3.4 HURRICANE SEA TO AIR HEAT TRANSFER

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1.0 INTRODUCTION

Sea to air heat fluxes calculated using the interfacial heat transfer equation are much lower than the heat fluxes required to produce either observed hurricane precipitation or observed sea cooling. Maximum hurricane sea to air heat fluxes calculated using the interfacial heat transfer equation are approximately 1000 W m^{-2}, Black et al. (2007) and Drennan (2007). Figure 1 shows examples of sea to air heat flux calculations. In the tropics, sea to air heat fluxes calculated using the interfacial heat transfer equation range from 100 W/m^2 in 5 m/s wind to 600 W/m^2 in 50 m/s hurricane winds. The graph on the left of figure 1, based on CBLAST eddy correlation measurements, shows that the Dalton coefficient C_E is independent of wind speed and levels out at a value of 0.00118 at wind speed above 20 m/s.

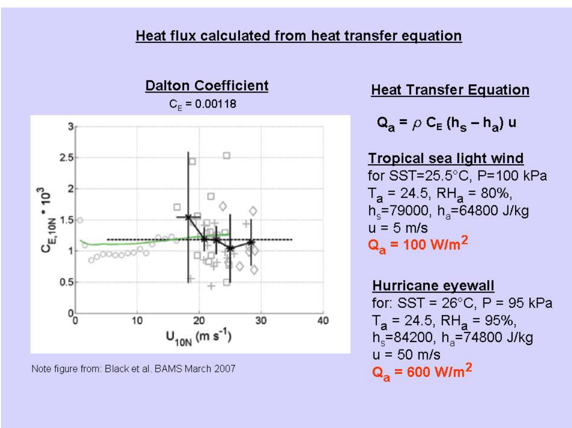

Fig.1 Examples of sea to air heat fluxes calculated using the interfacial heat transfer equation.

Figure 2 shows the effect of hurricane Frances on sea surface temperature. The hurricane is moving to the left and the colors are sea surface temperature reduction compared to pre storm conditions. The calculations at the upper right show that producing 10 mm/hr of rain over a 300 km diameter circle requires 491 TW of thermal power. Similar values were obtained by Trenberth et al. (2007). The second calculation shows that cooling a strip of sea 100 km wide by 100 m deep by 2.5 ℃ advancing at hurricane speed requires a thermal power of 524 TW. 500 TW corresponds to a heat flux of 200,000 W/m^2 over the area represented by the green square in the right rear quarter of the hurricane called the *spray production area*; and to a heat flux of 40,000 W/m^2 over the larger area represented by the red circle called the *spray deposition area*.

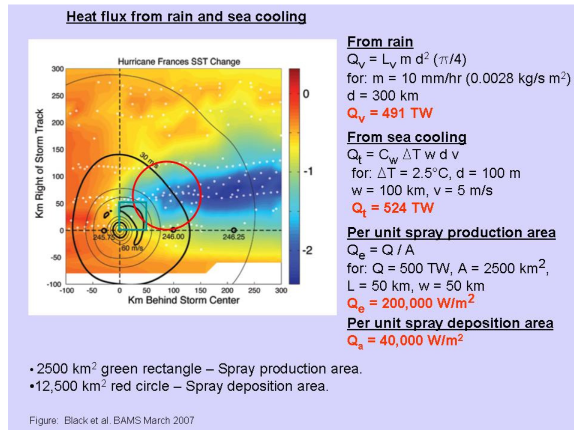

Fig. 2 Thermal power required to produce hurricane precipitation and sea cooling.

Spray production is highest in the right rear quarter of the hurricane because the wind is strongest on the right hand side of the hurricane, where the wind has just reversed direction and where well established waves coming from the right are suddenly hit by wind coming from the left tearing off the top of the waves and sending lots of spray in the air. The spray is deflected to the right of the air flow by centrifugal force because water is denser than air. Spray drops cool to the wet bulb temperature of the air and can be 2 to 8 ℃ colder when they rerurn to the sea than when they left the sea thus transferring large quantities of heat from sea to air.

Figure 3 shows a front view of the process. The cooling in the spray production area under the eyewall results from upwelling of cold water. The cooling in the spray deposition area to the right of the hurricane track is due to dilution of sea water by cold spray. Both types of cooling make the temperature contours rise. The cooling is more pronounced to the right of the hurricane track because mixing cold spray with warm surface water temperature is more effective at reducing ocean temperature than upwelling.

