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 m^{-2} in light wind to 1000 W m^{-2} 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 m^{-2}. Drops of spray falling back in the sea and are typically 1 to 3 °C colder than the drops leaving the sea thus transferring a huge amount of heat from sea to air. The heat of evaporation is provided by the sensible heat of the remainder of the drop; evaporating approximately 0.3% of a drop is sufficient to reduce its temperature to the wet bulb temperature of the air. The heat required to evaporate hurricane precipitation is roughly equal to the heat removed from the sea indicating that sea cooling is due to heat removal from above and not to the mixing of cold water from below. The paper shows how ideal thermodynamics processes case studies could help explain hurricane intensity.

1. Introduction

Several methods of establishing hurricane maximum potential intensity (MPI) have been proposed; the two leading methods are E-MPI, Emanuel (1986) and H-MPI Holland (1997). Persing and Montgomery (2003) and Bell and Montgomery (2008) noted that E-MPI has gained much acceptance, but that E-MPI can not account for observed super-intensities. E-MPI is based on the heat transfer from sea to air multiplied by a Carnot efficiency calculated using the temperatures of the sea for the hot source temperature and the temperature at the top of the hurricane for the cold source temperature. H-MPI is based on the pressure at the bottom of a column of air approaching equilibrium with the underlying water at the reduced eyewall pressure. Camp and Montgomery (2001) reviewed the Holland and Emanuel MPI methods; they noted that H-MPI tends to overestimate intensity of strong hurricanes while E-MPI tends to underestimate the same. Persing and Montgomery (2003) suggested that a new MPI formulation from first principles is required; this paper shows that case studies of idealized processes could provide such a formulation.

High quality data for hurricane Isabel recently became available, Montgomery et al. (2006). The Isabel data comprised multiple dropsondes in four areas: eye, eyewall, outer core, and distant environment. Isabel was a large category 5 hurricane (wind speed > 67 m s^{-1}) during an intense observation period (IOP). The IOP took place on 13 September 2003 between 1600 and 2300 UTC when Isabel was located 1300 km east of Puerto Rico and was essentially at steady state. Bell and Montgomery (2008) noted that the observed wind of 76 m s^{-1} is well in excess of the E-MPI of 57 m s^{-1}.

Michaud (2000 and 2001) showed that MPI can be calculated by applying the total energy equation (TEE) to steady state ideal processes. This paper applies the TEE method to the Isabel data and shows that the method yields MPI's in agreement with observations. Eyewall sea surface temperatures (SST) of 26 °C and 27 °C yields velocities of 86 m s^{-1} and 110 m s^{-1} respectively. The large amount of spray at the eyewall causes the eyewall air temperature to approach equilibrium with the sea. The TEE method does not yield the high MPI's of the H-MPI method because eyewall SST is cooled by re-entrant spray. Section 2 calculates MPI from eyewall air temperature and relative humidity. Section 3 examines the effect of spray on eyewall air relative humidity and temperature. Section 4 looks at cumulative hurricane heat transfer and at the contribution of ocean heat content.

2. Effect of eyewall air temperature and humidity on MPI – Lifting process 3-4

The TEE method of analysis is based on the steady state ideal open thermodynamic process shown in Fig. 1. State 1 corresponds to distant environment surface air. State 3 corresponds to eyewall surface air. State 4 is the level of neutral buoyancy. The air in state 3 approaches equilibrium with SST at the reduced surface pressure (P_3). Entropy (s) is conserved in reversible adiabatic expansion processes 1-2 and 3-4. Process 1-2 is essentially an isentropic expander wherein the turbine work is equal to the decrease in the enthalpy (h). Process 2-3 represents the sea-to-air heat and mass transfer wherein enthalpy is transferred from sea to air; the enthalpy gain of the air in process 2-3 is equal to the enthalpy loss of the water in process 7-8. Process 3-4 represents the upward flow process in the eyewall; in the ideal process it is adiabatic and is assumed to be carried out in an insulated vertical tube.

The atmosphere is an engine wherein heat is partly converted to work. Idealizing engines to establish their maximum performance is a standard thermodynamic practice. In ideal process analysis velocities and frictional losses are initially assumed to be negligible. In Fig. 1 the kinetic energy of the air is considered to be negligible except at the exit of the turbine nozzles where it is immediately captured by the turbine blade. The turbine or expander removes the work from the system and prevents its dissipation. Reversibility requires that the work be removed from the system; after the reversible process is understood irreversibilities can be introduced to study their effect.

The TEE method calculates the pressure (P_3) at the base of a column of warm humid air rising to its level of neutral buoyancy (P_4). The calculation is based on the realization that P_3 is the pressure for which the isentropic work of expansion from P_3 to P_4 is equal to the increase in the potential energy of the air in process 3-4. P_3 is calculated by iteration; interpolation is used to determine the value of P_3 for which the net work in process 3-4 is zero. The TEE method is simple and direct; one or two iterations are sufficient to calculate P_3. Once P_3 is known expander work w_{12} is readily calculated by expanding ambient surface air isentropically from P_1 to P_2.

