Atmos. Chem. Phys. Discuss., 8, 17423–17437, 2008
www.atmos-chem-phys-discuss.net/8/17423/2008/

Atmospheric
Chemistry
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Discussions

On the validity of representing hurricanes as Carnot heat engine

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Received: 7 May 2008 – Accepted: 10 July 2008 – Published: 19 September 2008

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

It is argued, on the basis of detailed critique of published literature, that the existing thermodynamic theory of hurricanes, where it is assumed that the hurricane power is formed due to heat input from the ocean, is not physically consistent, as it comes in conflict with the first and second laws of thermodynamics. A quantitative perspective of describing hurricane energetics as that of an adiabatic atmospheric process occurring at the expense of condensation of water vapor that creates drop of local air pressure, is outlined.

1 Introduction

Wind velocities in hurricanes and tornadoes reach 30–120 $\mathrm{m\,s^{-1}}$ (Businger and Businger, 2001). The question of how solar energy absorbed by the planetary surface is ultimately transformed into kinetic energy of air masses has long puzzled scientists (Lorenz, 1967). Regarding hurricanes, that admittedly remain a geophysical enigma, it was proposed that the ultimate source of their dynamic power might be heat input from the ocean (Emanuel, 1991, 2003, 2006; Holland, 1997) and that the hurricane represents a Carnot thermodynamic engine. Briefly, according to the Bernoulli equation, acceleration of air masses under adiabatic conditions leads to their cooling. If the acceleration occurs along the isothermic oceanic surface, and no drop of air temperature is observed, this means that there is a heat input from the ocean. This heat input is thought to be partly transformed into the kinetic energy of air masses and partly lost to space (heat sink) via radiation of the greenhouse components of the upper atmosphere, the latter being colder than the oceanic surface.

Here we analyze several fundamental physical aspects of this approach. First, in thermodynamic engines the value of heat input is set externally and quantitatively determines all processes within the engine. In the process of isothermal acceleration of air masses over the oceanic surface the value of presumed oceanic heat input is related to wind velocity. In order that wind velocity could be numerically predicted (the main target of hurricane's theory) from the value of heat input, the latter should be determined independently. However, independent physical determinants of oceanic heat input are lacking. Second, at sufficiently high velocities the dynamic power developed per unit planetary surface within the area occupied by the hurricane exceeds the power of absorbed solar radiation (the latter equal to the heat flux released into space) by many times. Since the power of thermal radiation into space is, via radiative equilibrium, linked to the temperature of the upper atmosphere, in order to release this power into space via thermal radiation one would need atmospheric temperatures greatly exceeding the global mean surface temperature (+15°C) and the effective temperature of the planet (−18°C). This would imply heat transfer from a cooler object (oceanic surface) to a warmer object (the radiating upper atmosphere), which is impossible. Finally, the assumption that high wind speeds in hurricanes are due to the heat input from the ocean leaves one to seek for different physical mechanisms allowing for the even higher wind speeds observed in tornadoes that develop over the land surface. Could not these high-speed wind structures have a single physical cause? We explore these and related issues and provide a theoretical perspective of quantitatively accounting for hurricanes and tornadoes as adiabatic dynamic processes driven by phase transitions from gas to liquid (water vapor condensation) in the atmosphere.

2 Hurricane energetics and laws of thermodynamics

According to the first law of thermodynamics, work A performed by thermodynamic engines that receive heat $\Delta Q_s>0$ at temperature T_s and lose heat $\Delta Q_0>0$ at temperature T_0, is equal to

$$A = \Delta Q_s - \Delta Q_0, \quad T_s > T_0. \tag{1}$$

The second law of thermodynamics relates ΔQ_s and ΔQ_0 to temperatures T_s and T_0 in the reversible heat engines as

$$|\Delta S| \equiv \frac{\Delta Q_s}{T_s} = \frac{\Delta Q_0}{T_0}, \qquad \Delta Q_0 = \frac{T_0}{T_s}\Delta Q_s. \tag{2}$$

From the first and second laws of thermodynamics we have:

$$A = \frac{T_s - T_0}{T_s}\Delta Q_s, \qquad \varepsilon \equiv \frac{A}{\Delta Q_s} = \frac{T_s - T_0}{T_s} < 1. \tag{3}$$

The magnitude of ε, which is the efficiency of Carnot's reversible heat cycle, determines the maximum possible efficiency at which work can be produced in reversible heat engines. Inside real engines there are always irreversible heat losses on friction; their efficiency is invariably lower than ε (Eq. 3). Work produced by heat engines can be converted to potential energy of chemical or gravitational nature, or it can be transformed into practically non-dissipating kinetic energy like, for example, the kinetic energy of satellites rotating around the Earth, and stored in these forms. Or it can dissipate with the release of an amount of heat equal to A, but this can only occur outside the work-producing heat engine.