Heat transfer from spray to air is much higher than interfacial heat transfer because drops have high surface to mass ratio. For the same water mass 50 μm drops have one hundred times more area than 5 mm drops. The cooling of the drops takes place in seconds because evaporation occurs rapidly so long as the vapor pressure of the water in the drop is higher than the vapor pressure of the water in the air. Andreas (1995) and Andreas and Emanuel (2001) showed that small drops take less than a second to cool to the wet bulb temperature of the air. *The heat of evaporation is provided from the sensible heat of the remainder of the drop.* Evaporating 0.3 to 1% of a

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drop is sufficient to reduce its temperature to the wet bulb temperature of the air.

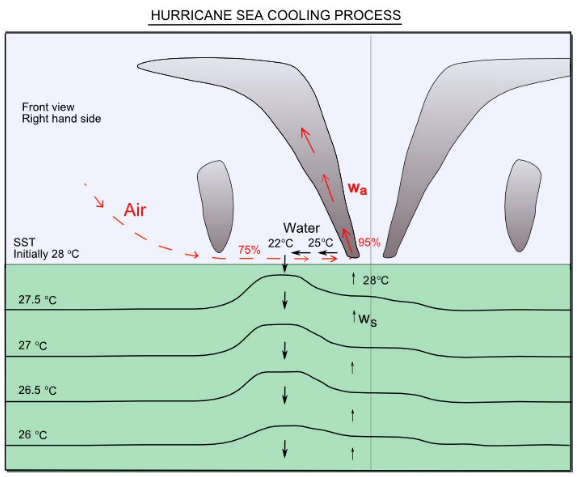

Fig. 3. Front view of hurricane heat exchange process.

Nature has found a very effective heat transfer process. The 28 ℃ spray cools to 25 ℃ when it meets the 95 % relative humidity eyewall air and to 22 ℃ when it meets the 75 % relative humidity air converging towards the eyewall. The spray exchanges heat and mass with the counter flowing air; the humidity of the air increases and the temperature of the drops decreases.

The relative humidity of eyewall air is usually close to 95 %. When the hurricane Ophelia passed over a moored buoy in 2011, eyewall air temperatures and relative humidity were 26 ℃ and 95%. Dropsondes in hurricane Isabel measured eyewall air temperatures and relative humidity of 25 ℃ and 97%.

Figure 4 shows how high relative humidity eyewall air can be produced by spraying dryer air with warm water. The calculation can be either per unit mass of air or per unit mass per unit time. Isenthalpic mixers are widely used in engineering. Andreas and Emanuel (2001) used the same isenthalpic mixing process but with lower water flow. The calculation determines the mass of water, shown in red at the upper left, required to increase the relative humidity of the air from 75% at the mixer inlet on the left to 95% at the mixer outlet on the right. The wet bulb temperatures at the mixer inlet and outlet air are 21.7 ℃ and 25.4 ℃ respectively.

The mixing ratio of the air increases from 15.7 to 21.2 g/kg and the enthalpy of the air increases by 14930 J. The sea to air heat flux is equal to the increase in the enthalpy of the air which is equal to the decrease in the enthalpy of the water. The tallies under the inlet and outlet columns show that enthalpy and mass are both conserved. *Irrespective of specific conditions, the temperature of the drops returning to the sea approaches the wet bulb temperature of the air, and the sea to air heat transfer is equal to the reduction in the enthalpy of the spray.*

For the conditions shown, an upward eyewall air velocity (v_a) of 2 m/s would produce a heat flux of 34,000 W/m^2 which would correspond to an upward velocity in the water rising under the eyewall (v_w) of 12 m/hr.

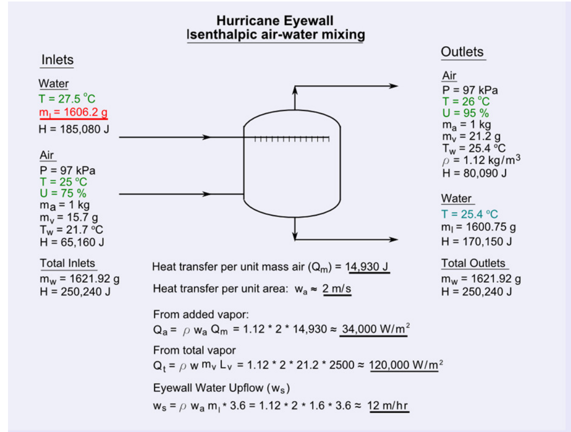

Fig. 4 Isenthalpic air water mixer.

