Ocean–Atmosphere Energy Exchange and Its Role in Hurricane Intensity

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Hurricane Lee (2023)
GOES-16 True Color Satellite Image

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Motivation and Scientific Questions

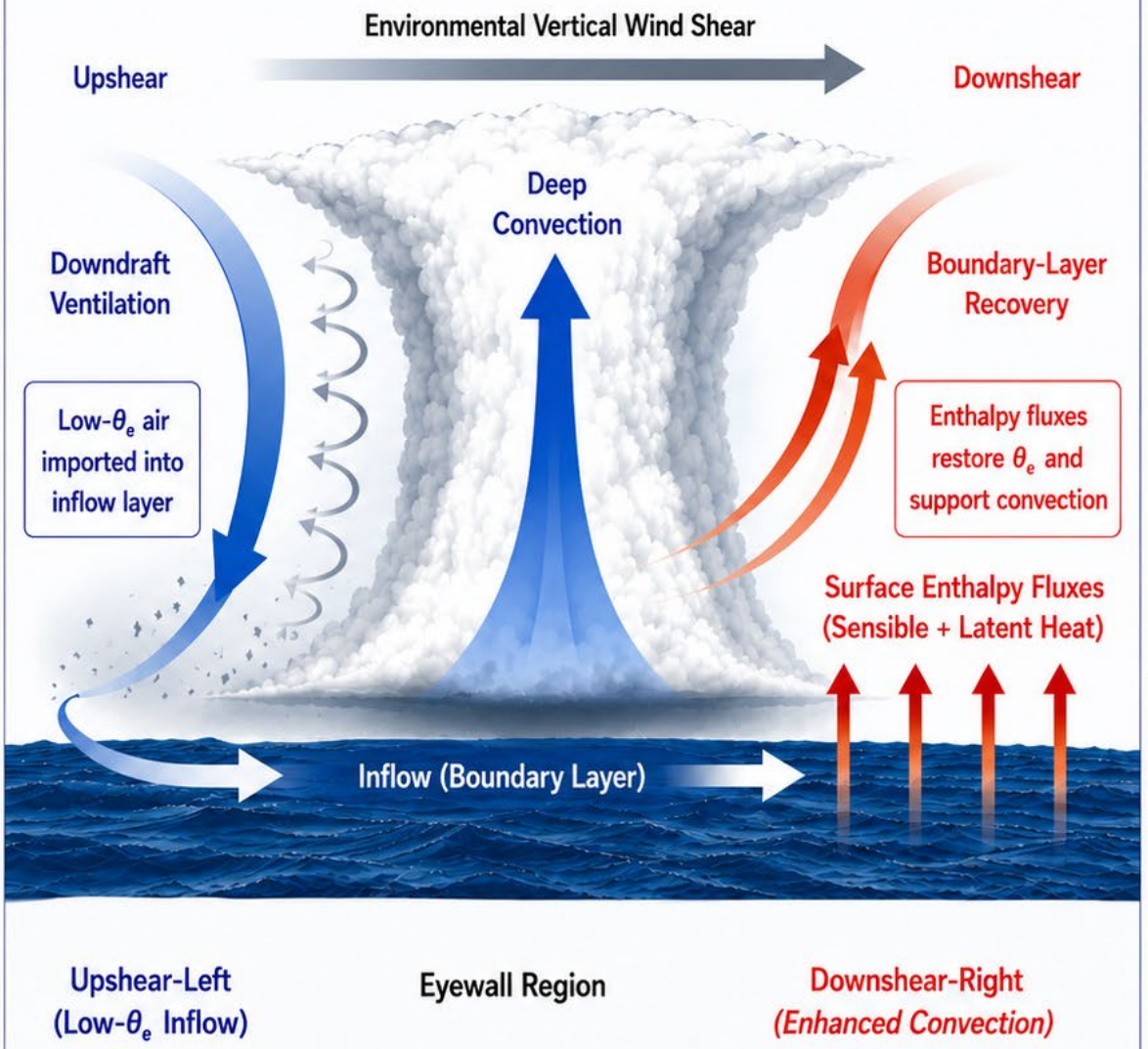
Key Scientific Questions

1. How does environmental vertical wind shear modulate boundary-layer thermodynamics?

2. Can surface enthalpy fluxes offset downdraft ventilation and restore low-energy inflow?

3. What controls the transition between intensification and weakening in shear?

Conceptual Framework: Ventilation vs. Boundary-Layer Recovery



Boundary-Layer Recovery: Role of Surface Fluxes

How do surface fluxes restore equivalent potential temperature (θ_e)?

1. θ_e Recovery Equation

$$\frac{d\theta_e}{dt} = \underbrace{\frac{\theta_e}{\theta}\frac{d\theta}{dt}}_{\text{Thermal (rewarming)}} + \underbrace{\frac{\theta_e L_v}{c_p T_{LCL}}\frac{dq}{dt}}_{\text{Moisture (rehumidification)}}$$

2. Link to Surface Fluxes (Bulk Form)

$$\frac{d\theta}{dt} = \frac{\theta}{c_p T}\frac{F_{H0}}{\rho \Delta z} \qquad \frac{dq}{dt} = \frac{F_{q0}}{\rho L_v \Delta z}$$

F_{H0}: surface sensible heat flux (↑ positive)

F_{q0}: surface latent heat flux (↑ positive)

