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Putting to rest WISHE-ful misconceptions for tropical cyclone intensification

Michael T. Montomery[1], **John Persing**[1], **and Roger K. Smith**[2]

[1]Department of Meteorology, Naval Postgraduate School, Monterey, California, USA, [2]Meteorological Institute, Ludwig Maximilians University of Munich, Munich, Germany

Key Points:
- WISHE is not the essential intensification mechanism for TCs
- WISHE is inconsistently represented in educational material
- Some minimal enthalpy fluxes are only needed to maintain convection

Correspondence to:
M. T. Montgomery,
mtmontgo@nps.edu

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Abstract The purpose of this article is twofold. The first is to point out and correct several misconceptions about the putative WISHE mechanism of tropical cyclone intensification that currently are being taught to atmospheric science students, to tropical weather forecasters, and to laypeople who seek to understand how tropical cyclones intensify. The mechanism relates to the simplest problem of an initial cyclonic vortex in a quiescent environment. This first part is important because the credibility of tropical cyclone science depends inter alia on being able to articulate a clear and consistent picture of the hypothesized intensification process and its dependencies on key flow parameters. The credibility depends also on being able to test the hypothesized mechanisms using observations, numerical models, or theoretical analyses. The second purpose of the paper is to carry out new numerical experiments using a state-of-the-art numerical model to test a recent hypothesis invoking the WISHE feedback mechanism during the rapid intensification phase of a tropical cyclone. The results obtained herein, in conjunction with prior work, do not support this recent hypothesis and refute the view that the WISHE intensification mechanism is the essential mechanism of tropical cyclone intensification in the idealized problem that historically has been used to underpin the paradigm. This second objective is important because it presents a simple way of testing the hypothesized intensification mechanism and shows that the mechanism is neither essential nor the dominant mode of intensification for the prototype intensification problem. In view of the operational, societal, and scientific interest in the physics of tropical cyclone intensification, we believe this paper will be of broad interest to the atmospheric science community and the findings should be useful in both the classroom setting and frontier research.

1. Introduction

Over the past five decades, substantial scientific efforts have been devoted to constructing paradigms of tropical cyclone intensification. The four most prominent paradigms are: (1) the CISK paradigm [*Charney and Eliassen*, 1964; *Ooyama*, 1964; *Carrier*, 1971]; (2) the cooperative intensification paradigm [*Ooyama*, 1969, 1982; *Willougby*, 1990, 1995]; (3) a thermodynamic air-sea interaction instability paradigm [*Rotunno and Emanuel*, 1987; *Emanuel*, 1989; *Emanuel et al*., 1994; *Emanuel*, 1997, 2003; *Holton*, 2004]; and (4) a new rotating convective paradigm (*Nguyen et al*. [2008] [hereafter M1]; *Montgomery et al*. [2009] [hereafter M2]; *Smith et al*. [2009]; *Bui et al*. [2009] [hereafter M4]; *Fang and Zhang* [2011]; *Persing et al*. [2013]). These paradigms are reviewed and compared by *Montgomery and Smith* [2014].

The first three intensification paradigms assumed axisymmetric flow (no departures from axial symmetry about the vortex rotation axis, i.e., no azimuthal eddies) and a simple tropical environment without uniform flow or vertical shear. The quiescent environment has served historically as the prototype configuration for understanding basic aspects of tropical cyclone intensification not involving strong interactions with the storm environment.

The air-sea interaction instability paradigm for vortex intensification comprises a postulated *multistep feedback loop* involving, in part, the near-surface wind speed and the evaporation of water from the underlying ocean, with the evaporation rate being a function of wind speed and thermodynamic disequilibrium. The evaporative-wind feedback mechanism is now commonly known as the Wind-Induced Surface Heat Exchange (WISHE) mechanism. Until very recently, the WISHE mechanism has been presented as a finite-amplitude instability that requires a *finite-amplitude precursor disturbance* generated by some independent

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14. ABSTRACT
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means (such as an easterly wave) to “kick start the heat engine” [cf. *Hakim*, 2011; *Holton and Hakim*, 2012, to be discussed later].

While the evaporation of water from the underlying ocean had been long recognized as the energy source for tropical cyclones [*Kleinschmidt*, 1951; *Riehl*, 1954; *Malkus and Riehl*, 1960; *Ooyama*, 1969], Emanuel’s contributions with colleagues refocused attention on the air-sea interaction aspects of the intensification process. Instead of viewing latent heat release in deep convective towers as the “driving mechanism” for vortex amplification, Emanuel showed that certain aspects of these storms could be understood in terms of a simple time-dependent, axisymmetric model [*Emanuel*, 1989] in which the latent heat release was implicit. Moreover, Rotunno and *Emanuel op. cit*. emphasized also the nonnecessity of convective available potential energy in the storm environment for intensification.

In this paper, the term “WISHE mechanism” will be used with its widely accepted meaning [e.g., *Holton*, 2004] as an amplification mechanism (i.e., a feedback process) that supports an intensifying tropical cyclone. We say more about the details of this envisaged mechanism below. In some subcircles, however, the term “WISHE mechanism” is being used more loosely as simply the bulk-aerodynamic transfer of moist enthalpy from the ocean to the atmosphere by the local prevailing winds. In this view, the term “WISHE mechanism” is indistinguishable from “bulk-aerodynamic enthalpy transfer”, and the latter is arguably more meaningful than its corresponding acronym. Here the enthalpy flux is invoked to offset the entrainment of drier air aloft into the boundary layer by convective and mesoscale downdrafts so that convective activity in the storm’s central region can be maintained. We find this definition too imprecise to be useful in a quantitative setting because such a mechanism would operate throughout the broad-scale summertime tropics in the trade easterlies and/or monsoonal westerlies and is not special to tropical cyclone intensification. Moreover, this view is historically inconsistent because the air-sea interaction instability was articulated first without explicit consideration of downdrafts [*Rotunno and Emanuel*, 1987, section 5]; the effects of downdrafts on intensification process are refinements of the envisaged development process. Our stance is supported by a leading tropical meteorologist and coworkers [*Molinari et al*., 2004] who wrote:

“The wind-induced surface heat exchange (WISHE) theory of *Emanuel* [1986] and *Rotunno and Emanuel* [1987] has continued to be refined [e.g., *Emanuel*, 1989, 1997]. The essence of the theory has remained the same, however: the pre-hurricane vortex must be of finite amplitude to develop, axisymmetry and slantwise neutrality are assumed, and development occurs basically as a feedback between surface wind speed and speed-dependent surface moist entropy flux. The WISHE-based developing hurricane contains no cold downdrafts nor strongly buoyant updrafts, and no asymmetric convection.”