Isenthalpic mixers permit checking the effect of parameters such as inlet air temperature and relative humidity and inlet water temperature. The quantity of water required to produce 95 % relative humidity air would be higher if the inlet air were dryer. For completely dry inlet air the heat transfer per unit mass of air could be 120,000 W/m^2 and the upward velocities of the water upwelling under the eyewall could be 50 m/hr.

The drops produced under the eyewall can be lifted several tens or even hundred of meters because the upward velocity of approximately 1 to 5 m/s of the rising air can be higher than the downward velocity of the drops, Lighthill (1999), Aberson et al. (2006). At a wind velocity of 160 km/hr, the drops would take approximately 15 minutes to cover the 40 km distance from the main spray production area to the main spray deposition area. The eyewall upward air velocity prevents the drops from falling back from where they were produced and as a result the majority of the drops fall 20 to 60 km to the right of where they were produced. The inner edge of the spray production area could correspond to the inner edge of the eyewall and the inner edge of the spray deposition area could correspond to the outer edge of the eyewall.

The cooling of drops is a time asymmetrical process; drops warmer than the wet bulb temperature of the air cool by evaporation within seconds; drops colder than the wet bulb temperature warm up slowly because sensible heat must be transferred from the air to the drop. Andreas and Emanuel (2001) showed that the time required to evaporate a drop after it reaches its equilibrium temperature is much longer than the time required for a drop to reach its equilibrium temperature. As a result a drop cooled to 19.5 ℃ by encountering 60 % relative humidity air which later goes through 75 % relative humidity air with a wet bulb temperature of 21.7 ℃ may not have time to warm up to the wet bulb temperature of the 75 % relative humidity air before falling back in the sea.

Industrial direct contact counter current cooling towers where the water is repeatedly broken up in small drops can have heat transfer of over 200,000 W/m^2. The one step mixing process of figure 4 could be replaced by a tower with trays to better represent the counter flow heat exchange process. The temperature of the outlet water would approach the wet bulb temperature of the inlet air rather than that of the outlet air.

2.0 SOURCE OF SEA COOLING

Hurricane Sea cooling is usually attributed to upwelling and mixing of cold water from below. Price (1981) wrote: "Entrainment is the primary mechanism that lowers SST beneath a hurricane. Air-sea exchange only plays a minor role". D'Asaro et al. (2007) who produced the excellent temperature profiles used in this manuscript wrote: "The cooling was almost entirely due to vertical mixing, not air-sea heat fluxes". This manuscript proposes the opposite hypothesis, namely that: "*Hurricane sea cooling is almost entirely due to heat removal from above and not to cold water from below".*

Sea temperatures tend to be stratified as shown in panels (a) and (d) of figure 5. Cold deep water is denser than warmer surface water and tends to stay down. Cooling by a hurricane can temporarily disturb the horizontal stratification as shown in panels (b) and (c); once the hurricane has passed hydrostatic forces tend to reestablish the stratification as shown in panel (d).

The driving force for the upwelling under the eyewall is the wind picking up eyewall water which is replaced with water from below. One can imagine the wind removing water from the top of a large diameter vertical pipe. The water swept off the top of the pipe must be replaced with water from below. Figure 5 shows that upwelling occurs throughout the eye and eyewall areas between arrows (D) and (E). The spray is strongest under the right rear eyewall at arrow (E) but upwelling occurs throughout the eyewall/eye area because warm eye water from a depth of 50 m is less dense and easier to lift than colder eyewall water from a depth of 150 m.

The cooling under arrow (F) of figure 5 and under arrow (B) of figure 6 is the result of cold spray mixing with warmer water and of the resulting cold dense mixture sinking. At arrow (B) of figure 6 the surface water is cold enough to push the 26 ℃ isotherm down and to temporarily increase the temperature between depths of 60 and 120 m. At arrow (C) of figure 6 where the cooling is at its maximum the cooling has extended to a depth of 160 m. The reduction in water temperature under arrow (C) of figure 6 is due to the sinking of surface water cooled by cold spray. The reduction in water temperature under arrow (D) and (E) of figure 5 is the result of upwelling.