The amount of heat released in the course of dissipation of work A is unrelated to the amount of heat ΔQ_s consumed by the heat engine from the heat source. When work A is identified with ΔQ_s or if ΔQ_s is interpreted as the sum of ΔQ_s and A, the first (Eq. 1) or second (Eq. 2), (Eq. 3) laws of thermodynamics are violated. This is the main physical inconsistency of the existing theoretical accounts of hurricanes.

Indeed, as is shown below, in the works of Emanuel (1986, 1991, 1995) it is assumed that $\Delta Q_s = A$, which means that $\varepsilon = 1$, see Eq. (3). Consequently, in these cases either $\Delta Q_0 = 0$, or $T_0 = 0$. If $T_0/T_s = 2/3$, as it is assumed in the works of Emanuel (1986, 1991, 1995, 2003, 2005, 2006), then from the second equality in Eq. (Eq. 2) and the condition $\Delta Q_0 = 0$ it follows that $\Delta Q_s = 0$ and $A = 0$, i.e. the heat engine does not exist.

If, on the other hand, one assumes that the heat that forms in the course of dissipation of work A can be added to heat ΔQ_s, as it is done in the works of Bister and

Emanuel (1998) and Emanuel (2003, 2005, 2006), then, instead of Eq. (1), we have

$$A = \frac{T_s - T_0}{T_s}(\Delta Q_s + A), \quad A = \frac{T_s - T_0}{T_0}\Delta Q_s. \tag{4}$$

This relationship, that is explicitly present in the above papers, can be written in the following form

$$A = \Delta Q_s - \Delta Q_0 + \varepsilon A, \quad \varepsilon \equiv \frac{T_s - T_0}{T_s} \approx \frac{2}{3}. \tag{5}$$

which makes it clear that Eq. (4) comes in conflict with the first law of thermodynamics, Eq. (1). Generally, the very appearance of the multiplier $(T_s - T_0)/T_0$ in the second expression of Eq. (4) should have raised concerns in a physicist (see, e.g., Emanuel, 2006): temperature $T_0 < T_s$ can be chosen such that $(T_s - T_0) > T_0$, so that $A > \Delta Q_s$; besides, at $T_0 \to 0$ we have $A \to \infty$. These cases are extreme manifestations of the violation of the first law of thermodynamics.

3 Specific critique

3.1 Calculating heat input from the horizontal difference in the values of thermodynamic atmospheric parameters

The work of Emanuel (1991) on the theory of hurricanes summarizes much of the previous work. We start with the analysis of this paper to specifically point out where the assumption $\Delta Q_s = A$ was made. In Sect. 3.2 it is shown where the assumption $\varepsilon(\Delta Q_s + A) = A$ was made in subsequent works. Everywhere below numbers of formulae taken from the work of Emanuel (1991) are preceded by “E”.

Formula (E15) is, according to Emanuel (1991), obtained by integrating the Bernoulli Eq. (E1)

$$d\left(\frac{1}{2}|\boldsymbol{V}|^2\right) + d(gz) + \alpha dp + \boldsymbol{F} d\boldsymbol{l} = 0 \tag{E1}$$

(where $\boldsymbol{V}$ is velocity vector, g is acceleration of gravity, z is height, $\boldsymbol{F}$ is turbulent friction forces, $\boldsymbol{l}$ is streamline vector, $\alpha \equiv 1/\rho$, p is pressure, ρ is gas mass density) along the horizontal ($z=0$) streamline ac from the outer environment (a) to hurricane center (c).

