

Sea-to-Air Heat Transfer

On Hurricane Energy

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Abstract

Warm sea water is the energy source for hurricanes. Interfacial sea-to-air heat transfer without spray ranges from **100 W/m²** in light wind to **1000 W/m²** in hurricane force wind. Spray can increase sea-to-air heat transfer by **2 orders of magnitude** and result in heat transfers of up to **100,000 W/m²**. Drops of spray falling back in the sea and are typically 2 to 4 °C colder than the drops leaving the sea thus transferring a huge amount of heat from sea to air.

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AIR–SEA EXCHANGE IN HURRICANES

Synthesis of Observations from the Coupled Boundary Layer Air–Sea Transfer Experiment

BY PETER G. BLACK, ERIC A. D'ASARO, WILLIAM M. DRENNAN, JEFFREY R. FRENCH, PEARN P. NIILER,
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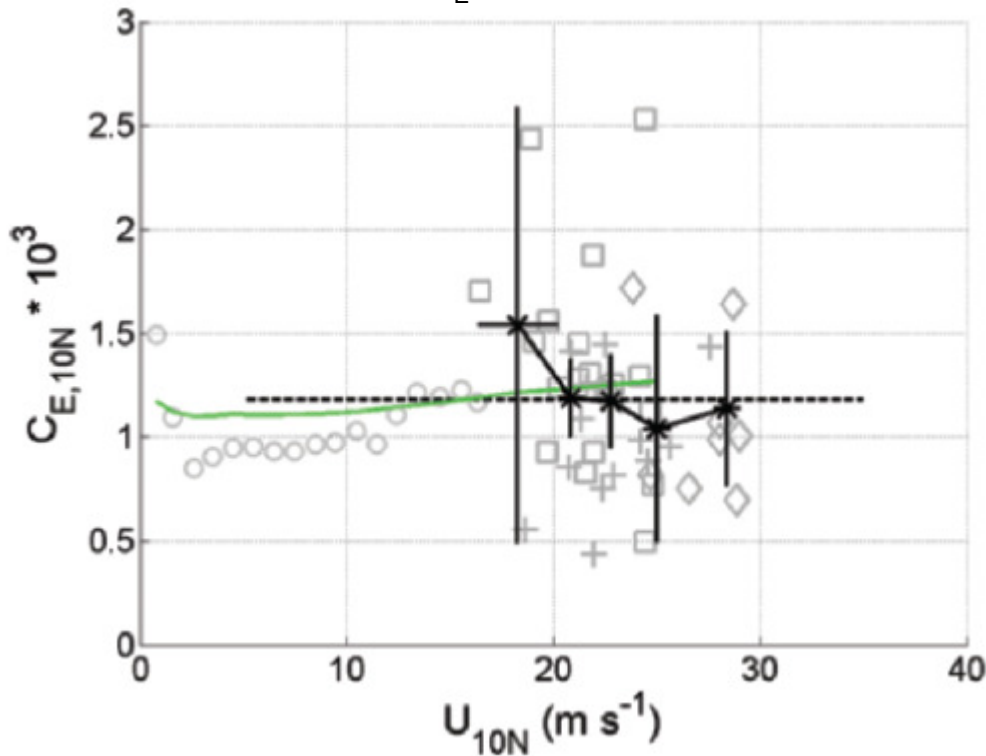
Combining airborne remote, in situ, and expendable probe sensors with air-deployed ocean platforms provides a strategy for expanding knowledge of illusive high-wind air–sea fluxes in difficult-to-predict storms.