Like the first three paradigms, the rotating convective paradigm is illustrated most easily for the prototype intensification problem as defined in M1 involving a quiescent environment, a circularly symmetric, cloud-free, cyclonic initial vortex of finite amplitude (say at or below tropical storm strength), a three-dimensional representation of explicit moist convection, and explicit air-sea transfer of momentum and latent and sensible heat. Unlike the first three paradigms, the rotating convective paradigm is intrinsically three-dimensional, but it contains an azimuthally averaged (mean field) dynamics that is forced in part by the averaged eddy momentum and eddy heat fluxes and their divergence, etc. The mean field dynamics of the rotating convection paradigm constitute an extended cooperative intensification paradigm in which eddy processes can contribute positively to amplifying the tangential winds of the vortex [*Persing et al*., 2013]. The positive contribution to vortex spin up by eddy processes demonstrated in *Persing et al*. [2013] contrasts with previous assumptions and speculation of the downgradient action of asymmetric motions (referred to as “turbulence,” but including vortical convection and vortex Rossby waves and their wave-mean flow and wave-wave interactions), which would lead to spin down [*Bryan et al*., 2010].

The similarities and differences of the foregoing intensification paradigms are discussed by *Montgomery and Smith* [2014]. The findings of *Persing et al*. [2013] suggest that previous studies using strictly axisymmetric models, and their attendant phenomenology of axisymmetric convective rings, have intrinsic limitations for understanding the intensification process.

Despite this significant progress in understanding tropical cyclone intensification in three dimensions and the demonstration in M2 that the WISHE mechanism is not essential to explain intensification, the WISHE intensification paradigm continues to be entrenched in meteorological descriptions of the intensification process [e.g., *Miyamoto and Takemi*, 2013] and textbook teachings of tropical cyclone intensification. Indeed, the paradigm still enjoys widespread acceptance in the leading dynamic meteorology textbook of *Holton and Hakim* [2012], and basic introductory textbooks [*Ahrens*, 2008; *The COMET Program*, 2013].

In this paper, we review first the mainstream descriptions of the WISHE intensification process often used in the teaching of hurricane dynamics. We move then to assess a recent description by *Miyamoto and Takemi* [2013] of the rapid intensification of the vortex in an idealized high-resolution hurricane simulation. These authors implicate the WISHE mechanism because of an association between the amplifying tangential wind; the increase of surface enthalpy fluxes; the increase of upper tropospheric equivalent potential temperature θ_e; and the lowest 1 km vertically-averaged θ_e near the high wind region of the vortex during the rapid intensification phase of the simulated cyclone (their Figures 3a and 3b). As is well known, the association of one effect (increase of near-surface wind speed) with another (increase of surface enthalpy flux) does not necessarily imply the two effects are causally linked. By conducting new idealized, three-dimensional numerical experiments using a state-of-the-art cloud model with capped wind speed in the latent and sensible heat fluxes at near trade wind values, we will demonstrate that the implied linkage between the increasing near-surface wind speeds and surface enthalpy fluxes is merely incidental. Indeed, the results of these calculations affirm that the putative multistep WISHE feedback mechanism is not an important pathway of tropical cyclone intensification in the idealized configuration that has been used to underpin the paradigm.

The outline of the paper is as follows. In section 2, we discuss the basic idea behind the WISHE mechanism as well as the many corruptions of this idea. In section 3, we review also the study of M2 that sought to provide a careful articulation of the mechanism and gave an analysis of nonhydrostatic, cloud representing numerical model simulations showing it to be unessential for explaining intensification. In section 4, we review the interpretation of the recent study by *Miyamoto and Takemi* [2013] on the role of WISHE in intensification. In section 5, we summarize a model that will be used to carry out new numerical experiments. In section 6, we analyze the results from these experiments. The main findings from this study are summarized in section 7, which should be useful in both the classroom setting and frontier research.

2. The WISHE Model

The evaporation-wind feedback intensification mechanism known as WISHE has been presented as a finite amplitude instability of an incipient tropical depression vortex and has achieved widespread acceptance in meteorology textbooks and other didactic material [e.g., *Rauber et al*., 2008; *Holton*, 2004; *Ahrens*, 2008; *The COMET Program*, 2013], tropical weather briefings, and the current literature [*Lighthill*, 1998; *Smith*, 2003; *Molinari et al*., 2004; *Nong and Emanuel*, 2004; *Montgomery et al*., 2006; *Terwey and Montgomery*, 2008; *Braun et al*., 2010; *Fang and Zhang*, 2010]. Indeed, the last five citations and others have talked about "igniting/commencing the WISHE mechanism" after the vortex (or secondary maximum in the tangential wind) has reached some threshold intensity.

For the purposes of this paper, the hypothetical WISHE mechanism is defined to be the intensification mechanism articulated by *Montgomery et al*. [2009] and *Montgomery and Smith* [2014]. As described by those authors, the WISHE mechanism is a multistep feedback loop of the axisymmetric flow and requires in part that the sea-to-air moisture fluxes increase with wind speed (see Figure 1 of M2). In the standard WISHE paradigm as articulated in M2, the vortex will *not* intensify *without* the wind-speed dependence of the moisture fluxes.

As will be illustrated below, there is a variety of explanations of the WISHE mechanism that possess notable ambiguities or inconsistencies for newcomers to the field and experts alike.

2.1. AMS Glossary 2013

In the American Meteorological Society's online glossary [*American Meteorological Society*, 2013], the term WISHE is used as "a hypothesis for the amplification of certain atmospheric circulations, including tropical cyclones, polar lows, and the Madden-Julian oscillation."

Quoting from the online glossary:

"The mechanism involves a positive feedback between the circulation and heat fluxes from the sea surface, with stronger circulation giving rise to larger surface fluxes of heat, which are then quickly redistributed aloft by convection, in turn strengthening the circulation. In this theory, emphasis is placed on the surface fluxes as the principal rate-limiting process; convection serves only to redistribute heat. This can be contrasted with conditional instability of the second kind (CISK), in which circulations amplify through their interaction with the convection itself."

Although the AMS explanation appears to share some similarity with the explanation presented in M2 for the problem of tropical cyclone intensification, there is ambiguity about which circulation is pertinent to the feedback process and what circulation is being amplified (i.e., the primary (swirling) or secondary (overturning) circulation, or the juxtaposition of both?). Also, the connection between the redistribution of heat aloft and the strengthening of the primary circulation is not clearly explained. What physical mechanism(s) are envisaged to strengthen the circulation(s)? The explanation fails also to mention whether the feedback process requires a finite-amplitude initiating disturbance as originally presented [*Rotunno and Emanuel*, 1987; *Emanuel*, 1989, 1991]. Finally, the explanation implies that the intensification rate is limited by the surface heat fluxes suggesting that, if the heat fluxes are greatly reduced from their nominal values, the intensification rate should be greatly reduced also. (As will be demonstrated later, this putative rate limiting property does not hold true when the heat fluxes in the high-wind region are effectively reduced by a factor of four, and thus this property does not appear to hold true in general.) The increase in the rate of surface heat transfer with increasing winds is noted explicitly.

