Energy From Humid Air

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Abstract

The atmosphere is an engine wherein heat is converted to mechanical energy. It is heated from the bottom by solar radiation and cooled from above by infrared radiation to space. There is a potential for producing work because the work of expansion of warmed rising surface air is greater than the work of compression of descending cooled air.

Steady-state open and close thermodynamic processes are used to analyse the atmospheric heat to work conversion process. The *total energy equation approach* explains the energy of tornadoes and of hurricanes and is compatible with the more conventional convective available potential energy (CAPE) approach. The technique is illustrated using the Jordan mean hurricane season West Indies sounding.

The ideal work produced when oceanic tropical surface air is raised from the surface to the tropopause is typically 1000 to 3000 J/kg. Ideal work can be calculated from the initial and final conditions of raised air; there is no need to consider intermediate environmental conditions. The low frequency and small area coverage of deep convection is due to entrainment of dry ambient air in the updraft and to convective inhibition. In vortical flow, centrifugal force reduces entrainment.

Sea-spray is responsible for hurricane intensity and for the associated sea cooling. Heat is transferred from sea to air by spray. Spray drops are quickly cooled to the wet bulb temperature of the air. Approximately 99.5 % of the spray falls back in the sea at temperatures up to 5 °C colder than the sea surface temperature; thereby, transferring enormous quantities of heat from sea to air. Sea-spray produces saturated air whose temperature increases with the spray-to-air mass ratio. Ideal work increases with surface air wet bulb temperature by about 1100 J/kg °C. There is a potential for converting 25 % of heat added to humid surface air to mechanical energy. The contributions of sea-surface to air heat transfer and of upwelling of cold water are minor compared to that of spray.

The focus of the article is on the thermodynamics of the atmospheric process, on mechanical energy production. The conclusions are applicable to the atmosphere in its natural state and to processes for harnessing its energy such as the solar chimney and the atmospheric vortex engine (AVE). This article does not discuss AVE implementation, which have been done elsewhere, Michaud (1975, 1999). The article is based on atmospheric science and on engineering experience; references are not limited to the peer reviewed literature.

1. Introduction

The determination of efficiency is the fundamental problem of atmospheric energetics, Lorenz (1967). Estimates of atmospheric efficiency range from over 12 %, based on the Carnot efficiency for the average temperatures at which heat is received (290 K) and given up (255 K) to less than 1 % based on estimates of dissipation, on models, and on observations. Estimates of average per unit area atmospheric power production range from 1 to 10 W/m^2. Estimates of total atmospheric power production potential range from 600 to over 6000 TW. Human primary and electrical power productions are 30 and 3 TW, respectively 0.5 and 0.05 % of the upper 6000 TW estimate of the atmospheric potential.

The wide range of atmospheric efficiency is due the fact that actual efficiency can be much lower than ideal efficiency. The efficiency of early steam engines was much lower than their Carnot efficiency because, without appropriate mechanisms, work degrades to heat. The efficiency of an idling thermal engine is zero.

This article uses steady-state open thermodynamic processes and close thermodynamic cycles to show that the atmosphere has the potential to produce energy at the higher 12 % efficiency. The total energy equation approach widely used in engineering is verypowerful.

The divisor for efficiency is the upward convective heat flux at the bottom of the atmosphere of ≈50,000 TW (≈100 W/m^2) and not the incoming solar radiation of 178,000 TW; 6000 TW is 12 % of 50,000 TW and 3.4 % of 178,000 TW. Solar radiation reflected to space and heat carried upward by infrared radiation from the lower atmosphere to space do not contribute to work production because the heat is not carried upward by convection; there is no associated expansion-compression. .

A photovoltaic solar power plant requires a collector area of 200 km^2 to produce 2 GWe. Atmospheric work production can be concentrated in a small area. An atmospheric vortex engine (AVE) would have an area of less one square kilometer and produce 2 GWe, as much electrical energy as a large thermal power plant. AVE's could convert 25 % of low temperature heat to work. A tornado with vortex diameter of 300 m can produce ≈2 GW of mechanical energy. A large hurricane can produce ≈10 TW of mechanical energy, three times more than human produced electrical energy. Work production can be increased by increasing the enthalpy of the raised air with low temperature heat sources. Increasing enthalpy of the air by spraying it with warm water could produce mechanical energy from heat sources with temperatures as low as 25°C.

Section 2 shows that the mechanical energy produced when warm humid air is raised can be calculated from energy balance in a steady-state open thermodynamic system and that the energy can be transmitted to where the flow is restricted. Section 3 investigates the effect of surface air temperature and humidity on energy production and shows that the *incremental-efficiency*, the increase in mechanical energy production per unit of heat supplied, can be 25 to 30 %. Section 4 uses close cycles to show that the efficiency can be 12% of the total heat input. Section 4 also shows that energy is transferred upward and poleward mainly by work of compression. Section 5 shows that spraying surface water can increase specific work from 2000 to 10000 J/kg. Section 5 shows that sea-water spray is responsible for hurricane intensity and for the associated sea cooling. Section 6 shows that atmospheric energy production can be calculated with easy-to-use drag-and-drop engineering steady-state process simulators.

2. Steady-State single input single output system

The atmosphere can be viewed as an array of air reservoirs. Moving air from one reservoir to another can produce work. The source reservoir can be the lower atmosphere. The receiving reservoir, the environment to which the air is moved, can be the upper troposphere. The work is *free* in the sense that there is no need to provide costly high temperature heat. The work is produced from the pre-existing natural heat content of humid surface air.

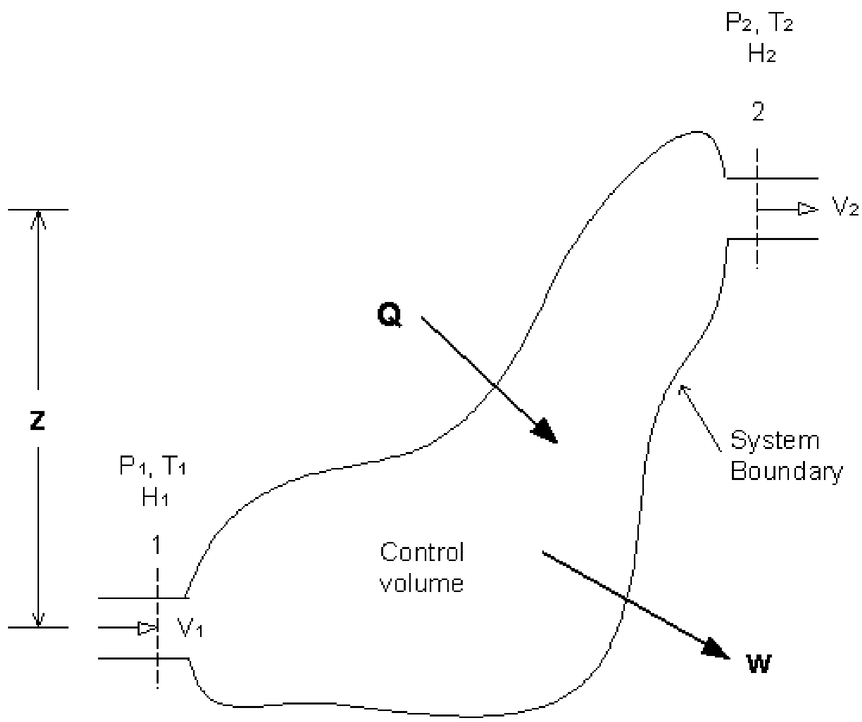


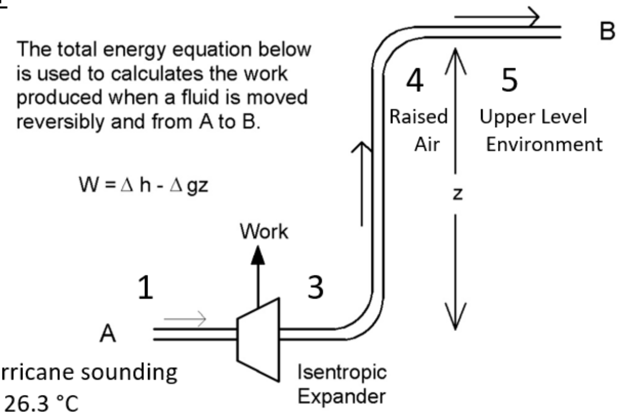
Figure.1 Energy balance for open continuous steady-state thermodynamic system,with one inlet and one exit.
Based on Smith and Van Ness Figure 2.6

Fig. 1 shows a thermodynamics system applicable to any open steady-state, continuous flow, single-input and single-output process. Conservation of energy requires that external energy inputs equal external energy output. The first law of thermodynamics, for an open, steady-state, continuous flow system is:

$$W = Q - \Delta H - \Delta gz - \frac{\Delta v^2}{2} \qquad (1)$$

where: *W* is the work leaving the system, *Q* is heat received, *H* is enthalpy, *g* is acceleration of gravity, z is height, and v is velocity. See Smith and Van Ness (2001) “Introduction to Chemical Engineering Thermodynamics” chapter 2, Eq. 2.32. The energy unit can be in Joules/kg-pure air; Joules/kg-substance; Watts per unit of flow; or Watts. This article energy uses Joules per kilogram of pure air including the energy of water content in any phase. Using a constant air mass of 1 kg of pure air simplifies calculations and facilitates case comparisons.

EXERGY vs EZERGY



Basis:
Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa, T_1 = 26.3 °C
U_1 = 84.03 %, M_1 =18.20 g/kg
True adiabatic with ice. s1 = s3 = s4 = 253.0 J/(K.kg). h1 = 72822 J/kg.
s_{15} = 226.1 J/(K.kg), h_{15} = - 76517 J/kg
$W_b = W_{13}$ = Turbine Work. W_p = PE of condensed water. $W_t = W_b + W_p$.

EZERGY / Total Energy Equation Method: $W_b = (h_1 - h_4) - (1 + M_1)\Delta gz$

P_4 (kPa)	P_3 (kPa)	z_4 (m)	Δh (J/kg)	Δgz (J/kg)	W_b (J/kg)	v (m/s)	W_p (J/kg)	W_t (J/kg)	ΔT_4 (K)
20	99.36	12400	125621	123736	1885	60.3	2186	4071	9.8
15	98.99	14182	143731	141516	**2215**	65.4	2525	4740	5.3
12.64	99.05	15292	153855	151692	**2163**	64.6	2710	**4873**	0.0

EXERGY / Gibbs Method: $A = (h_1 - h_5) - T_0 (s_4 - s_5) - (1+ M_1)\, gz$

P_4(kPa)	z_4(m)	Δh(J/kg)	$T_0\Delta s$(J/kg)	Δgz(J/kg)	A(J/kg)	W_p(J/kg)	W_t(J/kg)
20	12400	136272	10417	125117	2119	2204	4324
15	14182	149338	5535	141516	**2286**	2527	4813
12.64	15292	153862	6	149002	**2163**	2710	**4873**

@ 15 kpa: $A - W_b$ = 2286 – 2215 = 71 J/kg is the extra work produced by cooling the raised air from T_4 to T_0 with a reversible Carnot engine.
@ 12.64 kPa: at temperature equilibrium, $A - W_b$ = 2163 - 2163 = 0

Fig. 2 Ideal work for surface air raised to a range of levels.

Ideal work (W_b) for a reversible process with no heat transfer, with negligible velocities and with no degradation of work to heat by friction is:

$$E_z = W_b = -\Delta H - (1+m)\, g\, \Delta z = -\Delta\mu \qquad (2)$$

Q and Δv are zero for adiabatic ideal processes. μ is the moist static energy of the flowing air. This ideal work will be called ***ezergy*** (E_z) to highlight change in elevation (Δz). *Ezergy is equal to* *the decrease in enthalpy minus the increase in potential energy of the raised air*, and more concisely to decrease in the air's moist static energy. *Ezergy* is the maximum quantity of work that can be made available when an air mass is moved reversibly without heat transfer. *m* is the mixing ratio for water in any phase. In the atmosphere, *m* has a maximum value of about 0.03 kg-w/kg-air. W_b stands for work of buoyancy and is equal to E_z; the corresponding W_p stands for potential energy of condensed water and is not shown explicitly in (2) because it is included in the "(1 + *m*) *gΔz"* term. The contribution to enthalpy of the water content of the air in any phase is included in the *ΔH* term.

Figure 2 shows an example of an ideal open reversible adiabatic process moving air from the bottom to the top of the troposphere. Figure 2 is based on the Jordan (1958) mean West Indian hurricane-season sounding. Work degradation through friction and kinetic energy are negligible because velocity can be low in ideal processes. There is no heat transfer because the conduit is perfectly insulated. Work production requires an ideal, constant entropy expander or turbine with a shaft to get the mechanical energy out of the system.

The three cases of Figure 2 show the effect of final pressure on ideal work. *Ezergy* peaks at ≈2215 J/kg for surface air raised to the 15 kPa (14182 m) level. An adiabatic reversible process is a constant entropy (*S*) process. From known initial air conditions and final pressure, the final temperature for a constant entropy process can be calculated using a solver. Ezergy can then be calculated from the known initial and final enthalpy and the change in elevation. There is no need to consider density, buoyancy, potential, equivalent or virtual temperatures. Knowing three properties of a two components system at equilibrium permits calculation of all other properties.