Bulletin of the American Meteorological Society – March 2007

Heat flux calculated from heat transfer equation

Dalton Coefficient

$$C_E = 0.00118$$



Heat Transfer Equation

$$Q_a = \rho C_E (h_s - h_a) u$$

Hurricane eyewall

for: SST = 26°C, P = 95 kPa

$T_a = 24.5$, $RH_a = 95\%$,

$h_s = 84200$, $h_a = 74800$ J/kg

$u = 50$ m/s

$$Q_a = 600 \text{ W/m}^2$$

Tropical sea light wind

for SST = 25.5°C, P = 100 kPa

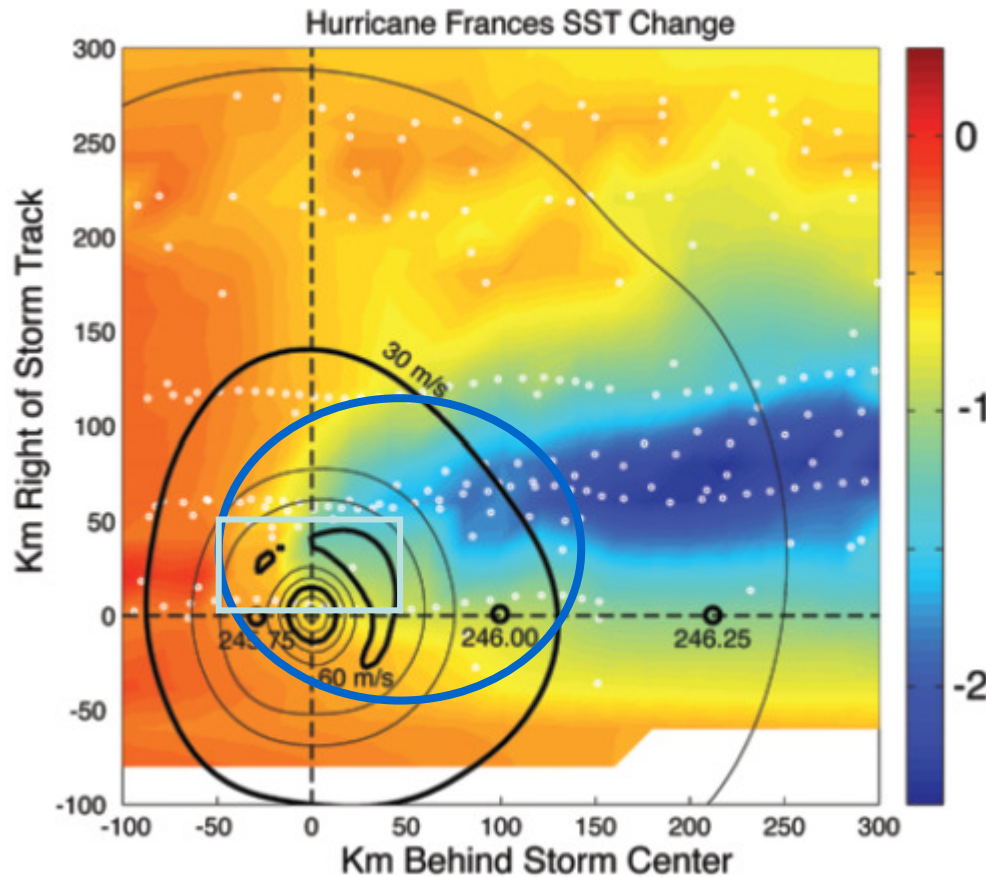
$T_a = 24.5$, $RH_a = 80\%$,

$h_s = 79000$, $h_a = 64800$ J/kg

$u = 5$ m/s

$$Q_a = 100 \text{ W/m}^2$$

Heat flux calculated from sea cooling and from rain



Heat flux from sea cooling

$$Q_t = C_w \Delta T w d v$$

for: $\Delta T = 2.5^\circ\text{C}$, $d = 100 \text{ m}$,
 $w = 100 \text{ km}$, $v = 5 \text{ m/s}$

$$Q_t = 524 \text{ TW}$$

Heat flux from rain

$$Q_v = L_v m d^2 (\pi/4)$$

for: $m = 10 \text{ mm/hr}$, $d = 300 \text{ km}$

$$Q_v = 491 \text{ TW}$$

Heat flux per unit eyewall area

$$Q_e = Q / A$$

for: $Q = 500 \text{ TW}$, $A = 5000 \text{ km}^2$,
 $L = 100 \text{ km}$, $w = 50 \text{ km}$