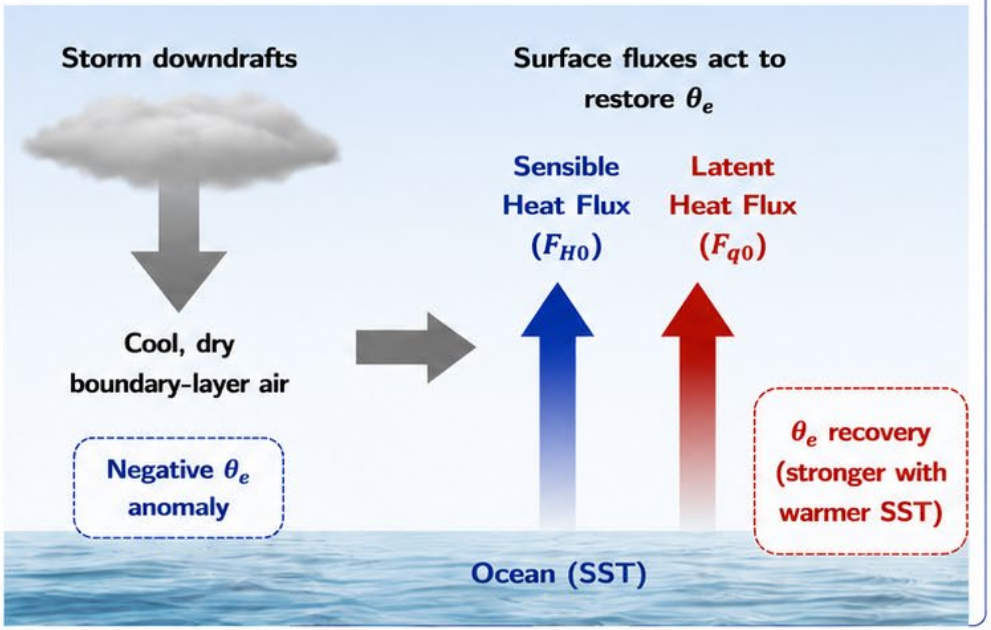
3. Flux Bulk Formulas

$F_{H0} = \rho c_p C_h U_{10}(SST - T_{10})$ — depends on SST difference

$F_{q0} = \rho L_v C_e U_{10}(q_0 - q_{10})$ — depends on humidity difference

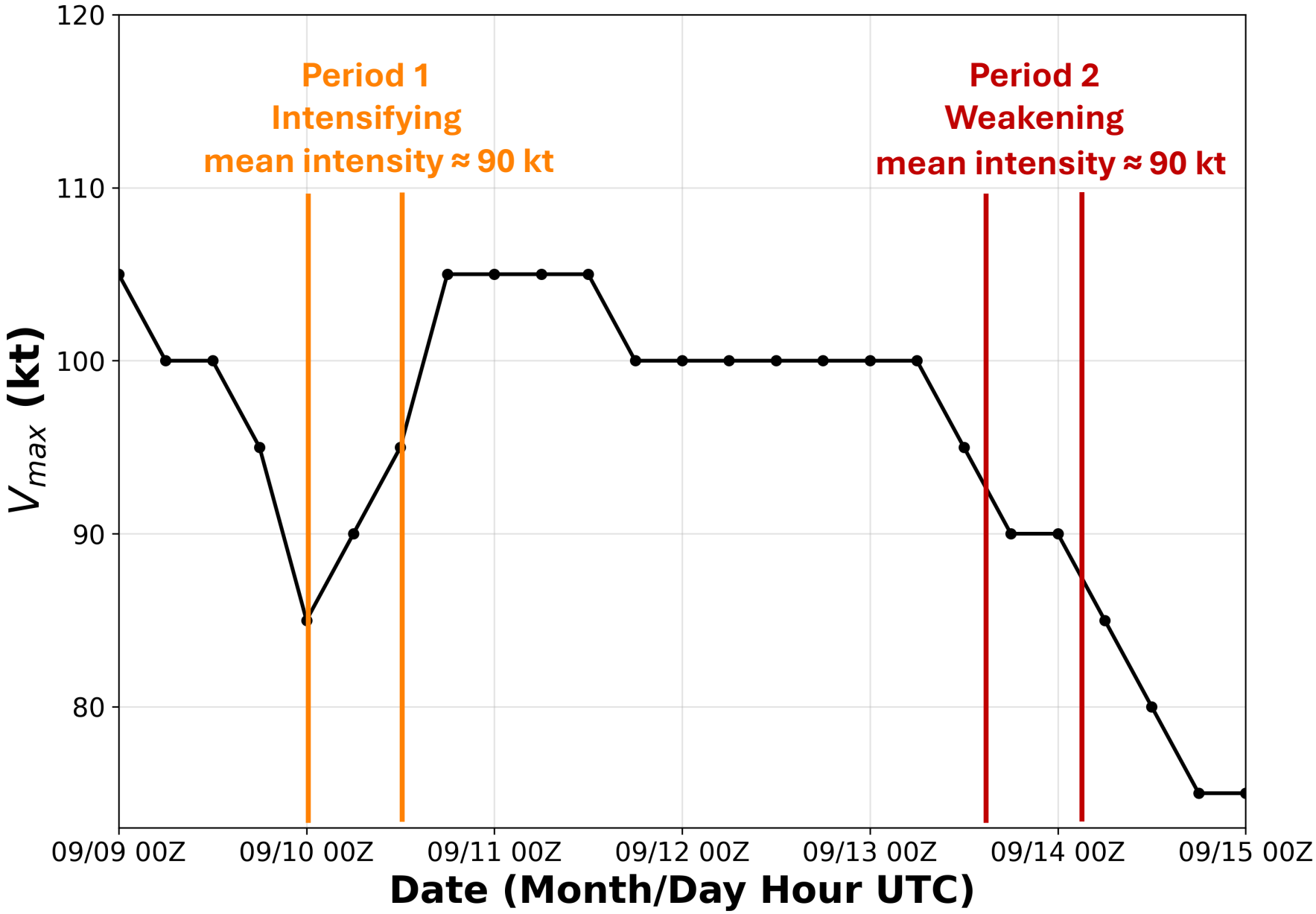
F_{H0} and F_{q0} decrease when SST is cooler → slower θ_e recovery.

4. Conceptual View of Boundary-Layer Recovery



- Surface sensible heat flux (F_{H0}) **warms** the boundary layer.
- Surface latent heat flux (F_{q0}) **moistens** the boundary layer.
- **Cooler SST** → smaller F_{H0} and F_{q0} → **slower θ_e recovery**.
- Stronger fluxes with **warmer SST** → **faster recovery**.

Boundary-layer recovery depends on surface fluxes.
Cooler SST reduces heat and moisture fluxes, leading to **slower θ_e recovery**.


Hurricane Lee (2023) Intensity Evolution
Period 1
Intensifying
mean intensity ≈ 90 kt
Period 2
Weakening
mean intensity ≈ 90 kt
120
110
100
90
80
V_{max} (kt)
09/09 00Z
09/10 00Z
09/11 00Z
09/12 00Z
09/13 00Z
09/14 00Z
09/15 00Z
Date (Month/Day Hour UTC)

Coordinated Air–Sea Observations

Key Messages

Simultaneous measurements of the atmosphere and ocean across the air–sea interface during Hurricane Lee (2023).

Enables quantification of ocean–atmosphere energy exchange and boundary–layer recovery in vertical wind shear.

Provides observations needed to diagnose processes controlling hurricane intensity change.

Aircraft Campaign

P–3 Orion	G–IV	C–130 (AFRC)
		
12 missions (NHC/EMC)	10 missions (NHC)	16 missions (NHC)

Coordinated Observations Across the Air–Sea Interface

Dropsondes / IRsondes



Profiles of wind, temperature, humidity, and pressure from the upper troposphere to the ocean surface

+ SST sensor

AXBTs



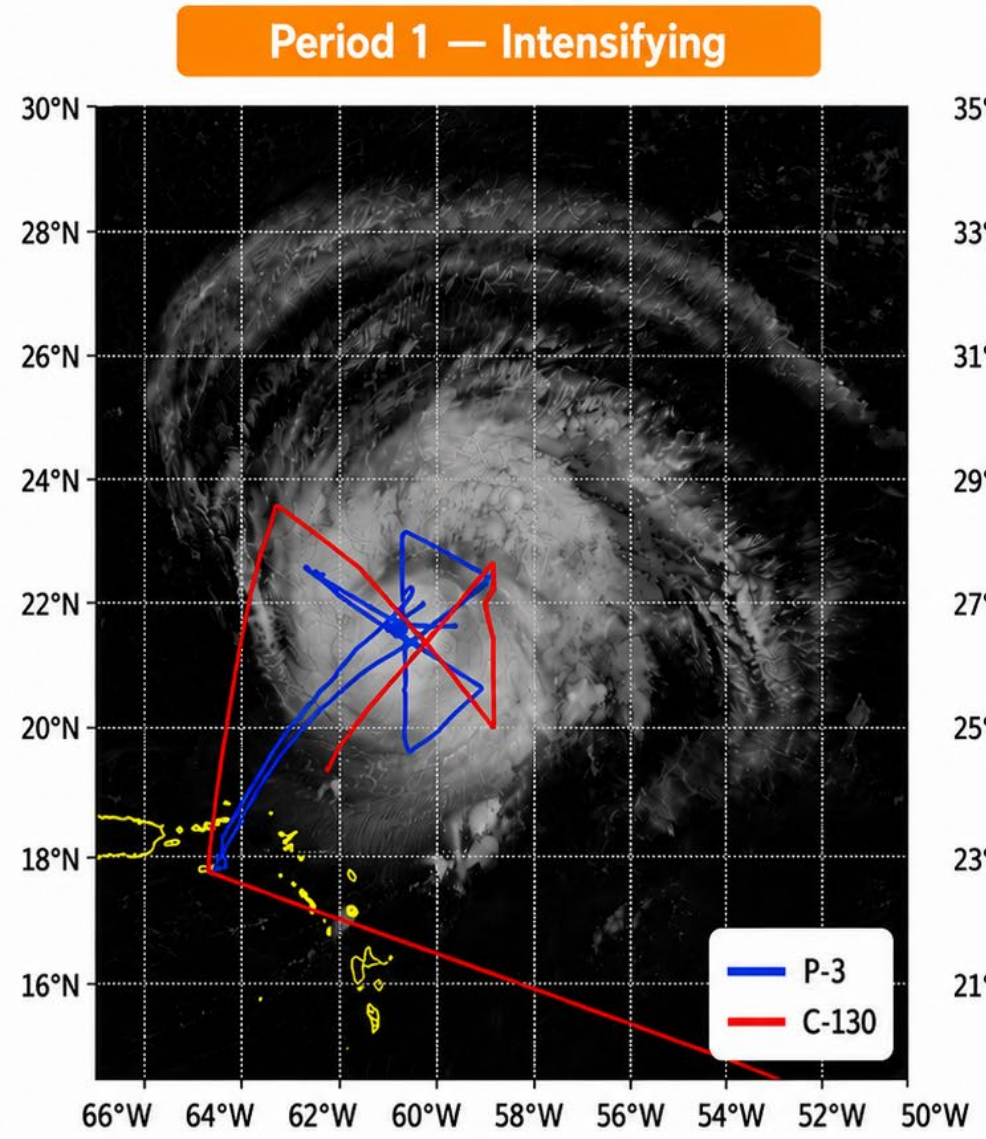
Upper–ocean temperature profiles to ~800 m depth within and ahead of the storm

