IOVWST · Air-Sea Interaction
2026

A Model-Based Study of *Power Input to Hurricane Boundary-Layers*

How does the spatial distribution of energy intake within the boundary layer evolve across storm quadrants during the evolution of a tropical cyclone?

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THE CORE QUESTION

What fuels a tropical cyclone — and from where?

This study uses WRF simulations to determine how radial inflow and surface fluxes independently fuel cyclone intensification.

01

Central Question

How much of the enthalpy flux reaching the eyewall arrives via inflow transport from distant ocean vs. direct local air–sea fluxes?

02

Approach

Integrate enthalpy fluxes over WRF storm regions; compare uncoupled, coupled, and coupled+spray configurations.

03

Expected Result

Inflow transport dominates the budget; ocean coupling reduces inner-core fluxes; sea spray partially offsets SST cooling.

TWO AIMS

Do the WRF model configurations reproduce these results? · Can they illuminate its physical drivers?

BACKGROUND

Tropical cyclones are thermodynamic heat engines.

Emanuel (1988): the warm ocean surface powers the storm like a Carnot engine.

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1 **The Carnot Analogy**

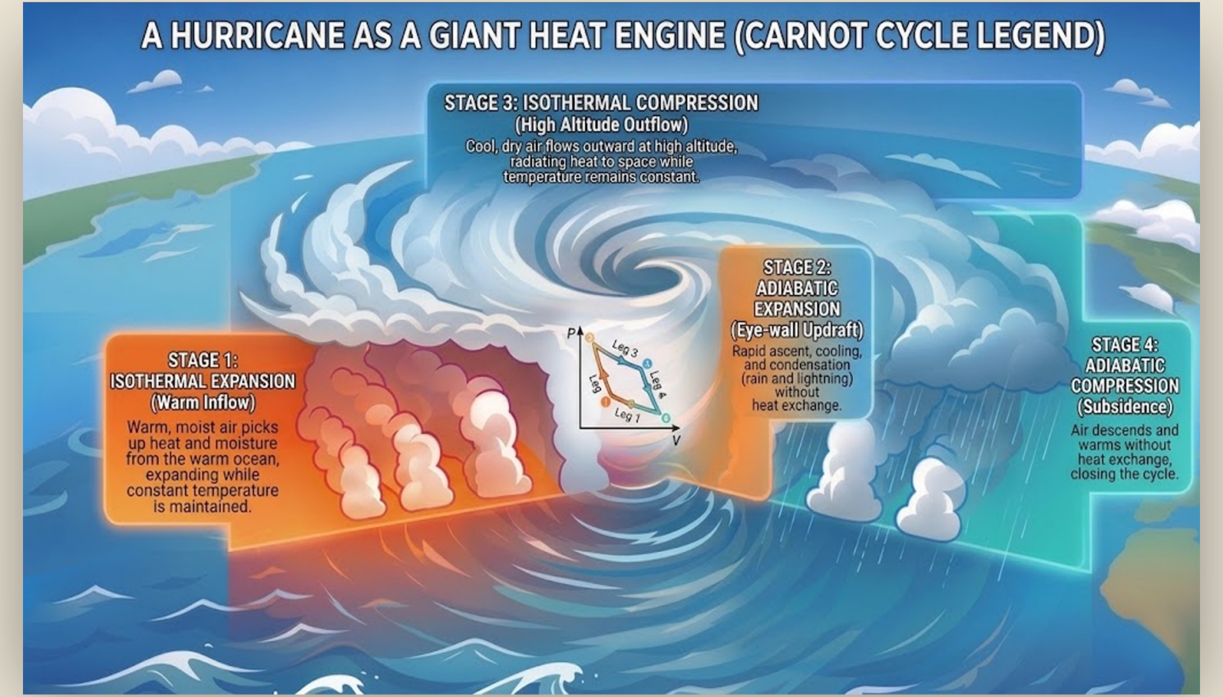
SST provides heat; the cold upper troposphere is the exhaust. Maximum potential intensity (MPI) derived from SST and outflow temperature.

2 **What Remains Open**

WHERE does energy enter? Beneath the eye, the eyewall, or the outer inflow boundary? The Carnot model says fuel must come from the surface — not which part.

3 **Sea Spray Complication**

Fine droplets dramatically change bulk flux estimates, especially in the high-wind eyewall region.



A HURRICANE AS A GIANT HEAT ENGINE (CARNOT CYCLE LEGEND)