The TEE method was applied to the Isabel data. Table 1 shows results for three cases. Thermodynamic properties are per unit mass of pure air and are in accord with those of Ooyama (2001). Relevant equations and relationships are shown in Fig. 1 and in Table 1. The temperature (27.8 °C) and relative humidity (75%) in state 1 are those of the distant environment surface air in Fig. 4 of Montgomery et al. (2006). In case 1, there is no water spray and work (W_{12}) is 2180 W kg^{-1}. Work W_{12} is identical to convective available potential energy (CAPE) for true adiabatic expansion with freezing because the work for all reversible processes with the same initial and final conditions must be the same. There is no need to calculate difference in density or virtual temperature at intermediate levels. The use of the ideal process greatly simplifies work calculation; the work only depends on the conditions of the air in state 1 and on the pressure and elevation at the top of the tube in state 4.

The newly available Isabel eyewall air temperature and humidity are used as the calculation starting point for case 2. Case 2 state 3 conditions are based on the hurricane Isabel eyewall air temperature and air humidity of 24.5 °C and 97% respectively taken from Fig. 4 of Montgomery et al. (2006). Sea surface temperature (SST) prior to the passage of Isabel was 29 °C. COMET (2006) microwave satellite data indicate that Isabel reduced SST from 29°C to 26°C. The eyewall sea surface temperature (SST) during the passage of the eyewall is estimated to have been 26 °C. The air is sprayed with 26 °C water until its temperature and relative humidity are 24.5 °C and 97% respectively. In cases 3, eyewall SST is 27 °C and the air is sprayed with water until its temperature and relative humidity are 25.5 °C and 97% respectively. In case 2, the eyewall pressure (P_3) is

96.9 kPa and the work w_{12} is 3750 W kg^{-1} corresponding to a velocity (v) of 86 m s^{-1}. In case 3, P_3 is 94.3 kPa, W_{12} is 6160 W kg^{-1} corresponding to a velocity of 110 m s^{-1}. Hurricane Isabel dropsondes measured sustained wind speed of and peak wind speeds of 77 and 110 m s^{-1} respectively, Montgomery (2006).

The heat to work conversion efficiency of approximately 30% is calculated in two ways to provide an independent check:

1. The Carnot efficiency using T_3 for the hot source temperature and T_4 for the cold source temperature.
2. The work produced in process 1-2 (W_{12}) divided by the heat received in process 2-3 (Q_{23}). Incremental efficiency is used because the CAPE of the distant ambient air (case 1) is 2190 W kg^{-1} and not zero. In case 2, adding 5090 W kg^{-1} of heat in process 2-3 increases process 1-2 work from 2190 to 3750 W kg^{-1} resulting in an incremental heat to work conversion efficiency of 30.7% ((3750-2190)/5090).

Pressure (P_3), work (W_{12}) and velocity (v) are very sensitive to air temperature (T_3). The sensitivity of eyewall pressure to T_3 is -2.64 kPa K^{-1}. The sensitivity of work of convection W_{12} to T_3 is 2410 J kg^{-1} K^{-1}. The sensitivity of velocity to T_3 is 24 m s^{-1} K^{-1}. T_3 has to be at least 23.8 °C to increase work W_{12} beyond the initial CAPE of 2190 W kg^{-1}. Fig. 2 shows how eyewall pressure is affected by eyewall air temperature and relative humidity. The isobaric curves show the combinations of state 3 temperatures and relative humidity capable of producing a given surface pressure P_3. Decreasing eyewall air relative humidity by 8% has approximately the same effect on MPI as reducing eyewall air temperature by 1 °C. The eyewall pressure 96.9 kPa of case 2 could also have been produced by 25.5 °C air with relative humidity of 89%.

The level of neutral buoyancy (LNB) for hurricanes is typically between 15 and 10 kPa. The 15500 m elevation of the 12 kPa in Table 1 is based on the Jordan (1958) mean hurricane season sounding for the West Indies. Geopotential heights in the tropical upper troposphere are governed by the earth's energy budget and are fairly constant. P_3 is not very sensitive to P_4 because the buoyancy of the raised air whether positive or negative is small near the level of neutral buoyancy. The LNB's in cases 2 and 3 are 12 kPa and 11 kPa respectively. A LNB of 12 kPa was used for all three cases in Table 1 for ease of comparison. Additional iterations can be used to find the level of neutral buoyancy by searching for the pressure (P_4) which maximizes the work. The LNB could be close to 12 kPa in most hurricanes because the temperature of rising air decreases rapidly (by approximately 5 °C kPa^{-1}) as the tropopause is approached.

Hurricanes transport heat from the sea to the upper troposphere, but they do not increase the temperature of the upper troposphere in their immediate vicinity because the raised air tends to descent far from the hurricane where the subsiding air is cool and easier to compress. The upper troposphere warming can take place at long distances from the hurricane and may be unnoticeable in the tropics because subsidence heating is spread over a very large area. In spite of the enormous heat flux from the sea, hurricanes produce little warming in their own latitude. The heat must go somewhere; hurricanes are often associated with warming and clear weather in higher latitudes.