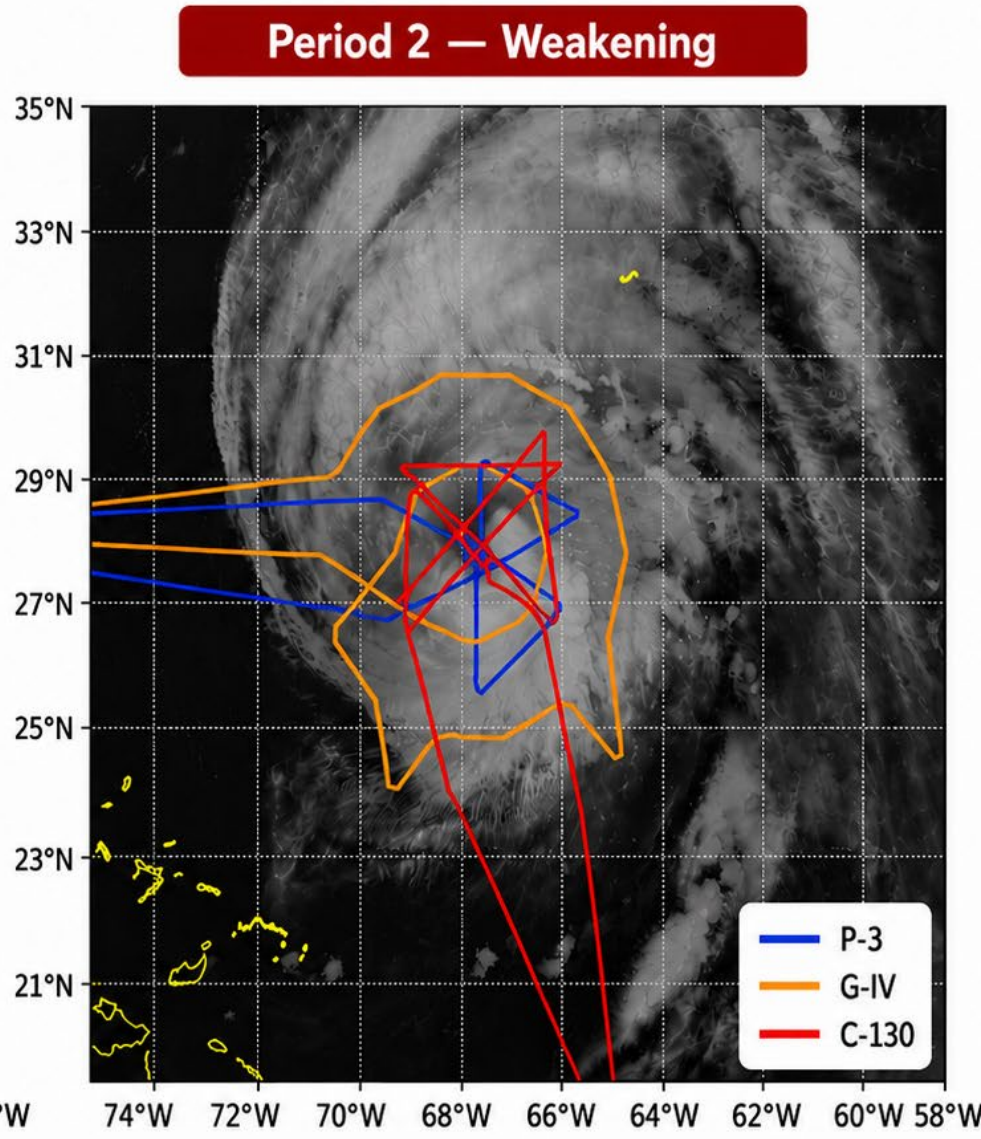
Saildrone



Sea surface measurements within and ahead of the storm: sea surface temperature, wind, temperature, humidity, and air–sea fluxes, and more

