Hurricane Sea-to-Air Heat Transfer

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Hurricane Sea-to-Air heat fluxes:

- from C_E - 100 W/m^2 to 1000 W/m^2
- from precipitation – 100,000 W/m^2
- from sea cooling – 100,000 W/m^2

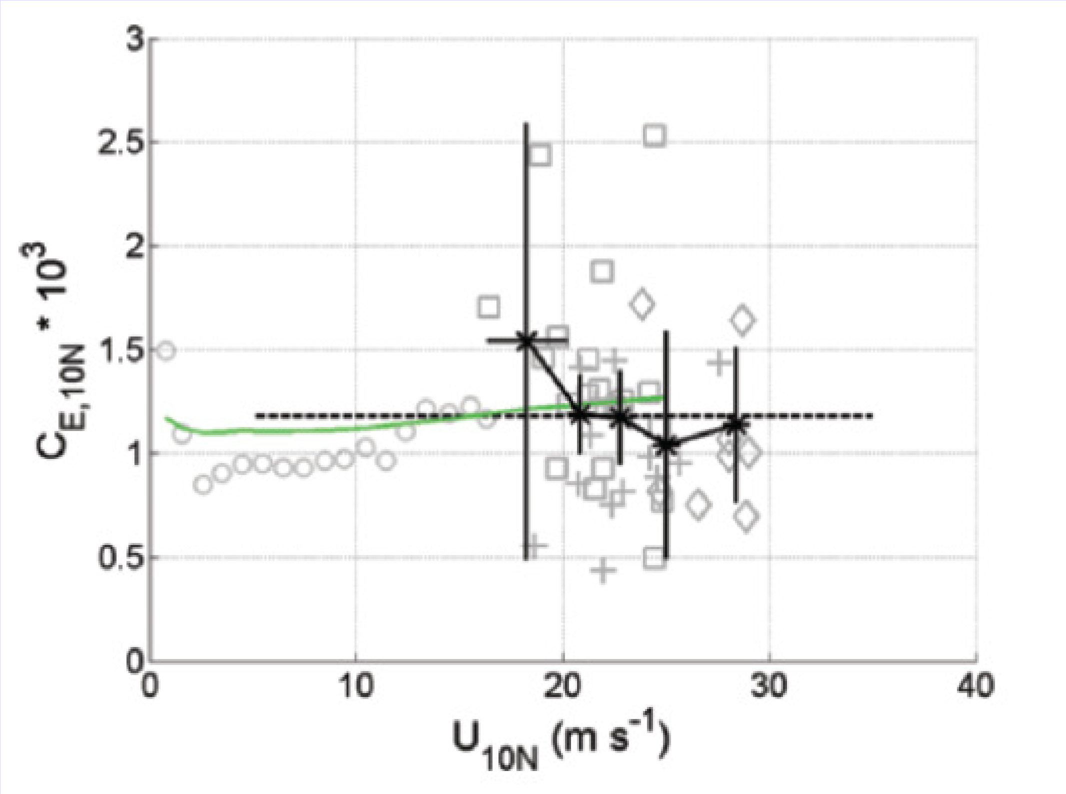
Outline:

- Review of calculation methods
- Spray heat transfer
- Eddy correlation
- Evidence in favor of high heat flux