Willard Gibbs showed that ideal work, which he called free energy, for a fluid brought reversibly to full equilibrium with a different environment with reversible heat transfer is:

$$A = -\Delta H - T_o\,\Delta s - g\Delta z \qquad (3)$$

See Smith and Van Ness (2001) Eq. 5.24 and 5.27. Gibbs free energy is now called *exergy for which* "*A*" is the standard symbol. T_o is the temperature of the final environment; Δ*H* is the difference between the enthalpy of the raised air in its initial state and of its enthalpy at the pressure and temperature of the final environment. In Figure 2, for surface air raised to the 15 kPa level, the *exergy* is 2286 J/kg. The *exergy* is slightly larger than the *ezergy* of 2215 J/kg because a Carnot engine producing a small amount of work could be used to bring the temperature of the raised air to the temperature of the final environment. The third, 12.64 kPa case, of Figure 2 shows that *exergy* and *ezergy* are identical for air raised to the level of temperature equilibrium, the level of neutral buoyancy (LNB), because there is no need to transfer heat via a Carnot engine to reach temperature equilibrium. The 15 kPa case shows that *ezergy* peaks at the 15 kPa level, at the 14180 m level.

Exergy is the maximum work that can be produced when a fluid is brought reversibly to full equilibrium with an environment. The name *exergy* was coined by Rant who realized the need for a name for this thermodynamic property, see appendix of Marquet (2014). There is no currently defined name for the ideal work of eq. (2) “where a fluid is brought reversibly to a different pressure, without heat transfer and without bringing the fluid to temperature equilibrium with the final environment.” Eq. (2) is widely used in engineering. There is a need for a name for this property; it is proposed that it be called *ezergy* (E_z) to indicate that there is a change in elevation (z) in accord with the Rant naming system. This article proposes names for additional kinds of free energy.

Ezergy is equal to reduction in enthalpy minus increase in potential energy. Ezergy is a function of the initial conditions (pressure, temperature, and mixing ratio), of the final pressure and of change in elevation.

For deep convection, the ezergy (E_z) of air raised to the 15 kPa level is a fair approximation of the *peak ezergy* (E_{zp}). Warm humid surface air has exergy and ezergy. *Ezergy* is more appropriate than *exergy* for atmospheric energy calculations because there is no practical way of producing work from small temperature differences, especially when the Carnot engine has to be located at the tropopause. For atmospheric problems, *exergy* is overkill.

To the flow of heat is due all motion including every form of atmospheric motion. Mechanical energy is more valuable than thermal energy. In ideal reversible processes, mechanical energy can be transformed from one form to another and be transferred from one place to another without loss. Mechanical energy can degrade to heat. In the atmosphere, the fraction of heat that can be converted back to mechanical energy is limited to less than 20 % by the second law of thermodynamics, by Carnot efficiency.

In a process without change in elevation, the $g\Delta z$ term in (3) is zero. Ezergy when there is no change in elevation will be called ***emergy*** (E_m), where the *“m”* indicates same (même) elevation. *The emergy of a gas turbine is simply its ideal work.* In figure 2, the *ezergy* of overall process 1-4 (E_z) is equal to the *emergy of turbine process 1-3* (E_m). The ezergy of upflow process 3-4 is zero, which is akin to Emanuel (2017) statement: “The upward flow above the boundary layer is always neutral to slantwise moist convection”. The present conservation of energy calculation technique will be called the ***ezergy approach*** because there is no ezergy change in the upflow process. The work is transferred to the preceding constant elevation process where it either leaves the system as shaft work or degrades to heat.

For given inlet and outlet conditions, ezergy is the same for all reversible adiabatic processes. There are many possible lifting processes; the process could be a batch discontinuous process rather than a continuous one; the conduit could have a snaky or spiral shape. The conduit could have an expanding cone shape making exit velocity negligible. The conduit need not be vertical and can have a gradual slope because horizontal distance does not matter in a frictionless ideal process.

In an ideal process, there must be an isentropic expander or turbine to get the work out of the system. The ezergy is produced by the expanding air and is captured by the turbine where the flow is restricted wherefrom it leaves the system as shaft work. There is no need for the diagram of figure 2. All that is required to calculate ezergy is to know the initial and final conditions. Ezergy can be calculated from pure thermodynamics; drawing showing the limits of the thermodynamic system are useful but are not essential. *Ezergy is simply the maximum quantity of mechanical energy that can be produced when a fluid is moved from one location to another without heat transfer.*

Actual work, W_a , for an irreversible adiabatic process is less than ezergy because ezergy easily degrades to heat. For the same initial and final conditions, the enthalpy reduction is smaller for an irreversible than for a reversible process. In a fully irreversible process actual work, $W_a = 0$ and $\Delta H = g\Delta z$; all the work degrades to enthalpy. The process of Figure 2 can be made irreversible by replacing the turbine with one or more restrictions. Actual work (W_a) is less than ezergy (E_z) in irreversible processes or in processes with significant exit kinetic energy.

Ezergy is akin to Convective Available Potential Energy (CAPE). With CAPE, upward acceleration depends on the difference in density between the rising air and the surrounding air; this density difference changes with elevation. With CAPE, the kinetic energy of the air increases as it rises. With ezergy, the mechanical energy is produced wherever the flow is restricted. CAPE is based on Newton's laws, on the Archimedes (260 BC) buoyancy principle. *Ezergy* is based on conservation of energy, on the first law thermodynamics, Clausius (1850).

There are many flavors of CAPE: CAPE-500 based on average properties of bottom 500 m of the atmosphere; surface CAPE (SCAPE); 2-m CAPE; and 10-m CAPE. CAPE-500 is the default and is usually smaller than SCAPE. CAPE calculations can be based on actual or virtual air temperature. There are various methods of calculating the expansion temperatures used to calculate CAPE, Holland (1997), and Bechtold (2019). CAPE calculations start at the level of free convection (LFC) and terminate at the level of neutral buoyancy (LNB). Ezergy calculations can start and finish at any elevation; the default is from the earth's surface to the LNB. Ezergy includes CAPE and Convective Inhibition (CIN). CIN is negative and typically between 0 and -100 J/kg. For expansion without separation of condensed water, ezergy is the algebraic sum of CAPE and CIN, E_z = CAPE + CIN. E_z is slightly less than CAPE because CIN is negative.

Ezergy and CAPE both assume that there is no dilution of the rising air by surrounding ambient air and no friction. Deep convection (>10 km) is rare; shallow convection (<3 km) is ubiquitous. Deep convection requires that evaporative cooling be reduced by centrifugal force or by high humidity aloft. Shallow updrafts increase humidity aloft eventually making the environment more favorable for deep convection. Evaporative cooling associated with entrainment reduces buoyancy, Michaud (1998), Bechtold (2019).

Exergy is produced when warm/humid air is raised. In steady-state conduit flow, the shaft work is produced wherever in the conduit the isentropic turbine is located. In a conduit, work is transferred from where it is produced to where the flow is restricted. Figure 2 shows that the work can be transferred to a horizontal turbine located at grade. The horizontal conduit at the bottom of Figure 2 could be several thousand kilometers long because there is no friction loss in an ideal process and no heat transfer. The turbine could be located at the upstream end of this conduit. The point where the shaft work is produced could be several thousand kilometers away from where the upflow and most of the expansion occur. Ezergy can produce a velocity of $\sqrt{2E_z}$ throughout the length of the conduit. An ezergy of 2500 J/kg corresponds to a force 4 hurricane velocity of 70 m/s. The kinetic energy can be the exit velocity or can be partly extracted with expanders located anywhere in the conduit.

In a continuous process, the ezergy of the raised air is determined by the pressure and elevation of the final reservoir. The density of the environment does not matter except for its effect on the final elevation. CAPE calculations must consider the density at every level. Ezergy calculation only need to consider the pressure and elevation of the final position. The ezergy approach is far simpler than CAPE. The ezergy approach calculates work directly; the CAPE approach requires integrating the buoyancy area.

The effect of subsidence warming on final elevation is negligible because the downflow takes place far from the upflow locations. The passage of a large hurricanes has little effect on the geopotential height of the 15 kPa pressure level in the hurricane formation areas. The effect of change in the level of the final elevation is small compared to that of surface air temperature or humidity.

Ezergy is real work, it can produce shaft work or kinetic energy; it can produce vertical or horizontal velocity; it can increase potential energy; and it can produce electricity which can be transmitted anywhere.

Computational fluid dynamics models (CFD) have difficulty arriving at the conclusion that work of convection can be concentrated and captured at a remote location. CFD calculates the flow, which is very difficult since there are many possible paths. Thermodynamics specifies the flow and calculates the maximum work. Atmospheric efficiency is an oxymoron because, in the atmosphere, there is no shaft through which work can leave the system. Since there is no way for work to leave the system, all the work eventually reverts to heat. Atmospheric energy calculations do not show the expander because there is none in the atmosphere. The expansion cannot be isentropic without a way of getting the work out of the system.

Mechanical energy can be converted reversibly from one form to another. It can degrade to heat due to viscous friction, mixing or because there is nothing to push against like in an unrestrained piston. Actual energy (W_a) production is difficult to calculate because most of the ezergy degrades back to heat without producing significant kinetic energy. Zipser and LeMone (1980) show that the kinetic energy of strong GATE updraft is typically less than 4% of CAPE.

Enthalpies and entropies values are based on Dufour and Van Mieghem: "Thermodynamique de l'Atmosphère". The zero for enthalpy (H) and entropy (S) is 0 °C and 100 kPa for air and liquid water at 0 °C. A 20 °C freezing band is used to avoid having a discontinuity at the freezing point. The condensed water starts to freeze at 0 °C and is 50 % liquid at -10 °C. The freezing band has no effect on ezergy when the final air temperatures is under -20 °C, at which point the condensed water is all in the ice phase.

Michaud (HP48) provides a link to the HP48 calculator atmospheric thermodynamics program AT1 used for the calculations of this article. The program is available at the vortexengine.ca web site and is a invaluable tool. HP48 calculator emulators are available for most computers and smart phones are widely available and are free.

Ezergy calculations are based on expansion without separation and with freezing of the condensed water. Williams and Renno (1993), WR (1993) hereafter, recommended that CAPE be calculated based on no separation and freezing. Expansion with immediate separation is at time called irreversible or pseudo-adiabatic. In this article irreversible relates to mechanical energy degradation in the thermodynamic sense and not to separation. Molinari (2012) avoided the name pseudo-adiabatic; all three WR (1993) processes are reversible constant entropy processes.

WR(1993) and Molinari (2012) shows that CAPE for expansion with no separation and freezing is almost identical to CAPE for expansion with immediate separation and without freezing. Latent heat of fusion more than offsets the negative-buoyancy contribution due to condensed water loading. WR (1993) state that while it may be unrealistic to carry condensed water to the upper troposphere, is even more unrealistic to prevent the water from freezing. In addition, the absence of separation keeps the composition constant making eq (2) and steady-state open system techniques applicable. The cumulative potential energy of the condensed water is smaller with separation.

The enthalpy (*H*) of moist air is the sum of the enthalpy of one kilogram of pure air plus the enthalpy of its water content in any phase. In Figure 2, 1 kg of dry air contains 1.0182 kg of substance because the mixing ratio is 18.2 g-water/kg-air. The potential energy term is multiplied by (1 + *m*) = 1.0182 where *m* is the mixing ratio in kg-water/kg-air. The ezergy is 2215 Joules per 1.0182 kg of substance or per kilogram of pure air plus its water content. The ezergy per kilogram of substance is 2215/1.0182 = 2175 J/kg of substance. Both values correspond to a velocity of 66 m/s.

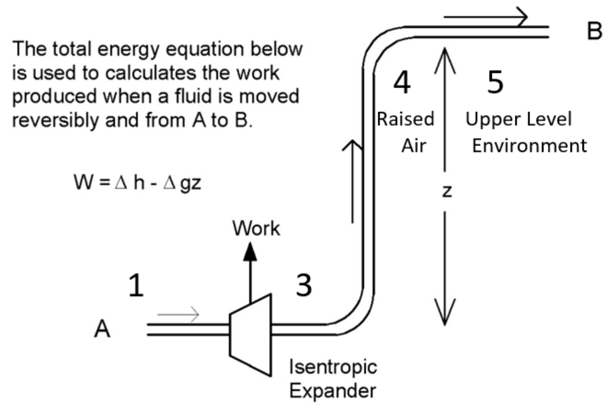
The enthalpy of the 85 % relative humidity air at the base of the Jordan sounding is 72,820 J/kg; the enthalpy of pure air at the same pressure is 26,420 J/kg. The contribution of water vapor to enthalpy is 46,400 J/kg. Water vapor contributes 1.82 % of the mass content and 63.7 % of the heat content! The enthalpy of pure air at 15°C is 15,070 J/kg. Taking the temperature base as 15°C, water vapor could contribute 80 % of the upward heat transport. The vapor content must condense to contribute to the upward heat transport; latent heat is only released above the lifting condensation level (LCL). The temperature of rising air decreases by ≈9.8°C/km and by ≈4°C/km below and above the LCL respectively. At lapse rate of 6.5°C/km, rising air loses buoyancy below the LCL and gains buoyancy above the LCL.

