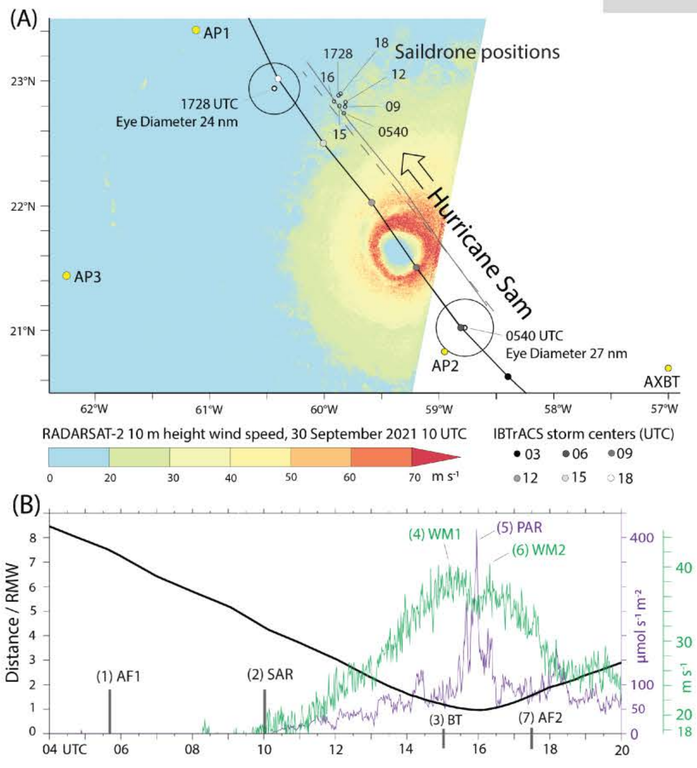
Surface ocean warming near the core of **Hurricane Sam** and its representation in forecast models

Andrew M. Chiodi[1,2], Hristina Hristova[1,2], Gregory R. Foltz[4], Chidong Zhang[1], Dongxiao Zhang[1,2], Edward Cokelet[1], Jun A. Zhang[4,5], Calvin Mordy[1,2], Catherine Edwards[6], Christian Meinig[1*], Edoardo Mazza[2], Eugene Burger[1], Francis Bringas[4], Gustavo Goni[4], Hyun-Sook Kim[4], Sue Chen[7], Kathleen Bailey[8], Kevin O'Brien[1,2], Noah Lawrence-Slavas[1], Shuyi S. Chen[2]

[1] NOAA Pacific Marine Environmental Laboratory [2] University of Washington [3] University of Hawaii [4] NOAA Atlantic Oceanic and Meteorological Laboratory [5] University of Miami [6] Skidaway Institute of Oceanography, University of Georgia [7] Marine Meteorology Division, U.S. Naval Research Laboratory [8] U.S. Integrated Ocean Observing System [*] present affiliaiton: Pacific Northwest National Laboratory