Aircraft Sampling during the Two Analysis Periods

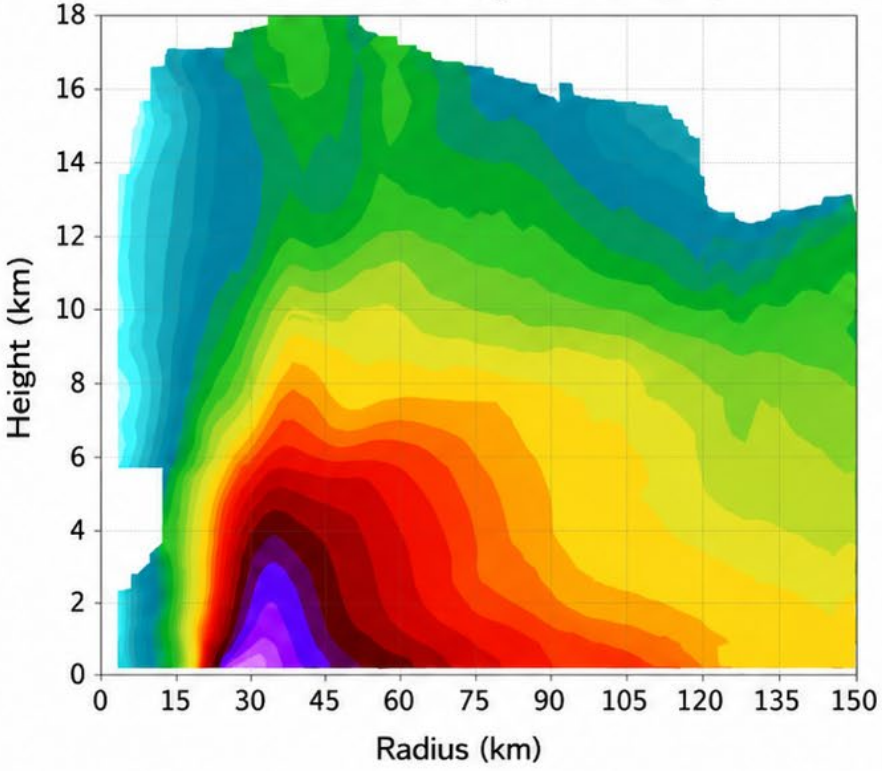




Vortex-Scale Structure during the Two Analysis Periods

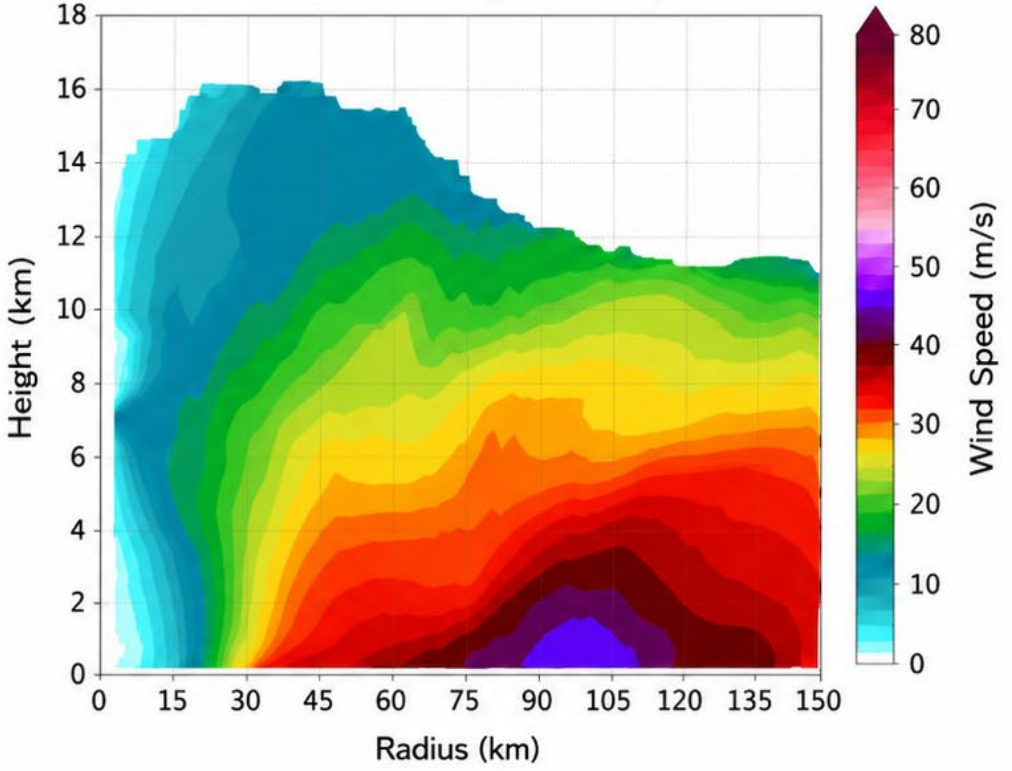
Period 1 — Intensifying

23091011 (LEE)
092200 to 124754 UTC
Azimuthal-mean Tangential Wind (m/s)



Period 2 — Weakening

230913H1 (LEE)
222030 to 255536 UTC
Azimuthal-mean Tangential Wind (m/s)



Intensifying period characteristics

- Strong, compact inner-core wind maximum
- Peak winds within ~30–40 km of the center
- More upright, concentrated vortex structure

Weakening period characteristics

- Weaker winds near the center below ~6 km
- Peak winds shifted outward to ~70–110 km
- Broader, more diffuse tangential-wind structure

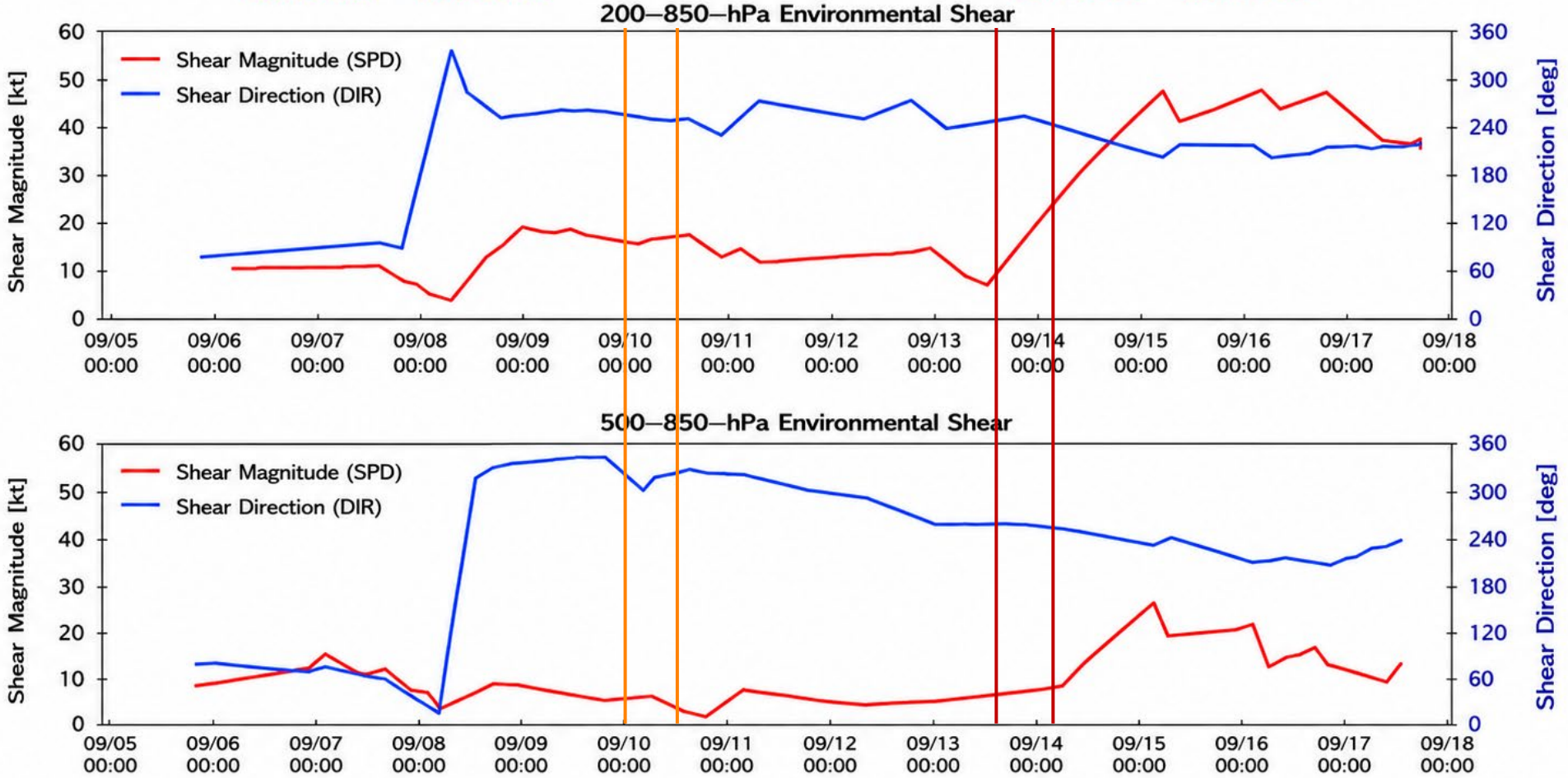
Environmental Shear Evolution during Hurricane