2.2. Wikipedia [2013]

From Wikipedia [*Wikipedia*, 2013], the description of WISHE is as follows:

"The wind-induced surface heat exchange (WISHE) is a positive feedback mechanism between the ocean and atmosphere in which a stronger ocean-to-atmosphere heat flux results in a stronger atmospheric circulation, which results in a strong heat flux. It has been hypothesized that this is the mechanism by which low pressure areas in the tropics develop into tropical cyclones".

As with the AMS Glossary description, it is not clear what circulation is pertinent to the feedback mechanism and what circulation is being amplified. Also, it is strictly unclear what type of heat transfer is involved (i.e., sensible, latent or radiative heat transfer?). How precisely does the "stronger ocean-to-atmosphere heat flux" lead to a stronger atmospheric circulation? Interestingly, no explicit mention is given to the wind-speed-dependent nature of the heat flux.

2.3. Rauber et al. [2008]

In their textbook covering severe and hazardous weather, the authors present an informative chapter on Tropical Cyclones [*Rauber et al*., 2008, Chapter 24]. In this chapter, on pages 485–487, the authors pose the important question of "How thunderstorms organize into a hurricane"? They state that when the known necessary environmental conditions for development are met, "individual thunderstorms can quickly organize into a vortex." They go on to state that "scientists are still studying this process. The most promising theory about how this happens, called Wind Induced Heat Exchange (WISHE), considers the feedback that occurs between the heat and moisture transfer from the ocean surface and the development of the vortex (Figure 24.18)."

Their view of the WISHE feedback mechanism is described succinctly in the caption for their Figure 24.18:

"… Tropical cyclone intensification occurs as sensible and latent heat and moisture are extracted from the ocean surface by the action of the wind, and carried into the core of the tropical depression. Subsidence in the center of the cloud cluster leads to adiabatic warming and the lowering of surface pressure, intensifying the surface winds, and significantly increasing the rate of transfer of heat from the ocean to the atmosphere. The heat is transferred upward to the tropopause with the developing eyewall."

Unlike the WISHE mechanism as explained in M2 or the AMS Glossary, adiabatic warming on account of subsidence in the central region of the cloud cluster is envisaged to create the warming of the troposphere, which is then linked hydrostatically to the surface pressure drop and the presumed increase in maximum tangential wind speed, and so on. The increase in the rate of heat transfer with increasing winds is noted explicitly.

2.4. Fang and Zhang [2010]

In their study examining the initial development and genesis of Hurricane Dolly (2008), *Fang and Zhang* [2010, p. 655–656] summarized their view on the CISK and WISHE paradigms and in particular "the way in which mesoscale deep convection is organized to form a larger-scale TC (tropical cyclone - our addition) vortex. … In the framework of WISHE, winds associated with a surface vortex enhance fluxes of sensible and latent heat from the ocean surface, and vigorous convection transports the energy from the ocean surface to the upper troposphere and then fuels the intensification of the vortex."

A question that arises in this explanation of the WISHE development process is how does the transport of energy from the ocean surface to the upper troposphere "fuel the intensification of the vortex"? In particular, how does the vortex actually intensify by upward energy transport?

2.5. Kepert [2011]

Kepert [2011, p. 13] presents WISHE in the context of a steady state vortex as "The role of the surface enthalpy fluxes in making the expansion of the inflowing boundary layer air isothermal rather than adiabatic … ". Thus Kepert appears to associate the elevation of boundary-layer θ_e with just the sensible heating. Despite this, Kepert does not mention the necessity of the wind-speed dependence of the surface heat fluxes and does not make a distinction between dry and moist enthalpy in his discussion.

2.6. The COMET Program: Introduction to Tropical Meteorology, Chapter 8, Tropical Cyclones 2013

The public-domain web course provided by *The COMET Program* [2013] supports the education and training for the environmental sciences. Chapter 8 of the course offers a useful overview of basic tropical cyclone science. However, in the presentation, the WISHE acronym appears to have two different meanings.

In their section 8.4.1.2, the acronym WISHE first appears in the subsection title as an overarching acronym for "the Carnot cycle theory of potential intensity" [*Emanuel*, 1986, 1988]. On page 50, the tutorial states:

"An alternative view of a tropical cyclone is to consider it to be a closed system, a 'Carnot engine' [*Emanuel,* 1986, 1988] (Figure 8.32), rather than the moist, frictionally driven convective 'chimney' of CISK. A Carnot engine is a closed system in which heat energy is converted to mechanical energy. As with the CISK theory, this WISHE tropical cyclone intensity theory relies on the presence of a finite amplitude incipient disturbance [*Wroe and Barnes,* 2003]."

In the foregoing paragraph, WISHE is used as a theory for tropical cyclone potential intensity, and neither the wind-speed dependence of the fluxes of latent and sensible heat nor the putative wind-evaporative feedback mechanism that supports the intensification of the vortex are mentioned. Consistent with prior views of the WISHE concept by *Emanuel* [1989, 1991] and *Emanuel et al*. [1994], WISHE is presented as a process that will not operate without a finite-amplitude initial disturbance. (We will return to this latter point a little later.) However, the CISK theory is incorrectly implied (via a citation to *Wroe and Barnes* [2003]) to be a finite-amplitude instability [see *Montgomery and Smith*, 2014, and refs. for the CISK paradigm].

The discussion in this section of the COMET tutorial equates WISHE with the steady state "Carnot cycle" theory for potential intensity [*Emanuel*, 1986, 1988], which is now understood to be only a theory for the maximum gradient wind. The Carnot cycle theory has been shown to have both practical and fundamental limitations to the originally advertized "upper bound/maximum intensity" for tropical cyclone intensity [*Montgomery et al*., 2006; *Bell and Montgomery*, 2008; *Smith et al*., 2008; *Bryan and Rotunno*, 2009]. Moreover, questions have been raised recently about whether a realistic global steady state solution (presumed in the theory) is even possible without imposing an external cyclonic torque to offset the sink of cyclonic relative angular momentum that is lost to the sea by surface friction [*Smith et al*., 2014]. These technical points notwithstanding, in this section 8.4.1.2 where the WISHE term is first introduced, it is used as shorthand for the Carnot cycle potential intensity theory and not as an acronym for a vortex intensification mechanism. In fact, the *steady state* Carnot cycle model [*Emanuel*, 1986, 1988, 1991] was constructed without explicitly invoking the hypothetical feedback mechanism.

In the subsequent section 8.4.3 entitled “Links between Inner Core Dynamics, Cyclone Structure and Intensity”, one does find an intimation to WISHE as an intensification mechanism:

“As we have discussed, the key to a storm maintaining its current intensity or intensifying further is the maintenance of the deep convection surrounding its core. Maintenance of intensification by the WISHE process (*described in Section 8.4.1.2*) (our emphasis) requires a very moist boundary layer [*Bister,* 2001]. Subsaturated convective downdrafts will lower the relative humidity (and thus, the moist static energy) of the boundary layer [*Emanuel,* 1995], limiting the energy available to the storm. It will take a number of hours for evaporation to recover the boundary layer moisture before intensification can resume”.