Formula (E15) does not contain squared velocity $\boldsymbol{V}^2$, which is present in the Bernoulli Eq. (E1) and, as such, corresponds to the equality between work of turbulent friction forces $\oint \boldsymbol{F} d\boldsymbol{l}$ and work of pressure gradient forces A. Work of turbulent friction forces on the other parts of the trajectory of air masses is considered to be negligible (see p. 185, third paragraph from bottom in the work of Emanuel, 1991), i.e. $\oint \boldsymbol{F} d\boldsymbol{l} = \int_a^c \boldsymbol{F} d\boldsymbol{l}$. Already from Eq. (E15) it can be concluded that hurricane cannot exist: pressure gradient forces are exactly compensated by turbulent friction forces $\boldsymbol{F}$, only in this case velocity $\boldsymbol{V}=0$ can be dropped from Eq. (E15). In the result, Eq. (E15) can be written as

$$A = \int_a^c \boldsymbol{F} d\boldsymbol{l} = -\int_a^c \alpha dp = RT_s \ln\frac{p_a}{p_c} \approx \alpha_s \Delta p. \tag{E15}$$

Here p_a and p_c is atmospheric pressure in the center of the hurricane and outside the hurricane, respectively, $\Delta p \equiv p_a - p_c$, T_s is surface temperature, low index s refers to surface values of all variables, R is mass-specific gas constant ($R \equiv R_{\text{univ}}/M_d$, $M_d = 29\,\text{g mol}^{-1}$, $R_{\text{univ}} = 8.3\,\text{J mol}^{-1}\,\text{K}^{-1}$).

Joint consideration of Eq. (E15) and the following formulae of Emanuel (1991)

$$\oint T dS = \oint \boldsymbol{F} d\boldsymbol{l}, \tag{E4}$$

$$\varepsilon T_s \Delta S = \oint \boldsymbol{F} d\boldsymbol{l} \tag{E11}$$

(where integration is again made over the closed trajectory of air movement, S is entropy), in the view of Eq. (1) and Sect. 3.4 in this paper yields $\varepsilon=1$

$$\Delta Q_s - \Delta Q_0 = \varepsilon \Delta Q_s = \oint \boldsymbol{F} d\boldsymbol{l} = \int_a^c \boldsymbol{F} d\boldsymbol{l} = A,\ \text{i.e.},\ \varepsilon = 1,\ \text{as}$$

$\Delta Q_s \equiv T_s \Delta S, \quad \Delta Q_0 \equiv T_0 \Delta S, \quad \Delta Q_0 = 0$, see Sect. 3.4.

At ε=1 Formulae (E16) and (E7),

$$\varepsilon T_s \Delta S = RT_s \ln \frac{p_a}{p_c} \quad \text{(E16)}$$

(in Eq. E16 the last term was dropped due to its negligibly small magnitude, as estimated by Emanuel, 1991),

$$T_s \Delta S = RT_s \ln \frac{p_a}{p_c} + L_v(q_c - q_a), \quad \text{(E7)}$$

where q_a and q_c are the mass shares of water vapor in the atmosphere outside the hurricane and in the hurricane center, respectively, L_v is the mass-specific heat of vaporization, yield

$$L_v(q_c - q_a) = 0.$$

This means that the flux of latent heat from the ocean to the atmosphere is zero. Taking this result into account and recalling that in the work of Emanuel (1991) it is assumed that the process along streamline *ac* is isothermic, ΔT=0, one obtains from Eqs. (E15) and (E2)

$$dQ = TdS = c_p dT + d(L_v q) - \alpha dp, \quad \text{(E2)}$$

that

$$\Delta Q_s \equiv T_s \Delta S = \alpha_s \Delta p = A.$$

To summarize, the observed mechanical work A of the hurricane is equated to heat increment ΔQ_s. This comes in conflict with the first and second laws of thermodynamics, Eqs. (1–3), at T_0>0.

3.2 Calculating heat input from the vertical difference in the values of thermodynamic atmospheric parameters

In later works, starting from the work of Emanuel (1995), the logic of calculations changes. Heat increment ΔQ_s is related not to the horizontal difference between the atmospheric thermodynamic parameters inside and outside the hurricane, but to the vertical difference between the thermodynamic parameters of air in the hurricane and air in the narrow layer above the air-sea interface. Thickness of this transition layer, where all processes are driven by molecular diffusion, is about 50 mm above the water surface. The contribution of processes within this layer to hurricane energy budget is of the order of the ratio between thickness of the transition layer and thickness of atmospheric layer $h \sim 10$ km where water vapor condensation and the hurricane actually take place. This ratio is about 10^{-6}, so the microscopic surface layer makes no impact on hurricane energetics.