Heat flux calculated from heat transfer equation

Dalton Coefficient

$C_E = 0.00118$



Note figure from: Black et al. BAMS March 2007

Heat Transfer Equation

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

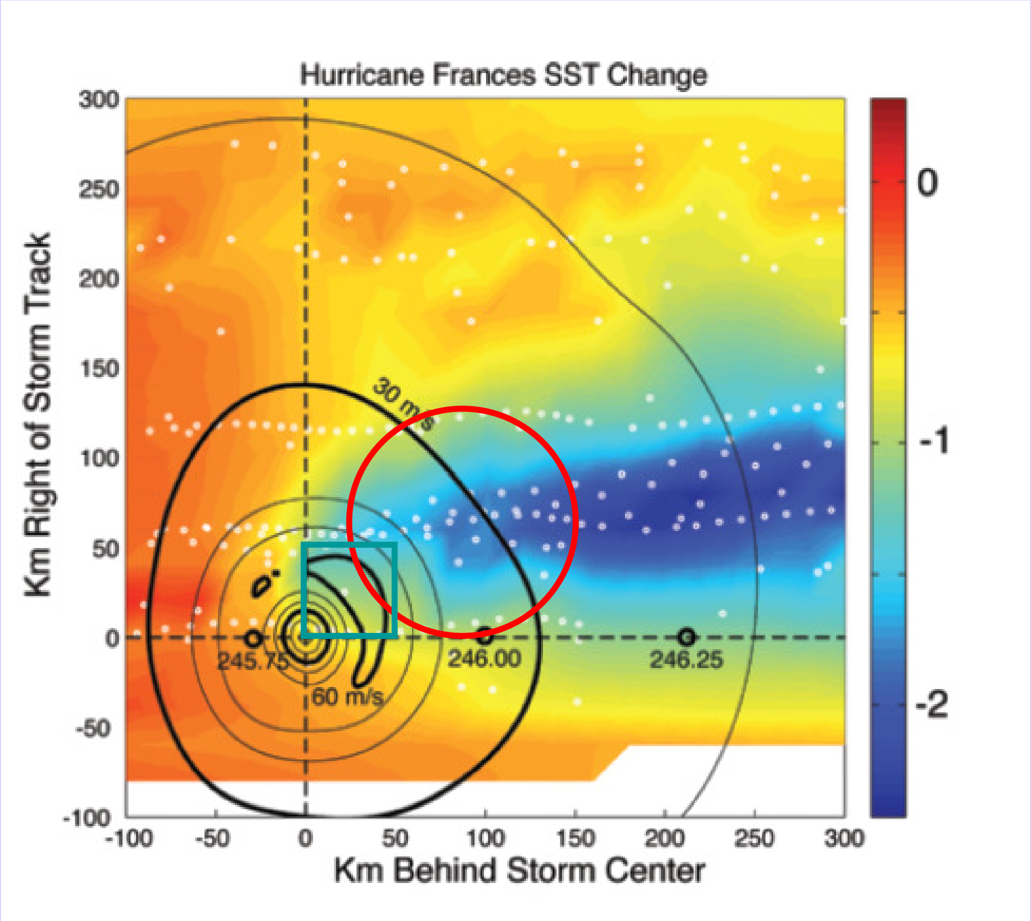
Tropical sea light wind

for SST=25.5℃, 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 W/m^2

Hurricane eyewall

for: SST = 26℃, 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 W/m^2

Heat flux from rain and sea cooling



From rain

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

for: m = 10 mm/hr (0.0028 kg/s m^2)