Here, the evaporation of surface water is mentioned explicitly, but again neither the wind-speed dependence of the evaporation rate nor the multistep process that comprises the putative intensification mechanism is explicitly mentioned. Also, it is not explained how moist the boundary layer must become for the WISHE intensification process to resume or be maintained.

2.7. Holton [2004]

In section 9.7.2 of *Holton* [2004] entitled “Hurricane Development”, there is a summary of the WISHE mechanism. In this section, the classical (linear) CISK and modern WISHE models are compared (see *Montgomery and Smith* [2014] for a contemporary comparison of these two intensification paradigms and a detailed discussion of their strengths and weaknesses). Although not the focus of the current study, the CISK theory is no longer considered a viable model for tropical cyclone intensification for several reasons. One of the reasons is because there is little evidence that the envisaged organized interaction between the cumulus-scale and the large-scale moisture convergence leads to a linear growth rate maximum on the observed spatial scale of hurricanes. Another reason is furnished by an argument articulated by *Raymond and Emanuel* [1993] who concluded that the CISK closure for tropical cyclone vortices “fundamentally violates causality because convection is not *caused by* the macroscale water supply”.

Holton’s description of WISHE is as follows:

“According to the WISHE view, illustrated schematically in Figure 9.15b, the potential energy for hurricanes arises from the thermodynamic disequilibrium between the atmosphere and the underlying ocean. The efficacy of air-sea interaction in providing potential energy to balance frictional dissipation depends on the rate of transfer of latent heat from the ocean to the atmosphere. This is a function of surface wind speed; strong surface winds, which produce a rough sea surface, can increase the evaporation rate greatly. Thus, hurricane development depends on the presence of a finite-amplitude initiating disturbance, such as an equatorial wave, to provide the winds required to produce strong evaporation. Given a suitable initial disturbance, a feedback may occur in which an increase in inward spiraling surface winds increases the rate of moisture transfer from the ocean, which by bringing the boundary layer toward saturation *increases the intensity of the convection, which further increases the secondary circulation* (our emphasis)”.

The description of the feedback process is presented in the system-scale context, presumably for the azimuthally averaged component of the flow, and explicitly notes the wind-speed dependence of the moisture fluxes as well as the importance of bringing the boundary layer toward saturation. The description notes also the necessity of an initiating disturbance of possibly independent origin. However, it is unclear to us what specific metric is meant by “increases the intensity of convection” and by what process(es) the increase in convective intensity results in an increase in the secondary circulation. The increase of the secondary circulation leads presumably to an increase of the primary circulation by angular momentum considerations, but the description is silent about this.

In basic terms, convective intensity could be measured by a local vertical velocity maximum, a local upward mass flux, a local diabatic heating rate, a local updraft buoyancy, or corresponding azimuthal averages of these quantities assuming the presence of a population of clouds and a robust and well-defined mesoscale circulation center, so that a traditional “mean-eddy” partitioning is meaningful. However, these local intensity measures are generally distinct metrics. Moreover, their azimuthal averages cannot be expected to behave like their local counterparts [*Persing et al*., 2013]. It is certainly physically incorrect to assume that all the mass that converges in the boundary layer can be ventilated by the convection, since the ability of the convection to "ventilate" the converged mass depends *inter alia* on the buoyancy of the convective updrafts, which, in turn, depends not just on whether the boundary layer air is near saturation, but on the thermodynamic properties of the converged air in relation to the stability of the air in the vortex aloft. Also, the vertical mass flux out of the boundary layer alone does not determine the diabatic heating rate within deep convection, or the radial gradient of this heating rate. However, it is precisely the radial gradient of the heating rate and its vertical profile that would determine the axisymmetric balance response of the vortex above the boundary layer (e.g., M4, and refs. therein). In short, one must be cautious of discussing a feedback with convection without considering a model or parameterization of convection. Indeed, different convective parameterizations can lead to quite different outcomes (see e.g., *Zhu et al*. [2001]) and one closure on cloud base mass flux that sets it equal to the mass convergence in the boundary layer is known to be unrealistic [*Raymond and Emanuel*, 1993].

2.8. Holton and Hakim [2012]

In the latest update to Holton's text [*Holton and Hakim*, 2012], there appears to be no difference in the description of the feedback process described above, and so the foregoing assessment continues to hold true. However, there is a significant deviation from the traditional viewpoint that the WISHE mechanism requires a finite amplitude initiating disturbance (p321): "While it appears that observed cases of tropical cyclogenesis require finite-amplitude initial disturbances, the reason is likely that such disturbances require a shorter period of time to reach maturity. As initial disturbance amplitude decreases, the time required to reach maturity increases, as does the probability of adverse environmental factors disrupting the process." The basis for this updated viewpoint appears to be rooted in the results presented in *Hakim* [2011] using a strictly axisymmetric numerical model to study tropical cyclogenesis and statistically steady hurricanes for 400 days. Inferring from what is presented in *Hakim* [2011] and the updated version of Holton's textbook, the WISHE mechanism and the problem of tropical cyclogenesis for an idealized quiescent atmosphere appear now to have descended to a CISK-like realm of a *linear axisymmetric instability of the tropical atmosphere*!

Observations have long suggested that tropical cyclogenesis is far from an axisymmetric process [e.g., *Ooyama*, 1982; *Montgomery and Enagonio*, 1998]. In view of the findings from *Persing et al*. [2013] summarized in the Introduction, one should be extremely cautious in a textbook when drawing inferences about the convective organization process in a three-dimensional tropical atmosphere using results from a strictly axisymmetric model and its corresponding phenomenology of moist convective rings, especially when these rings occur at large radius.

2.9. Summary

Examination of the widely available published literature reveals that there are sometimes contradictory definitions of WISHE as well as ambiguous and generally incomplete descriptions of the putative intensification mechanism. This is an undesirable state of affairs for students, researchers, forecasters, and the informed lay person who desire a clear understanding of how tropical cyclones intensify for the prototypical problem of an initially unsaturated balanced cyclonic vortex in a quiescent environment on an *f*-plane.

3. M2 Summary

As discussed in the foregoing section, the WISHE theory continues to be the widely accepted explanation of tropical cyclone intensification. However, M2 presented a critical examination of the base hypothesis: namely, that the positive feedback between surface moisture fluxes and surface wind speed (a function of vortex intensity) is the root cause of tropical cyclone intensification. Their study used both the MM5 numerical model [*Dudhia*, 1993; *Grell et al*., 1995] with a finest grid mesh spacing of 1.67 km and the *Rotunno and Emanuel* [1987] axisymmetric hurricane model with a horizontal mesh spacing of 3 km. On the whole, the axisymmetric results confirmed the results of the MM5 model, the latter of which will be the focus of this discussion. The environmental parameters of the idealized MM5 experiments were similar to those of *Rotunno and Emanuel* [1987]: an environment without vertical environmental wind shear, an initial atmosphere that is nearly neutral to convective instability (very low CAPE), and what is traditionally considered to be a marginal sea surface temperature for hurricane development (27 C).