Period 1 — Intensifying

09/10 00Z – 09/10 12Z

Period 2 — Weakening

09/13 15Z – 09/14 03Z



Period 1 — Intensifying

- 200–850–hPa shear: ~12–15 kt
- 500–850–hPa shear: ~5–7 kt

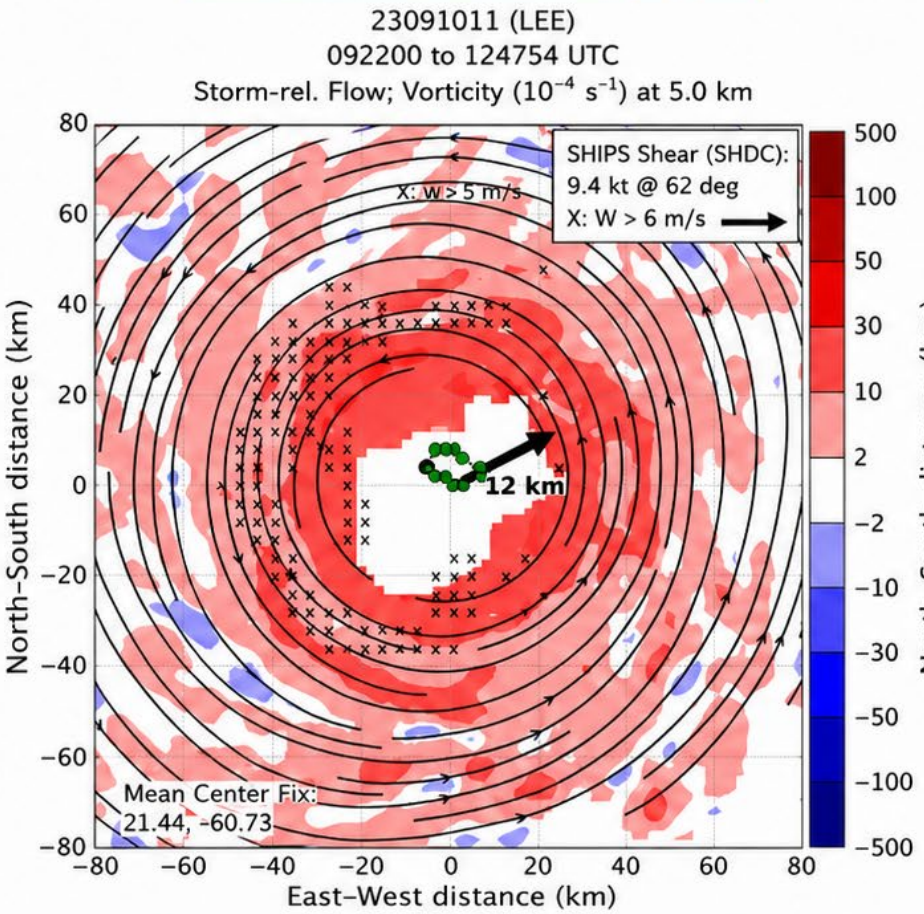
Shear magnitudes are comparable during the two analysis periods.

Period 2 — Weakening

- 200–850–hPa shear: ~7–12 kt (rising after 09/14)
- 500–850–hPa shear: ~6–9 kt

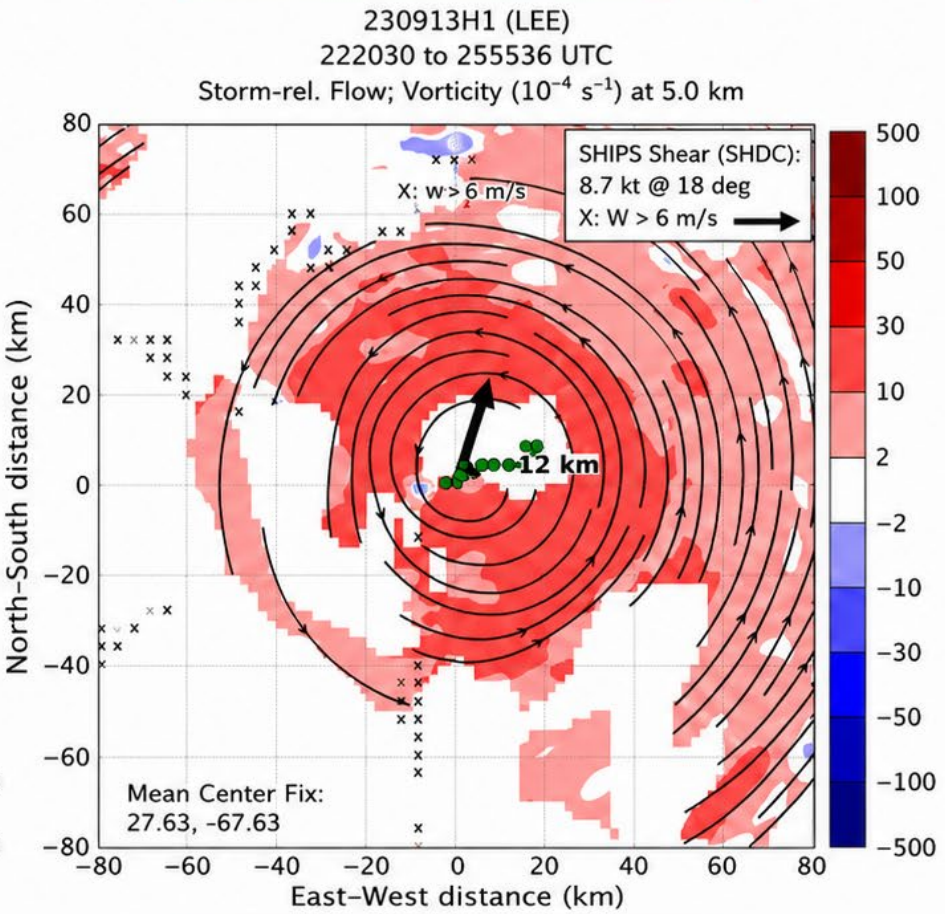
Convective-Scale Vortex Structure during the Two Periods

Period 1 — Intensifying



- ✓ More symmetric inner-core structure
- ✓ Stronger concentrated vorticity

Period 2 — Weakening



- ✓ Greater asymmetry
- ✓ Broader and disrupted circulation

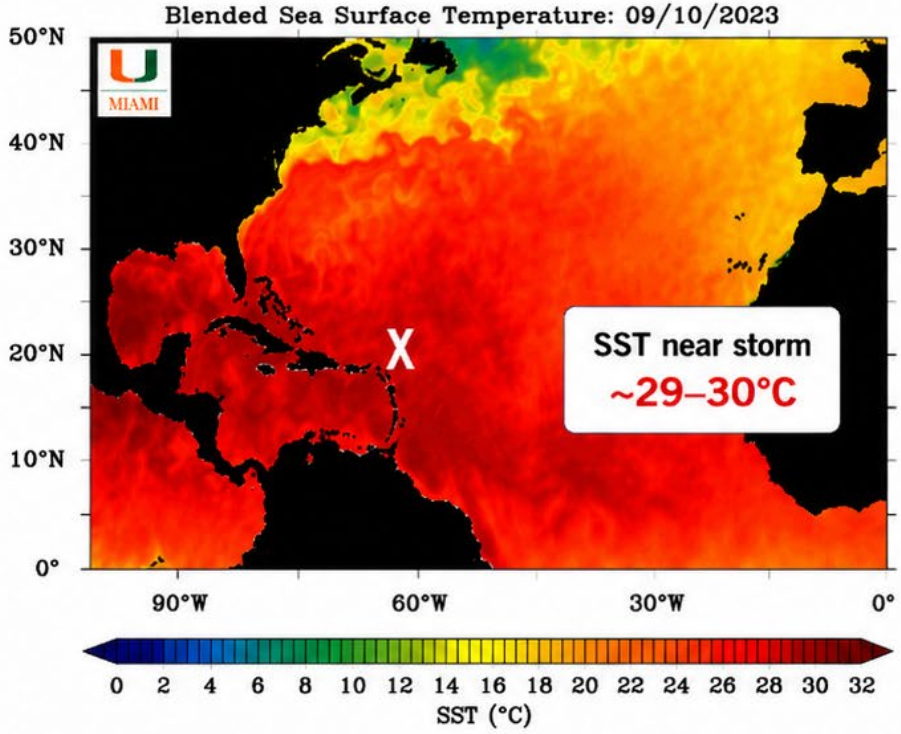
The weakening period exhibits a more asymmetric vortex structure consistent with enhanced ventilation and disrupted inner-core organization.

SST and Ocean Conditions during the Two Periods

Did the ocean help boundary-layer recovery?