The downward flow in the eye of a hurricane is small compared to the upward flow in the eyewall. The pressure reduction at the eye is the result of the air in the eye being entrained through friction by the eyewall. In a Rankine vortex, the pressure reduction in eye is twice the pressure reduction at the radius of maximum wind. The eyewall pressure reduction of 4.2 kPa in case 2 could therefore correspond to eye pressure reduction of 8.4 kPa. The sensitivity of eyewall and eye pressure to T_3 are -2.64 and -4.94 kPa K^{-1} respectively. Isabel minimum surface pressure during the IOP was 93.5 kPa, Beven and Cobb (2003). Table 1 is based on true-adiabatic expansion with freezing of the condensed water rather than on the more usual pseudo-adiabatic expansion without freezing. MPI for pseudo-adiabatic expansion without ice (PA_{ni}) are not much different MPI's for true-adiabatic expansion with ice (TA_{wi}). For eyewall air temperature and relative humidity of 24.5 °C and 97% respectively, eyewall pressure (P_3) are 96.9 kPa for TA_{wi} and 97.7 kPa for PA_{ni}. The type of expansion only has a minor effect on P_3 and does not significantly change the shape and position of the isobaric curves of Fig. 2.

3. Sea-to-air heat transfer - Isenthalpic Mixing Process 2-3

There are two hurricane sea-to-air heat transfer mechanisms: interfacial heat transfer and isenthalpic mixing of spray with air; interfacial heat transfer has traditionally been the only heat transfer mechanism considered, Emanuel (1995a) and Andreas and Emanuel (2001). Interfacial heat transfer without spray can range from 100 W m^{-2} in wind of 5 m s^{-1} to 1000 W m^{-2} in force 5 hurricane winds of 70 m s^{-1}, Ooyama (1969) and Black et al. (2007). Heat transfer by spray can be 2 orders of magnitude higher than interfacial heat transfer. Heat transfer from spray is much higher than interfacial heat transfer because drops have large surface. Small drops cool more quickly than larger drop because they have larger surface to mass ratios. Large drops do not have time to cool before falling back in the sea and therefore do not contribute as much to ocean cooling as smaller drop. High eyewall winds produce small droplets which may be further broken up by wind and by evaporation.

Heat transfer from spray is an isenthalpic mixing process, wherein the water and the air come to equilibrium, wherein the enthalpy gain of the gas phase is equal to the enthalpy decrease of the liquid phase and wherein the liquid phase separates from the gas phase and falls back in the sea. Heat transfer in a mixing process can be calculated from energy and mass balances, Andreas and Emanuel (2001). The temperature of the water falling back in the sea approaches the wet bulb temperature of the air. Heat is transferred from the ocean to the atmosphere because the temperature of the water returned to the sea is lower than that of the water taken from the sea. The heat transferred is essentially equal to the mass of the spray multiplied by the decrease in its specific enthalpy.

The lower section of Table 1 shows the mass of water per unit mass of air required to increase the temperature and relative humidity of air in process 2-3 of Fig. 1. Producing air of a specific temperature and relative humidity requires a *definite* quantity of water. In case 2, producing the 24.5 °C air with 97% relative humidity requires mixing 0.62 kg-water at 26 °C per kilogram of air. In case 3, producing the 25.5 °C air with 97%

relative humidity requires mixing 1.64 kg of water at 27 °C per kilogram of air. The 25.5 °C air in case 3 could be produced with 26 °C water instead of 27 °C water but the water to air ratio would have to increase from 1.64 to 3.51.

Andreas and Emanuel (2001) suggested that re-entrant spray could enhance sea-to-air heat transfer and calculated the effect of spray using essentially the same isenthalpic mixing approach as used in this paper. They realized that the spray is rapidly cooled to its wet bulb temperature. Their Fig. 1 shows that a 100 μm diameter drop of water injected in 80% relative humidity air cools to its equilibrium wet bulb temperature within 1 s. Spray droplets are cooled to their wet bulb temperature, which is typically between 22 and 25 °C, before falling back in the sea. The drops falling back in the sea are 1 to 3 °C cooler than the drops leaving the sea thus transferring a huge amount of heat from sea to air. Table 1 shows the wet bulb temperatures (T_w) in states 1, 2 and 3. The wet bulb of the 24.5 °C air with 97% relative humidity in case 2 state 3 is 24.1 °C. The temperature of the drops falling back in the sea would be 24.1 °C. The cooling of the drop is caused by the evaporation of approximately 0.3% of the drop because the heat of evaporation is taken from the sensible heat of the remainder of the drop. *Rapid evaporation occurs as long as the vapor pressure of the liquid water in the drop is higher than the vapor pressure of the gaseous water in the air.* In cases 2 and 3 the water is cooled by 1.9 °C. The heat transferred per unit mass of water sprayed is 1.9 cw = 8000 J kg^{-1}, where cw = 4200 J kg^{-1} is the specific heat of water. The quantity of spray required to transfer 100,000 W m^{-2} is 13 kg m^{-2} s^{-1}. There has been no reliable measurement of how much eyewall spray is produced per unit area per unit time. Spray in the eyewall can be very heavy; a spray production of 13 kg m^{-2} s^{-1} would not be unreasonable.