d = 300 km

Q_v = 491 TW

From sea cooling

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

for: ΔT = 2.5℃, d = 100 m

w = 100 km, v = 5 m/s

Q_t = 524 TW

Per unit spray production area

$Q_e = Q / A$

for: Q = 500 TW, A = 2500 km^2,

L = 50 km, w = 50 km

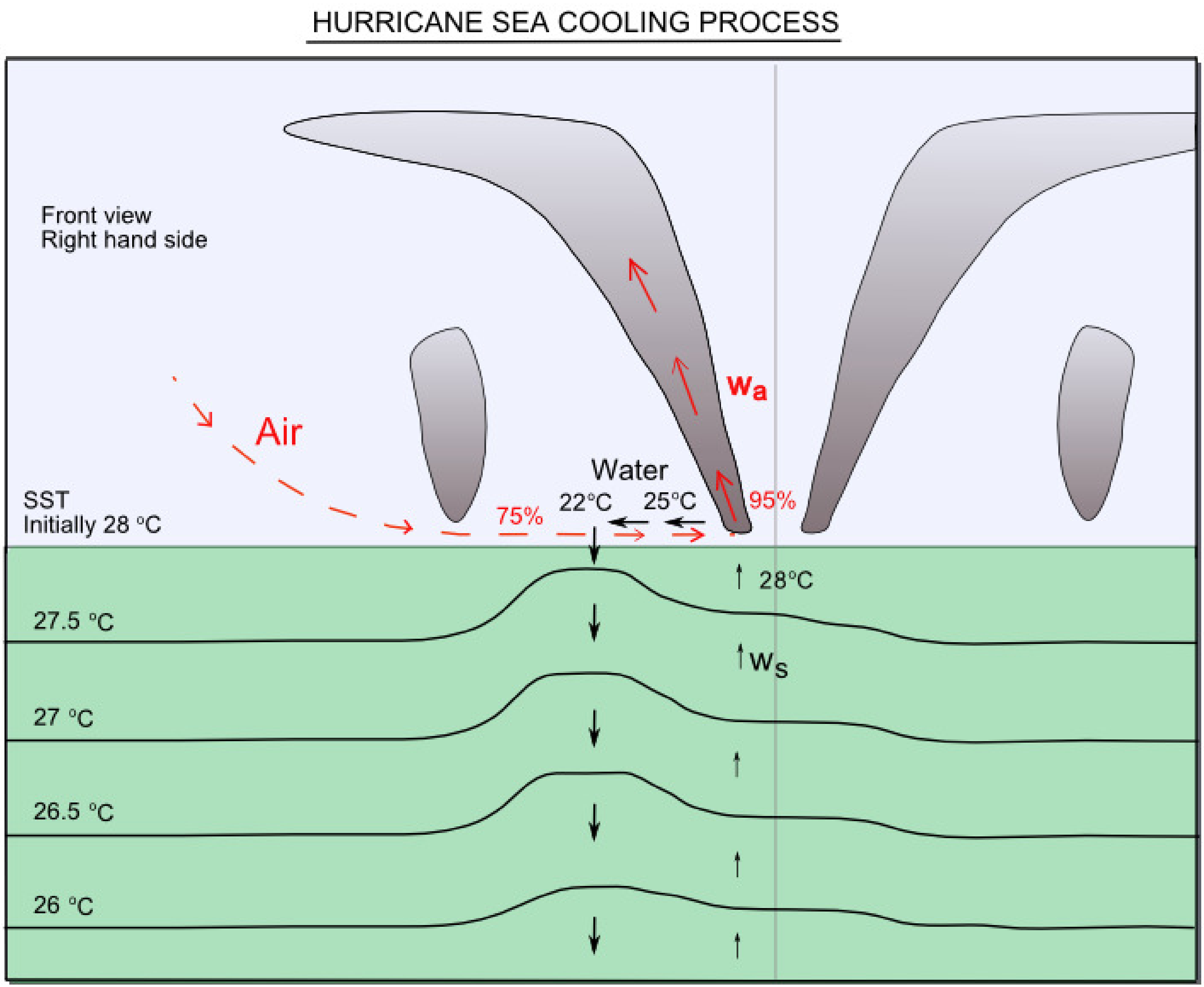
Q_e = 200,000 W/m^2

Per unit spray distribution area

Q_a = 40,000 W/m^2

- 2500 km^2 green rectangle – Spray production area.
- 12,500 km^2 red circle – Spray deposition area.

Figure: Black et al. BAMS March 2007


HURRICANE SEA COOLING PROCESS
Front view
Right hand side
Air
w_a
Water
22°C
25°C
75%
95%
SST
Initially 28 °C
28°C
w_s
27.5 °C
27 °C
26.5 °C
26 °C

Hurricane Eyewall
Isenthalpic air-water mixing

Inlets

Water

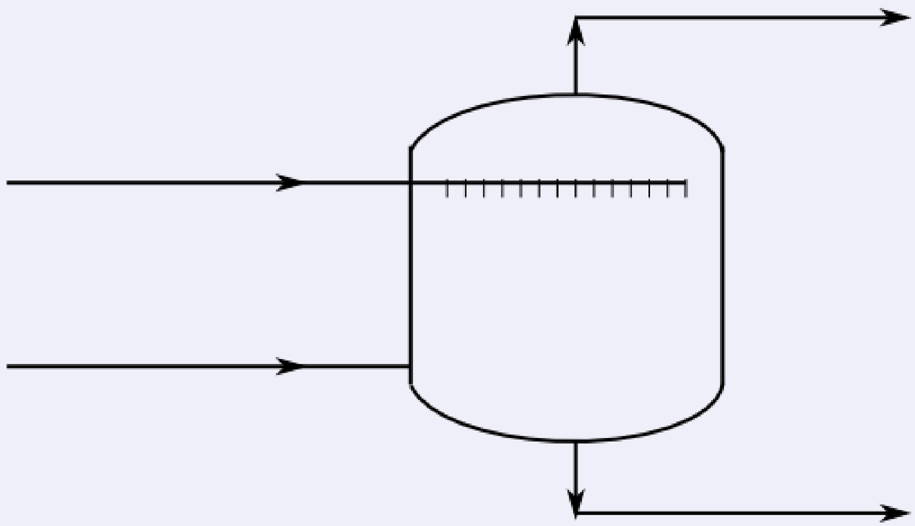
T = 27.5 °C
m_l = 1606.2 g
H = 185,080 J

Air

P = 97 kPa
T = 25 °C
U = 75 %
m_a = 1 kg
m_v = 15.7 g
T_w = 21.7 °C
H = 65,160 J

Total Inlets

m_w = 1621.92 g
H = 250,240 J



Outlets

Air

P = 97 kPa
T = 26 °C
U = 95 %
m_a = 1 kg
m_v = 21.2 g
T_w = 25.4 °C
ρ = 1.12 kg/m^3
H = 80,090 J