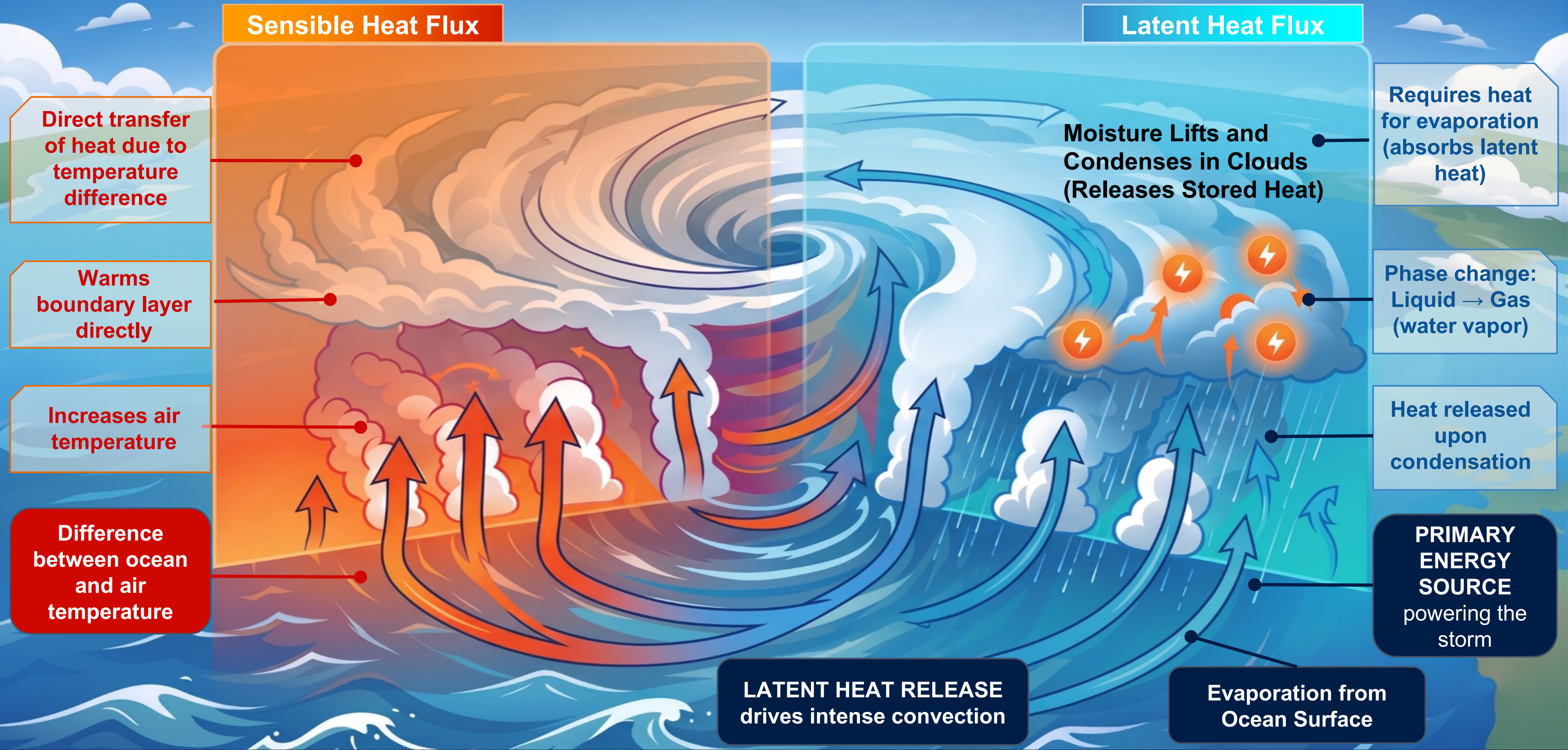
STAGE 3: ISOTHERMAL COMPRESSION (High Altitude Outflow)
Cool, dry air flows outward at high altitude, radiating heat to space while temperature remains constant.

STAGE 1: ISOTHERMAL EXPANSION (Warm Inflow)
Warm, moist air picks up heat and moisture from the warm ocean, expanding while constant temperature is maintained.

STAGE 2: ADIABATIC EXPANSION (Eye-wall Updraft)
Rapid ascent, cooling, and condensation (rain and lightning) without heat exchange.

STAGE 4: ADIABATIC COMPRESSION (Subsidence)
Air descends and warms without heat exchange, closing the cycle.

ENTHALPY FLUXES IN A TROPICAL CYCLONE



Sensible Heat Flux

Direct transfer of heat due to temperature difference

Warms boundary layer directly

Increases air temperature

Difference between ocean and air temperature

Latent Heat Flux

Moisture Lifts and Condenses in Clouds (Releases Stored Heat)

Requires heat for evaporation (absorbs latent heat)

Phase change: Liquid → Gas (water vapor)