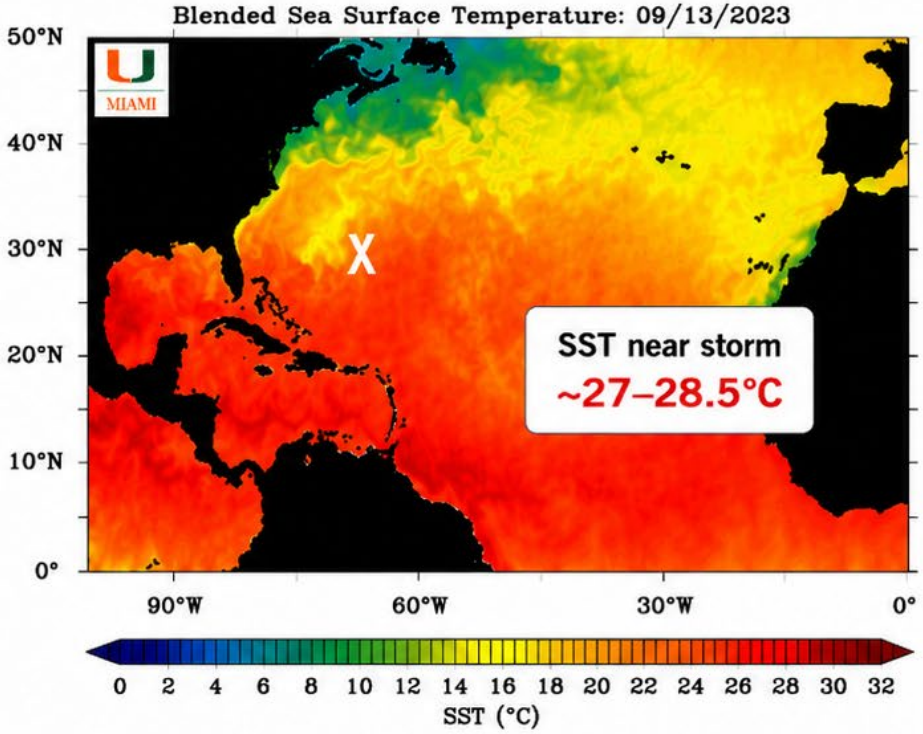
Period 1 — Intensifying

09/10 00Z – 09/10 12Z



Period 2 — Weakening

09/13 15Z – 09/14 03Z



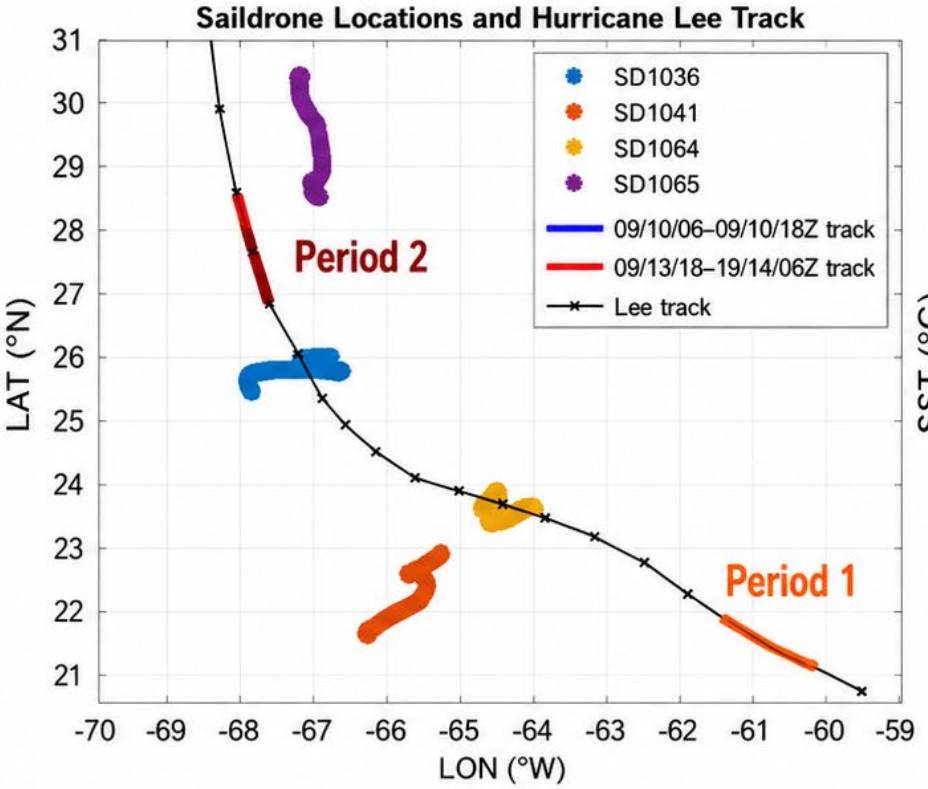
Both periods occurred over warm SSTs (>26°C) capable of supporting deep convection, but the warmer ocean in Period 1 likely provided greater surface enthalpy fluxes, which may have contributed to more efficient boundary-layer recovery and intensification.

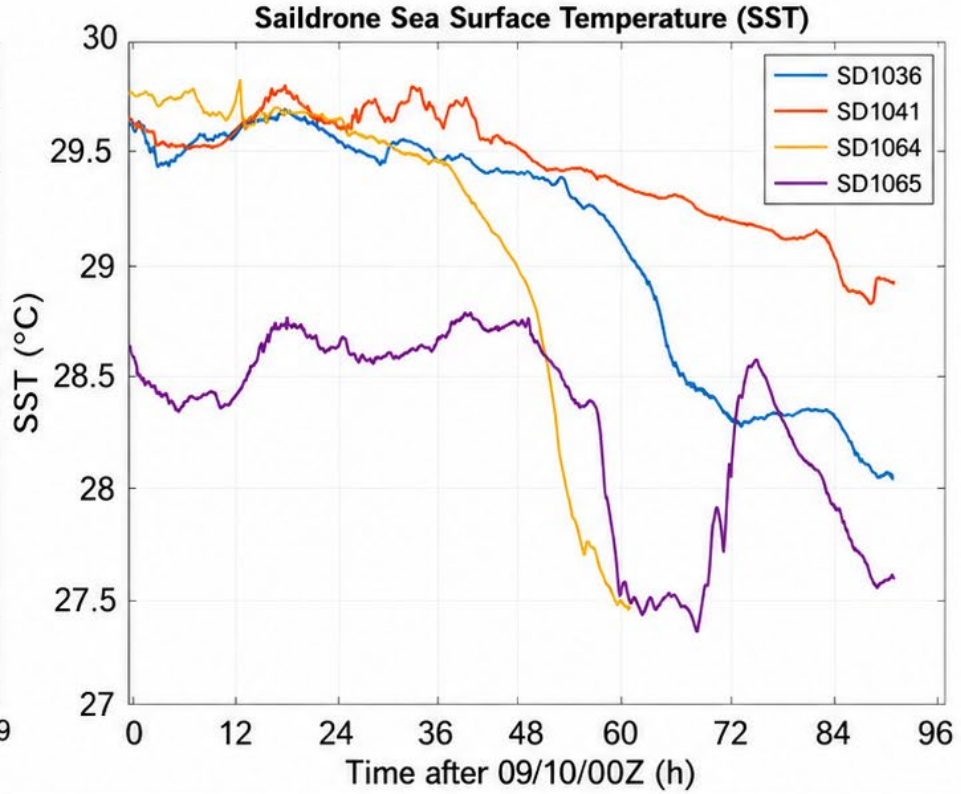
SST and Ocean Conditions from Saildrone Observations

Did the ocean help boundary-layer recovery?

Period 1 — Intensifying
09/10 00Z – 09/10 12Z

Period 2 — Weakening
09/13 15Z – 09/14 03Z





SST Cooling During Period 2

- All four Saildrones measured cooler SSTs during Period 2 (weakening).
- SSTs near the storm decreased by **~1.5–2.5°C** between the two periods.