$$Q_e = 100,000 \text{ W/m}^2$$

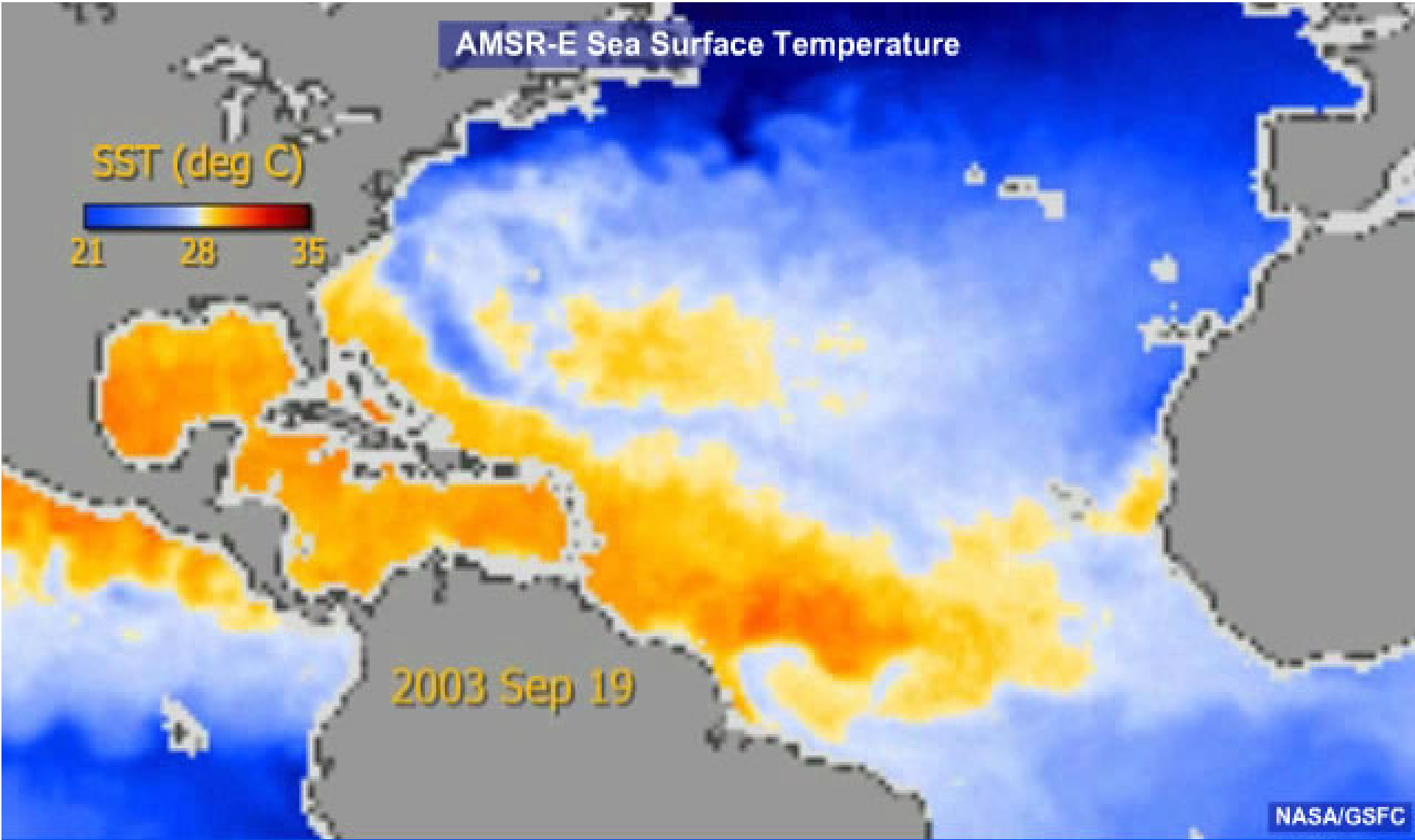
Heat flux per unit sprayed area

$$Q_a = 20,000 \text{ W/m}^2$$

Notes:

- The area of the gray rectangle is roughly equal to the eyewall area.
- The blue oval encloses the high heat flux area.
- Spray is produced preferentially on the right side of the hurricane where wind velocity is highest. The spray produced at an eyewall diameter of about 30 km is cooled by evaporation before being centrifuged out a further 30 km to right.