Water

T = 25.4 °C
m_l = 1600.75 g
H = 170,150 J

Total Outlets

m_w = 1621.92 g
H = 250,240 J

Heat transfer per unit mass air (Q_m) = 14,930 J

Heat transfer per unit area: $w_a \approx$ 2 m/s

From added vapor:

$Q_a = \rho\, w_a\, Q_m = 1.12 * 2 * 14{,}930 \approx 34{,}000\ \mathrm{W/m^2}$

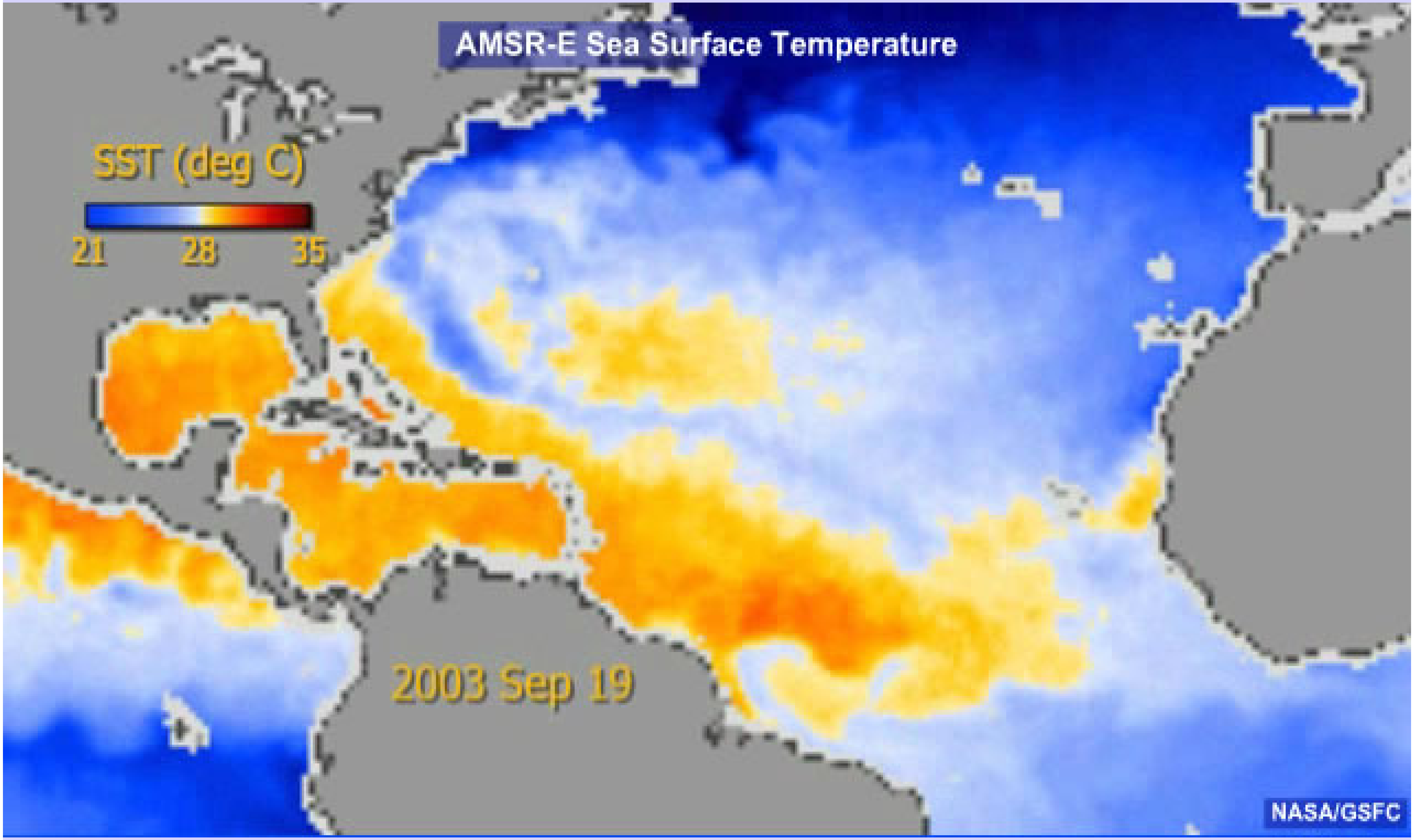
From total vapor

$Q_t = \rho\, w\, m_v\, L_v = 1.12 * 2 * 21.2 * 2500 \approx 120{,}000\ \mathrm{W/m^2}$