Heat released upon condensation

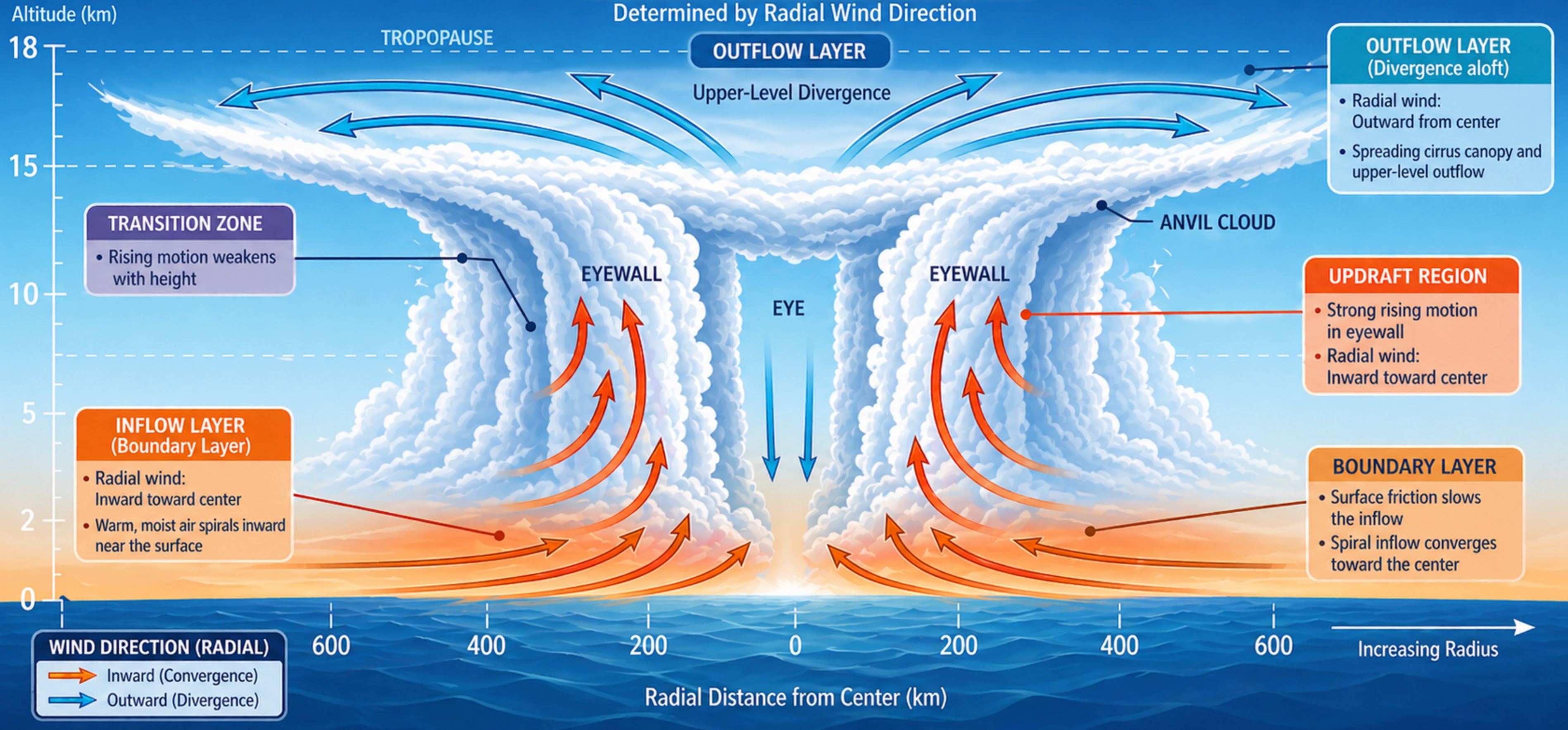
PRIMARY ENERGY SOURCE powering the storm

LATENT HEAT RELEASE drives intense convection

Evaporation from Ocean Surface

VERTICAL PROFILE OF INFLOW AND OUTFLOW LAYERS OF A TROPICAL CYCLONE

Determined by Radial Wind Direction



OUTFLOW LAYER (Divergence aloft)

- Radial wind: Outward from center
- Spreading cirrus canopy and upper-level outflow

TRANSITION ZONE

- Rising motion weakens with height

UPDRAFT REGION

- Strong rising motion in eyewall
- Radial wind: Inward toward center

INFLOW LAYER (Boundary Layer)

- Radial wind: Inward toward center
- Warm, moist air spirals inward near the surface

BOUNDARY LAYER

- Surface friction slows the inflow
- Spiral inflow converges toward the center

WIND DIRECTION (RADIAL)

→ Inward (Convergence)
→ Outward (Divergence)

THREE WRF CONFIGURATIONS

Identical storm simulated three ways to isolate physics.

WRF-ARW at ~1 km inner-domain resolution. Differences isolate ocean coupling and spray physics.

Run 1 — Uncoupled

- Fixed sea-surface temperature.
- No ocean feedback to the storm
- Upper bound on air–sea fluxes.
- Standard WRF slab-ocean setup.

Run 2 — Coupled

- WRF coupled to ocean model.
- SST cools beneath the storm.
- Negative feedback on intensity.
- More physically realistic.

Run 3 — Coupled + Spray

- Adds sea-spray parameterization.
- Droplets boost latent + sensible heat.
- Partially offsets SST cooling.
- Tests spray's net energy impact.

All three runs simulate the same storm — differences isolate ocean coupling and spray physics.

§3 METHODS

ANALYSIS PIPELINE

Five steps applied identically to all three model runs.

Step 1
Locate Center

Refined eyewall-center at each timestep from python algorithm stored as JSON catalog (maximizes azimuthal-mean tangential wind).

Step 2
Define Inflow Layer

Inflow-top level from diagnostics: level where time-mean radial wind changes sign, stored per timestep.

Step 3
Extract Flux Fields

Read LH + SH flux from WRF output. Compute moist enthalpy flux F = LH + SH at every grid cell.