Hurricane Isabel effect on sea surface temperature as observed from satellite



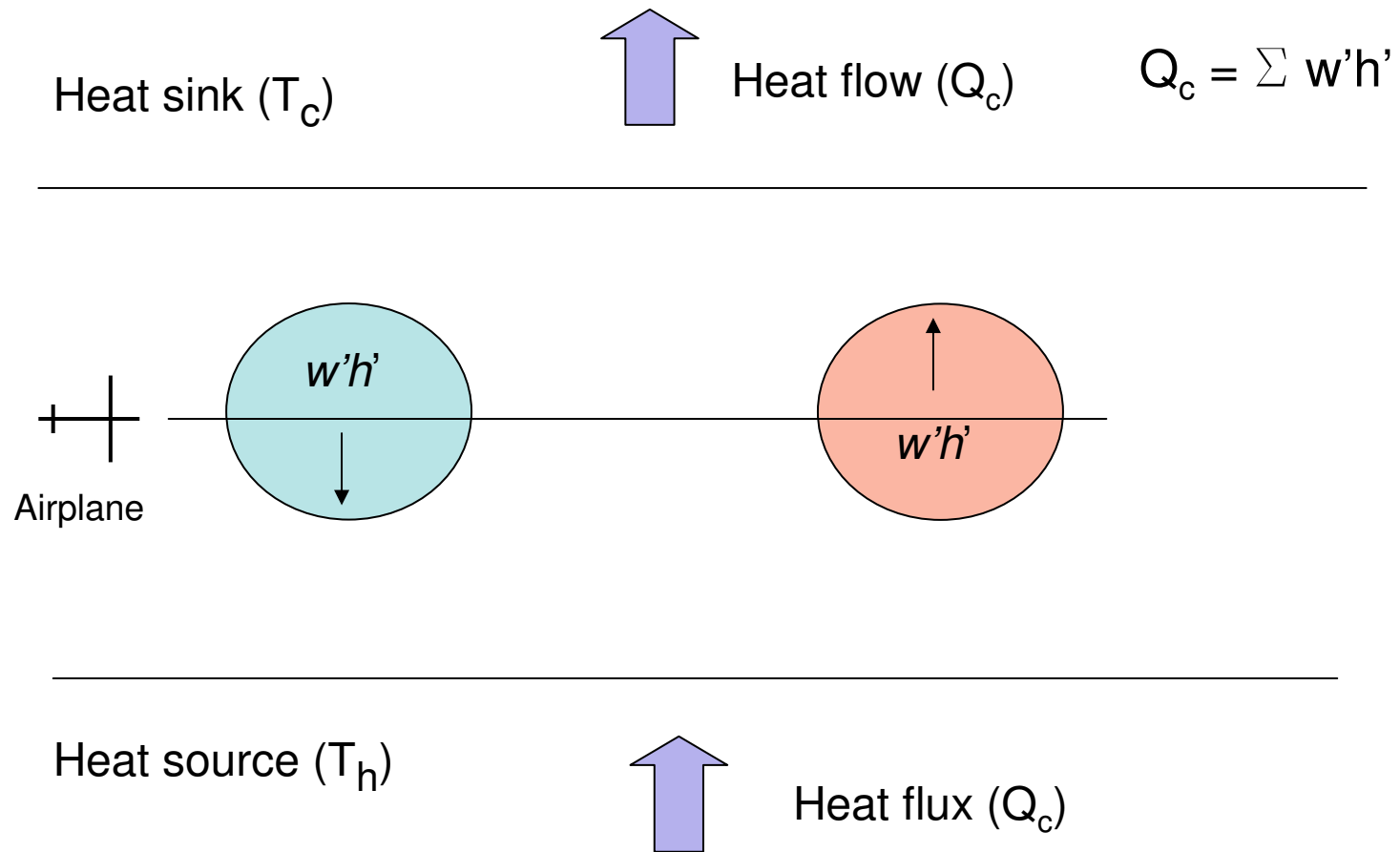
Eddy Correlation Heat Flux Probe