1. Saildrone-Hurricane Sam intercept logistics and characteristics

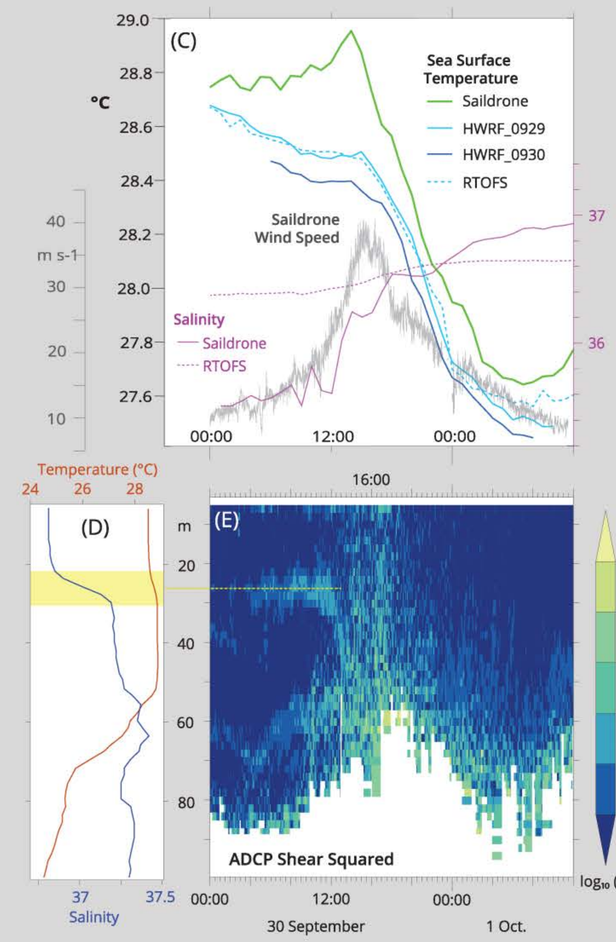


(A) 10-m wind speed from RADARSAT-2 (SAR). The SAR measurement occurred ~6 hours before the saildrone was closest to the center of Hurricane Sam, when Sam was moving toward the saildrone at 6.32 m s^{-1}. The saildrone's positions at the listed times are shown by small, open black circles. The black line intersecting the figure is the path of Sam's center according to IBTrACS. The gray lines to its right show the extent of the RMW estimated using aircraft (dashed) and IBTrACS (solid) center fixes. The eye diameters (black circular contours) and storm center positions at 0540 and 1728 UTC 9/30 (small white circles) were provided by aircraft reconnaissance. The locations of Argo Profile (AP) 1, 2 and 3, and the 1120 UTC 9/29 AXBT are shown with small yellow circles.

(B) The black line shows the distance between SD-1045 and the IBTrACS center of Sam on 9/30, normalized by the RMW (30km). The times of other relevant measurements are marked, as follows: 1) AF1 = First Air Force storm center fix; 2) SAR = collection time of winds shown in panel A; 3) BT = Infrared Brightness Temperature; 4) WM1 = First saildrone wind speed maximum; 5) PAR maximum; 6) WM2 = Second saildrone wind speed maximum; 7) AF2 = Second Air Force storm center fix. The green and purple lines show the 1-minute saildrone wind speed and PAR observations, respectively.

SAR = Synthetic Aperture Radar; IBTrACS = International Best Track Archive for Climate Stewardship; RMW = Radius of Maximum Winds; PAR = solar radiation

2. Saildrone observations in Sam



(C) Saildrone SST (green), wind speed (gray) and salinity (purple), with SST from RTOFS (dashed, light blue), HWRF_0929 (light blue) and HWRF_0930 (dark blue). Sea surface salinity from RTOFS is drawn with a dashed purple line.

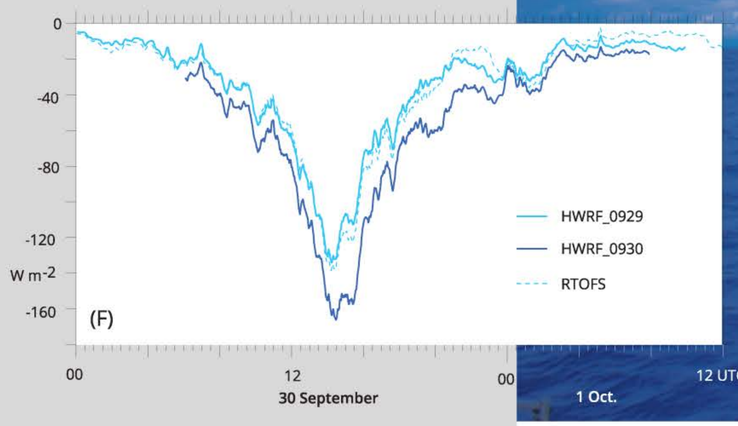
(D) Upper-ocean temperature (red) and salinity (blue) from the nearest Argo profile. Yellow shading highlights the halocline that initially trapped wind momentum in the upper 30 m.