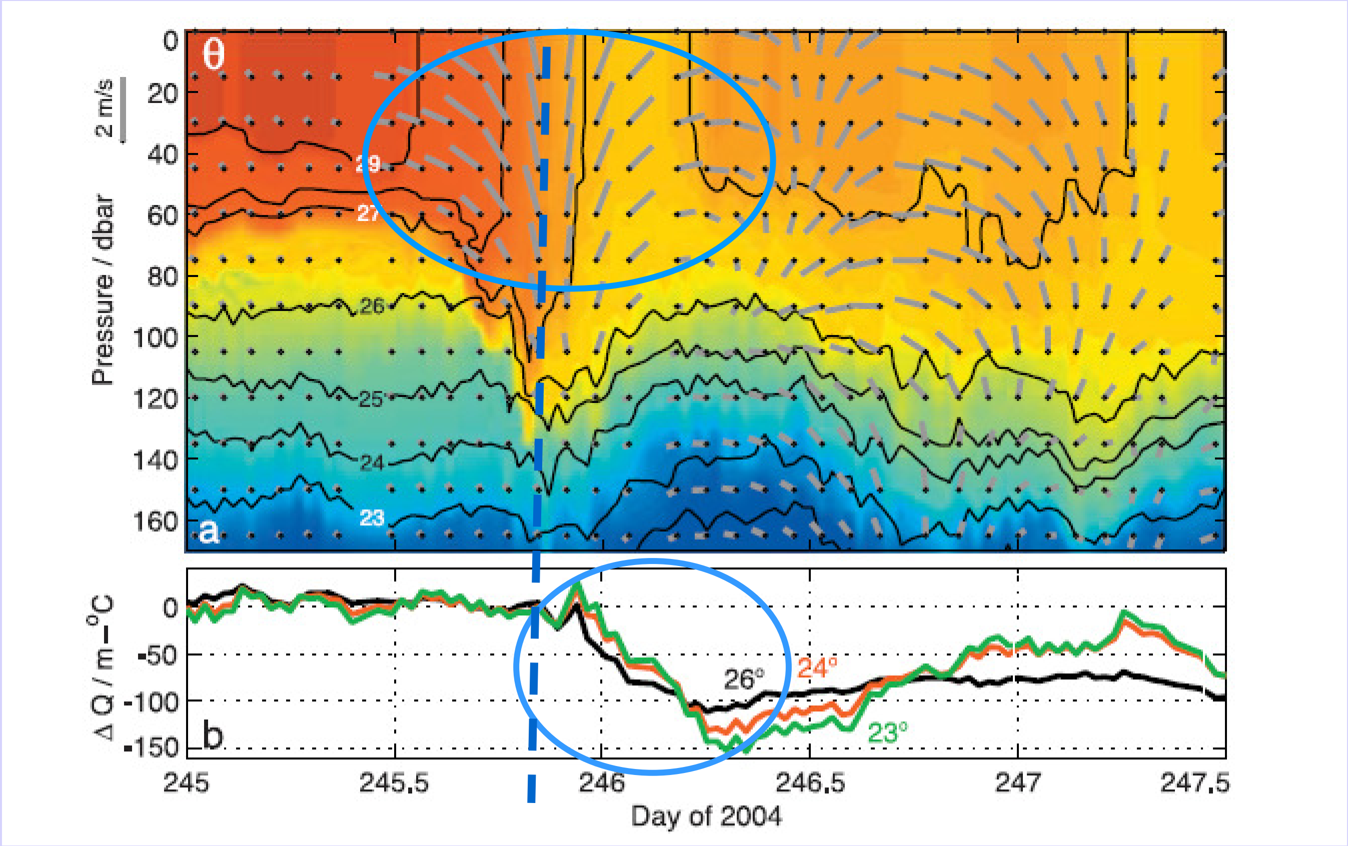
Eyewall Water Upflow (w_s)

$w_s = \rho\, w_a\, m_l * 3.6 = 1.12 * 2 * 1.6 * 3.6 \approx 12\ \mathrm{m/hr}$

Hurricane Isabel effect on sea surface temperature as observed from satellite



Hurricane Frances sea temperature profile



From: D'Asaro et al. GRL 2007.