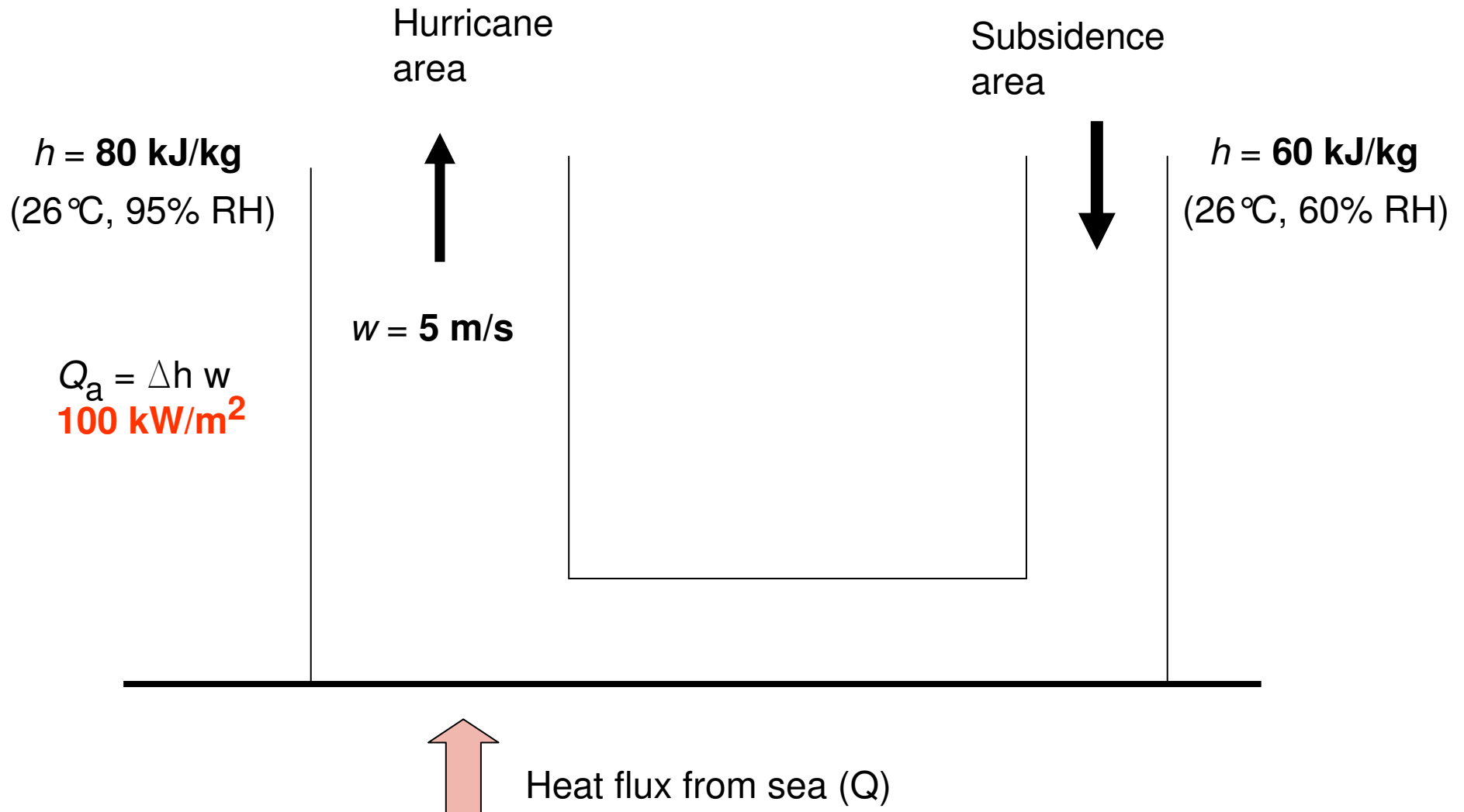
FIG. 3. Location of the BAT turbulence probe and LI-COR fast-response humidity probe on the WP-3D aircraft.