In the work of Emanuel (1991) the volume difference between the considered layers is not taken into account. The difference in heat increments between the transition layer and the atmosphere is calculated in terms of mass-specific values, i.e. per unit air mass. Air pressures in the atmosphere (a) and in the surface layer (s) being equal ($\Delta_z p \equiv p_s - p_a = 0$), the mass-specific difference of heat increments in these layers, $\Delta_z Q$, is equal to the difference of their mass-specific enthalpies, which is $k_s^* - k_a$ in the notations of Emanuel (1995), i.e., according to Eq. (E2) above, it is assumed by Emmanuel (1995) that $\Delta_z Q = k_s^* - k_a = c_p \Delta_z T + \Delta_z (L_v q)$. The value of $\Delta_z Q$ can be in principle calculated from the temperature and absolute humidity differences between the macroscopic layer at the surface and at some height in the atmosphere. However, $\Delta_z Q$ is not related to the horizontal heat increment $\Delta_x Q \equiv \Delta Q_s$ and is not related to the horizontal pressure change $\Delta_x p \equiv \Delta p \equiv p_a - p_c$ between the hurricane center and its outer environment, $\Delta_x Q = \Delta_x (L_v q) - \alpha \Delta_x p$ for isothermal process, see Eq. (E2). Substitution of $\Delta_x Q$ by $\Delta_z Q = k_s^* - k_a$ as applied by Emanuel (1991) and used in subsequent works, is not justified.

Starting from the work of Bister and Emanuel (1998) it is assumed (see Formulae 20 and 21 therein) that the power of mechanical work generation is added to heat input ΔQ_s, so that $A = \varepsilon(\Delta Q_s + A)$. The interpretation given is that heat formed during dissipation of work A, which is equal to work A in magnitude, is recirculated within the heat engine, so the greater the dissipative losses, the greater the work. Formula (8) in the work of Emanuel (2003) is equivalent to Eq. (4) of the present paper (see also Formulae 5–7 of Emanuel, 2003, where 8 is multiplied by $\rho \boldsymbol{V}$). As discussed above, this is in conflict with the first law of thermodynamics, where, fundamentally, the magnitude of ΔQ_s stands for the external input of heat into the engine and does not account for processes within the engine. A relationship equivalent to Eq. (4) of the present paper is present in the literature starting from the work of Bister and Emanuel (1998) including the works of Emanuel (2003, 2005, 2006).

3.3 Estimates of dissipative heating

In the work of Bister and Emanuel (1998), which aims to quantify the input of dissipative heating into hurricane energy budget, there is an additional physical problem. It is correctly stated in the paper that “frictional dissipation of kinetic energy ultimately occurs at molecular scales”, with molecular friction forces correctly described by Formula (1) of Bister and Emanuel (1998) (BE)

$$\frac{\partial}{\partial x_j}\left(\nu \frac{\partial u_i}{\partial x_j}\right), \tag{BE1}$$

where ν is the molecular kinematic viscosity; $\nu \sim u_m l_m \sim 10^{-5}\,\mathrm{m^2\,s^{-1}}$, where $u_m \sim 500\,\mathrm{m\,s^{-1}}$ is velocity of molecules, $l_m \sim 10^{-7}$ m is the mean free path length of air molecules. It is well-known that molecular kinematic viscosity is 10^8 times smaller than the eddy viscosity ν_e, which in hurricanes is of the order of $\nu_e \sim u_z h \sim 10^3\,\mathrm{m^2\,s^{-1}}$, i.e. $\nu/\nu_e \sim 10^{-8}$, where $h \sim 10$ km is atmospheric scale height, u_z is vertical wind velocity. For this reason the molecular friction forces that correspond to energy dissipation

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into thermal energy, are by the same amount smaller than the turbulent friction forces, these unrelated to dissipation into the thermal energy of chaotic molecular motion. As far as the linear scale of hurricane velocity change is macroscopic and is of the order of atmospheric height scale h, molecular friction forces are of the order of $\nu u/h^2$. Formula (5) used in the work of Bister and Emanuel (1998) is

$$\nu \frac{\partial u_i}{\partial x_3}\bigg|_0 = C_D u_i \sqrt{u_1^2 + u_2^2}. \qquad \text{(BE5)}$$