Per unit mass calculations permit case comparison. Ezergy is independent of time and velocity. Ideal power is specific ezergy multiplied by flow in kilogram per second. A standard flow of 10000 kg-air/s will be used to provide an appreciation of the power production potential.
A small tornado with a 30 m base diameter could have an upward flow of 10000 kg/s (10 t/s). At this standard flow, an ezergy of 2215 J/kg correspond to a power output of ≈22 MW. Flow increases with the square of diameter. Power potential is proportional to ezergy and to the square of vortex base diameter. A 300 m diameter tornado could have an upward flow of 1000 t/s and produce ≈2.2 GW of mechanical energy.

Friction losses are much higher for non-continuous cumulus batch flow than for continuous flow. For the same continuous flow friction losses are inversely proportional to the fourth power of conduit diameter for laminar flow and to the fifth power of conduit diameter for turbulent flow. Friction losses for the above standard flow of 10 t/s could be 20 MW for batch flow, 2 MW for turbulent flow in a tube or chimney and 0.1 MW for laminar flow in a vortex. Shear is much higher in turbulent flow than in laminar flow. Friction losses in the tuba of a tornado are a small fraction of *ezergy*.

3. Effect of surface air temperature and humidity – Tornadoes and dust devils

Fig. 3 and 4 show the effect of surface air temperature and humidity on ezergy. Increasing surface air temperature by 1°C, at constant mixing ratio, increases ezergy by 316 J/kg. Increasing surface air mixing ratio by 1 g/kg, at constant temperature, increases ezergy by 695 J/kg. Increasing surface air temperature by 1°C, at constant relative humidity, increases ezergy by 1044 J/kg. The incremental efficiency (IE), the ezergy increment divided by the heat supplied, ranges from 27.2 to 30.5 %. IE is slightly higher for sensible heat addition than for latent heat addition because there is no need to raise additional water.



Basis:
Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa,
P_4 = 15 kPa, Z_4 = 14,182 m
True adiabatic with ice.
$W_b = W_{13}$ = Turbine Work (Ezergy).

Total Energy Equation Method: $W_b = (h_1 - h_4) - (1 + M_1)\Delta gz$

Reversible								Irreversible	
T_1 (K)	U_1(%)	M_1(g/kg)	W_b(J/kg)	$\Delta W_b/\Delta x$	H_1 (J/kg)	ΔH_1 (J/kg)	RZ (%)	W_i(J/kg)	RI(%)
27	75	16.95	1564	Base	70361	Base	Base	2232	Base
28	70.6	16.95	1880	316 J/K	71397	1026	30.5	2679	43.6
27	79.4	17.95	2259	695 J/g	72912	2551	27.2	3183	37.3
28	75	18.01	2608	1044 J/K	74100	3739	27.9	3667	38.4

Carnot Efficiency = 1 – (T_4/T_1) = 1 – (209/301) = 30.5 %.

Figure 3. Effect of increasing surface air temperature and humidity on ezergy and on efficiency.

WR (1993) showed that CAPE increases by about 1000 J/kg per degree Celsius increase in surface air wet bulb temperature. They showed that CAPE values in the order of 1000 J/kg are present over large area of the tropics. Despite this wide availability of CAPE, deep convection only occurs a relatively small area. The mean convection area is only 7 % of the high CAPE area. They asked: "Why is the convection area such a small fraction of conditionally unstable area?" They suggested that CIN and mixing of dry ambient air in the rising updraft may be inhibiting convection. Michaud (1998) and Bechtold (2019) showed that entrainment of dry ambient air drastically reduces buoyancy.

Converting 30 % of heat received at a temperature of 30°C to work would be a feat for any engine. Conventional thermal engines typically require temperatures differences of at least 300°C. Thermosyphons are an exception and can produce intense circulation from a small temperature difference. Coffee percolators perform work by raising water from a small temperature difference; without the upflow tube the work degrades to heat.

The reason for the ability to produce work from small temperature differences is that a small reduction in density is enough to render a fluid buoyant and to make it rise. The reason for the high incremental efficiency is that the air previously received heat through natural processes as will be shown in the close cycle analysis in the next section.

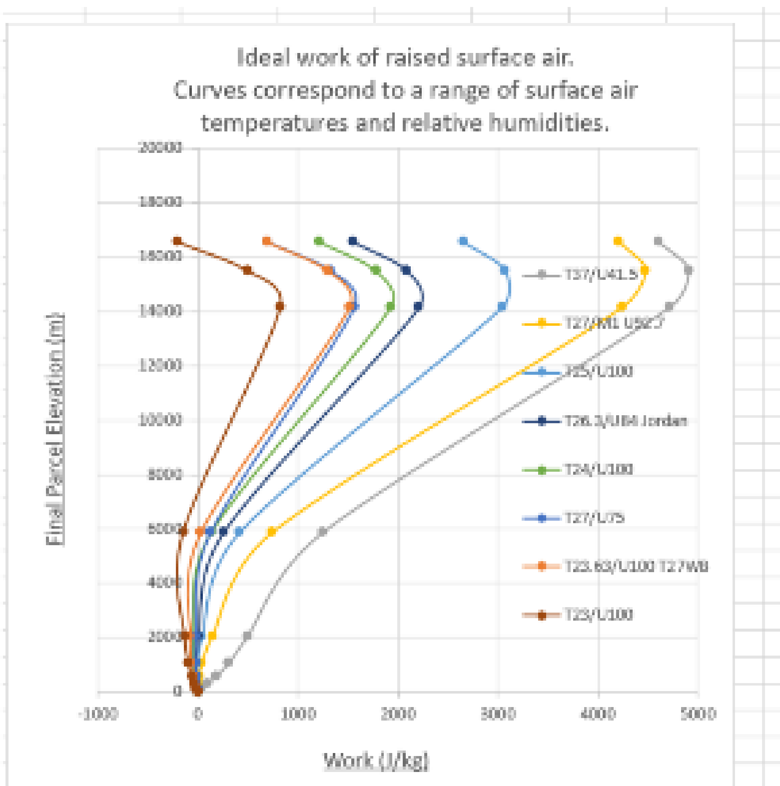


Fig.4 Effect of surface air temperature and humidity on ezergy. Based on Jordan hurricane-season sounding.

The previous calculations are for a reversible process where the work leaves the system. In a fully irreversible process, dissipated work is greater than the exergy because the dissipated energy becomes heat which produces additional work. In the second case of Figure 3, the reversible exergy and irreversible dissipated work are 1880 and 2679 J/kg respectively. Dissipation increases work production by 42 %. The pressures at the base of the updraft decreases by 0.9 kPa from 99.38 to 98.48 kPa. The work dissipated (E_i) in an irreversible process will be called ***inergy*** (E_i) where (*i*) stands for irreversible.

Fig. 4 shows the effect of surface air temperature and humidity on ezergy and on peak ezergy level. The ezergy maximum occurs close to the 15 kPa (14.2 km) level in every case. In the 27°C case reducing the relative humidity from 75 % to 64 % would reduce exergy from 1564 J/kg to zero.

There is a negative ezergy minimum, an *ezergy neap* (E_{zn}), at low level corresponding to CIN. In oceanic tropical areas, CIN and E_{zn} values are usually between 0 and -40 J/kg, WR (1993). Surface air can be in a metastable state and may have to be raised several kilometers to produce significant positive ezergy. In the 27°C, 75% relative humidity case, ezergy neap is -28 and 0 J/kg for air raised to the 85 and 70 kPa level respectively. The temperature of the air could be reduced to its wet bulb temperature of 23.63°C by spraying 1.4 grams of water per kilogram of air. The *ezergy neap* (E_{zn}) of saturated air at a wet bulb temperature of 23.63°C is -78 and 0 J/kg for air raised to the 81 and 54 kPa level respectively; E_{zn} absolute value increases by a factor of 2.8. In comparison, the *ezergy peak* (E_{zp}) decreases from 1565 to 1520 J/kg by 3%.

Ezergy equation (2) is applicable to any mass of fluid including all components in any phase. In figure 3, the mass of dry air is 1 kg in all three cases, the mass of water is 16.95 g in case 1 and 18.01 g in case 4. The ezergy equation is valid for ascending or descending air. For the Jordan sounding, lowering a kilogram of ambient air from the 15 kPa level adiabatically to the surface has an ezergy of -11100 J/kg. Lowering upper troposphere air requires rather than produces energy, because the work of compression is greater than the decrease in potential energy. CAPE and CIN apply to moving air from one specific position to another. *Ezergy* (E_z) is more generic and is applicable to moving air from any place to any other place, usually from the surface to the LNB and includes CIN. CAPE is the work produced when surface air is raised from the level of free convection (LFC) to the level of neutral buoyancy (LNB) and does not include CIN.

Ezergy is transferred downward to overcome resistance to flow wherever it occurs in the conduit, including raising surface air up to the level where it becomes buoyant. A temporary heat source or other disturbance may be required to overcome the metastable state and to start the flow. Starting the upward flow is akin to starting a syphon or a thermosyphon.

Fig. 5 shows the effect of initial pressure or elevation on ezergy. Ezergy decreases rapidly with source air level. The ezergy of air initially at the 95 kPa level is about half of that of surface air. The ezergy of air initially at 90 kPa is close to zero. Ezergy decreases rapidly with initial elevation because mixing ratio decreases with elevation. The relative humidity of maritime tropical air can be 85 % and 60 % at the sea surface and at the 3 km level respectively. The corresponding mixing ratio can be 17 and 6 g-water/kg-air. Mixing ratio and ezergy both decrease rapidly with initial elevation. WR (1993) showed that CAPE decreases by 150 to 250 J/kg per 100 m increase of initial elevation. The layer of high ezergy surface air is thin.

Raising high enthalpy surface air is the main atmospheric work production process; this should not be surprising since the atmosphere is heated from below and cooled from above. The energy of tornadoes is often attributed to descent from above. Figure 5 shows that such an attribution must be incorrect; lowering upper troposphere air does not produce energy, it requires energy. Cooling of the upper troposphere air by precipitation can produce intense downdrafts but prior updrafts are required to produce the condensed water. In an atmospheric vortex engine, a short tower helps prevent the base of a vortex from drifting away from a vortex engine since the ezergy of ambient air at the top of the stack is less than the ezergy of surface air.

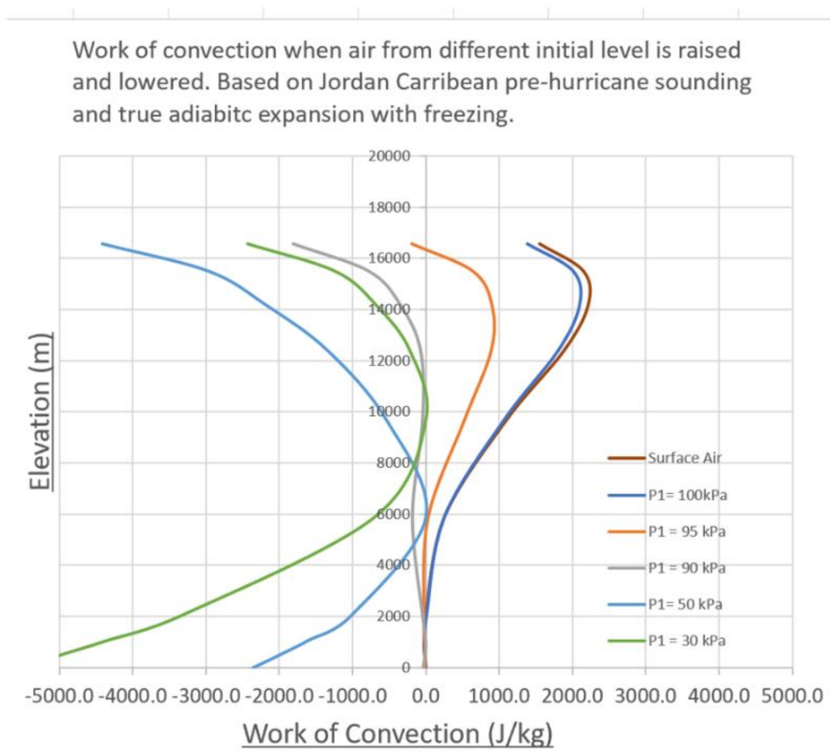


Fig. 5 Effect initial air level of on ezergy.

The ezergy of air initially above the 2 km level is negative whether the air is raised or lowered. Moving mid or upper troposphere air either up or down *requires rather than produces* energy. As a result, the upper troposphere is stable. There is little turbulence outside the updraft areas which are much smaller than the surrounding downdraft area. In the upper troposphere, friction losses associated with horizontal flow are small because stability suppresses turbulence.

Fig. 6 shows a continuous process wherein surface air is raised in a vortex or in an expanding spiral. Internal kinetic energy can be large without violating conservation of energy provided the kinetic energy is recovered so that the air leaves the system at low exit velocity. The high internal velocity provides centrifugal force and prevents the higher external pressure from driving the ambient air into the lower pressure air rising in the high velocity vortex annulus thereby suppressing mixing, turbulence, and frictional losses.