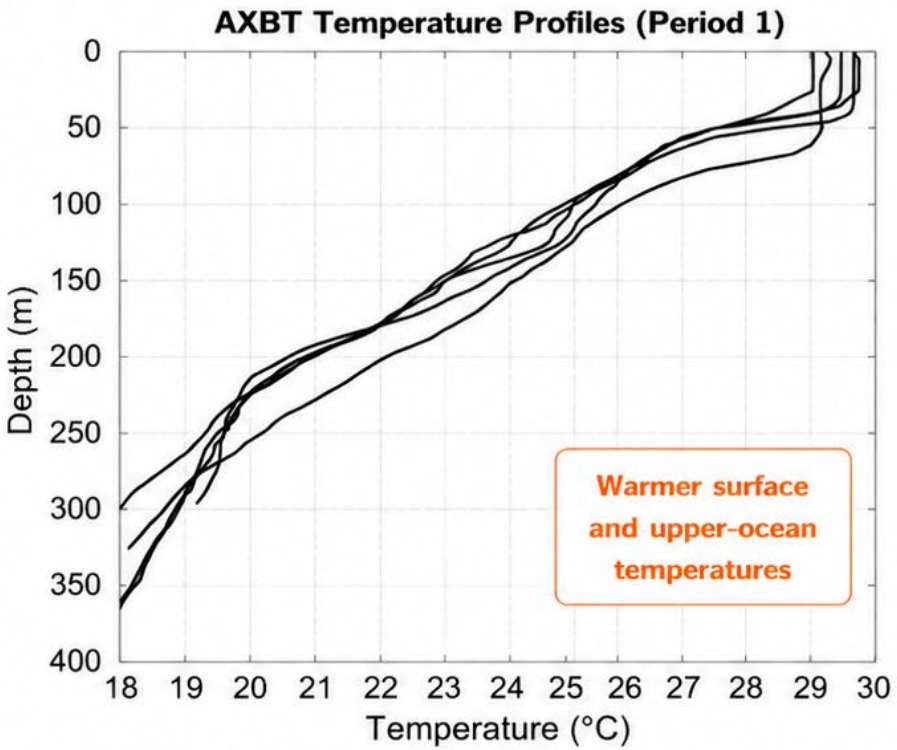
Cooler SSTs along Lee's path during Period 2 likely reduced surface enthalpy fluxes, providing less favorable oceanic support for boundary-layer recovery.

AXBT Upper-Ocean Temperature Structure

Did the ocean help boundary-layer recovery?

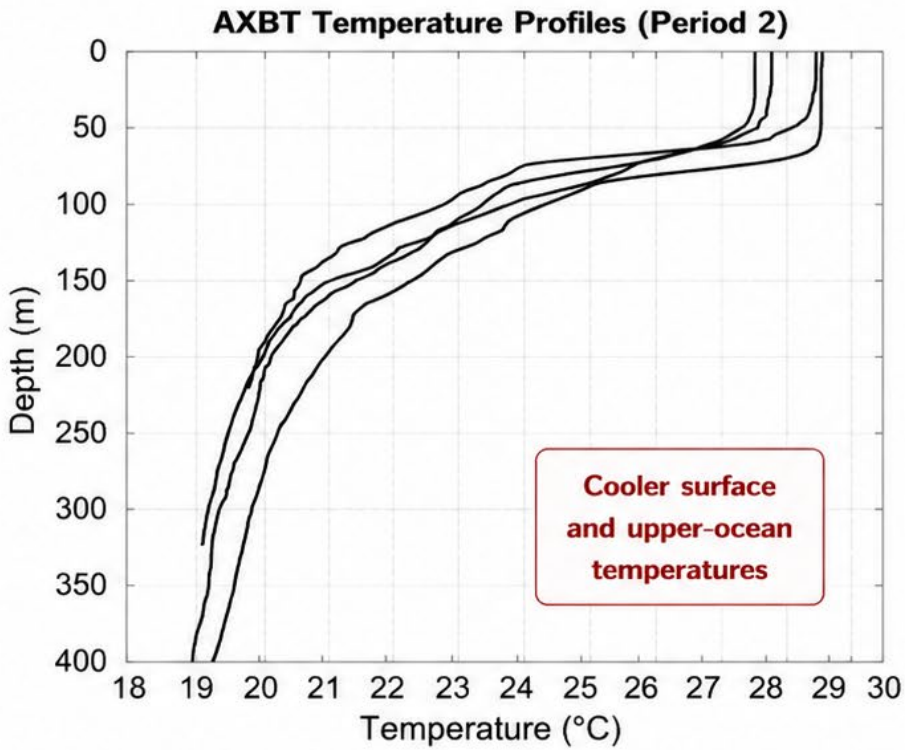
Period 1 — Intensifying

09/10 00Z – 09/10 12Z



Period 2 — Weakening

09/13 15Z – 09/14 03Z

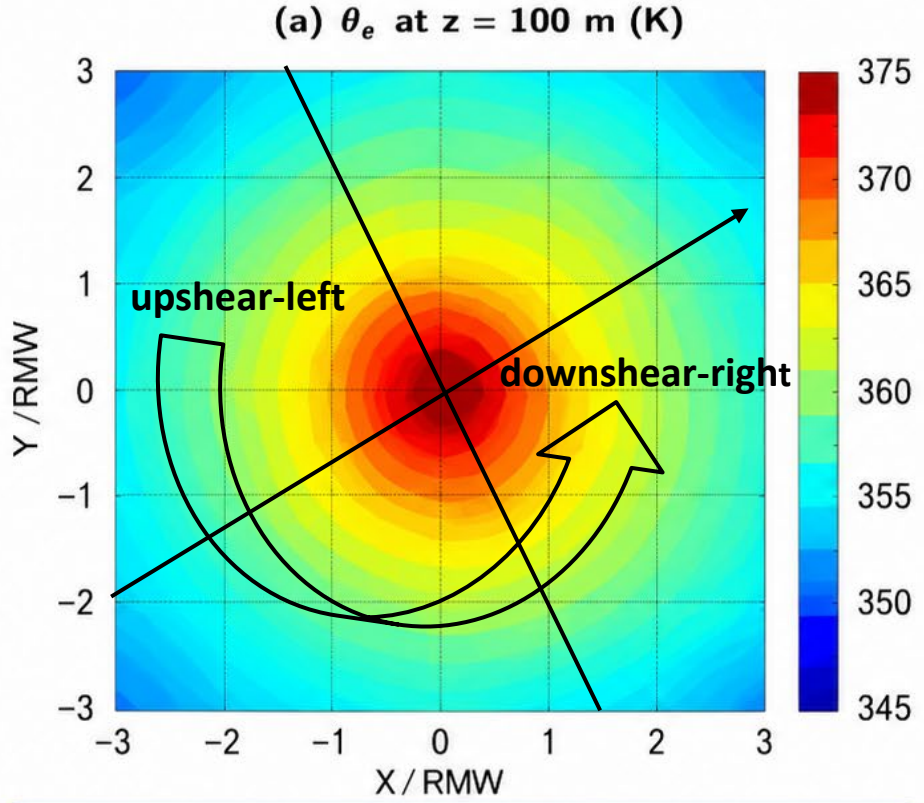


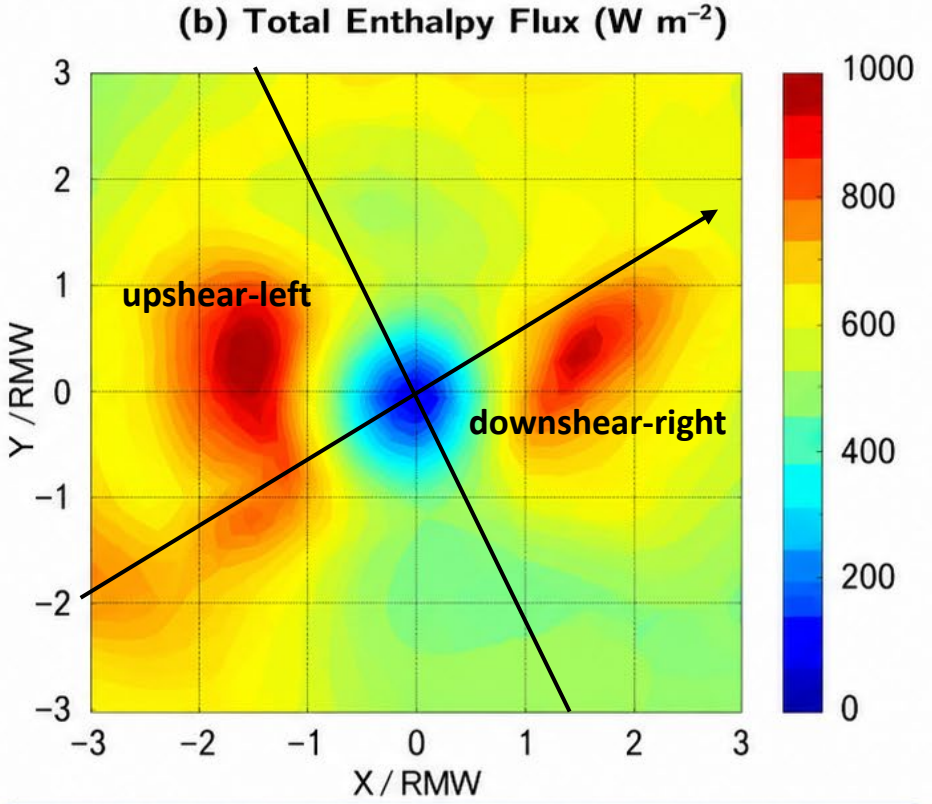
- AXBTs show **cooler** near-surface and upper-ocean temperatures during Period 2 (weakening).
- SSTs during Period 2 were **~1.5–2.5°C cooler** than during Period 1.