Step 4
Integrate Over Regions

Sum $F \cdot \Delta A$ over inner core, inflow layer, and full storm disk. Output: time series of integrated enthalpy fluxes in terrawatts for each region.

Step 5
Compare Across Runs

Uncoupled vs. Coupled vs. Coupled+Spray. Isolate effect of SST feedback and spray on the enthalpy budget.

§3 CHARACTERISTICS

CENTER REFINEMENT

Two-Stage Center Tracking with WRF data

Refining pressure-minimum centers through eyewall tangential wind maximization

1 **Identify Pressure Minimum First**

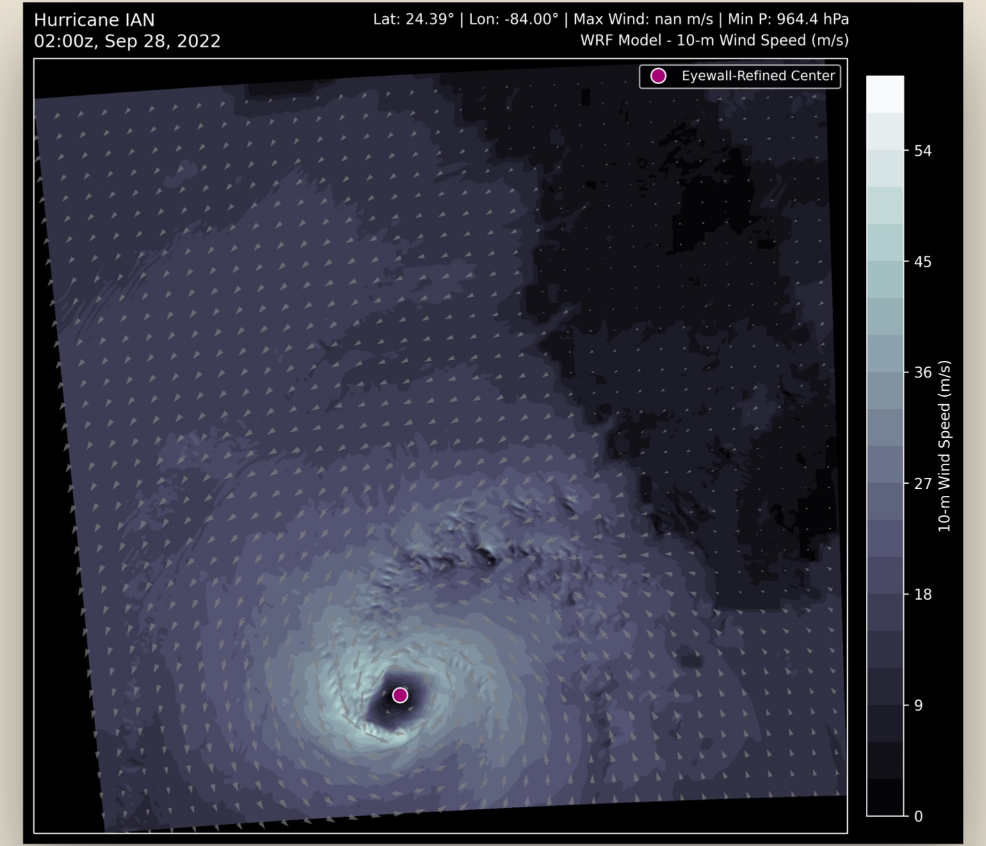
We identify the surface pressure minimum near peak 10-meter winds, providing a physically intuitive but potentially displaced first guess.

2 **Finding the True Center**

Use an RMW binning alogrithm to identify azimuthal-mean tangential winds, refining the center for superior eyewall circulation tracking.

3 **Why this is Important**

Quantifying the offset between pressure and wind centers enables precise flux integrations and better analysis of asymmetric, sheared storms.



INFLOW BOUNDARY LAYER

Inflow transport vs. local air–sea exchange.

The same moist enthalpy budget — two physically distinct routes that respond differently to ocean coupling and sea spray.