In a vortex, ezergy production takes place in an annulus of rising air near the radius of maximum tangential wind. The work is produced by the expansion of the air rising in the annulus. Ezergy equation (2) applies to the air in the rising annulus. The kinetic energy of the vortex is provided by air rising in the annulus and not by the original angular momentum of the rising air. The intensity of the vortex is partly attributable to centrifugal force in the annulus preventing the rising air from being diluted by surrounding ambient air. The initial rotation is not the energy source. Conservation of angular momentum requires that the tangential velocity increase as the air converges into the vortex base. Surface friction reduces angular momentum and centrifugal force permitting convergence in the thin surface layer.

The core of the vortex is dragged in solid rotation by friction. Some of the mechanical energy is transferred to the core by friction. The core plays no role in energy production. The effect is the same as if some of the work produced by the turbine were used to drive a vertical axis pump impeller located in the base of an open bottom chimney. Pulling down air from the troposphere would require ≈11000 J/kg, forced core rotation can not produce more than ≈5000 J/kg. The pressure reduction produced by the rotating core can pull down air from the upper troposphere by a few kilometers but is insufficient to produce significant downward flow on the axis of the vortex. Downward flow in the core would *require rather than produce* mechanical energy. Downward velocity in the core is insignificant compared to upward velocity in the rising annulus.

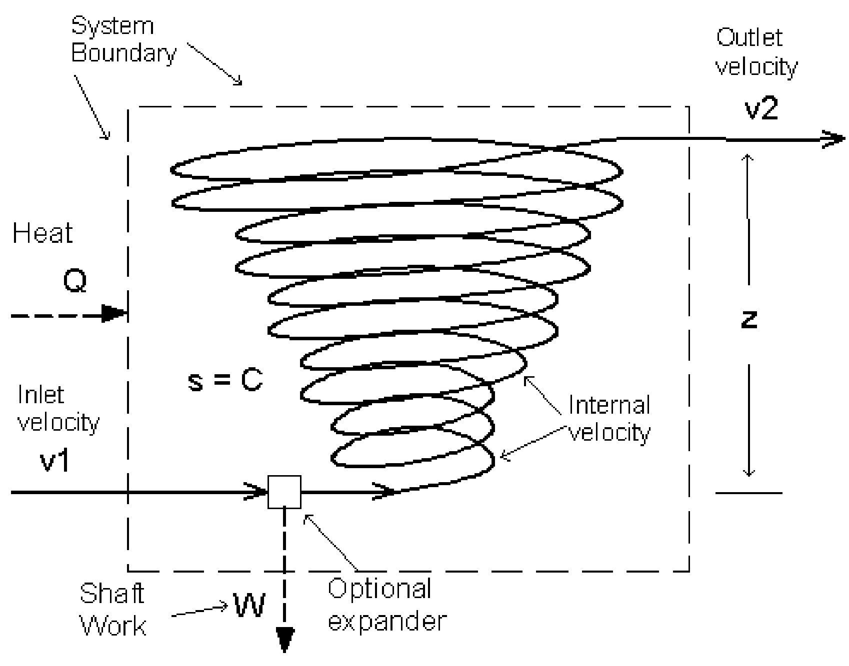


Figure 6. Continuous flow system with a spiral path. High internal velocities do not affect the energy balance which only depends on external energy flows.

Margules (1903) used closed thermodynamic systems and showed that available energy is equal to reduction in total system enthalpy. Open thermodynamic systems were not widely used before Heike Onnes coined the name enthalpy in 1909. Bounded steady-state continuous processes can be used to understand unbounded non-steady state processes because, for the same process conditions, ezergy is the same for all reversible processes.

Lorenz (1977) expanded the on the Margules system; he defined available energy as the difference between the actual enthalpy of the atmosphere and the enthalpy of a reference state. The reference state is the minimum total enthalpy that could be achieved by rearranging the mass via reversible adiabatic processes. The Lorenz reference state method is valid for dry air but not for moist air. Heating the atmosphere from below and cooling the atmosphere from above increase available energy. Convection decreases available energy. The reference state is not reached so long as the ezergy of moving any air mass from one place to another is positive. The total enthalpy of the atmosphere goes up and down but is always far away from a reference state. The atmosphere never comes close to the reference state.

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Initial Surface Air Conditions			Work Potential - Reversible			
Temperature T_1 (°C)	Mixing Ratio M_1 (g-w/kg-air)	Relative Humidity U_1 (%)	Ezergy E_z (J/kg)	Potential Velocity (m/s)	Updraft Base Pressure P_3 (kPa)	Central Pressure (kPa) ΔP 30 % **
26.3	18.2	84.0	2215	65	99.0	97.9
29.4	18.2	68.9	**3033**	77	**98.1**	96.7
35	18.2	49.5	4762	97	96.3	94.1
35	22.0	60.5	7163	117	93.8	90.5
35 *	22.0	60.5	7985	125	92.9	89.3
45	18.0	27.7	7855	124	93.3	89.8
45	22.0	34.0	10001	140	91.2	86.7

Table 1a. Effect of initial air condition on Ezergy for reversible process. Based on Jordan pre-hurricane sounding. Initial pressure 101.51 kPa. Initial elevation, sea level, 0 m.
Final pressure and elevation 15 kPa and 14182 m.
* Final pressure and elevation 10 kPa and 16577 m case.
** based on updraft to center ΔP 30 % of overall ΔP.

Initial Surface Air Conditions			Work Potential – Irreversible			
Temperature T_1 (°C)	Mixing Ratio M_1 (g-w/kg-air)	Relative Humidity U_1 (%)	Inergy E, (J/kg)	Potential Velocity (m/s)	Updraft base Pressure P_3 (kPa)	Central Pressure (kPa) ΔP 30% **
26.3	18.2	84.0	**3114**	78	**98.0**	96.5
35	18.2	49.5	6641	114	94.3	91.2
35	22.0	60.5	9541	137	91.3	87.0
35 *	22.0	60.5	11760	152	89.1	83.7
45	18.0	27.7	10843	146	90.3	85.5
45	22.0	34.0	13247	161	88.0	82.2

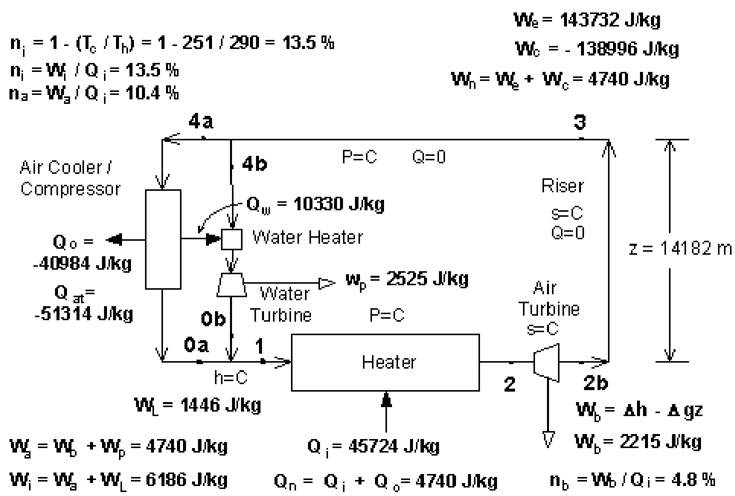
Table 1b. Effect of initial air condition on Ezergy. Irreversible expansion. Based on Jordan Pre-hurricane sounding. Initial pressure 101.51 kPa. Initial elevation, sea level, 0 m.
Final pressure and elevation 15 kPa and 14182 m.
* Final pressure and elevation 10 kPa and 16577 m case.
** based on updraft to center ΔP 30 % of overall ΔP.

There have been numerous articles expanding on the reference state concept. Several papers have pointed out that CAPE is unable to account for observed tornado wind speeds of up to 130 m/s. Lilly (1969) suggested that downward core flow could play a role in tornado pressure reduction. Snow and Pauley (1984) concluded that the thermodynamic method is not physically sound because it could not produce tornado velocities. Randall and Wang (1990) showed that, if the subsidence is local, the available energy is too small to explain observed tornado energy.

Tables 1a and 1b show the effect of surface air temperature and humidity on exergy and potential velocity for reversible and irreversible ascent. Potential velocities of greater than 130 m/s can be produced by raising 45 °C and 35 °C air in the reversible and irreversible cases respectively. Surface air temperatures can be over 35 °C; there is no need for axial downflow to explain axial pressure reduction. Ground temperatures in dust devil and tornado area can be over 50 °C. Heat transferred from dust to air can increase air temperature.
Bister and Emanuel (1998) showed that Irreversibility increases potential intensity. Dissipating the exergy of 3114 J/kg, first line of Table 1b increases the air temperature by 3.1 °C has approximately the same effect as raising the temperature in lines 1 and 2 of Table 1a by 3,1 °C, 3033 J/kg.

4. Close cycle

Close reversible cycles, widely used to calculate the efficiency of thermal engines, have rarely been applied to the atmosphere, Michaud (2000). Efficiency cannot be calculated for the open process of Fig. 2 and 3 because the cycle is incomplete, there is no heat input. Engine efficiency calculations require closed cycles wherein the same working fluid goes thru a complete close cycle such as shown in Figure 7.



State	P (kPa)	T (°C)	r (g/kg)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	101.51	8.89	18.20	95.56	27098	0	27098
2	101.51	26.30	18.20	253.01	72822	0	72822
2b	98.99	24.17	18.20	253.01	70607	0	70607
3	15.00	-62.27	18.20	253.01	-70910	141516	70607
4a	15.00	-62.27	0.03	254.99	-62489	138991	76502
0a	101.51	25.00	0.03	84.04	25193	0	25193
4b	15.00	-62.27	18.17	-32.02	-8427	2525	-5902
0b	101.51	25.00	18.17	6.67	1903	0	1903

Figure 7. Close, reversible, atmospheric cycle
Adiabatic expansion with freezing.
No separation during ascent
Lapse rate of 6.153 °C/km

The conditions in process 2-3 of the close cycle of Figure 7 are the same as in the 15 kPa case of open system of Figure 2. The air and condensed water separate at point 4. During their separate descents, the air is cooled, and the water is heated so that they both arrive at the surface at 25 °C. The descending air is cooled in a reversible polytropic process by radiation to space and by heat transfer to the descending water. There is no evaporation during the descent; the air and water follow separate paths to permit thermodynamic analysis.
The only unavoidable loss is mixing process 0-1. The temperature decreases from 25 °C to 8.89 °C in isenthalpic mixing process 0-1, during which a small part of the water evaporates. There is an increase in entropy and an unavoidable work loss in mixing process 0-1; the work loss (W_L) equal to $T\Delta s$ is 1446 J/kg. In the real atmosphere, where the moisture can be provided by mixing of ambient air with shallow updrafts, the work loss (W_L) could be smaller. In the ideal

cycle of figure 7, heating process 1-2 is reversible; the air and the water are in equilibrium; the heat source is at a temperature just slightly higher than the temperature of the saturated air water mixture. In the real atmosphere where the heat source is significantly warmer than the air, the heating process is irreversible. The cycle of Figure 7 is not identical to the atmospheric process; the cycle is analysed to arrive at thermodynamic understandings applicable to the atmosphere.

"*Overall Work*" (6186 J/kg) is defined as the sum of: air-turbine work (W_b = 2215 J/kg), water-turbine work (W_p = 2525 J/kg) and loss work (W_L = 1446 J/kg). "*Overall Efficiency*" is overall work divided by the heat received 13.5 % (=6186/45724). Overall Efficiency is also equal Carnot efficiency, $n_i = (1 - T_c/T_h)$, where T_c (251 K) and T_h (290 K) are the average temperatures of the cold and hot source respectively. In the ideal cycle, the work of the air and water-turbines leave the system. The work of the air-turbine could be used to produce valuable mechanical energy.

The heat received (Q = 45724 J/kg) is large compared to the ezergy of 2215 J/kg because the air has been dehumidified and must be re-humidified. In the real atmosphere, the re-humidification water need not be the water that ascended and can come from the sea via shallow updrafts. Unsaturated air has high affinity for water. As a result, oceanic surface air typically has relative humidity of ≈ 80%, WR(1993) and Holland (1997),

Fig.3 shows that adding heat to surface air increases ezergy by 27.2 to 30.5 % of the added heat. The reason for this high incremental efficiency lies in the metastable nature of moist air. The 15 kPa ezergies of 26.3 °C surface air with 84, 69.7 and 0 % relative humidity are 2215, 0, and -12353 J/kg respectively. The corresponding surface air enthalpies are 72800, 64900 and 26400 J/kg. Surface air enthalpy of ≈64900 J/kg can be viewed as the *enthalpy-zero.* The 38500 J/kg received under the enthalpy zero is insufficient to make ezergy positive. The ezergy is 4.8 % (2215/45724) of the total heat received and 28 % (2215/7900) of the heat received above the *enthalpy-zero*. WR(1993) used the name *wet-bulb potential temperature intercept,* a concept akin to *enthalpy-zero*.

Adding a small amount of heat can releases the potential of heat received from prior natural heating. Tropical ocean surface air ezergy is usually around 1500 J/kg. Surface air is often close to the point where a small amount of heat is sufficient to release the energy production potential of heat received previously. Adding heat to surface air increases ezergy (W_b) and has little effect on potential energy of condensed water (W_p) or loss work (W_L); the increase in overall work goes mainly to ezergy (W_b). As a result, incremental ezergy efficiency for heat received above the enthalpy zero is approximately 25 %.