M2 analyzed experiments designed specifically to suppress the standard WISHE feedback loop as described above. The suppression was executed by capping the value of surface wind speed to near trade wind values ($\sim$ 5–10 m s^{-1}) where it appears in the bulk aerodynamic scheme for moisture and sensible heat exchange. The surface scheme is posed as a function of near-surface wind speed and air-sea disequilibrium of moisture and heat (see M2 and M1 for details). Numerical experiments using the MM5 model were presented with and without evaporative downdrafts to show that intensification from a finite-amplitude initial cyclonic vortex does not require this hypothesized evaporation-wind feedback process. Thus the results were shown to transcend the specific representation of the rain-out process and related thermodynamical processes.

Compared to a control experiment without capping of the wind speed in the surface heat fluxes, the capped experiment did not fail to intensify, being only delayed in its initial gestation period by approximately 1 h and never being more than 15 m s^{-1} weaker than the control. Moreover, the vortex still intensified by the same pathway identified in the control experiments via the generation of locally buoyant vortical hot towers (VHTs) and the convergence of absolute angular momentum that the aggregate VHTs induce just above and within the boundary layer. Although the surface fluxes were artificially reduced in magnitude, they were nonetheless sufficient to restore the value of boundary layer equivalent potential temperature (θ_e) that had been reduced by downdrafts outside the eyewall to values sufficient to support development of eyewall convection in the form of VHTs. The insight that emerged from these experiments was that only modest enthalpy fluxes were necessary to support the intensification process, far less than previously assumed, and the hypothetical evaporative-wind feedback mechanism was not important.

3.1. Open Issues

Although M2 advocated further tests of their results, the evidence presented therein seemed sufficient to demonstrate the nonessential nature of the WISHE mechanism to the tropical cyclone intensification process. However, since the findings of M2 were restricted to only two models (the MM5 and the axisymmetric *Rotunno and Emanuel* [1987] model) at marginally cloud-resolving scales, critiques could be levied that further tests using more advanced models, higher resolution, more sophisticated microphysics, and boundary layer formulations, etc., are still warranted. To partly address these concerns, we will revisit the intensification phase of a small suite of idealized hurricane simulations using the state-of-art cloud model CM1 [*Bryan and Fritsch*, 2002].

4. A Recent Invocation of the WISHE Mechanism: *Miyamoto and Takemi* [2013]

As summarized in the Introduction, the new experiments conducted herein are motivated in part by the study of *Miyamoto and Takemi* [2013], who attempted to understand the transition between their simulated slow intensification phase (phase 1) and the rapid intensification (RI) phase (phase 2) of their simulated hurricanes as illustrated in their Figure 3. In their study, they described WISHE as a theory for the spontaneous intensification process (p112, right column):

"Given a cyclonic disturbance on the warm ocean, winds at the ocean surface drive sea surface enthalpy fluxes and the increased enthalpy fluxes, whose magnitude approximately depends linearly on the wind speed, enhance the radial gradient of equivalent potential temperature θ_{e} in the upper troposphere, which in turn *accelerates the tangential wind in the lowest layer of the atmosphere* (our emphasis) (See Figure 1 of *Montgomery et al.* [2009]). Such a spontaneous intensification is one of the fastest intensifying processes that a TC (tropical cyclone, our addition) experiences during its lifetime and therefore is referred to as RI in this study".

From the cited passage, it is unclear how the radial gradient of θ_e is enhanced in the upper troposphere and how this enhancement causes an acceleration of the tangential wind in the boundary layer ("the lowest layer of the atmosphere"). The explanation provided in M2 invoked the lofting of the hypothetically enhanced boundary layer θ_e into the upper troposphere and the conversion between latent heat and sensible heat during the phase change of water vapor to liquid water to yield an increase of the virtual temperature aloft. The tangential wind increase at the top of the boundary layer associated with the hypothesized increase in radial θ_e gradient was argued (following *Emanuel* [1986]) to be a consequence of integrating the axisymmetric thermal wind equation, together with a reversible Maxwell thermodynamic relation, downward along the absolute angular momentum surface that passes through the radius of maximum tangential wind at the top of the boundary layer (see Figure 1 of M2 and accompanying discussion).

(As a point of clarification, nowhere in M2 was the association between WISHE and RI ever made. The WISHE schematic articulated by M2 explains physically only the sign of the tangential wind tendency in the core region at the top of the boundary layer; it does not provide a means for quantifying the tendency. Efforts to quantify the tendency of the tangential wind associated with the hypothesized WISHE mechanism have been made by others, but these efforts fall short of an acceptable intensification theory for one reason or another [see *Montgomery and Smith*, 2014 for more details].)

These technical points notwithstanding, it seems clear that *Miyamoto and Takemi* [2013] effectively equate the RI process with the hypothesized WISHE mechanism. This interpretation is solidified by their own discussion of their Figure 3b, which is based on a time series of the surface enthalpy flux and the vertically averaged θ_e in the lowest 1 km at the radius of maximum tangential wind:

"The results shown in Figure 3 as well as the angular momentum field strongly suggest that during phase 2, the simulated TC vortex intensifies through the WISHE mechanism that is a spontaneous intensifying process, as described in the introduction."

In their Conclusion section (p127, rc), they appear to temper this inference somewhat:

"To examine the mechanism for the transition of TCs to the RI phase, numerical experiments are carried out by using a three-dimensional, fully-compressible numerical model (WRF). … Specific analysis focusing on the intensification phase including the RI phase of the simulated TC, reveals the following points. *The WISHE mechanism seems to play a role in the RI (phase 2) of the simulated TC (Figure* 3*)*. (our emphasis) …"

Nevertheless, on the basis of their own descriptions, it seems indisputable that *Miyamoto and Takemi* implicate an important role for the WISHE mechanism during the RI phase of their simulated storms. This implication seems to originate from their Figures 3a and 3b, which naively suggests a link between the amplifying tangential winds and the increase of surface enthalpy fluxes during the rapid intensification phase of the simulated vortex. However, as is well known, the association of one effect with another does not necessarily imply that the two effects are causally linked.

By suppressing the wind-speed dependence of the enthalpy fluxes in the state-of-the-art CM1 model, we demonstrate in the next section that the implied association between the amplifying tangential winds and the increase of surface enthaply fluxes during the rapid intensification phase of the simulated vortex is largely coincidental. The new simulation experiments will be shown also to support all of the key findings and interpretations of M2, and the summary thereof provided in the Introduction.