Humidity approach is the difference between 100% and actual relative humidity; temperature approach is the difference between eyewall SST and eyewall air temperatures. Eyewall relative humidity and temperature approaches could be close to 3% and 1.5 °C respectively in most hurricanes. Holland (1997) estimated eyewall relative humidity at 90% from the condensation level. Spray to air mass ratios of between 0.2 and 4 can produce air with a temperature approach of 1.5 °C and a relative humidity approach of 3% under most conditions.

In mixing process 2-3 of Fig. 1, the water and the air are mixed at once. In a hurricane the air is repeatedly sprayed with water rather than mixed with water all at once. The effect on the air of repeatedly spraying the air with small amounts of water is not much different than that of mixing all the water in the air at once. In fact spraying the water a bit at a time is slightly more effective at increasing the enthalpy of the air than adding the water all at once. Increasing the relative humidity of air from 80 to 97% requires that each kilogram of air be sprayed with approximately 1 kg of water. There is no need for the spraying to occur at once; each kilogram of air can be sprayed with 0.01 kg of water 100 times.

The heat capacity of water is much higher than that of air. The heat provided by cooling a layer of water 1 m thick by 1 °C is sufficient to increase the temperature of the bottom kilometer of the atmosphere by 4 °C which would be a large increase in the heat content of the boundary layer. The heat provided by cooling a layer of water 100 m thick by 3 °C is 1200 times the heat required to increase the temperature of the bottom kilometer of the atmosphere by 4 °C. Cooling a layer of water 100 m thick by 3 °C would provide 60,000 W m^{-2} for 6 hours. The heat content of the atmospheric boundary layer is not significantly different before and after the passage of a hurricane and therefore the heat must come from the sea and not from the original heat content of the atmospheric boundary layer. Thus curiously enough the humidity of the original oceanic air makes negligible contribution to the energy of the hurricane. In case 2, water spray increases the mixing ratio from 17.87 to 19.74 g kg^{-1}; the mixing ratio of the eyewall air is *only* 10% higher than the mixing ratio of the pre storm ambient air. The vapour content of the ambient air plays such a small role because the boundary layer is continuously diluted with dry air from above. Persing and Montgomery (2005) and Emanuel (1986) found that environmental CAPE has no significant influence on hurricane intensity. The CAPE of the ambient air in case 1 is sufficient to produce a velocity of 66 m s^{-1} corresponding to a category 5 hurricane. High ambient CAPE without heat transfer from spray is insufficient to sustain a hurricane because the heat content of the boundary layer ambient air would be rapidly depleted as a result of dilution by dry air from above. In a hurricane the relative humidity of eyewall air is maintained constant at around 97% because the dilution by dryer air from above is balanced by evaporation of water spray from below. Emanuel (1995a) investigated how the equilibrium between surface enthalpy flux and input of low entropy air from above controls the properties of the sub-cloud layer.

Eyewall surface air temperature approaches eyewall SST irrespective of whether the work is removed from the system or dissipated within the system. Replacing reversible isentropic expander 1-2 with an isenthalpic irreversible expander does not affect pressure P_3 because *the rising air approaches equilibrium with the water whether process 1-2 is reversible or irreversible*. Dissipating work in an isenthalpic process reduces the heat required to produce state 3 conditions by the work dissipated. The bottom item in Table 1 shows that the water to air flow ratio is lower for irreversible expansion ($M_{7\mathrm{i}}$ - process 1-2 constant enthalpy, $T_2 = T_1$) than for reversible expansion ($M_{7\mathrm{r}}$ - process 1-2 constant entropy, $s_2 = s_1$). For case 2, irreversibility reduces the water to air ratio of from 0.62 and 0.14, a reduction of 77%; the enthalpy supplied by the spray is reduced by the quantity of work dissipated. In case 2, the heat supplied by the water is reduced from 5090 to 1340 J kg^{-1}, by the quantity of work dissipated in the isenthalpic process, 3750 J kg^{-1}. Bister and Emanuel (1998) argued that dissipation can increase hurricane maximum wind by 20%; alternatively dissipation could reduce the heat required to produce a given wind. The quantity of spray required to produce a given relative humidity is reduced by dissipation. Dissipation could further contribute to reducing the approach to equilibrium by breaking up the drops and increasing the surface area of the drops thereby increasing the affinity of the air for the water.

4. Cummulative heat transfer

Interfacial heat transfer without spray is unable to account for the heat required to produce either the observed precipitation or the observed sea cooling. A large hurricane can produce an average of 1.5 cm d^{-1} of rain in a circle of 665 km radius, Landsea (2005 Hurricane FAQ D7). Converting to rain gives a mass of 20.9 x 10^{12} kg d^{-1}; multiplying by the latent heat of vaporization, the heat required to vaporize the water amounts to 600 x 10^{12} W. 600 TW is an enormous amount of energy and is 300 times greater than the world's average electrical energy production of 2 TW. Similar heat flux estimates were obtained by Ooyama (1969).