The close cycle of Fig. 7 can explain many features of the atmosphere. The ezergy is 4.8% (2215/45724) of the total heat received. The total turbine work is 10.4 % (4740/45724) of the heat received. The total turbine work is equal to the heat input minus heat output (45724 – 40984 = 4740 J), and to the work of expansion minus work of compression (143732 – 138986 = 4740 J). The enormous works of expansion and compression are not obvious in CAPE analysis. The work of expansion is 314 % (143,732 / 45724) of the heat received. The second law puts a limit on net work but does not limit the work of expansion. The ezergy is just 1.54 % (2215/143732) of the work of expansion. For a fully irreversible cycle, total actual work (W_a) is zero and heat out (Q_o) equals heat in (Q_i).

In the closed cycle of Figure 7, conservation of mass requires the upward and downward mass flow be equal. In the real atmosphere, subsidence occurs preferentially where the air is coolest and densest. Local subsidence would increase the local temperature and the 15 kPa elevation which would push the subsidence area away from the upflow area. Local subsidence compresses and warms underlying air thereby favoring remote subsidence. The subsidence process is self-regulating; the subsidence takes place preferentially where the subsiding air is coldest and needs warming.

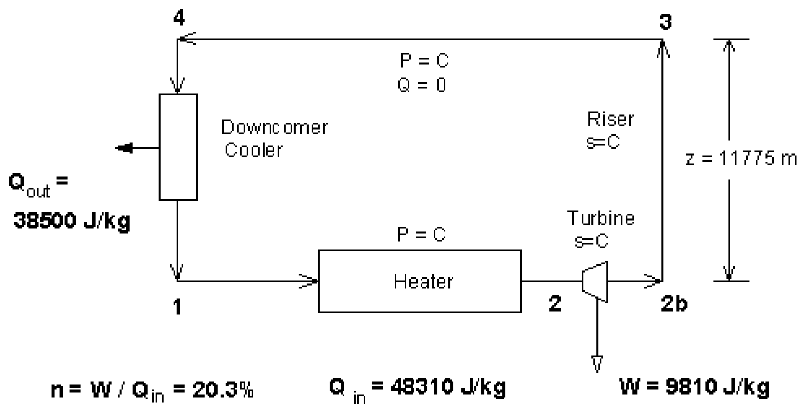
There is no change in potential energy in a steady-state closed cycle. Work not captured by the turbines becomes work of compression. Energy is transported poleward mainly by work of compression rather than by sensible or latent heat. The descending air received 138986 J/kg as work of compression which provides its increase in enthalpy of 87662 J/kg plus its heat loss of 51314 J/kg. The descent must be much slower than the ascent to give the air the time to cool by radiation to space. Radiating 41000 J/kg at 1.5 °C/d takes ≈27 days, corresponding to a subsidence velocity of ≈500 m/d (≈6 mm/s). An upward velocity of 3 m/s is ≈500 times the downward velocity corresponding to an ascent time of ≈ 1.3 h or ≈ 0.055 d. At a cooling rate of 1.5 °C/d, the descending air looses ≈41000 J/kg during its 27 days descent. The rising air only looses ≈80 J/kg during its ≈ 100 minutes ascent, justifying the choices of polytropic cooling for the descent and adiabatic isentropic for the ascent. Goody (2003) describes a close cycle similar to Figure 7; he recognised that downward velocity has to be much slower than the upward velocity to give the subsiding-air time to cool; he recognised that the only irreversible process in the close cycle is the mixing and heating near the earth's surface.

Raising 1 kg of surface tropical air can transfer 140,000 J of energy upward and poleward. Transferring 140,000 J of energy poleward by heat transfer would require cooling 28 kg of air by 5 °C, 28 times more air mass than by compression. The role of work of compression in transporting energy poleward is seldom recognised. The enthalpy of a column of air can be increased by adding air at the top of the column while removing the same quantity of air from the bottom because static energy increases with elevation.

Conservation of mass requires that downflow equals upflow which requires that the downflow area be ≈500 times the area of the upflow area. Hadley and Ferrel circulation cells with updraft and downdrafts of roughly equal area are inconsistent with the requirement that the downdraft area be much larger than the updraft area. The upflow and downflow processes are very different. *Upflow produces work, downflow requires work.* Expansion produces work, compression requires work. Upflow is essentially an adiabatic process, downflow is a polytropic cooling process. Upflow is fast ≈3 m/s, downflow is slow ≈500 m/d (6mm/s). Upward velocity is approximately 500 times the downward velocity. Energy is transferred poleward and upward to the subsidence areas by work of compression. The location of upflow areas is not fixed.

Hurricanes form in random locations and wander; the corresponding subsidence occurs preferentially where the air is coldest. Additional information can be found at Michaud (1998, 2000 and 2012).

Single component systems are easier to understand than binary ones and can be perfectly reversible. Figure 8 shows a pure air single component fully reversible cycle. Height is based on a lapse rate is 6.5°C/km. The raised air is at the temperature of the environment in state 3. The initial temperature of the rising air is 55°C which would be very unstable. The net work is transferred to the turbine where the flow is restricted.



State	P (kPa)	T (K)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	100	290	60.14	16929	0	16929
2	100	338.1	214.14	65239	0	65239
2b	90.25	328.3	214.14	55429	0	55429
3	20	213.5	214.14	-59567	115395	55429
4	20	213.5	214.14	-59567	115395	55429

Carnot Efficiency based on average source temperatures

$$n_c = 1 - T_c / T_h = 1 - 251.7 / 314.0 = 19.8\%$$

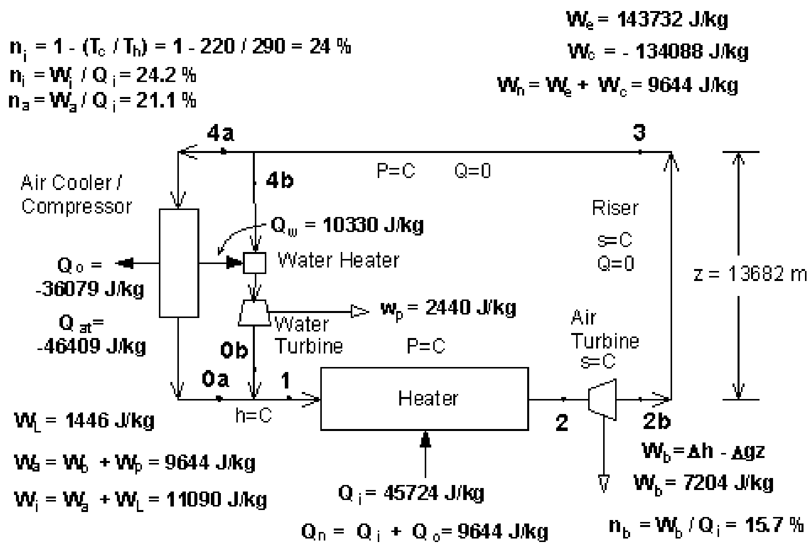
Carnot Efficiency based on **log** average source temperatures

$$n_c = 1 - T_c / T_h = 1 - 248.8 / 313.1 = 20.5\%$$

Figure 8. Reversible close cycle - Pure air - no water,
Doncomer cooling. Height based on lapse rate of 6.5 K /km

Figure 9 shows a case where the 15 kPa surface is 500 m lower than in Figure 7. Lowering the 15 kPa surface by 500 m increases ezergy by ≈ 5000 J/kg. The elevation of the 15 kPa pressure is approximately 1000 m lower at the poles than in the tropics. A 500 m height reduction corresponds to mid-latitude elevation. At 85 % relative humidity, the air temperature required to achieve an ezergy of 2215 J/kg is 26.2 °C in the tropics and only 21.5 °C in mid latitude because the 15 kPa air is 500 m lower. The name ***epergy*** will be used for exergy based on the use of an upper-level elevation lower than the local upper elevation. The "*p*" stands for poleward.

Raising tropical air in high latitudes where geo-potential heights are lower can produce more mechanical energy than doing so locally thereby increasing mechanical energy production. Satellite videos of tropical cyclones occasionally show hurricane exhaust air streaming towards colder regions. Descent in high latitude could contribute to increased hurricane intensity. Horizontal distance is not an impediment because friction losses can be small.



State	P (kPa)	T (°C)	r (g/kg)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	101.51	8.89	18.20	95.56	27098	0	27098
2	101.51	26.30	18.20	253.01	72822	0	72822
2b	88.36	19.36	18.20	253.01	65618	0	65618
3	15.00	-62.27	18.20	253.01	-70910	136527	65617
4a	15.00	-62.27	0.03	254.99	-62489	134087	71598
0a	101.51	25.00	0.03	84.04	25193	0	25193
4b	15.00	-62.27	18.17	-32.02	-8427	2440	-5987
0b	101.51	25.00	18.17	6.67	1903	0	1903

Figure 9. Close, reversible, atmosheric cycle
Adiabatic expansion with freezing, No separation,
Effect of reducing z4 by 500 m. Lapse rate 6.378°C//km..

According to Kleidon (2022), the maximum heat to work conversion efficiency of the atmosphere based on the temperatures at which heat is received and given up is ≈ 10 % in accord with present Figure 7. According to Kleidon (2021), the maximum wind energy production is 0.2 % of absorbed solar energy of 240 W/m^2, resulting in a global mean estimate for the wind energy potential of about 0.5 W/m^2. According to the ezergy approach, the maximum energy production is 10 % of the upward heat flux of 100 W/m^2 resulting in a global mean estimate energy production of ≈ 10 W/m^2. Kleidon's wind energy potential is based on horizontal temperature gradient, on horizontal heat flux, and on Betz turbine efficiency limit. Kleidon's wind energy potential is 50 times smaller than his potential based the temperatures at which the atmosphere receives and gives up heat. Figure 2 shows that upward heat convection can produce horizontal wind at remote location. Kleidon (2011) did not consider the contribution of upward heat flux to horizontal wind.

The fact that polar energy transfer is mainly via work of compression has seldom been recognised. The winter pole looses ≈ 150 W/m^2 by radiation to space, Kleidon (2021); its temperature is roughly constant throughout the winter. There must be an energy source to make up for this heat loss. Work of compression must be this energy source.

Over a century ago in his last paper, which received little attention, Margules (1906), wrote:

1. I hold vertical movement under the influence of gravity to be the essential cause of storms.
2. The energy source is not to be found in gradients but in the sinking of colder air and the rising of warmer and moister air. The energy potential of horizontal pressure difference is very small.
3. One could gain a closer understanding, when better method than presently known, for the handling of aerodynamic problems are found.

Ezergy can be calculated in several ways:

1) Reduction in moist static energy Eq. (2).
2) Heat received multiplied by Carnot efficiency based on average hot and cold source temperatures minus the potential energy of condensed water and the mixing loss.

$$E_Z = \Delta H - \Delta gz = Q_i\left(1 - \frac{T_c}{T_h}\right) - W_p - W_L \qquad (4)$$

3) Acceleration of buoyant air (CAPE).
4) Reduction in pressure at base of a buoyant air column, Holland (1997).

5. Sea water spray – Tropical cyclones and waterspouts.

Work production can be increased by spraying the air with sea water. Figures 10 and 11 and Table 2a and 2b show the effect of spraying air with sea water. Spraying ambient air, to produce 25°C 90% relative humidity air increases ezergy from 1564 to 2983 J/kg. Available work with sea spray will be called ***esergy** (E_s)* , where "*s*" stands for "Spray*"*. Hurricane maximum velocity which can be anywhere in the system can be:

$$v = \sqrt{2\,Es} \qquad (5)$$

WORK TO SPRAY SENSITIVITY

Basis:

Jordan Caribbean hurricane sounding

P_1 = 101.51 kPa, T_1 = 27 °C

U_1 = 75%, M_1 =16.95 g/kg

SST = T_7 = 28 °C

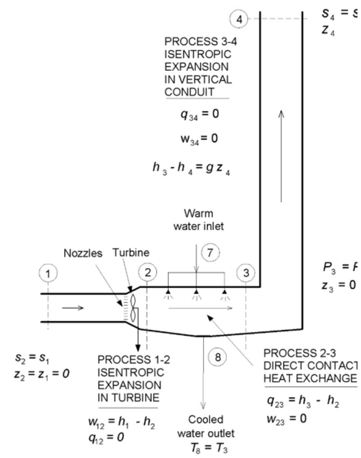
True adiabatic with ice.

W_b = W_{12} = Turbine Work (Ezergy)

P_3 = Updraft base (eyewall) pressure

Observations

1. Ezergy and P_3 reduction increase with state 3 temperature and %RH.
2. Ezergy increases with water flow.
3. Sensitivities are 25% higher when the air is raised to its level of neutral buoyancy.
4. Sensitivities to water flow would be 30 to 50% higher when flow is irreversible .