Correlation heat flux measurement principle

The entire upflow/downflow area must be sampled.



Heat flux calculation – Steady-State Flow Case



Correlation heat flux measurement must include the whole area.

otherwise correlation flow meter only measures fluctuations.

$h = 80 \text{ kJ/kg}$

$w = 5 \text{ m/s}$

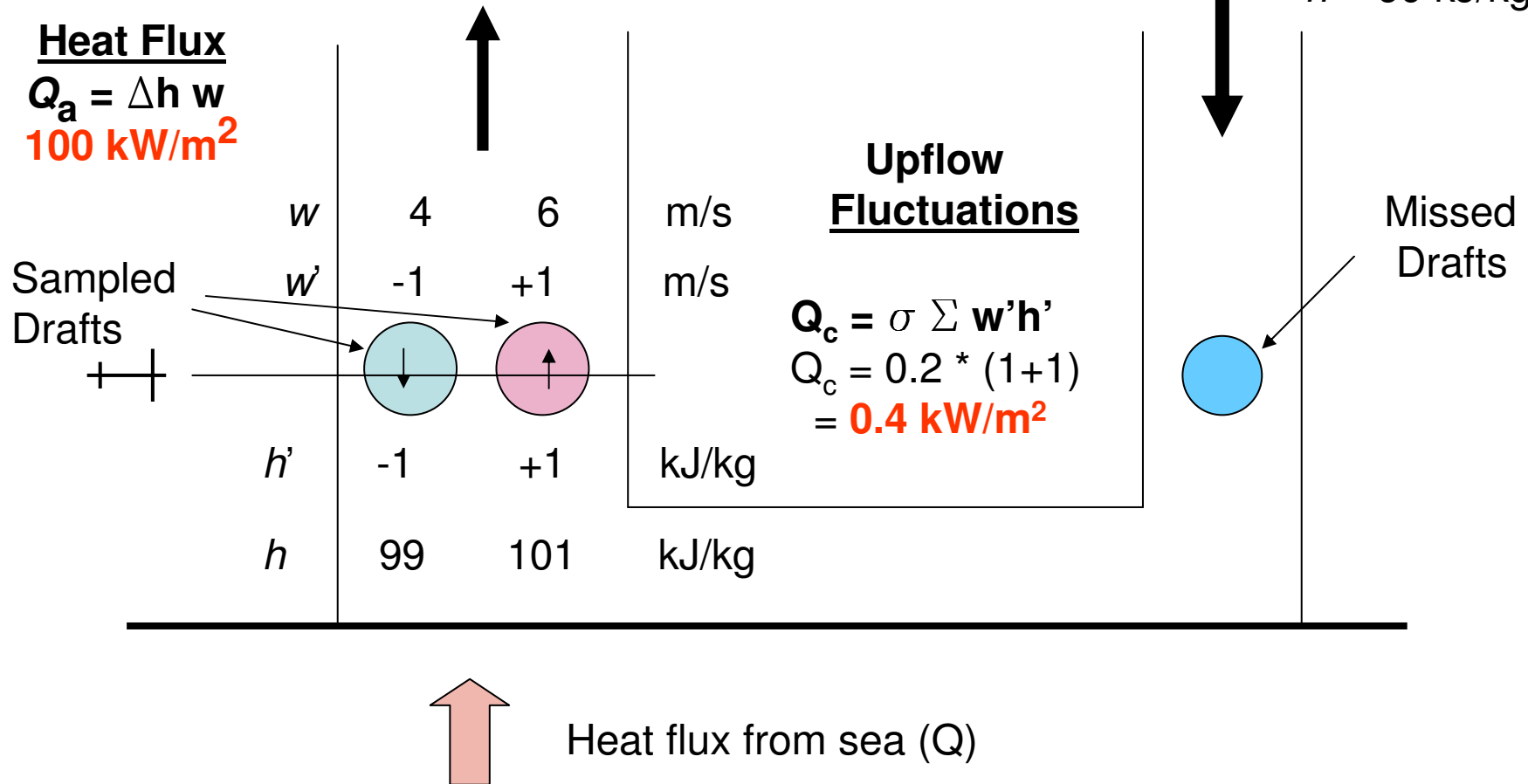
Hurricane
area

Subsidence
area

$h = 60 \text{ kJ/kg}$

Heat Flux

$Q_a = \Delta h w$
100 kW/m²



Problems of Eddy Correlation heat flux measurements

Sea to air heat fluxes measurements are almost invariably taken using eddy correlation type heat flux instruments.

Eddy correlation heat flux measurements are only valid when there is no net convergence or divergence in the sampled area.

Eddy correlation heat flux measurement in the vicinity of hurricanes are not valid because of strong convergence.

The presence of water drops makes eddy heat flux impractical because the heat content of individual rising and descending drop would have to be measured.

Measurement above the spray level are invalid because of convergence.

Measurements in the spray are invalid because the heat content of individual drop can not be measured.

Slide 8 shows that with convergence steady state flow can result in high heat fluxes. Slide 9 shows that convergence eddy correlation heat flux meters measure heat flux fluctuations and not upward heat flux.

There have been numerous sea to air heat flux measurements carried out using eddy correlation heat flux instruments from fixed platforms, buoys, ships and aircrafts.

Dalton heat transfer coefficients C_E are almost entirely based on the results of eddy correlation type heat flow measurements.



Water and energy budgets of hurricanes: Case studies of Ivan and Katrina

Kevin E. Trenberth,¹ Christopher A. Davis,¹ and John Fasullo¹

“From analysis of model results Trenberth *et al.* estimated that: **about 70% of hurricane precipitation comes from moisture already in the atmosphere at the time the storm formed**, while the rest comes from surface evaporation”.

- This means that on average, the storm-scale circulation **reaches out about factor of 3 to 5 times the radius of the precipitating area to gather the available moisture in the atmosphere.**
- One would have to integrate out to about **1600 km radius** to obtain a rough energy balance. Slides 4 and 5 show that sea cooling is restricted to a band approximately **100 (not 3200) km wide.**

Trenberth *et al.* quote continued:

“The moisture budget in tropical cyclones is dominated by the inflow of moisture, mainly in the lowest 1 km of the storm. Inside about 100 km of the center of the storm, the moisture inflow is about a factor of 10 greater than the latent heat flux from the surface (12.9 for Ivan and 9.1 for Katrina), in spite of the fact that it is ultimately the latter that mainly causes the inflow to occur”.

“Together these moisture fluxes contribute to the heavy rainfall in tropical cyclones and thus latent heat that drives the storms”.

“The moisture budget of tropical cyclones is dominated by the large-scale convergence of moisture, as is the case for most meteorological phenomena”.

Note: Trenberth *et al.* may have simply been trying to point out that the sea to air heat transfer used in the hurricane models are too low.

New Insights into the Ocean Heat Budget Closure Problem from Analysis of the SOC Air–Sea Flux Climatology

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Journal of Climate, Sept 1999, Vol 12, pg. 2856-2880.

“The global climatological mean net heat flux should average to zero; however, **mean heat gain of 30 W/m² have been found in many studies**”.