5. The Model and the Numerical Experiments

The model to be used in the examination of the putative WISHE mechanism is the numerical model CM1 version 14, a nonhydrostatic and fully compressible cloud model [*Bryan and Fritsch*, 2002]. (For a complete description of the three-dimensional model and variable definitions, see the technical document "The governing equations for CM1", available for download at http://www.mmm.ucar.edu/people/bryan/cm1 and from G. Bryan.)

5.1. The Model Set Up

The control simulation, denoted as "EX-1", is the "3D3k" simulation of *Persing et al*. [2013]. Ice microphysical processes and dissipative heating are neglected for simplicity. The reference sounding is a nearly moist-neutral sounding generated from the *Rotunno and Emanuel* [1987] model. Radiative effects are represented crudely by a simple Newtonian relaxation to the potential temperature of the basic state sounding, capped to 2 K d^{-1}. A simple rainfall scheme is used with fixed fall speed of 7 m s^{-1}. Calculations are carried out on an *f*-plane corresponding to 20° N with a fixed sea surface temperature (SST) of 299.3 K.

Subgrid-scale turbulence is represented by choosing the available option ("iturb=3") in the model, which is designed for problems that do not resolve any part of the turbulent Kolmogorov inertial range. This option follows *Smagorinsky* [1963] and *Lilly* [1962]. The horizontal and vertical mixing lengths required in this subgrid-scale formulation are chosen to be consistent with recent observations of intense hurricanes at the base of the eyewall region for horizontal wind speeds ≈ 50 m s^{-1} [*Zhang and Montgomery*, 2012; *Zhang et al.*, 2011]: $l_h = 700$ m and $l_v = 50$ m, where l_h and l_v are the horizontal and vertical mixing lengths, respectively.

The air-sea interaction is modeled using bulk aerodynamic formulae, with bulk enthalpy coefficient $C_k = 1.29\times10^{-3}$ and a surface drag coefficient that is twice that value, i.e., $C_D=2.58\times10^{-3}$. The value of C_k is close to the mean value (1.2×10^{-3}) derived from the Coupled Boundary Layers/Air-Sea Transfer (CBLAST) experiment (Figure 6 of *Black et al.* [2007]; Figure 4 of *Zhang et al.* [2007]), a recent laboratory study (Figure 1 of *Haus et al.* [2010]) near and slightly above marginal hurricane wind speeds, and an energy and absolute angular momentum budget analysis of the lower-tropospheric eyewall region at major hurricane wind speeds [*Bell et al.*, 2012]. The drag coefficient is close to the estimated mean value of $C_D=2.4\times10^{-3}$ from the CBLAST-derived observations for major hurricane wind speeds [*Bell et al.*, 2012].

In the center of the computational domain (400 by 400 km), a fine mesh region is employed with a grid spacing of 3 km in the horizontal. This fine grid mesh is then stretched gradually outside this region to a square outer boundary of the 2880 by 2880 km model domain. The vertical grid mesh with 40 points is stretched gradually up to the 25 km top boundary, with 25 m spacing at the lowest model level.

5.2. The Experiments

In addition to the control experiment EX-1 as described above, two "capped flux" simulations are carried out.

These are like the control experiment, except that the wind speed is capped in bulk aerodynamic formulae for the surface exchanges of moisture and potential temperature. The capped wind speed (cap) has a maximum fixed value (10 m s^{-1} for "EX-2", 5 m s^{-1} for "EX-3")

$$\left\{\overline{w'\theta'}, \overline{w'q_v'}\right\} = C_k c\left\{\left(\theta_s-\theta_{25}, q^{\star}_{v,s}-q_{v,25}\right)\right\} \tag{1}$$

which shows, respectively, the resulting parameterized surface sensible and latent heat fluxes. Here C_k is the bulk aerodynamic coefficient for enthalpy as defined above, $c=\min\left\{\text{cap}, \sqrt{u^2_{x,25}+u^2_{y,25}}\right\}$ is the capped, near-surface wind speed (first grid level $z=25$ m) in the simulation Cartesian geometry, $\theta_s-\theta_{25}$ is the simulated air-sea disequilibrium of potential temperature between first grid level and the ocean value, which is a function of surface pressure and a SST of 26.13 C. Also, $q^{\star}_{v,s}-q_{v,25}$ is the air-sea disequilibrium of vapor mixing ratio between first grid level and the saturated value at the ocean surface, which is also a function of surface pressure and SST. Since the putative WISHE mechanism posits among other things a cooperative interaction between surface wind speed and the surface flux, the proposed experiment presents a situation lacking the WISHE mechanism.

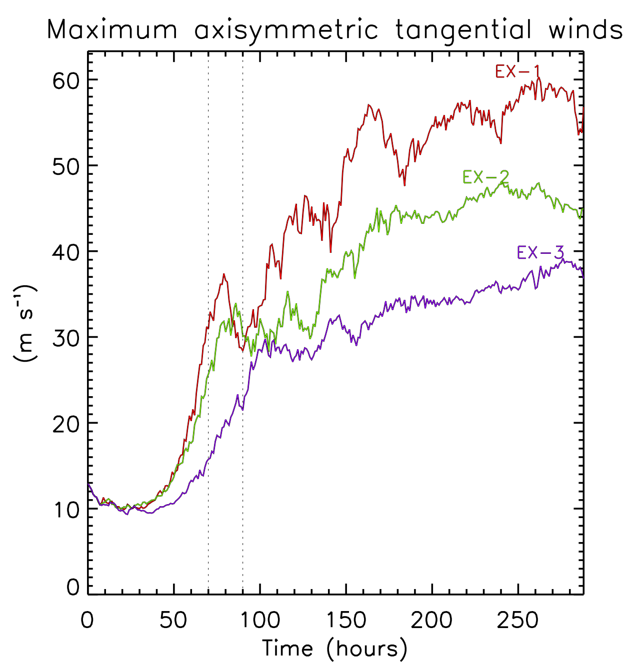

Figure 1. Time series of maximum tangential winds from the control "EX-1" and the capped flux experiments "EX-2" and "EX-3" (see text). Two vertical, dotted lines show times noted below to represent rapid intensification; 70 h for EX-1 and EX-2 and 90 h for EX-3.