P_4(kPa)	z_4(m)	T_3(°C)	U_3(%)	P_3(kPa)	M_3(g/kg)	W_b(J/kg)	F_7/F_3(kg/kg) REV.	IRR.
Without water spray								
15	14180	25.49	80.75	99.73	16.95	**1564**		
With water spray								
15	14180	25	90	98.13	18.64	**2983**	0.28	0.12
15	14180	25	100	95.61	21.28	**5258**	1.09	0.68
15	14180	26	90	96,12	20.25	**4791**	0.86	0.51
15	14180	26	100	93.73	23.10	**6981**	2.50	1.67
10	16577	26	100	91.78	23.60	**8797**	2.86	1.81

Sensitivites

$\Delta W_b/\Delta U_3$ = 281 (J/kg)/% (at T_3 = 25)
$\Delta W_b/\Delta U_3$ = 219 (J/kg)/% (at T_3 = 26)
$\Delta W_b/\Delta T_3$ = 1760 (J/kg)/K (at constant U_3)
$\Delta W_b/\Delta T_3$ = 2200 (J/kg)/K (at U_3 = 100%, P_4 = 10 kPa)

$\Delta W_b/\Delta(F_7/F_3)$ = 2810 J/kg (at T_3 = 25°C, reversible)
$\Delta W_b/\Delta(F_7/F_3)$ = 1340 J/kg (at T_3 = 26°C, reversible)
$\Delta W_b/\Delta(F_7/F_3)$ = 3120 J/kg (at U_3 = 90%, reversible)
$\Delta W_b/\Delta(F_7/F_3)$ = 1220 J/kg (at U_3 = 100%, reversible)

Figure 10. Effect of sea water spray on ideal work (Evergy)

The relative humidity of air at equilibrium with fine water droplets must be 100 %. Otherwise, the vapor pressure of the liquid water in the droplets is greater than the vapor in the air. The water and the air come to equilibrium within seconds, Andreas, and Emanuel (2001, Sroka and Emanuel (2021).

The temperature of the saturated air increases with the water-to-air mass flow ratio. At very high spray-to-air mass flow ratio, the temperature of the saturated air approaches the temperature of the sea water. Spray can produce saturated air at temperatures approaching the sea surface temperature, but the quantity of spray required increases exponentially with the saturated air temperature. Air with less than 100 % relative humidity can be produced by diluting 100% relative humidity with dry air or by warming the air with sensible heat which can be provided by the sea water. U_3 is specified based on observations. Montgomery (2005) reports observations of 98% in hurricane Isabel. P_3 is calculated with a solver as the pressure for which the ezergy of process 3-4 is zero.

A small fraction of the spray evaporates, typically 0.3 %; the remaining 99.7 % falls back into the sea at the temperature of the saturated air. The heat of evaporation is provided by the part of the spray which does not evaporate, and which falls back in the sea. The enthalpy transfer process is an equilibrium process and not a surface to air energy transfer process. Producing saturated air of a given temperature requires more spray at lower initial air temperature or relative humidity. The effect of low initial air temperature and humidity can be compensated for by increasing the water spray.

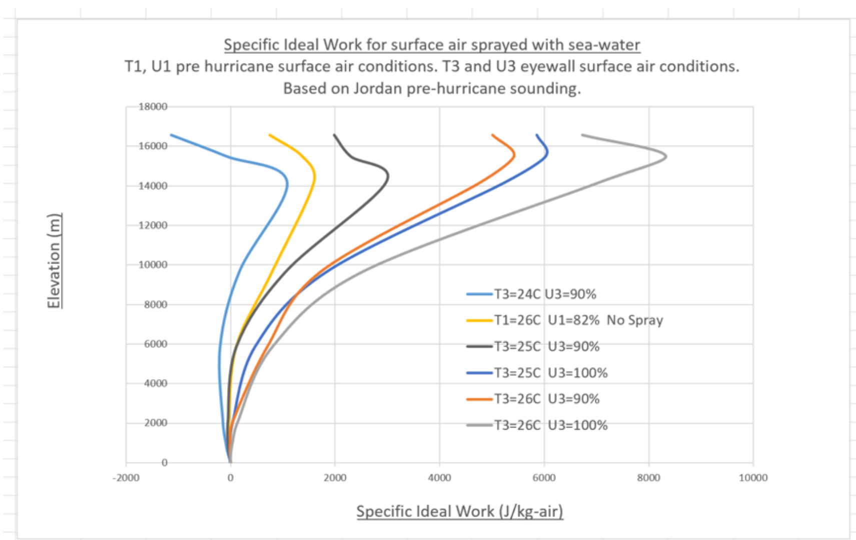


Figure 11. Effect of water spray on ideal work (Evergy). Curves show effect of eyewall temperature and relative humidity.

The mass and heat transfer from spray-to-air is much faster than from the sea-surface-to-air because drops have more surface area per unit mass than the sea surface. Affinity is zero for water at the dew point temperature of the air and increases rapidly with water temperature.

Several indices of hurricane maximum potential intensity (MPI) have been used. E-MPI, Emanuel (1987), used maximum velocity. H-MPI, Holland (1997), used minimum central surface pressure. The central pressure is not important in energy calculations because the eye plays no role in the energy production. The ezergy approach yields ideal work, velocity, and the pressure at the base of the updraft, but not the central pressure. The central pressure reduction can be 1.4 to 1.8 times the pressure reduction at the rising air annulus (T_3). According to Willoughby (1998), hurricane eyewall to the center pressure reduction can be 30 % of the overall pressure reduction which corresponds to a factor of 1.43. In Table 2a, the central pressure reduction (P_c) is taken as 1.43 times the base of the updraft pressure reduction (P_3), for central pressure comparison purpose.

Sea Surf. Temp SST	Conditions at Updraft Base			Potential Intensity					Spray to Air Mass Flow Ratio
T_7 (°C)	T_3 (°C)	U_3 (°C)	M_3 Mixing Ratio (g/kg)	E_v Esergy (J/kg)	Velo-city (m/s)	P_3 (kPa)	P_c (kPa) ΔP_e = 1.43 ΔP_3	P_c (kPa) Holland Fig. 13	F_7/F_3 g-w / kg-a
<u>Without sea water spray</u>									
N/A	27	75	16.95	1560	55	99.7	99.0		0
<u>Section 1: $T_7 - T_3$ = 1 °C U_3 = 90 % per Holland (1997)</u>									
25	24	90	17.1	1090	46	100.3	99.7	100	N/A
26	25	90	18.6	2980	76	98.1	96.7	98	530
27	26	90	20.3	4790	96	96.1	93.8	95	1230
28	27	90	22.0	6500	112	94.2	91.1	92	1940
<u>Section 2: T_7 = 28 °C U_3 = 90 %</u>									
28	24	90	17.1	1090	46	100.3	99.7		N/A
28	25	90	18.6	2980	76	98.1	96.7		280
28	26	90	20.3	4790	96	96.1	93.8		860
28	27	90	22.0	6500	112	94.2	91.1		1940
<u>Section 3: T_3 = 25 °C U_3 = 90 %</u>									
24	25	90	18.6	2980	76	98.1	96.7		4780
25	25	90	18.6	2980	76	98.1	96.7		960
<u>Section 4: T_7 = 28 °C U_3 = 100 %</u>									
28	23.5	100	18.8	2480	69	98.7	97.5		175
28	24	100	19.6	3430	81	97.6	96.0		400
28	25	100	21.3	5260	100	95.6	93.1		1090
28	26	100	23.1	6980	116	93.7	90.4		2500

Table 2a. Effect of sea water spray on esergy. Based on Jordan sounding. P_1 = 101.51 kPa, T_1 = 27 °C, U_1 = 75 %, M_1 = 16.95 g/kg, P_4 = 15 kPa, z4 = 14182 m. Symbols are defined in Figure 10.
Sensitivity of central pressure to updraft temperature: 2.7 kPa/K, versus 2.6 and 3.3 kPa/K from Holland Figure 13 and Table 5 respectively, versus Emanuel 1.05 kPa/K (Holland Table 2).
Sensitivity of central pressure to updraft relative humidity: 0.36 kPa/%, versus Holland 0.48 kPa/%, versus Emanuel 0.62 kPa/%.

In the 26 °C 90 % relative humidity case, the mixing ratio increases from 16.95 to 20.25 g/kg, by 19 %; the available work increases by a factor of 3 from 1564 to 4790 J/kg. The work of expansion is transferred from process 3-4 to process 1-2. The *emergy* is the work of expansion from distant surface pressure to eyewall surface pressure P_3. The ideal work is transferred to the turbine where the flow is restricted. The *emergy* of expanding 101.51 kPa air to 96.1 kPa is 4790 J/kg.

Rising air conditions are important because the work of expansion is produced during the upflow is used to raise the air and to drive the turbine. Holland (1997) recommended using updraft temperature 1 K colder than SST and an updraft relative humidity of 90% because the condensation level in hurricanes is typically around 500 m. In addition, sea-surface temperature at the eyewall can be 1 to 2°C lower than pre-hurricane sea surface temperature. Table 2a shows that Holland's recommendations are appropriate. Minimum axial pressures P_a and sensitivity to T_3 agree with Holland (1997) figure 13.

The two methods are equivalent. Holland calculates axial pressure from hydrostatics. The *esergy* approach calculates annular updraft base pressure from energy conservation. In both cases the air is brought to equilibrium with the sea water. Holland uses isentropic expansion with immediate separation and no freezing. The present calculations are based on isentropic expansion without separation and with freezing of condensed water. WR(1993) showed that CAPE is almost identical for these two types of expansion.

Sea surface temperature and the quantity of spray are by far the dominant environmental contributors to hurricane intensity. The effects of surface air temperature and humidity and of upper-level elevation are minor compared to the effect of sea surface temperature. Without spray, the quantity of high *ezergy* ambient surface air is small because the high humidity layer is thin. Spray can produce large quantities of high humidity air because the heat content of the ocean is far greater than that of the thin surface air layer. Higher sea water temperature can increase either specific *esergy* or air flow. The *esergy* of sprayed air need not be larger than the *ezergy* of pre storm ambient surface air. Pre-storm surface air can have *ezergy* of 3000 J/kg able to produce force 5 hurricane wind of 75 m/s. The intensity of hurricanes is probably more attributable to air quantity than to specific esergy. Spray can produce *esergy* of over 10,000 J/kg.

In per unit mass simulation, the air flow is constant making it easy to see that the *esergy* intensity increase is due to both water quantity, and to the spray-to-air flow ratio. Sroka and Emanuel (2021) pointed out that sea-to-air energy transfer is well approximated by using spray flux alone and that drop radius is not important. Spray to air flow ratio, which is a key feature of process simulation, is rarely considered by atmospheric models.

Spray decreases rapidly with height. The rising air can be a combination of air from different elevations and need not be saturated. The 90 % relative humidity rising air could be a combination of saturated surface air and of unsaturated air from slightly higher elevations, such as 80 % relative humidity air from an elevation of 50 m where the spray has completely evaporated.

Section 1 of table 2a shows that producing saturated air 1°C colder than sea surface temperature requires water to air mass flow ratios of 530 to 1940 g-w/kg-air. The flow ratio increases with temperature. Section 2 shows that for a fixed water temperature of 28°C, the mass ratio increases exponentially from 280 to 1940 g-w/kg-air. Section 3 shows that 90 % relative humidity air can be produced by spray colder than the air. Section 4 shows that for a water temperature of 28°C, producing saturated air requires higher mass ratio than producing 90% relative humidity air.

Sea Surf. Temp SST	Conditions at Updraft Base			Potential Intensity					Spray to Air Mass Flow Ratio
T_7 (°C)	*T_3* (°C)	T7 – T3 (°C)	*U_3* (%)	*M_3* Mixing Ratio g-w / kg- air	*E_v* Esergy (J/kg)	Velo-city (m/s)	*P_3* (kPa)	*P_c* (kPa) $\Delta P_e = 1.8 * \Delta P_3$	*F_7/F_3* g-s / kg-a
Without sea water spray									
N/A	27	N/A	75	16.95	1560	55	99.7	98.3	0
Section 1: $T_3 = 24 + (T_7-27)/4$									
23	23	0.0	98	17.53	1050	45	100.31	99.36	N/A
25	23.5	1.5	98	18.29	2020	62	99.21	97.37	N/A
27	**24.0**	**3.0**	**98**	**19.08**	**2980**	**76**	**98.13**	**95.43**	**375**
29	24.5	4.5	98	19.90	3910	87	97.09	93.56	429
31	25.0	6.0	98	20.75	4820	96	96.08	91.74	459
33	25.5	7.5	98	21.62	5710	105	95.11	90.00	479
35	26.0	9.0	98	22.52	6570	112	94.18	86.84	493
Section 2: *T_7* = 27 °C									
27	**24.0**	**3**	**98**	**19.08**	**2980**	**76**	**98.13**	**95.43**	**375**
27	25.0	2	98	20.75	4820	96	96.08	91.74	1280
27	26.0	1	98	22.52	6570	112	94.18	88.31	3650

Table 2b. Effect of sea water spray on esergy. . Based on Jordan sounding. P_1 = 101.51 kPa, T_1 = 27 °C, U_1 = 75 %, M_1 = 16.95 g/kg, P_4 = 15 kPa, z4 = 14182 m, Ez without spray 1560 J/kg . Symbols are defined in Figure 10.