- The form and the coefficient in empirical sea to air heat transfer relationships such as the one on slide 3 are difficult to determine. The coefficient is **usually based on eddy correlation heat flux measurements**.
- There is no easy way of checking the result other than global energy balance because: the upper layer of the ocean can gain heat from solar radiation, lose heat by infrared radiation, exchange heat horizontally and vertically, and exchange sensible and latent heat with the overlying atmosphere.

Deductions

- In the sub-tropics, the temperature of the approximately 100 m thick mixed ocean upper layer increases by 5 to 10 °C during the spring and summer and decreases by a corresponding amount during fall and winter. The temperature changes slowly because the heat received and the heat given up by the water are **nearly in balance**.
- The temperature of the mixed layer can decrease by 2 to 5 °C during the passage of a hurricane which typically takes 6 hours. The rate of temperature change during the passage of a hurricane is much greater than the normal rate of temperature change - **not in balance**. It is therefore reasonable to attribute the temperature change to cooling from sea to air transfer.
- As shown in slide 9, the combination of influx of dry air from above and of spray can increase heat flux. This heat flux increase can not be measured with correlation heat flux techniques. The heat flux in hurricanes is very large. The spray process can increase in heat flux **in heavy breeze by 100 to 1000 W/m²**. The cumulative sea-to-air heat transfer from **non-hurricane spray** could more than that of **hurricane spray**.

Possible Sea-to-air heat transfer equation new form

Q_i - Previous
Interfacial
term

Q_s - New
Spray
term

$$Q = \rho C_E (h_s - h_a) (u + C_s u^5)$$

where:

$$C_e = 1.18 * 10^{-3}$$

$$C_s = 2.6 * 10^{-5}$$

Sample Results

Velocity (m/s)	Q_i (W/m ²)	Q_s (W/m ²)
50	600	100000
40	484	32800
25	302	3125
10	121	32
5	60	1

Rough Estimate of Convective Sea-to-Air Heat Fluxes

	<u>Average (W/m²)</u>	<u>Total (PW)</u>
Entire Earth	102	52
Land	102	16
Sea	102	36
Sea interfacial	72	25
Total Sea Spray	1-100000	11
Sea Tropical Cyclones	1000-100000	1
Non tropical cyclone spray	1-1000	10

- Sea-to-Air heat flux at low wind velocities (<10 m/s) can be determined by laboratory tests.
- Sea-to-Air heat flux at hurricanes eyewall is almost entirely due to convection and can be determined from either the sea heat loss or from the quantity of precipitation.
- Sea-to-Air heat flux at intermediate wind speed is very difficult to establish. The convective heat flux at sensor level is not necessarily the same as at the air-sea interface. Eddy correlation measurements are not valid when there is convergence from outside the sampled area.
- In CBLAST, Sea-to-Air heat flux determined from eddy correlation were much lower than Sea-to-Air heat flux required to produce the observed sea cooling.

Sea-to-Air Heat flux Adjustments

Josey *et al.*:

“Simple scale adjustments to flux component applied in a global sense are not appropriate”.

- Spray cooling increases with disequilibrium between the drops and the air ($h_s - h_a$) and with the mass (quantity) of drops. The heat flux from spray is approximately $100,000 \text{ W/m}^2$ at a wind velocity of 50 m/s , and negligible ($<1 \text{ W/m}^2$) at a wind velocity of 5 m/s .
- A **power of 5** reduces spray heat flux by a factor of $100,000$ when the wind velocity reduces by a factor of 10 . The mass of drops could be roughly proportional to the fifth power of wind velocity (u).
- Spray cooling increases with wind speed, therefore:
Adjustments based on an exponential function of velocity (u) are probably more appropriate than uniform adjustments.

Cold wake of Hurricane Frances

Eric A. D'Asaro, Thomas B. Sanford, P. Peter Niiler, and Eric J. Terrill

ABSTRACT

An array of instruments air-deployed ahead of Hurricane Frances measured the three-dimensional, time dependent response of the ocean to this strong (60 m/s) storm. Sea surface temperature cooled by up to 2.2C with the greatest cooling occurring in a 50-km-wide band centered 60–85 km to the right of the track. **The cooling was almost entirely due to vertical mixing, not air-sea heat fluxes.** Currents of up to 1.6 m/s and thermocline displacements of up to 50 m dispersed as near-inertial internal waves. The heat in excess of 26C, decreased behind the storm due primarily to horizontal advection of heat away from the storm track, with a small contribution from mixing across the 26C isotherm. SST cooling under the storm core (0.4C) produced a 16% decrease in air-sea heat flux implying an approximately 5 m/s reduction in peak winds.