A strong hurricane can cool a strip of water 100 km wide by 100 m deep by 3 °C and have a speed of 5 m s^{-1}, Bell and Montgomery (2008). The mass of water is 50 x 10^{9} kg s^{-1}; multiplying by the sensible heat of water and a temperature change of 3 °C amounts to 630 x 10^{12} W. The agreement between the heat required to evaporate the rain and that required to cool the sea indicates that the source of the heat of evaporation is the sensible heat of the sea. Assuming that the intense heat flux takes place under the eyewall where the spray or spume is heaviest, that the eyewall of the hurricane has an area of 5000 km^{2}, and that 80% of the heat transfer occurs in the eyewall results in an eyewall heat flux of 100,000 W m^{-2}. The contribution of the interfacial heat flux of 1000 W m^{-2} to the total sea-to-air heat flux is only 1%.

In the reversible process of case 2, increasing the relative humidity of the air to 97% with 26 °C water requires a water to air mass ratio of 0.6:1. The heat carried upward per unit mass of air rising in the eyewall is approximately 12,000 J kg^{-2}, (the work of 3750 divided by the efficiency of 0.3). Taking the upward heat flux per unit mass of rising air as 12,000 J kg^{-1}, an upward heat flux in the eyewall of 100,000 W m^{-2} requires an air flow of approximately 8 kg m^{-2} s^{-1} and a spray flux of approximately 5 kg m^{-2} s^{-1}.

Spray from below tends to reduce the humidity approach while dilution with dry air from above tends to widen the humidity approach. The humidity approach tends to be self regulating because the effect of dilution by dry air increase as the humidity approach is reduced. With a temperature approach of 1.5 °C, SST has to be at least 25.3 °C to produce work (W_{12}) higher than the CAPE of ambient air and above 26 °C to produce work significant higher than the CAPE of ambient air which explains why hurricanes development requires SST of at least 26 °C.

Hurricane maximum potential intensity is essentially a function of eyewall SST *only* because the height of the level of neutral buoyancy, the eyewall temperature approach and the eyewall relative humidity approach are rather constant. A small difference in eyewall air temperature makes a large difference in wind velocity. At an eyewall air relative humidity (U_3) of 97% increasing the eyewall air temperature (T_3) from 23.3 °C to 23.9 °C increases hurricane intensity from a category 1 (33 m s^{-1}) to a category 5 (70 m s^{-1}). *A 0.6 °C air temperature increase is sufficient to increase intensity from category 1 to category 5.* With a temperature approach of 1.5 °C, the corresponding eyewall SST would be 24.8 °C and 25.4 °C. Real hurricanes could require eyewall SST's about 1 °C higher than the ideal process because of the combined effect of pseudo-adiabatic expansion without ice, of relative humidity under 97% and of large drops size.

Eyewall SST is not uniform and can change rapidly. Patches of high temperature SST (>26 °C) could have more effect on MPI than average eyewall SST. The eyewall sea-to-air heat transfer could take place mainly on the front right quadrant of the eyewall where the SST has yet to be cooled and where the rotational and translational velocities combine to produce the highest relative wind. So long as there is warm water below there are possibilities of a hurricane intensifying because the warm water can rise in large bubbles.

Hurricane MPI calculations are usually based on SST prior to the storm, DeMaria and Kaplan (1994) and Emanuel (1986). E-MPI is calculated from pre-storm SST; H-MPI is calculated from eyewall SST; TEE MPI is calculated from eyewall air temperature. In hurricane Isabel pre-strom SST was 29 °C while the eyewall SST and eyewall air temperature were 26 °C and 24.5 °C respectively. The TEE method is not predictive; its purpose is simply to show that wind speed and pressure reduction can be calculated from actual thermodynamic conditions.

The heat content of the sea at temperatures above 26 °C is known as ocean heat content (OHC), Shay et al. (2000). OHC in the Caribbean can be as high as 1.5 GJ m^{-2}, which corresponds to a 3.6 °C temperature change in a layer 100 m thick and which is enough to support a heat flux of 60,000 W m^{-2} for 6 hours. OHC plays a major role in hurricane intensity because the availability of warm water from below is essential to prevent eyewall SST from decreasing. Cold water has negative buoyancy and sinks; warm water has positive buoyancy and rises. In an indirect way *MPI is as dependent on OHC as on eyewall SST because OHC prevents SST from decreasing*.

Sea-to-air heat transfer in hurricane winds is difficult to measure and was recently the subject of an intense study by the Coupled Boundary Air-Sea transfer Experiment (CBLAST), Black et al. (2007). Heat transfer rates based the assumption that the ocean cooling is entirely due to surface cooling may be more correct than heat transfer rates based on measuring sea-to-air heat transfer under eyewall conditions with correlation type heat flux probes. 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. The major reason for this low sea-to-air heat transfer estimate seems to be that the interfacial heat transfer is believed to be incapable of transferring enough heat to account for the observed ocean cooling. Water colder than the overlying water has negative buoyancy and tends to stay down; hurricane winds are unlikely to be able to make negatively buoyant cold water initially 100 m below the sea surface rise.