1 Inflow Transport

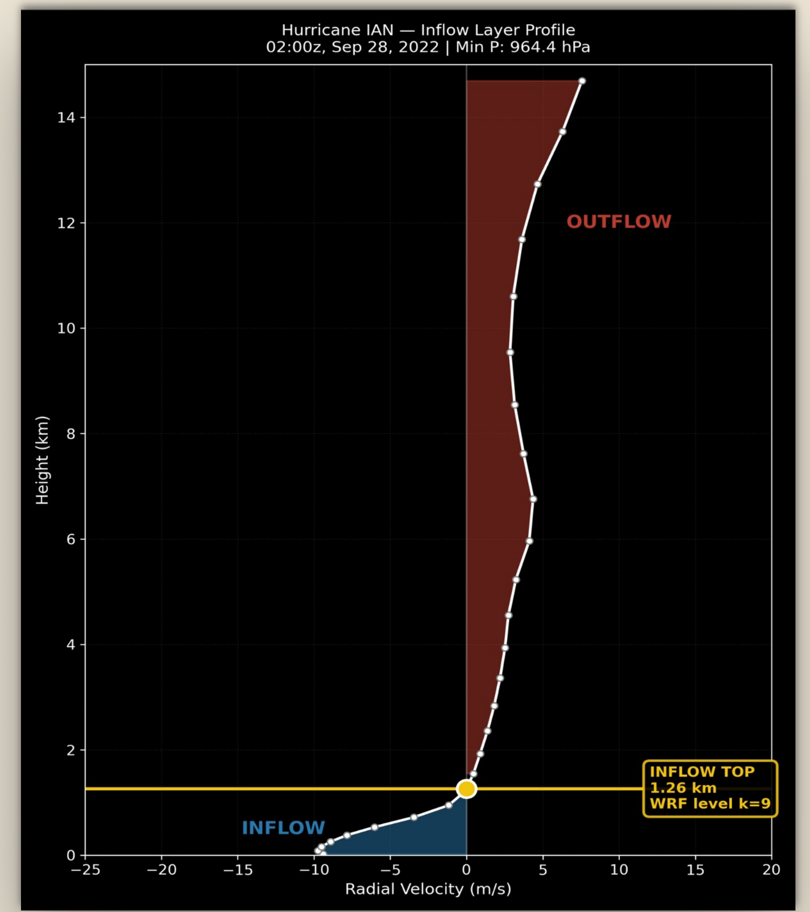
Air spiraling inward carries enthalpy absorbed over hundreds of km of warm ocean. Advected horizontally by inflow boundary layer.

2 Local Air–Sea Fluxes

Direct exchange beneath the storm's inner core: sensible heat, latent heat (evaporation), and sea-spray droplet evaporation. Suppressed in coupled runs as SST cools under the eyewall.

3 Why the Distinction Matters

SST cooling suppresses local fluxes but not inflow transport. Sea spray affects the local pathway only. Three runs isolate each effect.



A QUANTITATIVE YARDSTICK

Defining the Radius of Maximum Wind (RMW)

1 **Located the refined center**

Search within a 200 km radius of peak wind proxies to identify the initial surface pressure center as a tracking anchor.

2 **Perform radial averaging**

Compute azimuthal-mean tangential wind profiles in 1 km radial bins to filter local asymmetries and noise.

3 **Locate velocity peak**

Locate the radius where mean tangential wind reaches absolute maximum, defining the primary eyewall scale.

BENCHMARK AVERAGE

$\geq$ 25 km

Major hurricanes typically maintain a compact inner core with RMW values significantly smaller than weaker systems

MINIMAL HURRICANES	MAJOR HURRICANES
30–80km	20–40km

For structural analysis, RMW serves as a proxy for storm maturity. As a system intensifies, conservation of angular momentum leads to a "vortex contraction" where RMW values decrease, creating a more intense and efficient secondary circulation.

(Hsu & Yan 1998, Kimball & Mulekar 2004, DeMaria et al. 2006, Knaff et al. 2015, Nederhoff et al. 2019, Knaff et al. 2007, Vickery & Wadhera 2008, Stull 2017)

§4 FLUXES

ENERGY SOURCE

The fuel quantity: $k = c_pT + L_vq_v$.

Enthalpy flux measures the total thermodynamic energy content of boundary-layer air.

1 **Sensible Heat ($c_p\,T$)**

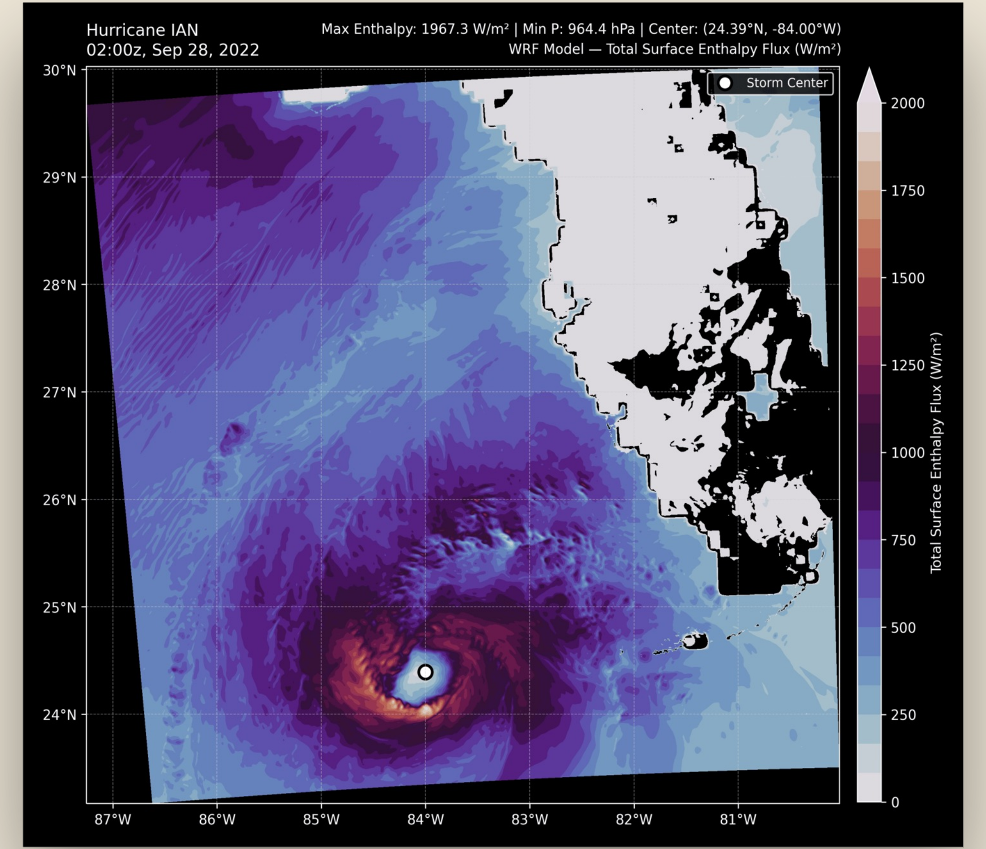
Kinetic energy of air molecules, felt as temperature. Warmer SST → larger air–sea temperature gradient → larger sensible flux.