The humidification of converging air by sea spray starts at high radius as soon as there is significant spray. The temperature of the saturated air and its esergy increase with water flow. The effect of spray is cumulative. In the 28 °C SST 100 % relative humidity section 4 of table 2a, increasing the saturated air temperature from 25 to 26 °C requires an additional water flow of 1410 g-w/kg-a. Humidification takes place as long as part of the circulation is in a heavy sea spray area. As a result, hurricanes intensity winds can persist well after the eyewall arrives over land.

Table 2b shows the effect of sea-water temperature (T_7) and of water-to-air mass flow ratio (F_7/F_3) on updraft temperature (T_3) and on specific work (E_s). The 27°C SST case is based on hurricane Isabel observed conditions, Montgomery (2005). Section 1 shows that the flow ratio is constant of roughly 400 g-w/kg-air when the increase in updraft temperature is a quarter of the increase in SST. There is a slight increase in flow ratio from 375 to 459 g-w/kg-air. Section 2 shows that 27°C SST can produce 26°C, 98% relative humidity air; but the flow ratio increases exponentially by a factor of 10 from 375 to 3650 g-w/kg-air.

The flow ratio is unlikely to be higher than 500 g-w/kg-a because increasing hurricane intensity increases both spray and air flows, thereby keeping the flow ratio roughly constant. Updraft temperature is unlikely to be over 25°C which is more than sufficient to account for observed maximum hurricane wind velocities. The specific ezergy of updrafts could be higher in atmospheric vortex engines than in hurricane because the air flow can be restricted, and the spray flow can be boosted.

Maximum hurricane velocity based esergy (5), using actual eyewall SST and a spray ratio of 400 g-w/kg-air could be as accurate as E-MPI and H-MPI. Initial default values could be based on E_x = 1500 J/kg, P_4 = 15 kPa, and z_4 = 14200 m. The effect of pre-hurricane surface air properties, equilibrium level and pressure are minor, but could be considered.

Section 2 of Table 2b shows that updrafts with temperatures 23°C and 24°C and a relative humidity 98% can produce category 1 and category 5 hurricane wind speeds of 45 and 75 m/s respectively.

Spray is an equilibrium process. The surface to air energy transfer equation is inappropriate when there is spray. Energy transfer by spray is at an order of magnitude larger than by conduction. The area of cooling ponds has to be at least 1000 times the area of a cooling tower of the same capacity. Eq. (5) is far simpler than the E-MPI equation . There is no need for enthalpy, drag coefficients, or efficiency. The discrepancy between E-MPI and observed hurricane Isabel values suggests a significant limitation of E-MPI theory, Montgomery (2005). The *esergy* approach eliminates the discrepancy; and the need for turbo-boost injection of eye air into the eyewall to explain the observed higher intensity.

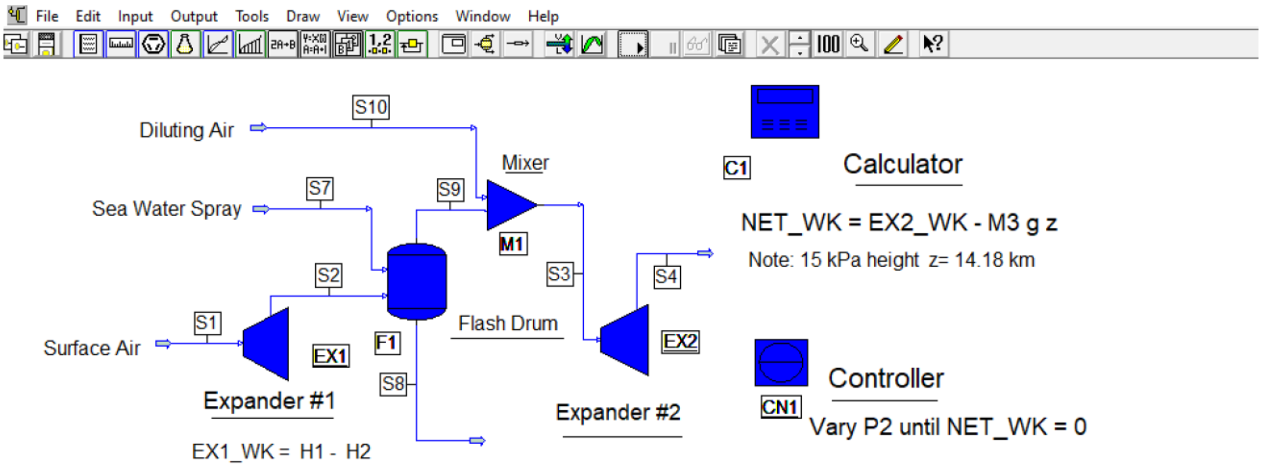
Tropical cyclones are driven by surface enthalpy fluxes, Emanuel (1987). Actual hurricane wind velocity occasionally exceed the Emanuel limit. Emanuel uses the temperature at the top of the troposphere for the cold source temperature. Renno (2008) used the average temperature of the troposphere as the cold source temperature. The open system ezergy approach does not need to use the cold source temperature.

According to NOAA frequently asked questions (FAQ) and Marks (2003), hurricane upward heat flux is 600 TW based on rain production; and hurricane mechanical energy production is 1.5 TW based on dissipation corresponding to an efficiency of 0.25 %. The total turbine work of 10.4 % in Figure 7 is 40 times greater than the dissipation estimate. This huge discrepancy is because work can dissipate in many ways such as in an unrestrained piston or in flow through an orifice.

600 TW can cool a block of sea-water 60 km wide by 60 km long by 100 m deep by 4.3 K during the 3 hours hurricane passage time over the block. At a heat input of 50 kJ/kg, the upward air flow required to carry 600 TW is ≈12 x 10^9 kg/s. At a spray flow of 24 x 10^9 kg/s, spray cooled by 6°C can account for observed sea cooling. There is no need to consider upwelling of deep water or spray-less sea to air heat transfer, Price (1981).

6. Steady-state engineering process simulator.

Hurricane intensity can be calculated with steady-state engineering simulators such as PRO/II from AVEVA. PRO/II is an easy to use drag and drop simulator for engineers in chemical industries. It has a library of thermodynamic properties and units of operations such as expanders, flash drums, mixers, custom calculations, and controllers which can be linked. It performs steady-state mass and energy balance calculations including isentropic expansion of moist air. There is a wide choice of thermodynamic methods. The selected thermodynamic system in Figure 12 and Table 3 is called SIMSCI-SRK. SRK does not use the same zero point as the previous sections. The zero point is not important since work and heat are calculated from enthalpy difference. SRK does not support ice phase; the calculated work is less than with freezing. WR (1993) and Molinari (2012) showed that CAPE for expansion without separation is approximately 50 % less without freezing than with freezing.



Stream Name		S1	S2	S3	S4	S7	S8	S9	S10
Stream Phase		Vapor	Vapor	Vapor	Mixed	Liquid	Liquid	Vapor	Vapor
Pressure	KPA	101.50	98.09	98.09	15.00	105.00	98.09	98.09	105.00
Temperature	C	26.00	23.11	24.63	-58.59	28.00	24.63	24.63	25.00
Total Sp. Entropy	KJ/KG-C	6.47	6.47	6.50	6.50	5.03	4.98	6.50	6.33
Total Sp. Enthalpy	KJ/KG	37.30	34.34	41.83	-97.13	100.67	85.63	41.83	-8.71
Total Mass Rate	KG/SEC	1018.0	1018.0	1020.4	1020.4	500.0	497.6	1020.4	0.0
Total Enthalpy	M*WATT	37.97	34.96	42.69	-99.12	50.33	42.61	42.69	-0.00

Figure 12. PRO/II process simulation. Upper section flowsheet showing units of operation and streams. Lower section stream data table.

Case	T_1	T_2	T_4	M_{w1}	M_{w9}	H_1	H_2	W_{12}	P_2	T_7	T_3 , T_8	M_{w7}	M_{w8}	H_7	H_8	Q_{78}	IE	IE
#	°C	°C	°C	kg/s	kg/s	MW	MW	MW	kPa	°C	°C	kg/s	kg/s	MW	MW	MW	%	Base
Reversible processes – EX1 efficiency 100% - W_{12} is ezergy																		
Ezergy – No water spray - No dilution air																		
1	26	25.01	-64.1	18	18	37.97	34.94	1.03	100.3	--	--	0	0	--	--	0	--	--
2	**30**	27.80	-61.5	18	18	42.14	39.85	2.29	98.93	--	--	0	0	--	--	0	30.2	1
3	26	24.25	-60.4	**20**	20	43.04	40.72	2.32	98.86	--	--	0	0	--	--	0	25.4	1
Effect of water spray – No dilution air																		
4	26	24.56	-62.6	18	19.1	37.97	36.47	1.50	99.79	28	23.81	**100**	98.9	10.07	8.11	1.96	24.0	1
5	26	23.11	-54.5	18	20.4	37.97	34.96	3.01	98.09	28	24.63	**500**	487.6	50.33	42.61	7.72	25.5	1
6	26	22.27	-55.4	18	21.6	37.97	33.79	4.18	96.78	28	25.28	**1000**	996.4	100.67	88.22	12.35	25.5	1
7	26	21.75	-51.6	18	22.9	37.97	32.48	5.49	95.34	28	26.03	**2000**	1995.1	201.33	183.31	18.02	24.7	1
8	26	21.27	-48.0	18	24.3	37.97	31.31	6.66	94.06	28	26.72	**4000**	3993.7	402.66	379.34	23.32	24.1	1
Effect of ambient air temperature and mixing ratio with 500 kg/s water spray																		
9	**30**	26.29	-56.4	18	21.2	42.14	38.28	3.86	97.19	28	25.07	**500**	496.8	50.33	43.53	6.80	27.4	5
10	26	23.62	-56.0	**20**	21.3	43.04	39.07	3.97	97.03	28	25.15	**500**	498.7	50.33	43.67	6.66	25.6	5
Effect of air dilution – 200 kg/s 25°C air with 10 g/kg mixing ratio																		
11	26	23.44	-59.7	18	23.5	37.97	35.30	2.67	98.47	28	25.56	**1000**	996.5	100.67	89.47	11.20	-13.5	6
Irreversible processes – EX1 efficiency 0.02% - W_{12} is dissipated work - IE = (Inergy – Ezergy)/Ezergy in percent.																		
12	26	25.99	-63.2	18	18	37.97	37.97	1.46	99.83	28	25.99	**0**	0	--	--	0	42	1
13	26	25.99	-56.6	18	21.1	37.97	37.97	3.73	97.28	28	26.03	**500**	496.9	50.33	43.44	6.89	24	5

Table 3. PRO/II simulations results. P1 = 101.5 kPa, P4 = 15 kPa in all cases. Figure 12 shows case 5. Incremental efficiency (IE) is 25 % of increase in latent heat and 30 % of increase in sensible heat.. 98.9 % and 99,8 % of spray fall back in the sea in cases 4 and 8 respectively. The spray is cooled by 4.19°C and 1.28°C in cases 4 and 8 respectively. Spray effectiveness decreases with spray flow mainly because spray ΔT and affinity both decrease.

The atmosphere is not a steady-state system, but PRO/II can be used to explain the energy of storms. Energy calculations are in per kilogram of air in the previous sections and per kilogram per second in the PRO/II simulation. The total flow of 1018 kg/s at the bottom of the table consist of 1000 kg/s of pure and 18 kg/s of water vapor corresponding to a relative humidity of 85 %. At an air flow of 1000 kg/s, a power output 3 MW corresponds to a specific work 3 kJ/kg-air.

Stream data such as pressure, temperature and composition are entered by clicking on the stream. Unit of operation data such as expander outlet pressure and efficiency are entered by clicking on the unit. Clicking the arrow on the top tool bar carries out the calculation and fills in the stream property table below the flowsheet.

Isentropic expansion is represented by expanders EX1 and EX2. Calculator C1 calculates the potential energy in the final state. A look up table based on the Jordan sounding is used to determines Z_4 based on P_4. Controller CN1 finds the value of P_2 required to make EX2 work equal to the final potential energy. Sea-spray is represented by optional stream S7 and flash drum F1. Flash drum F1 is an isenthalpic mixer; its two outlet streams are in equilibrium. Dry air dilution is represented by optional stream S10 and mixer M1.

Table 3 shows results for several cases. Results agree with the ezergy method. Steady-state simulation make it easy to distinguish between the significant and the unimportant.

- *Without spray,* W_{12} increases with the temperature and with the mixing ratio of ambient surface air.
- *With spray,* W_{12} increases with the quantity and temperature of the water spray.
- The air and water leaving the flash drum are in equilibrium and at the same temperature. The air leaving the top of the flash drum is saturated, 100 % relative humidity.
- Approximately 99.5 % of the spray falls back in the sea at a temperature up to 5 °C lower than the sea temperature thus transferring a huge quantity of heat from sea to air.
- The temperature of the air leaving the flash drum increases with spray flow and temperature.
- Incremental efficiency (IE) is 30 % for dry heat and 25 % for wet heat.
- The efficiency of the first expander can be decreased from 100 % to 0 % to check the effect of irreversibility.
    - For ambient air sensible heat input, inergy is 42 % higher than ezergy,
    - For heat supplied by water spray inergy is 24 % higher than ezergy.
- Mixing unsaturated air with the rising saturated air (S_{10}) reduces work and relative humidity.
- Large water spray (S_7 = 10 to 4000 kg/s) increase the air temperature because the latent heat is provided by the water.
- Very small water spray (S_7 < 5 kg/s) decrease air temperature to the ambient air wet bulb temperature because the heat of evaporation is supplied by the air. Increasing EX2

discharge pressure P4 from 15 t0 80 kPa show that small quantities of spray can make evergy neap (CIN) more negative and inhibit convection.