The decrease in the depth of the 24 ℃ isotherm close to the hurricane track, figure 5 panel (c) under arrows E and F, is caused by upwelling of cold water. The decrease in the depth of the 24 ℃ isotherm to the right of the hurricane track in the spray deposition area is caused by the sinking of water cooled by falling spray.

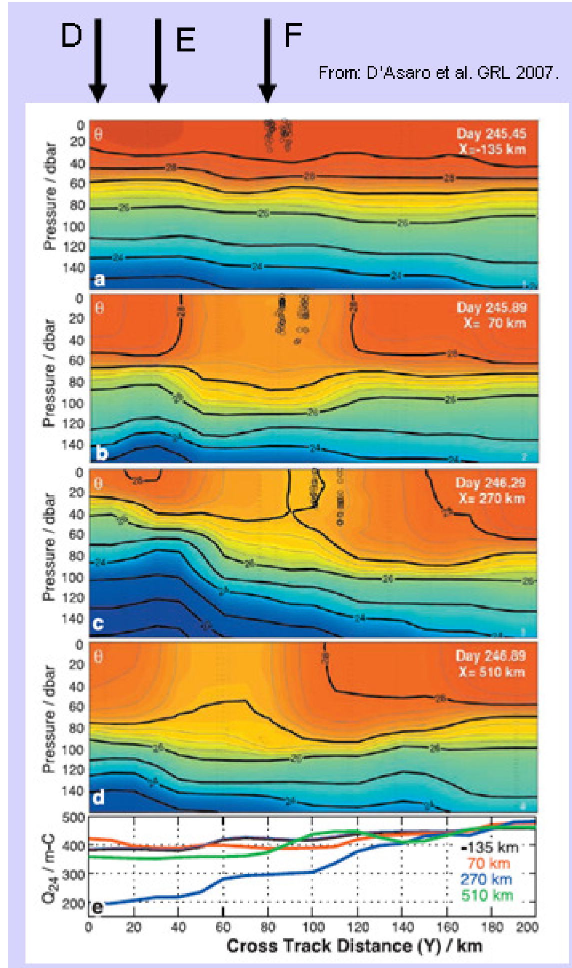

Fig. 5 (a, b, c, d) Crosstrack maps of temperature at four selected along-track positions. (e) Heat content above the 24 ℃ isotherm for each of the panels.
(D) hurricane eye, (E) 30 km to the right of eye,
(F) 80 km to the right of eye.

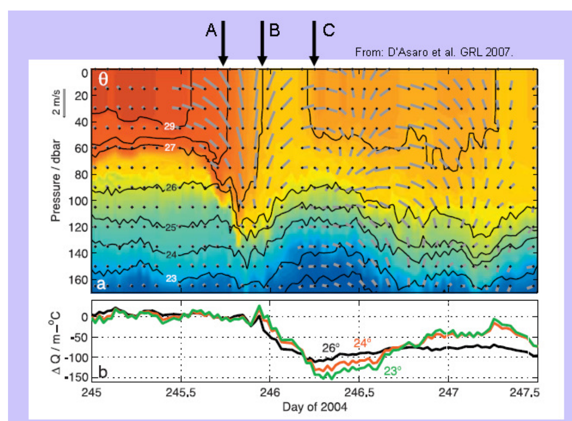

Fig. 6 (a) Depth-time contour of sea temperature 70 km to the right of hurricane Frances track. (b) Change in ocean heat content above 23, 24, and 26 ℃ isotherms. (A) in line with the eye, (B) 70 km behind the eye, (C) 270 km behind the eye.

The lower panel in figure 6 shows that at its maximum the reduction in heat content is 150 m-℃. The heat content recovers during the subsequent reestablishment of hydrostatic equilibrium but the total heat removed from the sea does not change; the reduction is heat content just gets spread out. The decrease in ocean heat content prior to day 246.3 is due to sea to air heat transfer associated with the hurricane. The increase in ocean content after day 246.3 is due to the reestablishing hydrostatic equilibrium and not to the hurricane.

Figure 5 panel (e) shows that the sea cooling is its maximum 270 km behind the eye. The average cooling for the 200 km cross track plot is 100 ℃-m. Figure 5 does not show the cooling on the left side of the track. Assuming that the cooling on the left side of the track is half of the cooling on the right side of the track, the hurricane cools a strip of sea 300 km wide, by 100 m deep, by 1 ℃ at a hurricane velocity of 5 m/s this corresponds to a thermal power of 630 TW which is not inconsistent with the 524 TW of Figure 2. The heat flux of 200,000 W/m^2 is based on a uniform heat transfer throughout the right rear quadrant. The heat transfer per unit of sea area could be much higher if the spray production is concentrated in a small part of the right rear quadrant.