2 **Latent Heat ($L_v\,q_v$)**

Energy stored in water vapor; released on condensation in the eyewall. Evaporation from the warm ocean is the dominant fuel source.

3 **Air–Sea Disequilibrium**

Ocean holds more enthalpy than overlying air. Bulk formula: $F = \rho\, C_k\, |V|\, (k_{sst} - k_{air})$. Deficit grows as air spirals inward.



§5 **FLUXES**

QUADRANT SPECIFIC

Hurricane Ian Enthalpy Budget

Flux analysis by shear quadrant and model variant using RMW.

1 Surface Flux Dominance

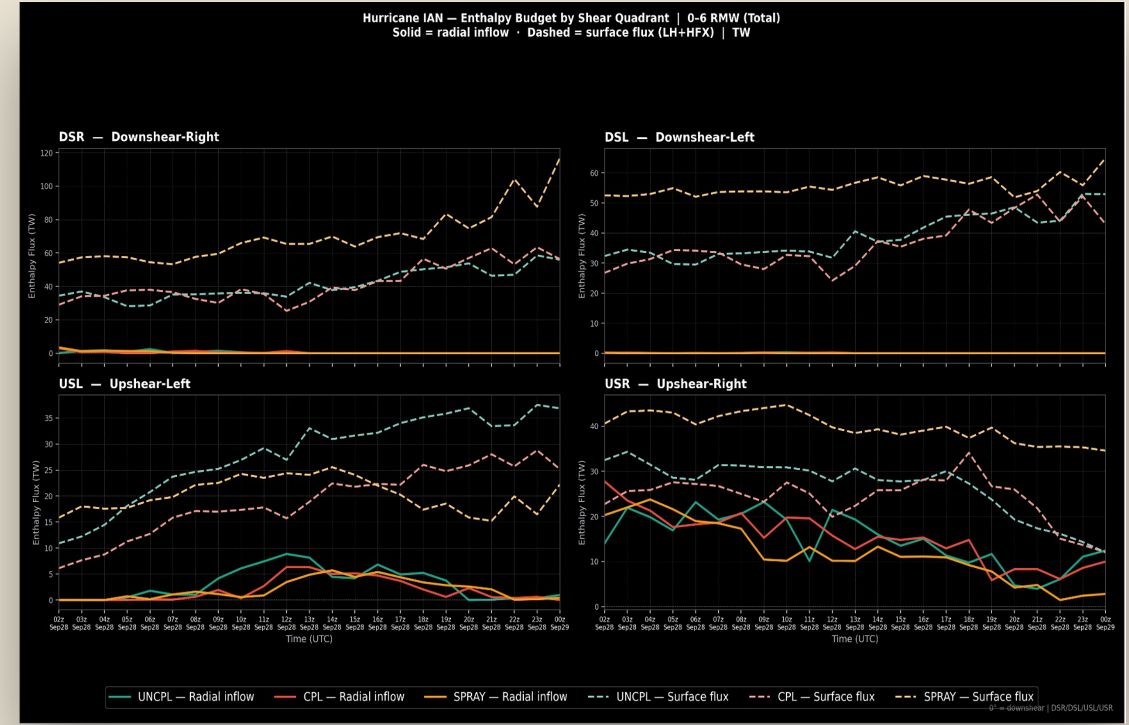
Surface fluxes heavily outweigh radial inflow, driving the energy budget across all four quadrants

2 Downshear-Right Peaks

The DSR quadrant receives the highest energy input, with surface fluxes surging past 100 TW

