The grey vertical dashed line is the storms landfall time.

3 Results

The initial glider profiles at the study-site (Figure 2) had an SST of 30.6°C and SSS of 32.6 with an MLD of 3m, ILD of 19m, and BLT of 16m. The surface to ILD salinity difference of was > 3, indicating a highly stratified water column. In the twin PWP model sensitivity experiments case 1 initial conditions used the observed profiles of temperature and salinity at the study-site, while in case 2 we extrapolated the salinity (36.24) from the initial ILD to the surface to remove the barrier layer (Figure 2) as in Wang et al., (2011). The potential energy anomaly (PEA), the amount of energy required to fully mix the water column (Simpson & Hunter, 1974), over the upper 50m in case 1 was 152.06 J m⁻³ and 62.78 J m⁻³ in case 2. This indicates that case 2, with no salinity barrier layer, requires 41% of the mechanical mixing required by case 1 to fully homogenize the upper 50 m.

Wind speeds gradually increased from 08/25 to near 10 m s⁻¹ by 8/28 at 12 GMT (Figure 3) and were generally westward. They increased rapidly through 8/29 at the study-site as Ida approached, reaching a peak of ~28 m s⁻¹ ahead-of-eye passage, and exceeding 30 m s⁻¹ after-eye passage. Winds fell to pre-storm (<10 m s⁻¹) levels on 08/30 as Ida moved northward and became a tropical storm.

Results from PWP experiments are presented in Figure 4. Ahead of eye-passage SSTs (Figure 4a) cooled by 0.19°C for case 1. By landfall time (~7 hours later) SST cooled by 0.42°C, with a total cooling of 0.58°C by 8/30 06z. We use the modeled MLD, ILD, and a temperature contour of 30.5°C (just below the ILD) to demonstrate the timing of cooling and deepening of the MLD. For case 1 the MLD was initially above the 30.5°C contour at 3m. As the MLD reached the 30.5°C contour on 08/29 at ~08 GMT the upper layer was homogenized 4 hours ahead of eye-
passage. In case 2 the SST cooling by eye-passage and landfall was 0.44°C and 0.69°C, respectively, with a total cooling by 08/30 06 GMT of 0.89°C. The MLD in case 2 was initially at 16m, below the 30.5°C contour. The upper ocean cooled earlier than case 1, with the 30.5°C contour reaching the surface at 08/28 19 GMT, 13 hours earlier than in case 1 and 17 hours ahead of eye-passage.

Temperature anomalies (Figure 4 c,d) show the differences in timing and magnitude of the cooling in both cases. The Richardson number dropped below the critical threshold (0.65) just above the MLD in both cases, highlighting regions of shear-driven mixing. In these areas heat was redistributed in the upper layer with upper ocean cooling and subsurface warming as the water column was homogenized. In case 2 this began on 08/26 during weaker pre-storm wind forcing. Without the presence of the barrier layer the low wind speeds ahead of the storm were able to begin to mix the upper water column resulting in reduced stratification and enhanced mixing during the peak storm forcing.

**Figure 4.** Cross-sections of PWP results for a,c) case 1, with barrier layers, and b,d) case 2 with the barrier layer removed at initialization. Panels a) and b) are temperature and c) and d) are temperature anomaly \((T - T_{\text{initial}})\) throughout the storm with contours of the MLD and ILD (blue), a reference contour of 30.5°C, eye-passage (dashed vertical line) and landfall (solid vertical line).

We calculate the enthalpy flux in each case to illustrate the impact of the removal of the barrier layer on the heat transfer to the atmosphere and potential impact on storm intensity. Bulk thermodynamic fluxes of momentum, latent heat, and sensible heat were calculated following Fairall et al. (1996), utilizing output from the HRRR model for atmospheric parameters and SST from PWP model sensitivities for ocean parameters (Figure 5c). Enthalpy flux differences (Figure 5d) increased from 10% at the beginning of the storm forced period (08/29 06 GMT) to over 20% as the storm moved inshore and weakened to a tropical storm (08/30 06 GMT) with higher flux in case 1. Time integrated enthalpy flux differences during this window were 17.3%
demonstrating a reduction in heat transport to the atmosphere during Ida if the barrier layer is removed.

Figure 5. a) Wind stress forcing at the study-site in all PWP experiments derived from HRRR output, b) The change in SST from the initial condition for case 1 (blue) and case 2 (orange), c) the total enthalpy flux in case 1 (blue) case 2 (orange), and d) the difference between case 1 and 2 enthalpy fluxes. Shaded regions indicated the area of cumulative enthalpy flux between 08/29 06z and 08/30 06z. The vertical gray line is Ida’s landfall time.