Cooler SSTs and upper-ocean temperatures during Period 2 likely reduced oceanic support for boundary-layer recovery.

Boundary-Layer Recovery and Surface Enthalpy Fluxes

Period 1 (Intensification): 09/10 00Z – 09/10 12Z





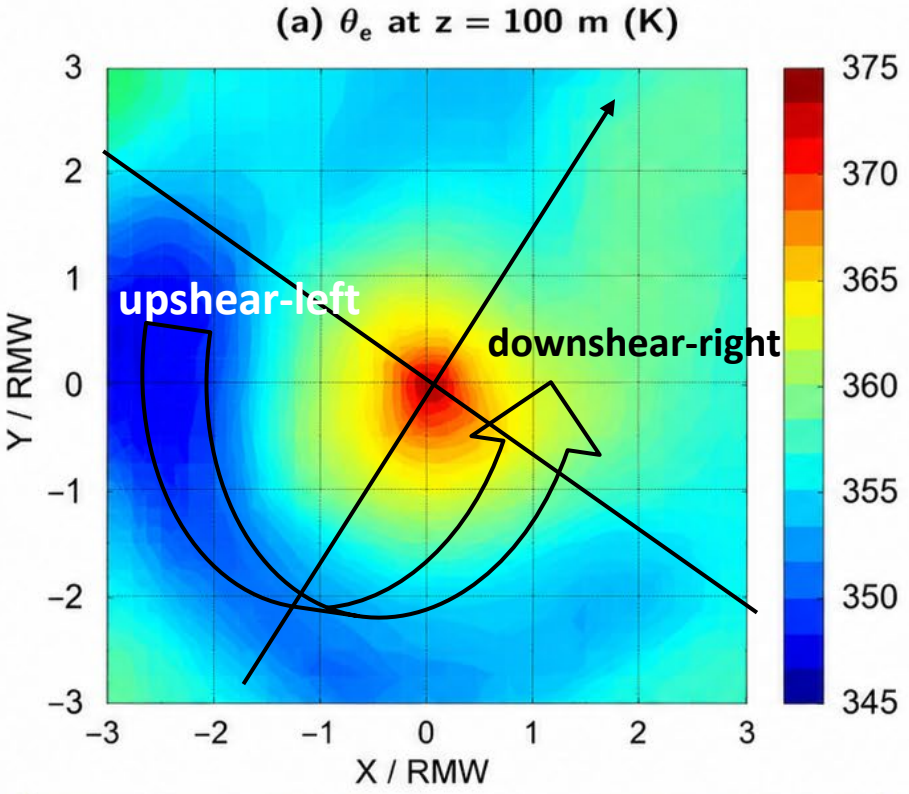
- θ_e near the inner core is **higher** and **more symmetric**, indicating stronger thermodynamic recovery.
- Surface enthalpy fluxes are **stronger** in the inner core and **centered** near the storm center.

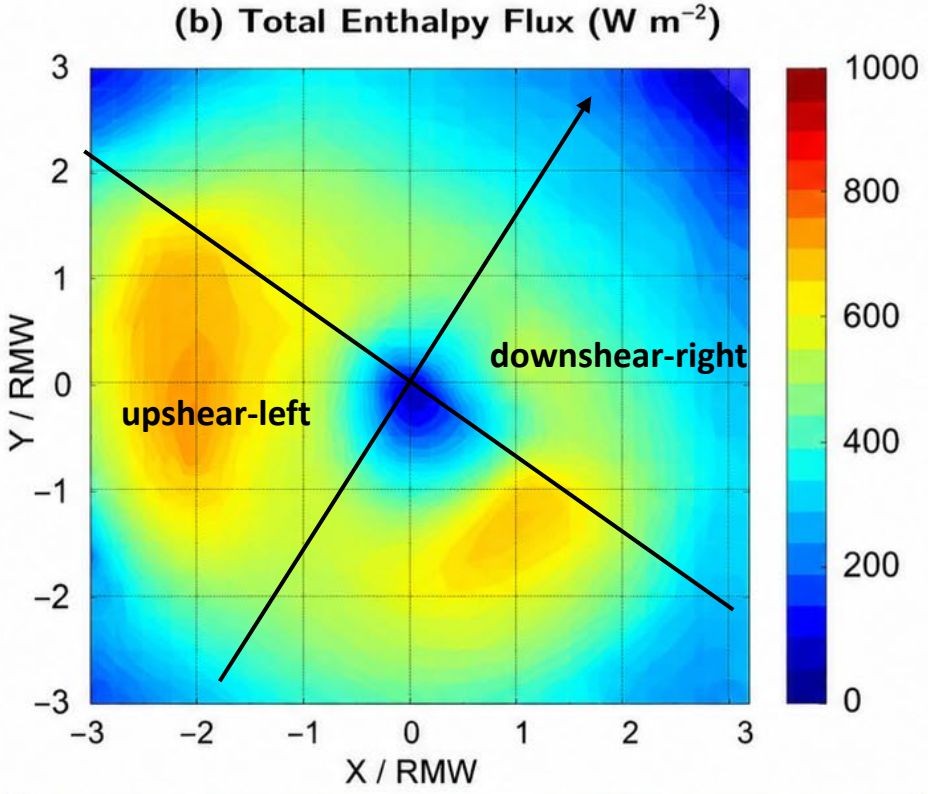
- Enhanced and more symmetric fluxes imply **stronger air–sea coupling** and more effective boundary–layer recovery.
- Recovery is **highly symmetric**, with strong support across all quadrants.

During Period 1, stronger and centered surface fluxes correspond to higher θ_e near the inner core, leading to more efficient boundary–layer recovery and intensification.

Boundary-Layer Recovery and Surface Enthalpy Fluxes

Period 2 (Weakening): 09/13 15Z – 09/14 03Z





- θ_e near the inner core is **lower** and **more asymmetric**, indicating weaker thermodynamic recovery.
- Surface enthalpy fluxes are **weaker** in the inner core and **shifted** away from the center.

- Reduced and displaced fluxes imply **weaker air–sea coupling** and less effective boundary–layer recovery.
- Recovery is **highly asymmetric**, with less support in the downshear–right quadrant.

During Period 2, **weaker** and **displaced** surface fluxes correspond to **lower** θ_e near the inner core, leading to less efficient boundary–layer recovery and **weakening**.

Summary

- Hurricane Lee (2023) experienced two periods with similar intensity but opposite trends: intensifying and weakening.
- The intensifying period featured warmer SSTs and stronger, more symmetric surface enthalpy fluxes.
- These conditions supported more efficient recovery of high-θ_e air in the boundary layer and inner core.
- The weakening period exhibited cooler SSTs, reduced/ displaced fluxes, and more asymmetric recovery.
- Boundary–layer recovery depends on both the magnitude and organization of surface enthalpy fluxes.
- Coordinated air–sea observations are essential for understanding tropical cyclone intensity change.