The same initial vortex is used for all simulations. The initial

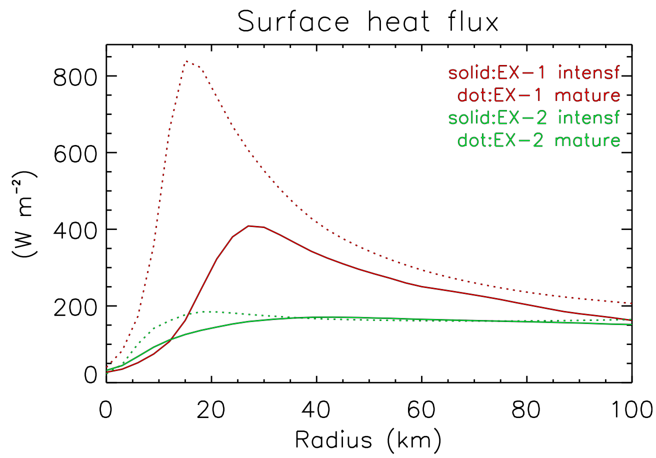

Figure 2. Axisymmetric mean surface enthalpy flux as a function of radius averaged over two periods (intensification $66 \leq t \leq 70$ h, solid; mature intensity $243 \leq t \leq 267$ h, dotted) from the control EX-1 (red) and EX-2 (green) where the surface enthalpy flux is capped by 10 m s^{-1} as described in the text.

radial and vertical velocity is set to zero. The initial tangential velocity is taken to be in gradient wind balance with a maximum of 13 m s^{-1} at the surface at 100 km radius from the center of circulation. The tangential velocity varies smoothly in space and tends to zero at large radii: it is effectively zero beyond 400 km radius and above $z=20$ km.

6. Results

The evolution of intensity (measured by the maximum value of azimuthally averaged tangential winds in the domain; Figure 1) is quite similar for both EX-1 and EX-2 experiments during spin-up to hurricane intensity (33 m s^{-1}) by 90 h, with EX-2 lagging the control only slightly. In fact, the maximum intensification rate for EX-1 and EX-2 is quantitatively similar ($\approx$ 16 m s^{-1} in 20 h versus 15 m s^{-1} in 20 h, respectively). A slower rate of intensification occurs in EX-2 beyond this time. The maximum of 48 ms^{-1} is attained after 260 h and is somewhat weaker than the 60 ms^{-1} maximum found in the control experiment. These results affirm the findings of M2 that the putative WISHE mechanism is not necessary for a developing tropical cyclone to reach hurricane intensity, nor for the further development of that storm. Some surface fluxes of enthalpy are necessary for intensification. Indeed, a separate simulation (not shown) without any surface flux of heat and moisture fails to intensify at all. However, the addition of just a minimal supply of enthalpy in the EX-3 simulation is sufficient.

The surface heat flux (Figure 2)

$$H=c_p\rho\overline{w'\theta'}+L_v\rho\overline{w'q_v'} \tag{2}$$

is reduced by the artificial capping used in EX-2, with the spin-up period (solid green curve) flux reduced at all radii in the near-storm environment (to 100 km radius shown) to a value of about 150 W m^{-2}. The control EX-1 shows at least twice this flux during the intensifying period between $20 \leq r \leq 50$ km radius. At maturity, the capped-flux experiment shows a region near $r=15$ km where the heat flux is about 190 W m^{-2}, due to enhanced air-sea disequilibrium, yet the capping scheme for the heat flux maintains an approximately constant value throughout the later slow intensification regime ($100 \lesssim t \lesssim 250$ h). The vortex in EX-2 experiences some weakening from the initial time to 25 h and there is a period until 45 h where the surface capping scheme is only weakly applied (Figure 3). After 60 h, the RMW in EX-2 is always in a region where the capping is active in the surface flux scheme, and all subsequent increases in intensity occur without any possibility of the putative WISHE feedback mechanism being involved. In EX-3 (Figure 3), the surface heat fluxes are capped at the RMW at essentially all times.

From the three experiments, we see that the wind-speed dependent heat fluxes (for wind speeds beyond 10 m s^{-1}) do augment the intensification process somewhat compared to the capped-flux experiments and support a noticeably stronger intensity in the mature stage. However, considering the hypothetical multistep feedback process of WISHE (M2), these results do not by themselves establish the operation of the feedback process. Rather, they suggest only that the enhanced latent heat energy input to the vortex augments the thermodynamic energy in the boundary layer, which can be then utilized by deep convection to enhance the spin up rate and mature intensity via the rotating convective pathway summarized in the Introduction.

6.1. Vorticity and Convective Organization in the Three Experiments

The vortical convective cells are illustrated via proxy in Figure 4 by the low-level relative vorticity distribution. The figures demonstrate that localized centers of cyclonic vorticity result as individual convective cells intensify, but the convectively intensified vorticity lingers after each cell has collapsed. These lingering

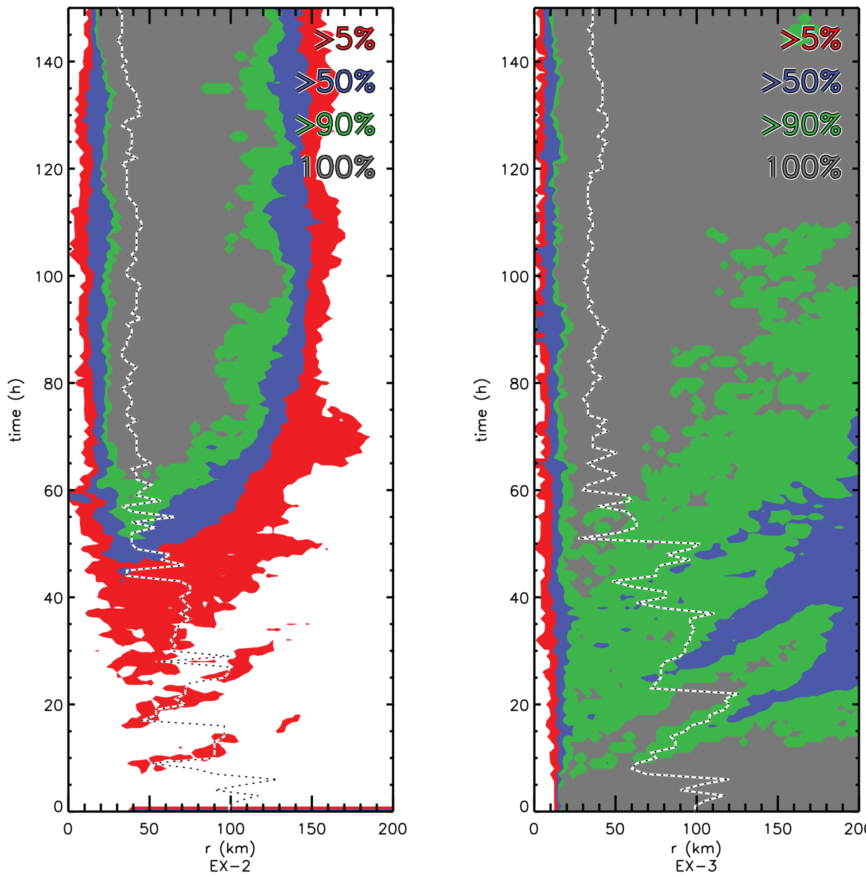

Figure 3. Radius-time plots of the degree of capping in the surface-capped-flux scheme. At each radius and time, some percentage of space on each circle has a near-surface wind speed that exceeds the capping wind speed as it appears in the capped surface flux scheme presented by (1). The percentages are displayed from (a) EX-2 where the wind speed exceeds the 10 m s^{-1} cap and (b) EX-3 where the wind speed exceeds the 5 m s^{-1} cap. The radius of maximum azimuthally-averaged tangential winds (as shown elsewhere in this paper) is shown by the dotted line.