3 Spray Model Impact

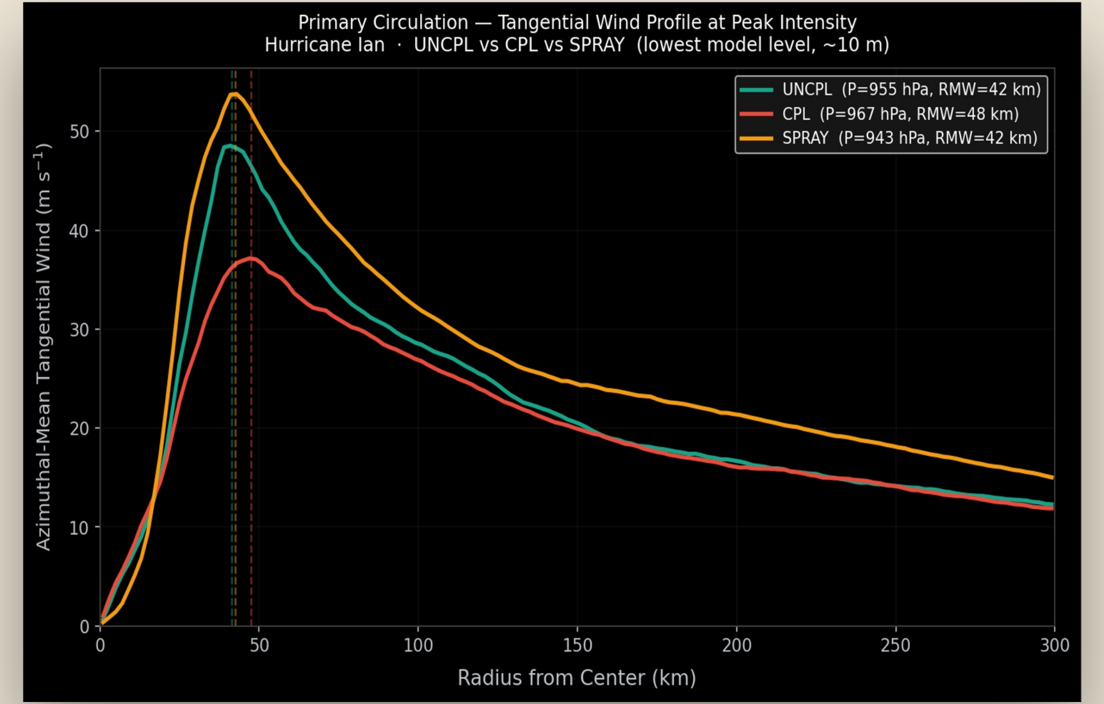
The spray+coupled consistently yields the highest surface fluxes, significantly amplifying downshear energy.



INNER CORE MECHANISMS

The primary circulation defines the inner core.

Tangential wind structure sets the key spatial scale used to define integration domains.


Primary Circulation — Tangential Wind Profile at Peak Intensity
Hurricane Ian · UNCPL vs CPL vs SPRAY (lowest model level, ~10 m)

1 Tangential Wind Field

Wind increases inward to a peak ring (the eyewall) then drops sharply inside the calm eye.

2 Intensity Differences

Inflow turns sharply upward in the eyewall. Rising air releases latent heat, driving pressure falls and storm intensification.

3 Upper-Level Outflow

Air diverges near the tropopause (~12–16 km), expelling warm moist exhaust and completing the thermodynamic cycle.

§5 CIRCULATION

ENERGY SOURCE

The overturning secondary circulation delivers the fuel.

Low-level inflow is the conveyor belt: it carries enthalpy acquired far from the storm into the eyewall.

1 **Low-Level Inflow**

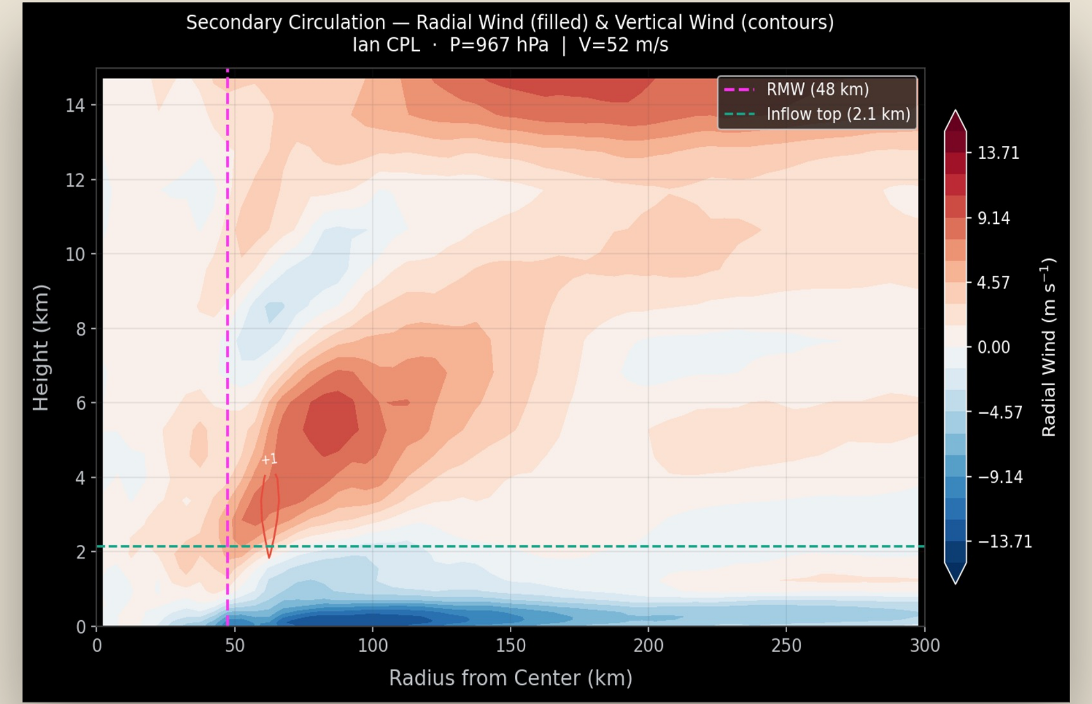
Air converges in the lowest ~1–2 km, absorbing heat and moisture as it spirals inward. Depth and strength control how much enthalpy is imported.