4 Discussion

The reduced cooling simulated here due to the barrier layer is consistent with previous studies focused on other regions. In these twin model experiments the salinity barrier layer inhibited SST cooling by 56% ahead-of-eye passage, 39% by landfall, and 35% as Ida transitioned to a tropical storm. For example, Balaguru et al., (2012) identified a 33% reduction in cooling due to barrier layers in a category 4 hurricane Omar (2008) in the northeastern Caribbean. In the Bay of Bengal Neetu et al., (2012) showed that monsoon generated barrier layers are responsible for a ~40% cooling reduction by TCs relative to post monsoon seasons. Idealized PWP experiments in Rudzin et al. (2018) were designed to represent a range of ocean features in the eastern Caribbean that showed cooling ranges of 0.4°C to 0.8°C, also consistent with the total cooling presented here. Balaguru et al. (2020) carried out more extensive PWP model experiments with and without salinity stratification for the Amazon-Orinoco River plume to evaluate the connection between RI and salinity barrier layer cooling inhibition. They found for idealized RI cases, salinity barrier layers reduced SST cooling by up to 0.3°C, similar to what we simulated for a rapidly intensifying Hurricane Ida. For non-RI cases in their study, salinity barrier layers were only responsible for inhibiting 0.15°C of cooling, highlighting potential feedbacks between barrier layers and RI. Despite their findings in the Amazon-Orinoco River plume, they found that
barrier layers had limited impact on storm intensity in the GoM. However, their study utilized global ocean model products to initialize PWP, rather than in-situ observations, which likely do not resolve the sharp upper ocean salinity gradients such as those observed by NG645. One of the few studies (Le Hénaff et al., 2021) of barrier layer and hurricane interactions in the GoM identified a barrier layer ahead of Hurricane Michael (2018). They identified SSS <34 to as far south as 27.5°N, above the 32.6 SSS observed in our study by NG645 (Figure 2) but ~75km further south. However, a study of the intensification of Hurricane Isaac (Jaimes et al., 2016), which followed a similar track to Ida, found no evidence of barrier layers in profiles collected from air-deployed expendables. These studies and our findings indicate that barrier layers in the GoM are highly variable and can cover broad areas that hurricanes, such as Michael (2018) and Ida (2021), must pass over before making landfall, and can have an impact on intensity.

Our study highlights in the importance of salinity stratification on the open ocean region to the north of the LC/LCE and south of the continental shelf. In the northern GoM a variety of thermal stratification regimes exist. In the nearshore environment it can be warm throughout the water column or highly thermally stratified as observed ahead of Hurricane Michael (2018), which showed subsurface temperatures of 22°C near 10m depth to the northeast of our study-site. This feature was removed during a marine heatwave that dramatically warmed the shelf waters to over 28°C in a few days. Further offshore the presence of LC/LCE waters can lead to warm and salty features that extend throughout the upper 100m and beyond (Elliott, 1982). In contrast, the region between the LC/LCE and continental shelf is typically warm at the sea surface but can have cooler waters beneath the seasonal thermocline in the upper ocean, as evidenced in the glider observations by NG645. In this “gap” region between the LC/LCEs and the continental shelf where the Mississippi River plume can be exported off the continental shelf, our findings suggest that salinity barrier layers can increase stratification and further isolate the subsurface cold water from mixing and cooling the surface. These warm and fresh surface waters would theoretically support storm intensification approaching landfall.

5 Conclusion

We have shown that the presence of the barrier layer from the Mississippi River plume south of the continental shelf-break in the open ocean inhibited sea surface cooling and enhanced enthalpy flux under a rapidly intensifying Hurricane Ida (2021). The removal of the barrier layer in our experiment led to earlier, more rapid, and greater cooling, which resulted in reduced enthalpy flux to the atmosphere. This is particularly critical as it highlights an essential ocean feature, a Mississippi River plume freshwater barrier layer, in the “gap” region south of the continental shelf and north of the LC/LCE that landfalling hurricanes must cross before impacting coastal communities. Salinity observations are severely lacking in this region by global scale ocean observing systems that support operational ocean models coupled to hurricane forecast systems. For example, between 1980 and 2022 only 7 Argo floats in the public archive (https://erddap.ifremer.fr/erddap/index.html) have surfaced in the region defined by the NG645 study-site northward to the coast, and within 50 km both east and west. This study highlights the need for expanded ocean observing assets along the shelf-break and continental shelf of the GoM to further confirm the importance of salinity barrier layers and improve intensity forecasts of landfalling hurricanes in this highly vulnerable region.
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Open Research

Data sources included glider NG645 (https://gliders.ioos.us/erddap/tabledap/ng645-20210613T0000.html), Buoy 42040 from the National Data Buoy Center (https://www.ndbc.noaa.gov/station_history.php?station=42040). The PWP model was adapted from https://github.com/earlew/pwp_python_00.
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