The microwave satellite photo of Figure 7 shows the effect of hurricane Isabel of sea temperature. The cooled track is over 5000 km long. It is difficult to imagine how upwelling could produce such cooling. Spray can produce very high heat fluxes; the heat which took months to be accumulated in the upper layer of the subtropical sea can be transferred to the atmosphere in a few hours.

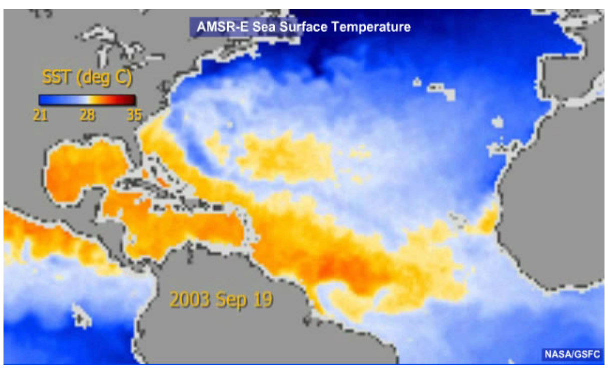

Fig. 7 Effect of hurricane Isabel on sea surface temperature as observed by satellite, COMET (2006).

There are difficulties with trying to explain hurricane ocean heat content reduction from upwelling and mixing. Hurricane wind can generate Eckman spiral but it is difficult to see how Eckman pumping could result in strong upwelling of cold water. Water tends to stay stratified by density. Layers of water of different density are difficult to mix. The cool water to the right of the hurricane track where down-welling is taking place appears well before eyewall upwelling has brought cold water to the surface. Where does the cold water to the right of the hurricane track come from if it is not from cold spray? Where does the warm surface that was to the right of the hurricane go? Such questions could be answered by measuring the temperature and the quantity of spray falling in the spray deposition area.

3.0 EDDY CORRELATION AND DALTON COEFFICIENT

Figure 8 illustrates the eddy correlation heat flux measurement principle. The heat flux is the sum of the product of the deviations from average of vertical velocity and enthalpy as shown at the upper right. High enthalpy updrafts and low enthalpy downdraft both increase heat flux. *Heat fluxes calculated from the Dalton coefficient ultimately depend on eddy correlation.* Eddy correlation requires that conditions be uniform in the horizontal direction. According to the LICOR manual there must be no net convergence. Hurricanes are areas of high convergence.

Figure 9 shows how a high heat flux can be produce by a steady flow. Figure 10 shows what eddy correlation could see in the steady flow example of Figure 9. The heat flux seen by eddy correlation is 800 W/m^2 while the heat flux produced by the steady flow is over 100,000 W/m^2. Figure 11 shows why eddy correlation techniques, which work well when the average upward velocity is zero, can lead to severe underestimate of heat flux if there is convergence.

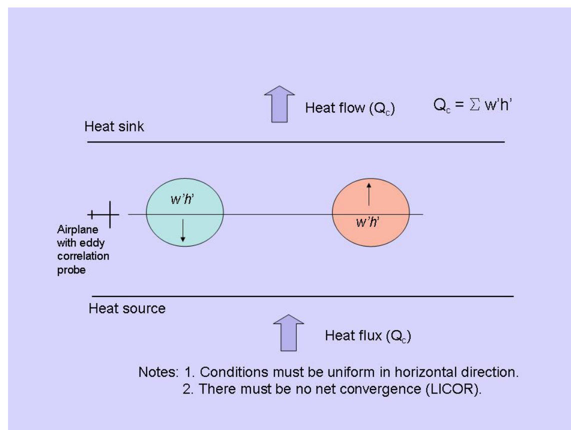

Fig. 8 Eddy correlation heat flux measurement principle.