2 **Eyewall Updraft**

Peak winds differ between runs. UNCPL sets the upper bound; SST cooling in CPL weakens the storm; spray partially compensates.

3 **Eye and Eyewall**

Eye: subsiding warm dry air, pressure minimum, winds nearly calm. Eyewall: ring of deep convection with maximum energy release and flux exchange.



BUDGET RECAP

A budget approach to hurricane energy pathways.

Inflow transport, local fluxes, and sea spray—three runs let us partition how the storm feeds itself.

1 **Physics Picture**

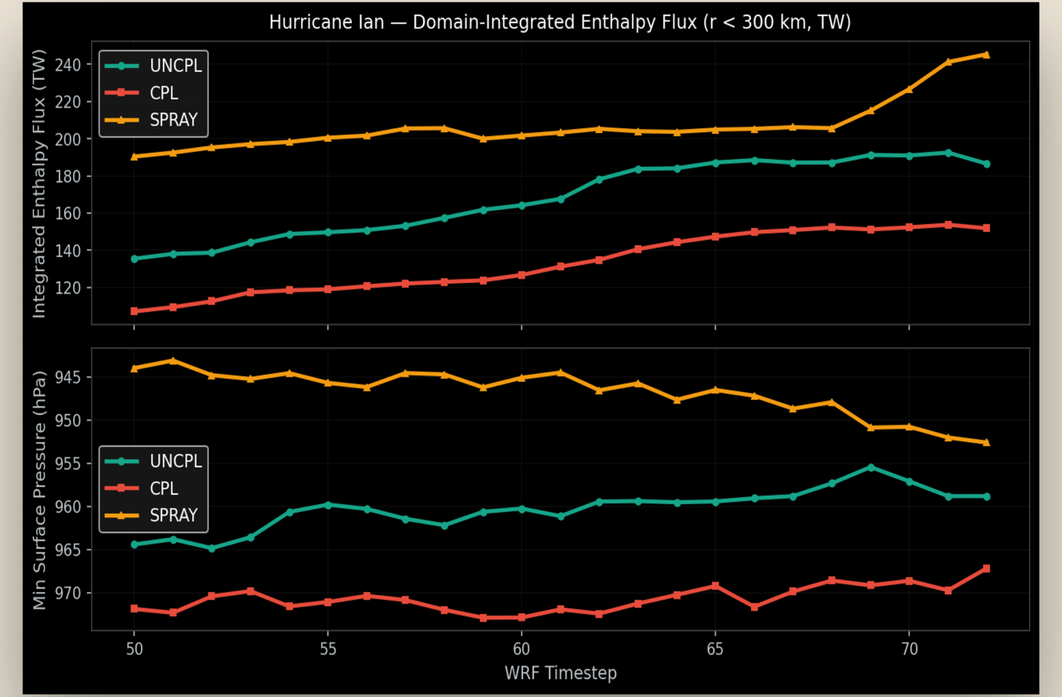
TC = Carnot heat engine. Primary circulation sets spatial scale (RMW). Secondary circulation (inflow layer) is the energy conveyor. Moist enthalpy $k = c_pT + L_vq$ carries the fuel.

2 **The Budget Method**

Integrate flux density F over storm regions to get total power. Repeat for uncoupled, coupled, and coupled+spray runs.

3 **Coming Up**

Results: time series of other variables across all three runs, radial profiles of flux density, and shear-quadrant asymmetries.



FUTURE STEPS

MORE TO EXPLORE

Extending the framework to more storms and deeper diagnostics.

Ian analysis establishes the methods. These current steps test its generality and potential of the WRF model to understand the physics and mechanics of a tropical cyclone’s energy budget.

1

Include More Case Studies

Apply the flux-budget framework to Harvey (2017), Idalia (2023), and Michael (2018). Each storm spans different SST environments, shear regimes, and intensification pathways. This will test whether Ian's budget structure holds generally or environmental regime is important.

2

Shear-Quadrant Decomposition

Partition flux fields into DSR, DSL, USL, USR quadrants relative to the 200–800 hPa shear vector. Quantify how shear redistributes air–sea fluxes around the storm for each run and each additional storm.

3

Intensification Windows

Isolate periods of intensification and examine whether flux budget anomalies precede or lag intensity jumps and RMW contraction. Is the inflow-layer flux a leading indicator?

Funding & Support

Recognizing the key partnerships that made this work possible.

This research was supported by grants from the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration's Global Ocean Monitoring and Observing (NOAA GOMO) program via Northern Gulf Institute.

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