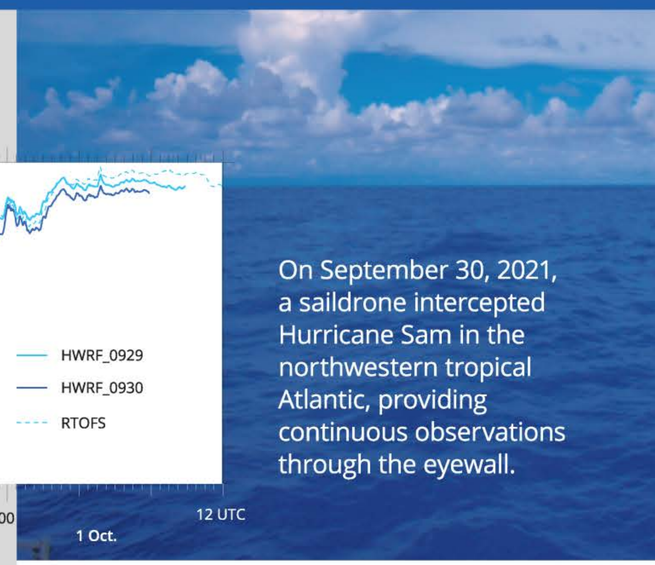
(E) Vertical ocean current shear squared; dashed yellow line marks the central halocline depth.

(F) Difference in surface enthalpy flux calculated using HWRF_0929 (light-blue curve), HWRF_0930 (blue curve) and RTOFS (dashed curve) versus Saildrone SST, and observed atmospheric parameters.

ADCP = Acoustic Doppler Current Profiler; SST = Sea Surface Temperature; RTOFS = Real-Time Ocean Forecasting System; HWRF = Hurricane Weather Research Forecast Model; HWRF_0929 = HWRF forecast initialized 2021-09-29 06 UTC; HWRF_0930 = HWRF Forecast initialized 2021-09-30 06 UTC

3. Model minus Saildrone SST-based enthalpy flux





On September 30, 2021, a saildrone intercepted Hurricane Sam in the northwestern tropical Atlantic, providing continuous observations through the eyewall.

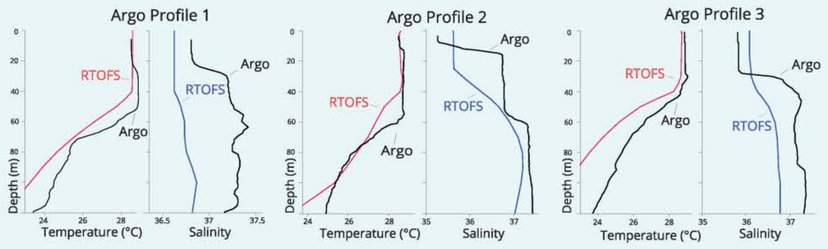
Surface ocean temperature unexpectedly increased during the first half of the storm. Saildrone current shear and upper-ocean structure from the nearest Argo profiles show an initial trapping of wind momentum by a strong halocline in the upper 30 m, followed by deeper mixing and entrainment of warmer subsurface water into the mixed layer.

The ocean initial conditions provided to operational forecast models failed to capture the observed upper-ocean structure, characterized by temperature inversions and haloclines.

The forecast models failed to simulate the warming and developed a surface cold bias of ~0.5°C by the time peak winds were observed, resulting in a 12-17% underestimation of surface enthalpy flux near the eyewall. Temperature inversions were evident in 29% of the Argo profiles collected in the broader study region implying that the potential for an approaching hurricane to drive surface warming via vertical mixing was not limited to the intercept vicinity.

Together, these results suggest that enhancing the regional upper-ocean observing system and improving the fidelity with which the observations are assimilated into ocean data assimilation systems could directly benefit Atlantic and Caribbean hurricane intensity forecasts.

4. Ocean Initial Conditions



Pre-storm temperature and salinity profiles from the nearest Argo Profiles (APs) and RTOFS (Real-Time Ocean Forecast System), which provided ocean initial conditions to HWRF (Hurricane Weather Research Forecast model) in 2021. Pre-storm Argo profiles exhibited upper-ocean temperature inversions capped by haloclines that were not apparent in RTOFS. This discrepancy explains why surface temperature maintenance and warming was simulated in our Argo-initialized 1D ocean model experiments but was not simulated in the RTOFS-initialized cases (not shown).

Key Points

- Storm-driven vertical mixing of an upper-ocean temperature inversion caused surface temperatures to warm under the eyewall of Hurricane Sam
- Operational hurricane forecast models failed to predict the observed surface warming because they were initialized with inaccurate upper-ocean conditions
- Model surface temperature cold biases peaked near the eyewall of the storm, where they likely caused surface enthalpy flux to be reduced by 12-17%

For more information

Chiodi et al., 2024. Surface ocean warming near the core of Hurricane Sam and its representation in forecast models, Frontiers in Marine Science.
DOI: 10.3389/fmars.2023.1297974