Experience with direct contact wet cooling towers could be used to help understand heat transfer in hurricanes because both processes are isenthalpic mixing processes. In a wet cooling tower, warm water is sprayed in air and the droplets are repeatedly broken up on splash bars. Wet direct contact cooling towers are used because of their high heat transfer rates. A cooling tower with a thermal capacity of 1000 MW might have a diameter of 100 m; the heat transfer area could be 5000 m^2 (an annulus with an average circumference of 300 m and a width of 17 m) resulting in a heat transfer of 200,000 W m^{-2}. The heat transfer per unit area in wet cooling towers is of the same order of magnitude as in the eyewall of hurricanes. Heat transfer rate in cooling ponds is typically around 200 W m^{-2}. Spray is a very effective heat transfer mechanism; in a bathroom shower the temperature of the water at the floor level can be 10 °C lower than at the showerhead. Understanding the process responsible for the energy of hurricane is important because there may be a possibility of harnessing the process to provide clean and sustainable energy, Michaud and Michaud (2010) and Michaud and Renno (2011). Sea-to-air heat transfer in hurricanes is not as straightforward as implied by heating process 1-3 of Fig. 1 but looking at ideal processes can nonetheless help understand the hurricane process. Steady state case studies are useful for analyzing processes even when the process conditions are neither uniform nor at steady state.

A hurricane with a speed of 5 m s^{-1} requires approximately 6 h to cover a 100 km eyewall diameter. The hurricane cools the water by 3 °C to a depth of 100 m in 6 h. A hurricane can cool a 5 m thick layer of water by 3 °C in just 18 minutes. A spray flux of 5 kg m^{-2} s^{-1} would produce a 1 m layer of cooled water in 4 minutes. In the short term, spray causes eyewall air temperature and humidity to approach equilibrium with the underlying water. In the intermediate term, cooled re-entrant spray reduces sea surface temperature and limits hurricane intensity. In the longer term warm water from below rises from buoyancy and keeps the SST from falling below 26 or 27 °C.

Andreas and Emanuel (2001) estimated that re-entrant spray could increase sea-to-air heat transfer by 20% to 400% but not by two orders of magnitude. They assumed spray to be proportional the cube of wind speed; it could be much higher. Landsea (2005 Hurricane FAQ D7) estimated the total upward flux in a large hurricane at 600 TW from the quantity of precipitation produced and the mechanical energy produced at 1.5 TW from the energy required to overcome friction resulting in a heat to work conversion efficiency of 0.25%. Emanuel (1986) calculated a hurricane heat to work conversion of 33% from Carnot efficiency. Converting 33% of 600 TW would result in a mechanical energy production of 200 TW. The Emanuel efficiency is 132 times the Landsea efficiency; this is a huge discrepancy which needs to be resolved. Landsea and Emanuel may both have underestimated the total mechanical energy production: in the Landsea case because if not captured the work is dissipated as a result of unrestrained expansion; and in the Emanuel case because the quantity of spray was underestimated. Emanuel (2003) estimated the work dissipated in a hurricane at 3 TW. Renno (2008) general theory of convective storms estimated hurricane efficiency at 20%.

SST and OHC both increase during the summer because ordinary non-cyclonic convection is unable to carry away as much energy as is received from net radiation even with SST as high as 30 °C, see COMET (2006) section 3.7. Increasing SST and OHC increase the probability of hurricanes developing and of their becoming intense. Hurricane are far more effective than ordinary convection at carrying heat upward and once established can use heat from SST's as low as 26 °C; they play a vital role in carrying heat away from the ocean's surface. Hurricane eyewall heat flux of 100,000 W m^{-2} can be 1000 times larger than the normal oceanic heat flux of 100 W m^{-2}.

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. Hurricane sea-cooling is primarily due to cooling from above and not to mixing of cold water from below. Hurricane intensity is essentially dependent on the actual eyewall SST which in turn depends on OHC. Ideal steady state thermodynamics processes and case studies could provide a new basis for understanding hurricane intensity and sea-to-air heat fluxes.