Hurricane horizontal velocities are of approximately one and the same order of magnitude, $u_i \sim u_1 \sim u_2 \sim u$ and $\partial u_i/\partial x_3 \sim u_z/h$ ($x_3 \equiv z$), consequently, from Eq. (BE5) we have $\nu \frac{\partial u_i}{\partial x_3}\big|_0 \sim \nu u_z/h \sim C_D u^2$. Since $C_D \sim u_*^2/u^2$ and $u_z \sim u_*$ (see, e.g., Businger and Businger, 2001), we have $\nu \sim u_z h \sim 10^3\,\mathrm{m^2\,s^{-1}}$, which means that instead of molecular kinematic viscosity in all subsequent formulae of Bister and Emanuel (1998) it is eddy viscosity that is used.

Eddy viscosity and turbulent friction forces characterize transformation of the kinetic energy of large macroscopic eddies into kinetic energy of smaller, yet also macroscopic, eddies. Eddy viscosity does not describe conversion of kinetic energy to heat; for this reason it cannot be used in the estimates of dissipative heating (e.g., Businger and Businger, 2001). In the result of the replacement of molecular kinematic viscosity by eddy viscosity in the work of Bister and Emanuel (1998) and subsequent papers the magnitude of dissipative heating was overestimated by about 10^8 times.

3.4 Quantifying heat loss to space

The discussed inconsistencies in the handling of the hurricane's energy budget essentially reflect the inherent theoretical problem of the hurricane-as-heat-engine approach, namely the absence of independent physical determinants of the presumed flux of heat from the ocean to the atmosphere within the hurricane area. This conceptual problem persists independently of the magnitude of wind velocities that are attempted to be explained. There is, however, an additional quantitative consideration that specifically shows that the high-intensity wind structures as hurricanes cannot represent a Carnot cycle with heat input from the ocean and heat loss to space.

The vertical flux of latent heat (LH) released in the ascending air masses within the hurricane can be estimated as $F_{LH}=u_z \Delta\rho_v L_v$, where $\Delta\rho_v$ is change of water vapor mass density over atmospheric scale height h. Exponential scale height of water vapor distribution being $h_v \sim 2$ km, we have $\Delta\rho_v \sim \rho_v$ (i.e. practically all ascending water vapor undergoes condensation). Taking into account that $L_v=2.4\,\mathrm{kJ\,g^{-1}}$ and $\rho_v \sim 50\,\mathrm{g\,m^{-3}}$, at vertical velocity of $u_z \sim 0.1\,\mathrm{m\,s^{-1}}$ we obtain $F_{LH} \sim 4\times10^3\,\mathrm{W\,m^{-2}}$, i.e., at least 20 times larger a flux than the flux of solar radiation absorbed by the surface in the tropics (Hatzianastassiou et al., 2005). This is a conservative estimate, because in intense hurricanes vertical velocities can be much higher than $10\,\mathrm{cm\,s^{-1}}$ (Samsury and Zipser, 1995; Eastin et al., 2005).

If this latent heat flux or its considerable part had been converted to thermal power in the area occupied by the hurricane, thermal radiation to space from this area would have been by the same magnitude greater than the global mean flux of thermal radiation into space. The latter flux corresponds to brightness temperature $T_b=255$ K that is by 33 K lower than the global mean surface temperature $T_s=288$ K. As far as, according to Stephan-Boltzmann law, the flux of thermal radiation is proportional to the fourth power of brightness temperature, in such a case thermal radiation to space from areas occupied by hurricanes would have had a mean brightness temperature in excess of $T_b\times(20)^{1/4} \sim 600$ K. Consequently, the hurricane's power cannot be maintained at the expense of the on-going heat absorption from some external medium like the ocean. This would violate the second law of thermodynamics: in the absence of heat sink, thermal energy of the ocean cannot be converted to mechanical work. It follows that in reality hurricane's energy, including kinetic energy of small eddies and the released latent heat, is transported far away from the hurricane area. It further dissipates to thermal radiation and is emitted to space from an area much larger than the one occupied by the hurricane and at a power similar in its order of magnitude to the global mean power of the absorbed solar radiation.