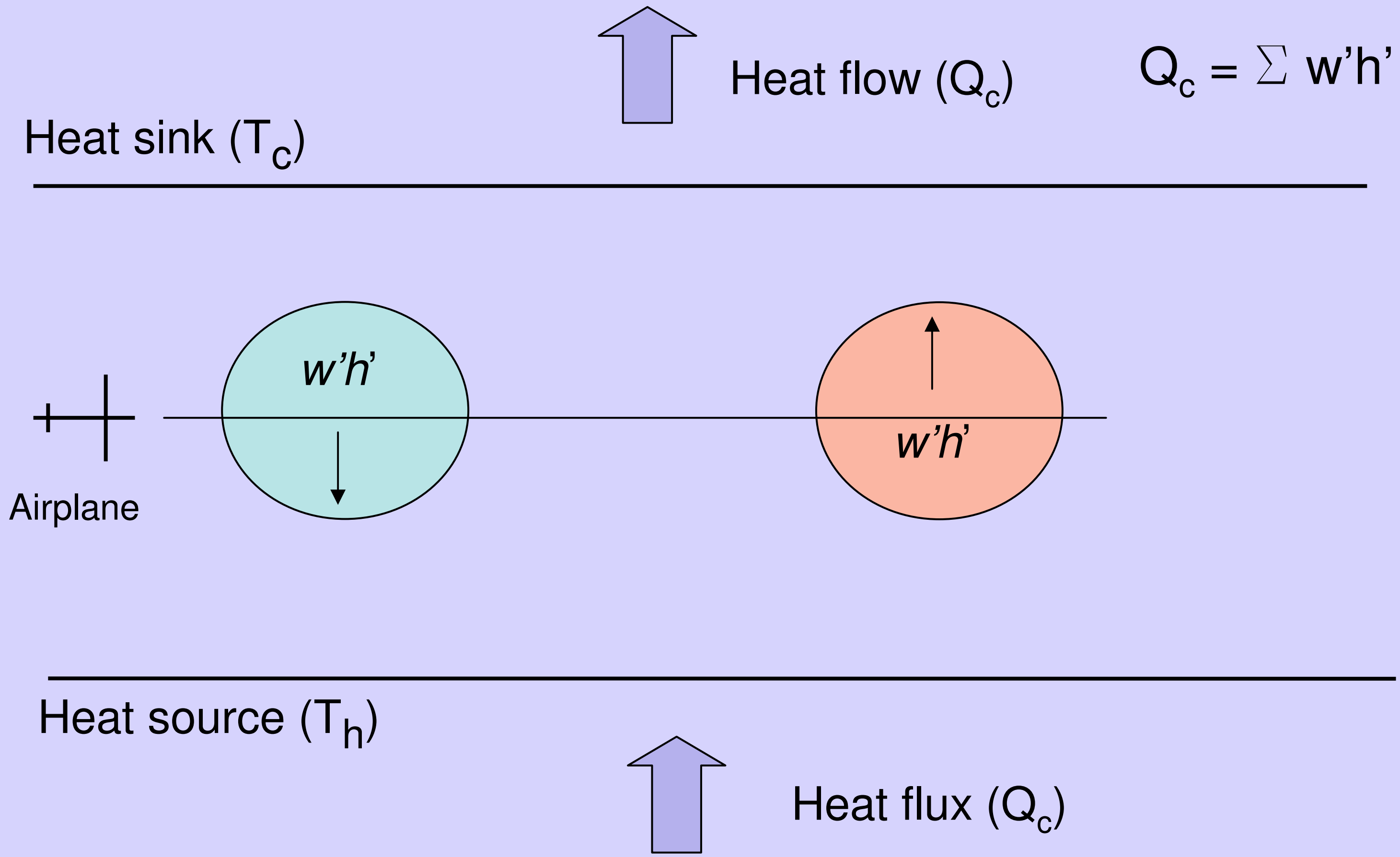
Sea cooling:

- **takes place during hurricane passage.**
- **is concentrated near the hurricane.**
- **extends to depths of 50 to 100 m.**

Notes:

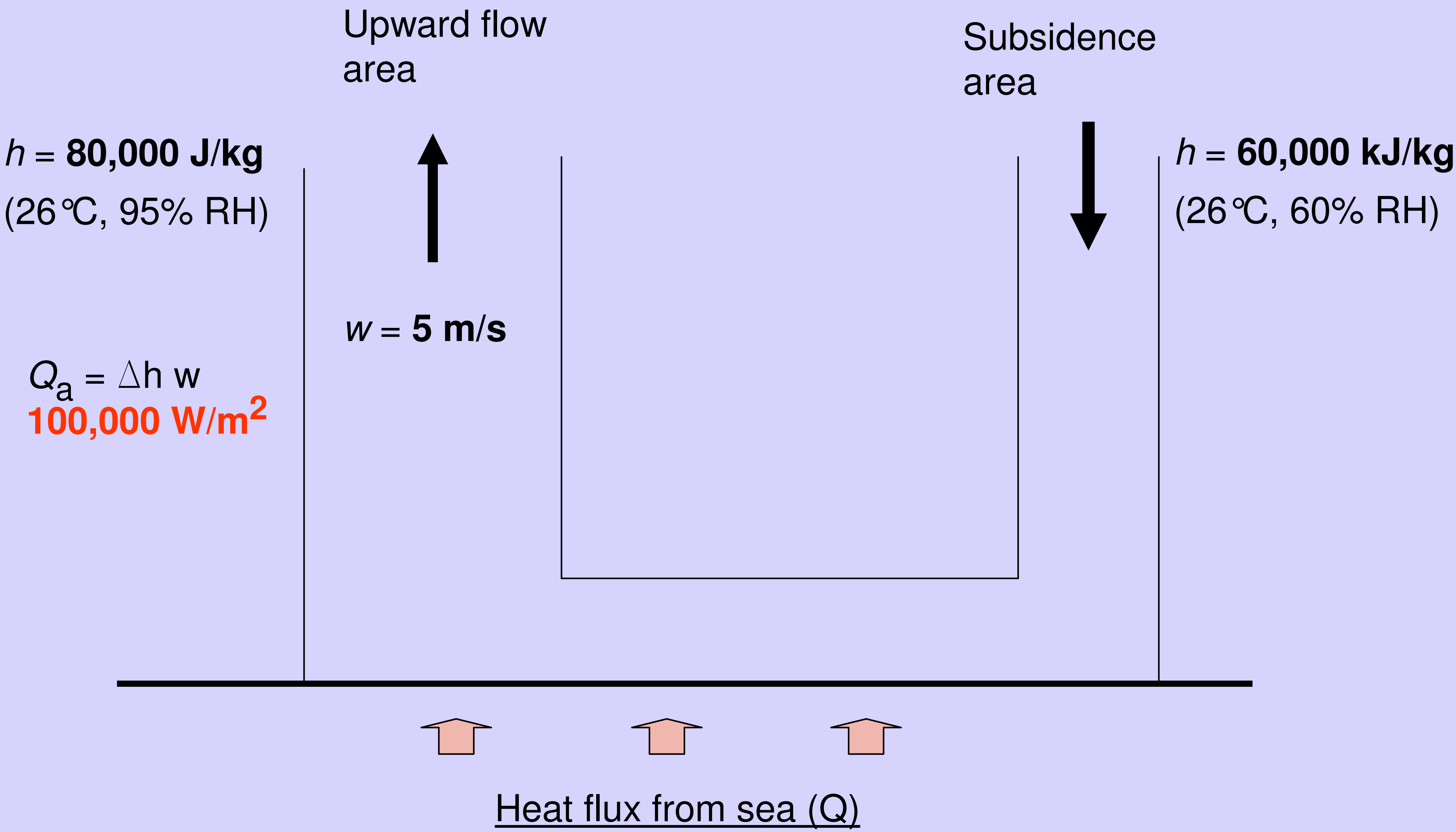
- Blue ovals zone of high cooling.
- Blue dashes hurricane position