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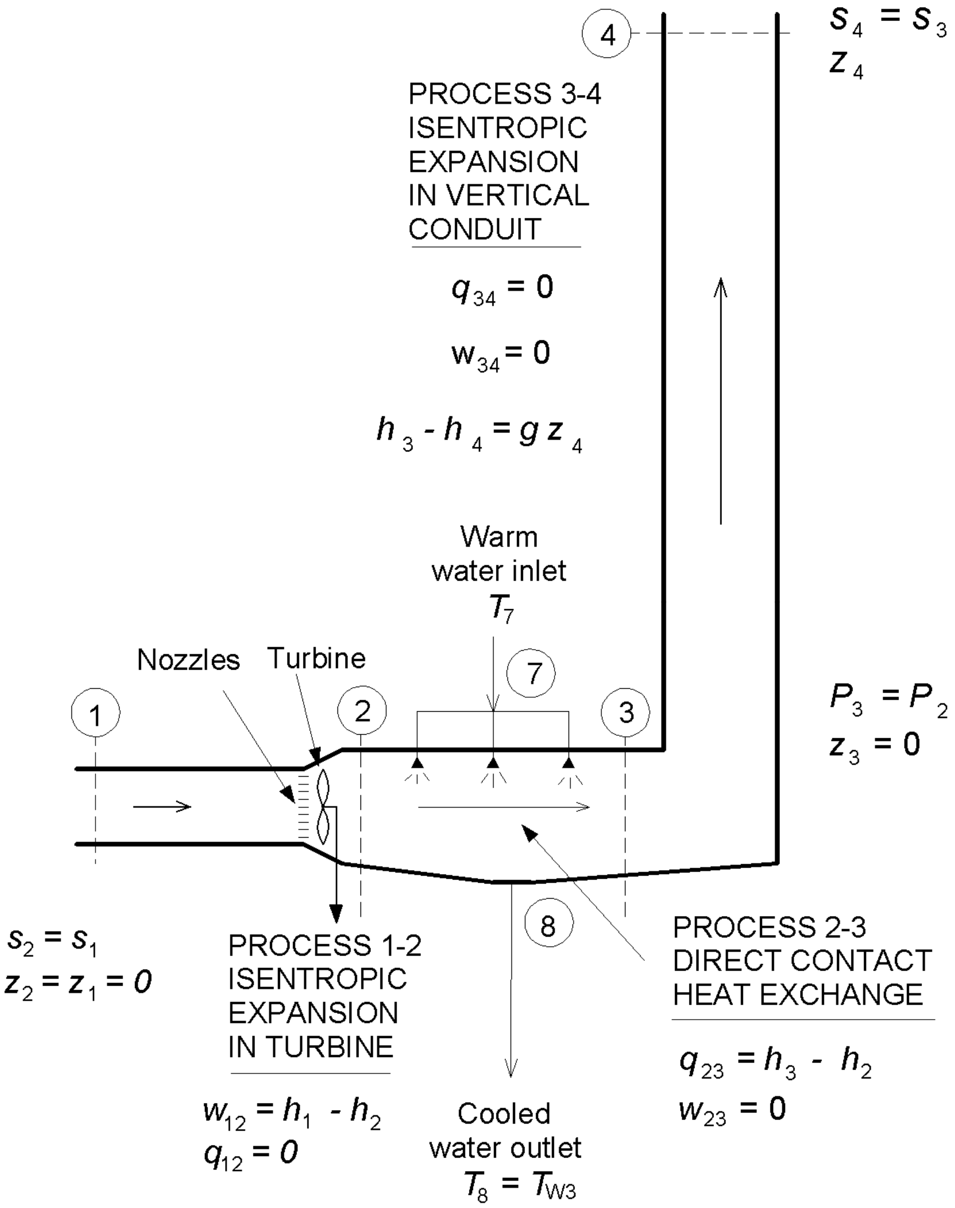

Fig. 1 Hurricane Steady-State Ideal Process

State 1 ambient surface air. State 2 air at reduced pressure prior to the mixing process. State 3 air at reduced pressure approaching equilibrium with SST after the mixing process. State 4 level of neutral buoyancy. Process 1-2 isentropic expansion in turbine. Process 2-3 isobaric-isenthalpic mixing. Process 3-4 isentropic expansion in upward flow conduit. State 7 water at eyewall SST. State 8 water at State 3 wet bulb temperature