Hurricane Frances sea temperature profile

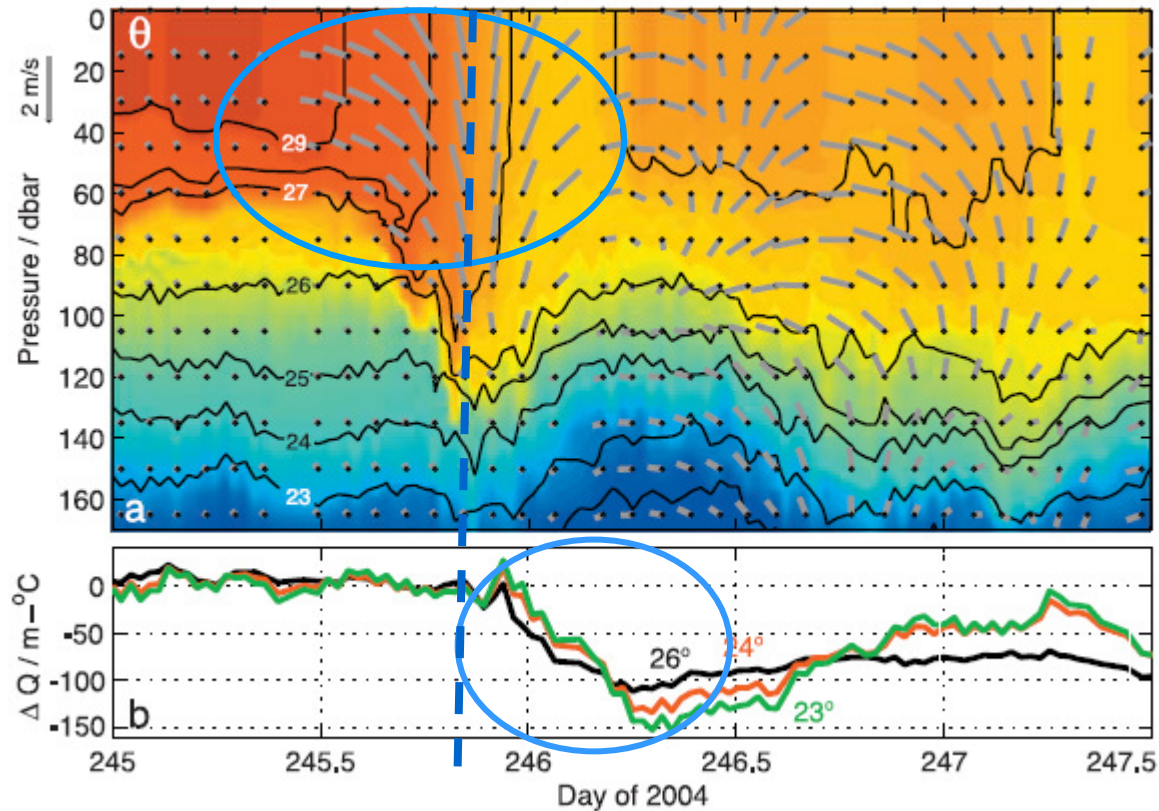


Figure 2. (a) Depth-time contours of potential temperature (colored); arrows of velocity change from prestorm. Northward currents point up; eastward currents point to the right. (b) Change in ocean heat above the 23C, 24C, and 26C isotherm.

Note: Blue ovals designate zone with high cooling rate.

Blue dashes represents hurricane core position

- **Sea cooling takes place during hurricane passage.**
- **Sea cooling is concentrated in the vicinity of the eyewall.**
- **Sea cooling can extend to depths of 50 to 100 m.**

Summary of evidence in favor of high sea to air heat flux hypothesis

- The heat loss from the sea is roughly equal to the heat required to produce the observed precipitation.
- Sea cooling is concentrated in a narrow band behind the hurricane.
- Eddy correlation heat flux measurements are unreliable when there is convergence of air from outside the sampled zone. This converging air can come from distant surrounding, from between the rain bands or from the eye.
- The heat content of sea water is much greater than that of air.
- Hurricanes significantly reduce the heat content of the sea.
- The heat content of the tropical air is not significantly reduced.
- Huge quantities of heat can be transferred from sea to air through isenthalpic mixing of spray and air. The physical mechanism whereby the heat stored in the sea is transferred from the sea to the atmosphere is well known.
- Hurricanes intensity decreases when the eyewall moves over land and lose its heat source.
- The addition of spray cooling eliminates the Josey 30 W/m² mean heat gain problem.
- If the sea cooling is due to mixing of cold water from below, where does the warm surface water go?
- The sea cooling could be primarily due to a combination of:
 - cold water rising under the right eyewall to makeup for surface water removed by spray,
 - and to the sinking of the cooled re-entrant spray to the right of the storm track.