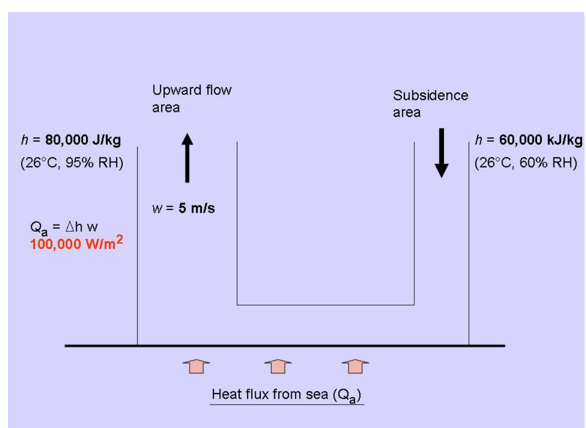

Fig. 9 Example of how a steady flow can produce an upward heat flux.

Heat flux calculated from the product of latent heat and upward mass flow of water could be more realistic than heat fluxes calculated from eddy correlation. The total upward flux of water vapor in the updraft areas should be equal to the total rain produced by the hurricane. Taking the average mixing ratio of the rising air as 20 g/kg, the average upward velocity of the updraft as 2 m/s, a hurricane with a thermal power of 500 TW would require an updraft area of 5000 km^2 corresponding to the surface of an eyewall annulus 200 km long by 25 km wide. The vapor content of the air in the updrafts must eventually come from the sea.

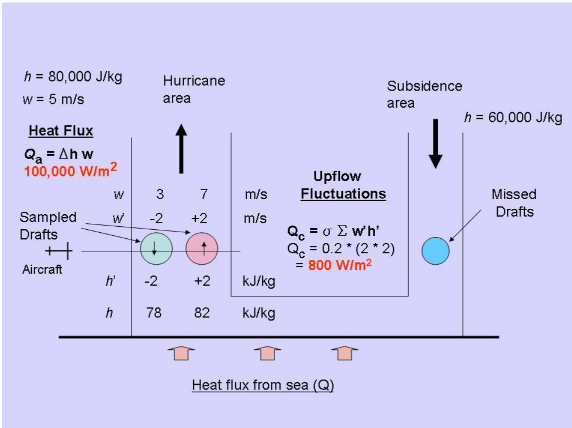

Fig. 10 Example of how the heat flux in Fig. 8 can be seen by eddy correlation.

Mean upward velocity contribution (Q_a) Eddy correlation Contribution (Q_c)

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

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

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

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

Fig. 11 The heat flux seen by eddy correlation is much less than the actual heat flux when there is convergence.

4.0 SEA TO AIR HEAT TRANSFER

Figure 12 how a term could be added to the Dalton heat transfer equation to account for spray. The basis for the fifth power is simply that increasing the wind velocity by a factor of 10 increases the heat flux from spray by a factor of 10^5. The actual exponent could be higher because there is not much spray produced at wind velocities under 25 m/s.

The two terms of the equation could be combined into one which would make C_E proportional to the fourth power of velocity which is a long way from a Dalton coefficient which is independent of wind speed. The lower equation, only valid at wind speeds close to 50 m/s, shows that the revised heat transfer coefficient C_F is approximately 100 greater than C_E.

The purpose of the new equation is simply to show that the heat transfer at hurricane wind speed is much higher than indicated by the traditional interfacial heat transfer equation. The sea to air heat transfer is the result of spray drops returning to the sea colder than when they left the sea. Only 0.3 to 1 % of the drop evaporates; the remaining 99 to 99.7% of the drop returns to the sea 2 to 8 °C colder than when it left the sea.

Q_i Interfacial term Q_s Spray term

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

$$Q \sim \rho\, C_F\, (h_s - h_a)\, u \qquad 48 < u < 52\ \mathrm{m/s}$$

where: $C_E = 1.18 * 10^{-3}$, $C_S = 2.6 * 10^{-5}$, $C_F = 0.19$

Sample heat Fluxes

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

Fig. 12 Possible new form for Sea to air heat transfer equation.

The use of the Dalton interfacial heat transfer equation or of the new equation of figure 12 is discouraged. Isenthalpic mixers are more appropriate for simulating mixing processes than interfacial heat transfer equations. The high heat flux is due to increase surface area and not to wind speed. A 1 cm water cube divided in 100 μm cubes has the same surface area as a 10 m cube. In addition all six sides are exposed to the air while only the top surface of the top cubic centimeter of the sea is exposed to air.