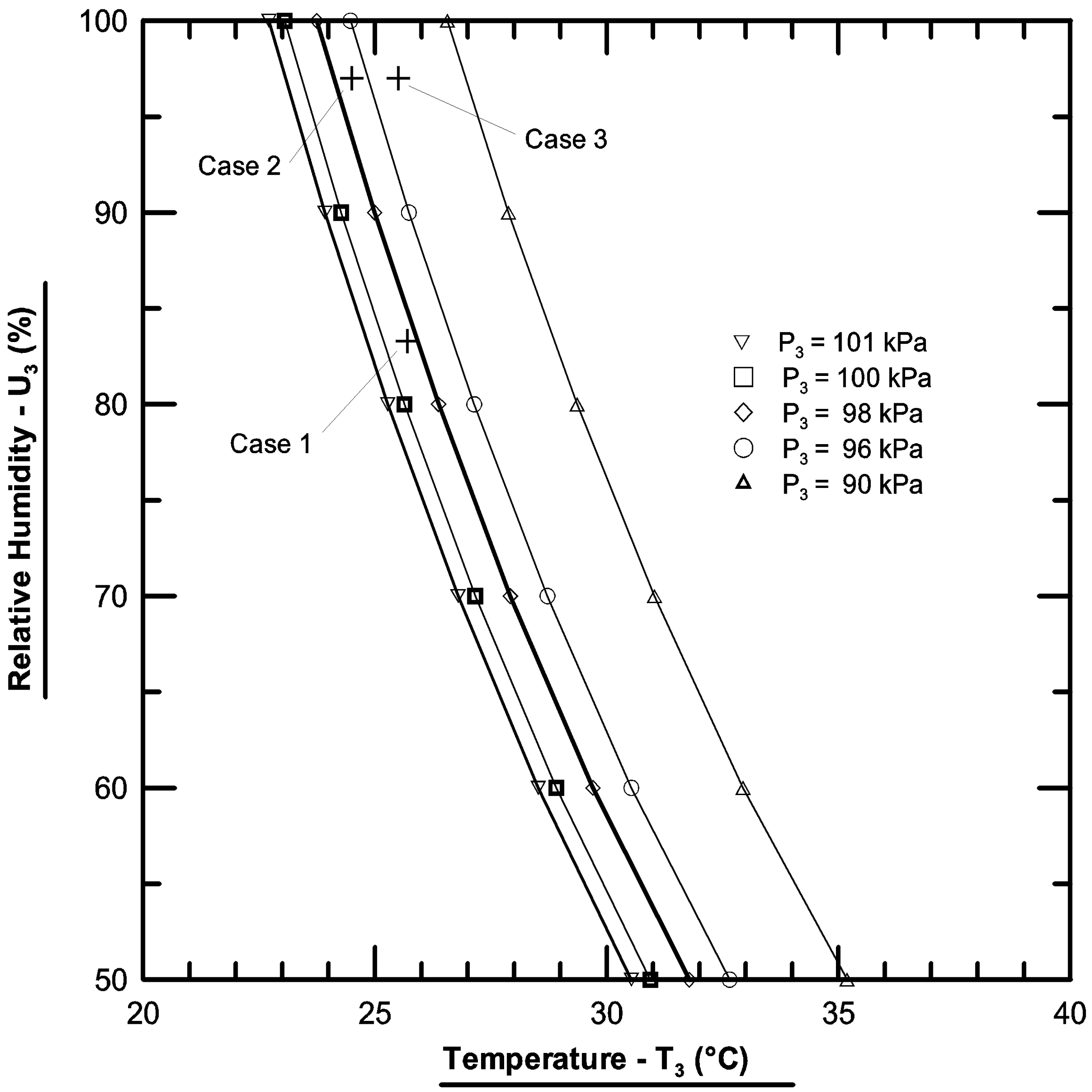

Fig. 2 Effect of eyewall temperature and relative humidity on eyewall pressure

Isobaric lines showing the combinations of state 3 temperature and relative humidity capable of producing a given surface pressure P_3. Based on true-adiabatic expansion with ice and P_4 = 12 kPa

Table 1 Hurricane intensity calculation based on hurricane Isabel data

Parameters: P pressure kPa, T temperature ℃, U relative humidity %, r mixing ratio g-water per kg-dry air, h enthalpy J kg^{-1}, s entropy J K^{-1} kg^{-1}, T_w wet bulb temperature ℃, W specific work J kg^{-1}, Q specific heat J kg^{-1}, v velocity m s^{-1}, n efficiency %, M water spray to air mass ratio kg-water per kg air.
Subscripts: “r” process 1-2 reversible and isentropic, “I” process 1-2 irreversible and isenthalpic.
Distant surface air properties: P_1 = 101.1 kPa, T_1 = 27.8 ℃, U_1 = 75%, $r_1 = r_2$ = 17.87 g kg^{-1},
h_1 = 73530 J kg^{-1}, $s_1 = s_2$ = 256.5 J K^{-1} kg^{-1}, T_{1w} = 24.4 ℃

Processes 1-4	**Case 1**	**Case 2**	**Case 3**
$P_2 = P_3$ (kPa)	98.63	**96.90**	**94.26**
T_2 (℃)	25.69	24.19	21.93
U_2 (%)	83.1	89.5	100.2
T_{2w} (℃)	23.5	22.9	21.9
h_2 (J kg^{-1})	71540	69780	67370
T_3 (℃)	25.69	**24.5**	**25.5**
U_3 (%)	83.1	**97**	**97**
$r_3 = r_4$ (g kg^{-1})	17.87	19.74	21.60
T_{3w} (℃)	23.5	24.1	25.1
h_3 (J kg^{-1})	71540	74870	80650
$s_3 = s_4$ (J K^{-1} kg^{-1})	256.5	273.7	301.3
P_4 (kPa)	12.0	12.0	12.0
T_4 (℃)	-74.22	-70.25	-64.21
z_4 (m)	15500	15500	15500
h_4 (J kg^{-1})	-83280	-80030	-74530
Base Pressure Reduction			
ΔP_{12} (kPa)	2.47	**4.20**	**6.84**
Work and Velocity			
$W_{12} = h_1 - h_2$ (J kg^{-1})	**2190**	**3750**	**6160**
$v = (2\ W_{12})^{0.5}$ (m s^{-1})	66.2	**85.8**	**109.8**
Efficiency			
$n\ (\%) = \Delta W_{12} / \Delta Q_{23r}$	n/a	30.6	29.4
$n\ (\%) = 1 - T_4 / T_3$	n/a	31.8	30.0
Sensitivity: Case 2 to 3			
$\Delta P_3/\Delta T_3$ = -2.64 kPa K^{-1}			
$\Delta W_{12}/\Delta T_3$ = 2410 J kg^{-1} K^{-1}			
$\Delta v/\Delta T_3$ = 24 m s^{-1} K^{-1}			
Mixing Processess 2-3 & 7-8			
T_7 (℃)	n/a	26	27
T_8 (℃)	n/a	24.1	25.1
Process 1-2 isentropic			
M_{7r} (kg-water kg-air^{-1})	n/a	0.62	1.64
$Q_{23r} = h_3 - h_2$ (J kg^{-1})	n/a	5090	13280
Process 1-2 isenthalpic			
$T_{2i} = T_1$ (℃)	n/a	27.8	27.8
M_{7i} (kg-water kg-air^{-1})	n/a	0.14	0.85
$Q_{23i} = h_3 - h_1$	n/a	1340	7120