<u>Eddy correlation heat flux measurement principle</u>

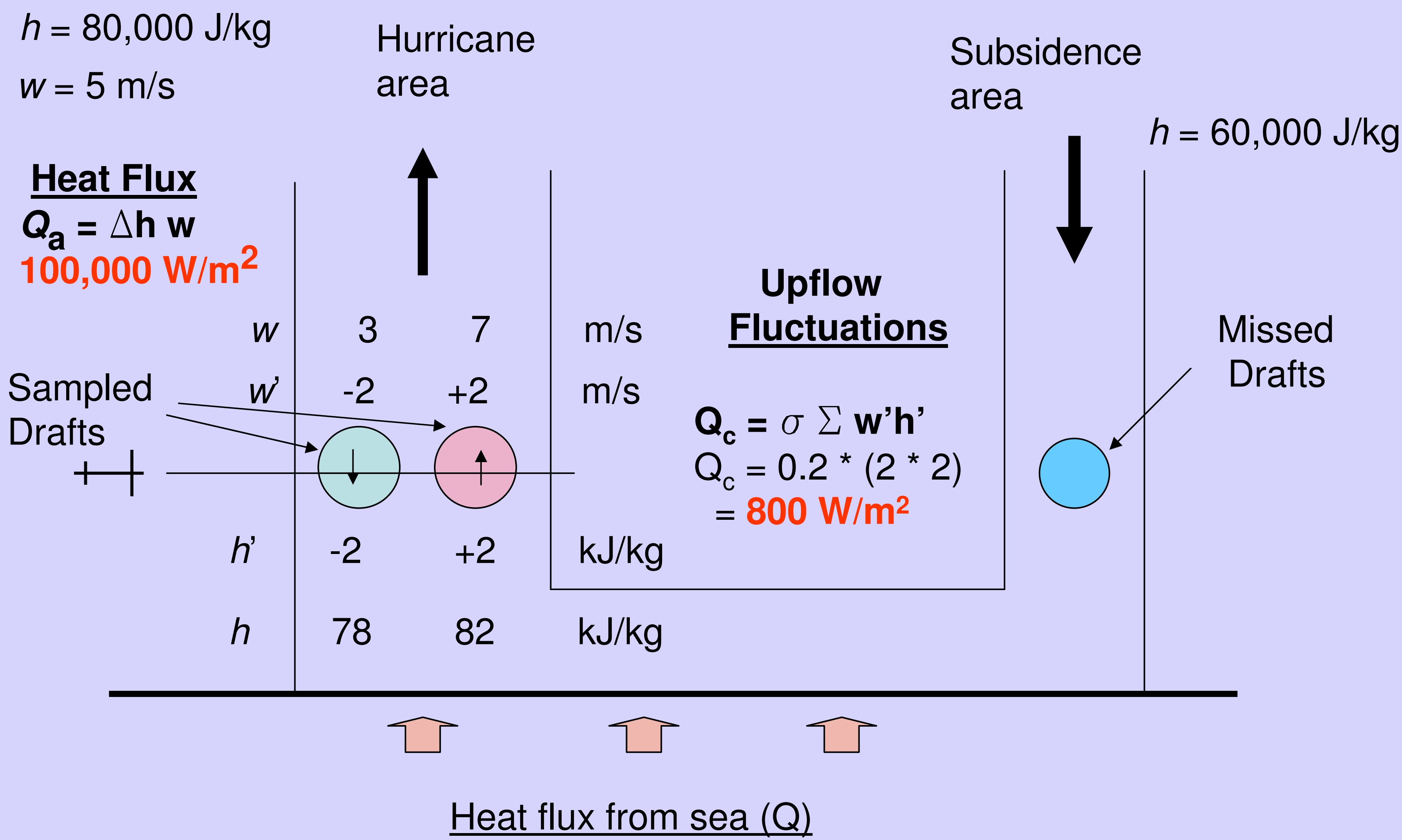


- Conditions must be uniform in horizontal direction.
- There must be no net convergence (LICOR).

Steady-State Flow - Heat Flow Example



What does Eddy Correlation see in the previous steady-state case?



Effect of mean upward velocity on heat flux

Mean upward velocity contribution

Eddy correlation contribution

$$Q = \overline{m}\, m_v L_v + \Sigma\, w'h'$$

$$Q = \rho\, \overline{w}\, m_v L_v + \Sigma\, w'h'$$

$$Q = 1.0 \times 2 \times 20 \times 2500 + 0.2\,(2 \times 2 \times 1000)$$

$$Q = 100{,}000 + 800 = 100{,}800 \text{ W/m}^2$$

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 heat Fluxes

Velocity w (m/s)	Interfacial Q_i (W/m²)	Spray Q_s (W/m²)
50	**600**	**100000**
40	484	32800
25	302	3125
10	121	32
5	**60**	**1**

Rough Estimate of Convective Sea-to-Air Heat Fluxes

	Average (W/m^2)	Total (PW)
Entire Earth	102	52
Land	102	16
Sea	**102**	**36**
Sea interfacial (Dalton Equation)	**72**	**25**
Sea Spray - Tropical Cyclones	**>10,000**	**2**
Sea Spray - non tropical cyclone spray	**<10,000**	**9**

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

• 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.

•The heat must come from the sea.

• Huge quantities of heat can be transferred from sea to air through isenthalpic mixing of spray and air.

Thank you

More information available in forthcoming paper:
On Hurricane Energy
by: Louis M. Michaud
in Meteorology and Atmospheric Physics

and at:
www.vortexengine.ca