Sea to air heat transfer is roughly proportional to the quantity of spray injected in the air. The sea to air heat transfer produced by a spray of 100 kg s^{-1} m^{-2} over a 250 km^2 area can be equal to the heat transfer produced by a spray of 10 kg s^{-1} m^{-2} over a 2500 km^2 area. Heavy spray in a small fraction of the right rear quadrant could result in an average heat flux of 200,000 W/m^2 in the green square of figure 2. Aberson et al. (2006) showed that strong local eyewall updrafts occur.

Hurricane intensity is affected by the temperature of the spray. SST cooling in hurricane Frances track was 2.2 °C to the right of the hurricane track and 0.4 °C along the hurricane track. The along the track cooling could be due to cooled spray falling in the sea after the passage of the eyewall. The cooling in the spray production area could less than the along the track cooling. Upwelling under the eyewall may not produce much SST cooling since there is little decrease in temperature with depth in the mixed layer. As a result air sea cooling, the so called air-sea interaction, may have very little effect on hurricane intensity.

According to Trenberth's energy balance, the convective heat flux at the bottom of the atmosphere averages 102 W/m^2 for a total convective heat flux for the whole earth of 52 PW. Assuming that the heat flux is the same over the land and the sea, the heat flux over the land and the sea would be 16 and 36 PW respectively. Table 1 is a preliminary estimate of the effect of spray on boundary layer heat fluxes

Josey, Kent and Taylor (1998) found that sea heat fluxes calculated using the Dalton equation result in a net heat flux in the sea of 30 W/m^2. They pointed out that simple scale adjustment is not appropriate and that other factors such as wave size and direction have to be considered.

	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

Table 1 Preliminary estimate of sea-to-air heat fluxes.

The last two lines of the Table 1 are a rough estimate of heat transfer from hurricane and non-hurricane spray. The 2 PW heat flux from hurricane spray was estimated from the number of hurricanes and their thermal power. The 9 PW heat flux from non-hurricane spray is a residual may be mainly due to high winds and high temperature contrasts in high latitudes in winter. Spray can produce islands of sea to air heat transfer much higher than calculated from the Dalton coefficient.

There have been numerous research programs aimed at getting better sea to air heat transfer measurements see for example Drennan et al. (2007). Several scientists have questioned the low heat fluxes calculated using the Dalton coefficient. Trenberth, Davis, Fassullo (2007) wrote: Numerical models results require that about 70% of hurricane precipitation comes from moisture already in the atmosphere at the time the storm formed; and that one would have to integrate out to a radius of 1600 km to obtain a rough energy balance.

Shay et al. (2000) estimated that only 10 to 15% of the ocean cooling is due to surface heat flux and that the remainder is due to mixing of cold water from below. Andreas and Emanuel (2001) considered the effect of spray and concluded that spray can provide a significant fraction of the sea to air heat flux. Their maximum heat fluxes are under 5000 W m^{-2}; their estimate of the quantity of spray may have been low.

Emanuel calculated hurricane heat to work conversion efficiency of 33%. 33% of 500 TW is an enormous quantity of mechanical energy and is equal to 60 times the world's present electrical energy production. The energy production potential of the atmosphere far exceeds that of either fossil fuel or nuclear energy. There could be ways of capturing the work of atmospheric convection that have not been considered in atmospheric science. Cooperation and discussion between atmospheric scientists and engineers could contribute to solving the carbon dioxide problem. Michaud (2012) showed that increasing the relative humidity of surface air increases the energy produced per unit mass of air and updraft intensity. This manuscript shows that heat transfer from sea to air can be increased with spray.

5. CONCLUSIONS

Interfacial heat transfer without spray is unable to provide the heat flux required to produce either the observed precipitation or the observed sea cooling. Eyewall spray can increase sea-to-air heat transfer by a factor of 100. *Spray provides a mechanism whereby the huge heat content of the sea can quickly be transferred to the lower atmosphere. Hurricane sea-cooling is primarily due to cooling from above and not to mixing of cold water from below.*

The heat content of sea water is much greater than that of air. The heat given up in cooling the top 100 m of the ocean by 1 °C is 400 times the heat required to warm the bottom 1 km of the atmosphere by 1 °C. Hurricanes significantly reduce the heat content of the sea and do not significantly decrease the heat content of the tropical atmosphere. Huge quantities of heat can be transferred from sea to air through the well understood isenthalpic mixing of spray and air process. Cooling of spray can account for both hurricane precipitation and sea cooling.

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