- The latent heat content of ambient air (S_1) is large compared to the latent heat provided by the spray.

7. Conclusion

Richard Smalley, who won the 1996 Nobel Prize of Chemistry, wrote: *"Without finding an abundant source of clean energy, there is no hope of stopping climate change."* Humans will not accept reduced energy availability; we must find a new energy source.

There is an urgent need for clean renewable energy; atmospheric upward convection could provide clean energy. The heat required to produce the work is already stored in surface air and in sea water. There is no need for large area solar energy collectors. The existing heat content of ambient air and warm sea water could produce abundant power.

A vortex can prevent loss of buoyancy by dilution and transfer work of buoyancy downward. The pressure reduction at the base of the vortex could drive turbines producing shaft work and electricity. Controlled anchored vortices would not be dangerous and could be used to produce clean power or to make rain fall where it is needed.

There is a potential for producing mechanical energy when moist surface air is raised to the tropopause. The ideal work (ezergy) of surface air is typically 1000 to 2000 J/kg. Ideal work could be increased to ≈10000 J/kg by spraying the air with warm tropical sea water or with low temperature waste heat. Surface air can be in a metastable wherein a short duration energy input can overcome initial negative buoyancy, prevent mixing, and enable the exergy to be captured at grade. Heat input and rotation could be controlled at grade.

There are many examples of human produced vortices, Michaud (V1 to V6). Energy production will require large costly prototypes because the vortex must extend over 5 km to produce significant ezergy. The vortex must be controllable and stable. There are many possible configurations, see Michaud (1975, AVE2007, AVE2021). A concerted development program would quickly find out what works. We cannot control natural storms, but we could learn to produce well controlled atmospheric vortices.

Margules figured it out in 1903. Margules (1906) calculated the maximum work produced when saturated air is raised and for one case and obtained results that agree with the *ezergy* method.

Engine efficiency is calculated by following a fluid through idealized closed cycles wherein properties such as pressure, temperature, entropy, enthalpy, and composition are conserved. The flow is constant. Flow and process are specified; heat, work and efficiency are calculated. Unit mass calculations make results for different cases easy to compare.

Calculating efficiency from models is difficult. Atmospheric models calculate future trajectories based on initial conditions and on forcings. Trajectories are not specified; there are many trajectories that satisfy the equation of motion including every weather pattern that has ever occurred. Hurricane models produce a spaghetti of trajectories. There is mixing of fluid with unrelated properties in unspecified proportions. The flow is different in every case making result difficult to compare. Atmospheric model performance is judged by how well they predict future weather and not on how much work could be produced if the convection process were controlled.

The energy of hurricanes is due to enthalpy transfer from the underlying warm sea. Wind energy is often attributed to horizontal and not to vertical gradients. The Lorenz (1967) reference state approach provides little information about where the work is produced. There is no need to consider the effect of subsidence on upper-level elevation because the subsidence occurs over a wide area and mostly well away from the updraft.

The ezergy approach shows that the available work can increase the kinetic energy of the rising air itself or produce other forms of mechanical energy and that the energy can be captured by constraining the flow in an expander located at grade. The thermodynamic basis is well established. Engineering tools such as PRO/I, designed for use on any continuous steady-state process including wet cooling towers, can be used to understand atmospheric convection.

Silo mentality can create counterproductive competitions, and hinder communication, creative thinking, and boundary-spanning collaboration. Climate leaders need to talk and forge productive working relationships with people holding differing perspectives, knowledge, and interests, Bateman and Mann (2016). To do so will require academic institutions to demolish some of the stovepipes (e.g. between science and engineering) that currently discourage basic researchers from more fully engaging in the practical problem of risk assessment, Emanuel (2018).

Chemical and power engineers welcome contributions from other disciplines and realise that experience acquired in other disciplines can improve process performance. One learns from experience, including failures and success; one finds out quickly what ideas works and improves on them at the next opportunity. Like with other inventions suggestions for improvements can come from anyone. Ideas that work are quickly identified and selected.

”You're unlikely to discover something new without a lot of practice on old stuff”

Richard Feynman.

References

AVEVA ProII Process Simulation. https://www.aveva.com/en/products/pro-ii-simulation/

Andreas, E. L., and Emanuel, L. A., 2001: Effect of sea spray on tropical cyclone intensity. *J. Atmos. Sci.,* 58, 4741-3751.

Bateman, T. S., Mann, M. E. (2016): The supply of climate leaders must grow. Nature Climate Change, 6, 1052-1054.

Bechtold, P., 2019: Atmospheric Moist Convection. ECMWF.

Bister M., Emanuel K. A., 1998 : Dissipative heating and hurricane intensity. *Meteorol. Atmos. Phys.,* 65, 233-240.

Chen, X., Zhang, J. A., & Marks, F. D. (2019). A thermodynamic pathway leading to rapid intensification of tropical cyclones in shear. *Geophysical Research Letters*, 46, 9241–9251. https:// doi.org/10.1029/2019GL08366

Dufour, L., Van Mieghem J., 1975: Thermodynamique de l'Atmosphère. Institut Royal Météorologique de Belgique.
English précis by P. Bechtold
https://www.ecmwf.int/sites/default/files/elibrary/2015/16954-atmospheric-thermodynamics.pdf

Emanuel, K., 1997: Some aspects of hurricane inner-core dynamics and energetics. *J. Atmos. Sci.*

Emanuel, K., 2003: Tropical Cyclones. Annu. Rev. Earth Planet 31 :

Emanuel, K., 2018: 100 Years of Progress in Tropical Cyclone Research. *Meteorological Monographs*, **59**, 15.11-15.68, doi:10.1175/amsmonographs-d-18-0016.1.

Emanuel, K., 2020: The Relevance of Theory for Contemporary Research in Atmospheres, Oceans, and Climate. AGU Advances.

Foltz, E. R. et. al., 2022; An unprecedented view inside a hurricane. *EOS News* July 2022.

Goody, R., 2003: On the Mechanical Efficiency of Deep, Tropical Convection. *J. Atmos. Sci.,*

Jordan, C. L., 1958: Mean sounding for the West Indies area. *J. Meteo.,* 13, 91-97.

Holland, G. J., 1997: The maximum potential intensity of tropical hurricanes. *J. Atmos. Sci.*. 54, 2519-2541.

Holopainen, E, O., 1963: On the dissipation of kinetic energy in the atmosphere. *Tellus* XV,1

Kleidon, A., 2012: How does the Earth system generate and maintain thermodynamic disequilibrium and what does it imply for the future of the planet? *Phil. Trans. R. Soc.,* 370, 1012-1040.

Kleidon, A.,2021: Physical limits of wind energy within the atmosphere and its use as renewable energy: From the theoretical basis to practical implications. Meteor. Zeitschrif

Kleidon, A.,2022: Working at the limit: A review of thermodynamics and optimality of the Earth system, Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2022-38.

Kleinschmidt, E., Jr., 1951: Grundlagen einer theorie der tropischen zyklonen. Arch. Meteor. Geophys. Bioklimatol., 4A, 53–72, https://doi.org/10.1007/BF02246793.

Lilly, D. K., 1969: Tornado Dynamics. *NCAR Manuscript* 69-117.

Lorenz, E. N., 1967: The nature and theory of the general circulation of the atmosphere. World Meteorological Organization.

Margules, M., 1903: Uber die Energie der Sturme, (On the energy of storms,) translated by Cleveland Abbe (1910).

Margules, M., 1906: Zur Sturmtheorie. *Meteorologische Zeitschrift*.

Marquet, P., (2014): On the concept of available enthalpy, application to atmospheric energetics. https://arxiv.org/pdf/1402.4610.pdf

Marks, F. D., (2003): Hurricanes. Encyclopedia of Atmospheric Sciences. Academic Press.

Michaud, L. M, (1975): Proposal for the Use of a Controlled Tornado-like Vortex to Capture the Mechanical Energy Produced in the Atmosphere from Solar Energy. *Bull. Amer. Meteor Soc.,* Vol. 56, No. 5 , pp. 530-534.
http://vortexengine.ca/VPS_ARTICLE.pdf

Michaud, L. M., (1998): Entrainment and detrainment required to explain updraft properties and work dissipation. *Tellus,* 50A.
http://vortexengine.ca/Ent_paper.pdf

Michaud, L. M., (1999): Vortex process for capturing mechanical energy during upward heat-convection in the atmosphere. *Applied Energy,* 62 (1999) 241-251.
http://vortexengine.ca/VPS_ARTICLE.pdf

Michaud, L. M., (2000): Thermodynamic Cycle of the Atmospheric Upward Heat Convection Process. *Meteor. Atmos. Phys*.
http://vortexengine.ca/Cycle/Tcycle_SV.pdf

Michaud, L. M., (2012a): On hurricane energy. *Meteor. Atmos. Phys.*
https://link.springer.com/article/10.1007/s00703-012-0208-6

Michaud, L. M., (2012b): Presentation made at the American Meteorological Society 18th Air Sea Interaction Conference, July 2012. Hurricane sea to air heat transfer.
Abstract: http://vortexengine.ca/Isabel/Michaud_AS18_Abstract_R1.pdf
Manuscript : http://vortexengine.ca/Isabel/Michaud_AS18_Manuscript_R1.pf

Michaud, L. M., (AVE2007): Atmospheric Vortex Engine Technical Description.
http://vortexengine.ca/VSC/AVE_WEB.pdf

Michaud, L. M. (AVE2021): Atmospheric Vortex Engine Description.
http://vortexengine.ca/VSC/Vortex_Story_W.pdf

Michaud, L. M. (HP48): Atmospheric thermodynamic calculator program -AT1,
http://vortexengine.ca/Calculator.shtml

Michaud, L. M., (PRO/II): PRO/II Process Simulator.
http://vortexengine.ca/Isabel/Isabel_Pro2.pdf
AVEVA PRO/II Simulation – The Trusted Steady-State Process Simulator

Michaud Vortex Producers
V1. Bearded Science Guy. https://www.youtube.com/watch?v=sIKrdIMz-EM&t=14s
V2. The Action Lab. https://www.youtube.com/watch?v=b1bOnD8v5sk
V3. Singapore Science C. https://www.youtube.com/watch?v=fwzKpKHRYo8&t=69s
V4. Burning Man. https://www.youtube.com/watch?v=nSJkydvQTJY
V5 Lambton College AVE https://youtu.be/_HoP6ZMdLSw
V6. One meter model. https://youtu.be/a58ebNYcBdQ

Molinary, J., (2012): CAPE in tropical cyclones. J. Atmos. Sci.

Montgomery, M.T., Bell, M.M., Aberson, S.D., Black, M.L., 2006: Hurricane Isabel (2003) Insight of the physics of intense storms. Part 1. *Bull. Amer. Meteor. Soc.*, 87, 1335-1347.

NOAA (2021): Hurricane FAQ.
https://www.aoml.noaa.gov/hrd-faq/
Hurricane FAQ – NOAA's Atlantic Oceanographic and Meteorological Laboratory

Peixoto, J. P. and Oort, A. H., 1992: Physics of Climate. American Institute of Physics.

Price, J. F., 1981: Upper Ocean response to a hurricane. *J. Phys. Oceanogr.,* 11, 153-175.

Randall D. and Wang. J., 1990; The Moist Available Energy of a Conditionally Unstable Atmosphere. *J. Atmos. Sci.*

Renno N. O., 2008: A thermodynamically general theory for convective vortices. *Tellus*.

Smith J. M., Van Ness H. C., and Abbott M. M., 2001: Introduction to chemical engineering thermodynamics, Sixth edition, McGraw-Hill.

Shade, L. R., 2000: Tropical cyclone intensity and sea surface temperature.
J. Atmos. Sci., 57, 3122-3131.

Snow J. T. and Pauley R. L., 1984: On the thermodynamic method for estimating maximum tornado windspeeds.

Sroka S. and Emanuel, K., 2022: Sensitivity of sea-surface enthalpy and momentum fluxes to sea spray microphysics. *Journal of Geophysical Research: Oceans*.

Trenberth, K. E., Cheng, L., Jacobs, P., Zhang, Y., & Fasullo, J. (2018). Hurricane Harvey links to ocean heat content and climate change adaptation. *Earth's Future,* 6, 730–744. https://doi.org/10.1029/2018EF000825

Williams, E., and Renno, n., 1993: An analysis of conditional stability of the tropical atmosphere. *Mon. Wea. Rev.,* 121, 21-36.

Willoughby, H. E., 1998: Tropical Cyclone Eye Thermodynamics.
Mon. Wea. Rev., 126, 3053-3967.

Zipser E. J. and LeMone M. A., 1980: Cumulonimbus vertical velocity events in GATE. Part II: Synthesis and model core structure. *J. Atmos. Sci.*