4 Discussion

We have argued that representing hurricanes as Carnot heat engine is not physically consistent. We will now outline a perspective of a quantitative description of hurricanes as adiabatic processes involving gas-liquid phase transitions[1]. Briefly, during condensation, water vapor disappears from the gas phase; in the result, local air pressure drops; this leads to the appearance of the wind-inducing pressure gradient force proportional in magnitude to the amount of water vapor in the atmosphere. The volume-specific store of potential energy responsible for hurricane formation can be thus estimated as the value of partial pressure p_v of saturated water vapor. (Vertical distribution of water vapor partial pressure p_v departs significantly from the aerostatic equilibrium; at any height p_v is over five times larger than the weight of water vapor column above this height (Makarieva et al., 2006; Makarieva and Gorshkov, 2007). For this reason practically all water vapor ascending in the hurricanes undergoes condensation, so the condensational potential energy coincides with p_v to a good approximation.)

According to Bernoulli's equation, potential energy p_v (J m^{-3}) is transformed to kinetic energy $\rho u_{\max}^2/2$ (J m^{-3}) of air masses having density ρ and moving at velocity $u_{\max}$ as $p_v = \rho u_{\max}^2/2$. At $\gamma_v \equiv p_v/p = 0.02$ at 15°C or $\gamma_v = 0.05$ (at 30°C) and $\gamma_v = 0.09$ (at 40°C on land), moist air pressure $p = 10^5$ Pa and $\rho = 1.2$ kg m^{-3} we have $u_{\max} = 50$ m s^{-1} or $u_{\max} = 90$ m s^{-1} and $u_{\max} = 120$ m s^{-1}, respectively. These values agree with observations of maximum wind velocities observed in hurricanes and tornadoes (Zrnić and Istok, 1980; Samsury and Zipser, 1995; Wurman et al., 1996; Businger and Businger, 2001). This approach also explains the pronounced dependence of hurricane's inten-

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[1] Gorshkov, V. G. and Makarieva, A. M.: The osmotic condensational force of water vapor in the terrestrial atmosphere, Preprint 2763, Petersburg Nuclear Physics Institute, Gatchina, 43 pp., available at: http://www.bioticregulation.ru/2763.php, 2008.

sity on surface temperature.

Hurricanes and tornadoes could be compared to an explosion reversed and prolonged in time. In the ordinary explosion potential energy concentrated in the explosion center is released in a burst, making local air pressure rise sharply and causing dynamic air movement in the direction away from the explosion center. Conversely, condensation of saturated water vapor within the column of ascending air in hurricanes and tornadoes leads to a sharp drop of local air pressure. This further enhances the ascending motion of yet accelerating air masses, as well as the compensating radial fluxes of moist air incoming to the area where the process of condensation is most intensive. Water vapor contained in the incoming air undergoes condensation in the same area; this sustains the pressure difference between the hurricane center and its environment. Hurricane could also be compared to a black hole, which sucks the surrounding air into the center, where it partially “annihilates” due to condensation of water vapor and its disappearance from the gas phase. Thus, hurricane is an “anti-explosion”. While in explosion the gas phase appears from either liquid or solid phase, in hurricanes and tornadoes, conversely, the gas phase of water vapor partially disappears from air due to condensation.

Unlike in explosion, the velocity of air masses in hurricanes and tornadoes is significantly lower than the velocity of thermal molecular motion. In consequence, all air volumes are in thermodynamic equilibrium, so that air pressure, temperature and density within the hurricane conform to equilibrium thermodynamics. The driving force of all hurricane processes is a rapid release, as in compressed spring, of potential energy previously accumulated in the form of saturated water vapor in the atmospheric column during a prolonged period of water vapor evaporation under the action of the absorbed solar radiation. Since the power of the practically instantaneous energy release in the hurricane greatly exceeds the power of energy exchange with the environment, all hurricane processes can be described as adiabatic. The outlined approach predicts that high wind velocities can develop anywhere in the atmosphere (over land as well as over the ocean), where absolute humidity is high and the process of condensation is spatially non-homogeneous. It thus provides a unifying theoretical framework for understanding both hurricanes and tornadoes.

Acknowledgements. This work is partially supported by NSF and UC Agricultural Experiment Station.

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