vorticity anomalies tend to be drawn inward by the diabatically driven system-scale secondary circulation above the frictional boundary layer and they tend to be sheared tangentially around the parent circulation. Although the vortex axisymmetrization process does not change the net absolute circulation within a fixed circuit around the convective region, the shearing of convectively generated cyclonic vorticity anomalies around the parent circulation does contribute to consolidating the convectively generated cyclonic vorticity anomalies into a single monopole of cyclonic vorticity [*Melander et al.*, 1987; *Montgomery and Enagonio*, 1998; *Enagonio and Montgomery*, 2001]. For each of the experiments shown in Figure 4, it is evident that vortical convective cells, highly asymmetric in nature, are present through the rapid intensification period.

The organization of vorticity in each simulation is very similar. The development in EX-2 is delayed approximately 5–10 h from that shown in the EX-1 control, and the vorticity development in EX-3 is further delayed by about 15 h. So long as the thermodynamics of the low-level boundary layer continue to support the development of deep convection, the process of building the mesoscale cyclonic vorticity region of the tropical cyclone will continue. Since deep convection is still operative in the capped-flux experiment, it follows that the reduced surface fluxes shown in Figure 2 still provide a sufficient supply of moisture to maintain convective instability and convective activity in the core region of the developing vortex. The persistent convective activity under these limited flux conditions is significant because it has been traditionally assumed that the heat fluxes need to increase in step with the wind speeds so as to maintain a degree of convective instability in the presence of a developing warm core aloft (cf. Figure 1 of M2). These experiments demonstrate that such is not the case.

The additional moisture provided by the enhanced surface fluxes in the control experiment does lead to more intense convection (as measured by local or azimuthally averaged vertical velocity) in the eyewall (Figure 5). However, the enhancement is much less than an order of magnitude. As an example, at maturity (e.g.,

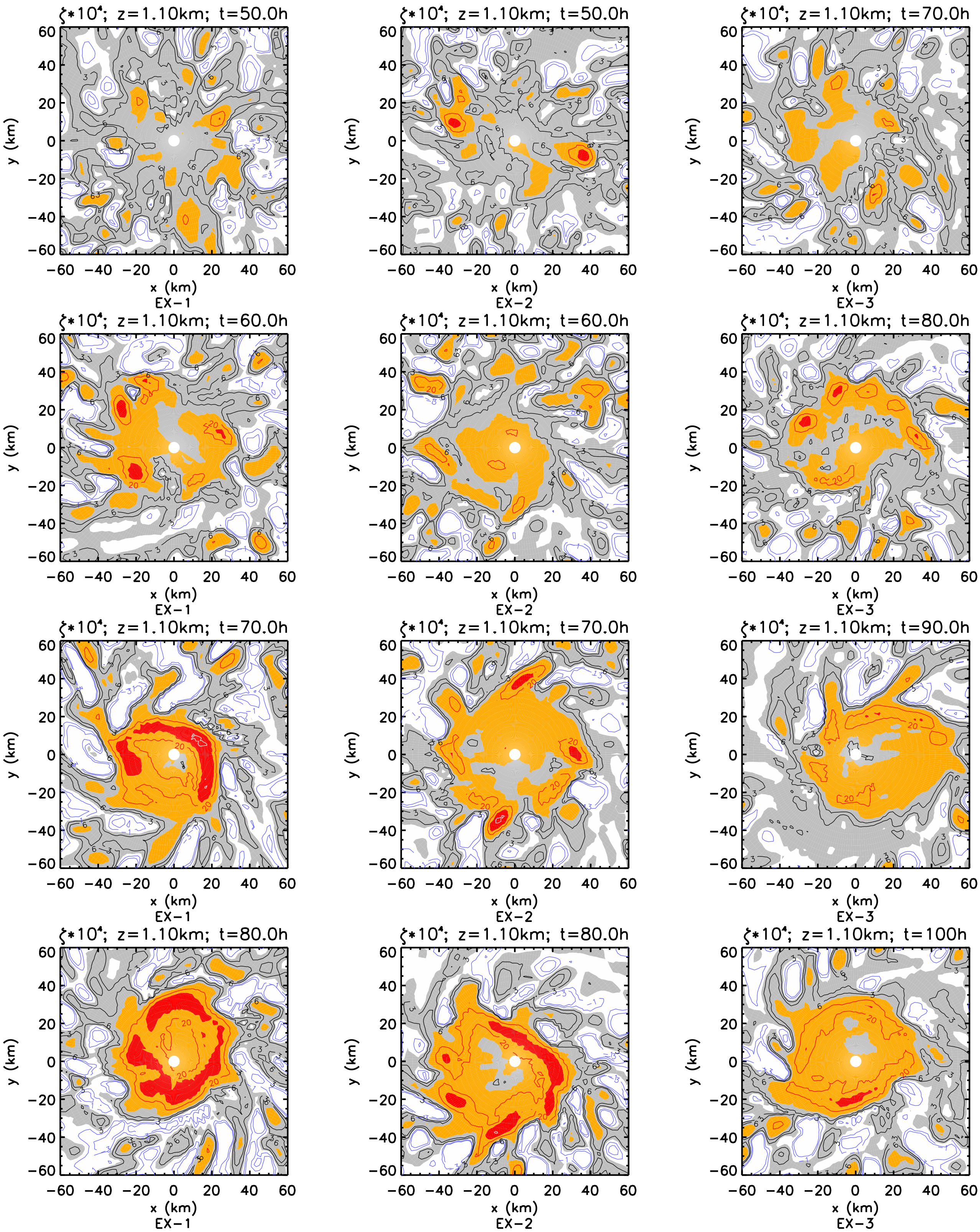

Figure 4. Plan-view plots of vertical vorticity $\zeta \times 10^4$ at the height $z = 1$ km level at a sequence of times through rapid intensification for (left) the control EX-1, (middle) EX-2 with fluxes capped to 10 m s^{-1}, and (right) EX-3 with fluxes capped to 5 m s^{-1}. White shading shows values less than 1 s^{-1}, with blue contour of -3 and -1 s^{-1}; gray shading shows values between 1 and 10 s^{-1}, with black contours of 3 and 6 s^{-1}; orange shading shows values between 10 and 30 s^{-1}, with red contour of 20 s^{-1}; red shading shows values greater than 30 s^{-1}, with white contour of 40 s^{-1}. The small, white circle at the origin marks the center of coordinates.

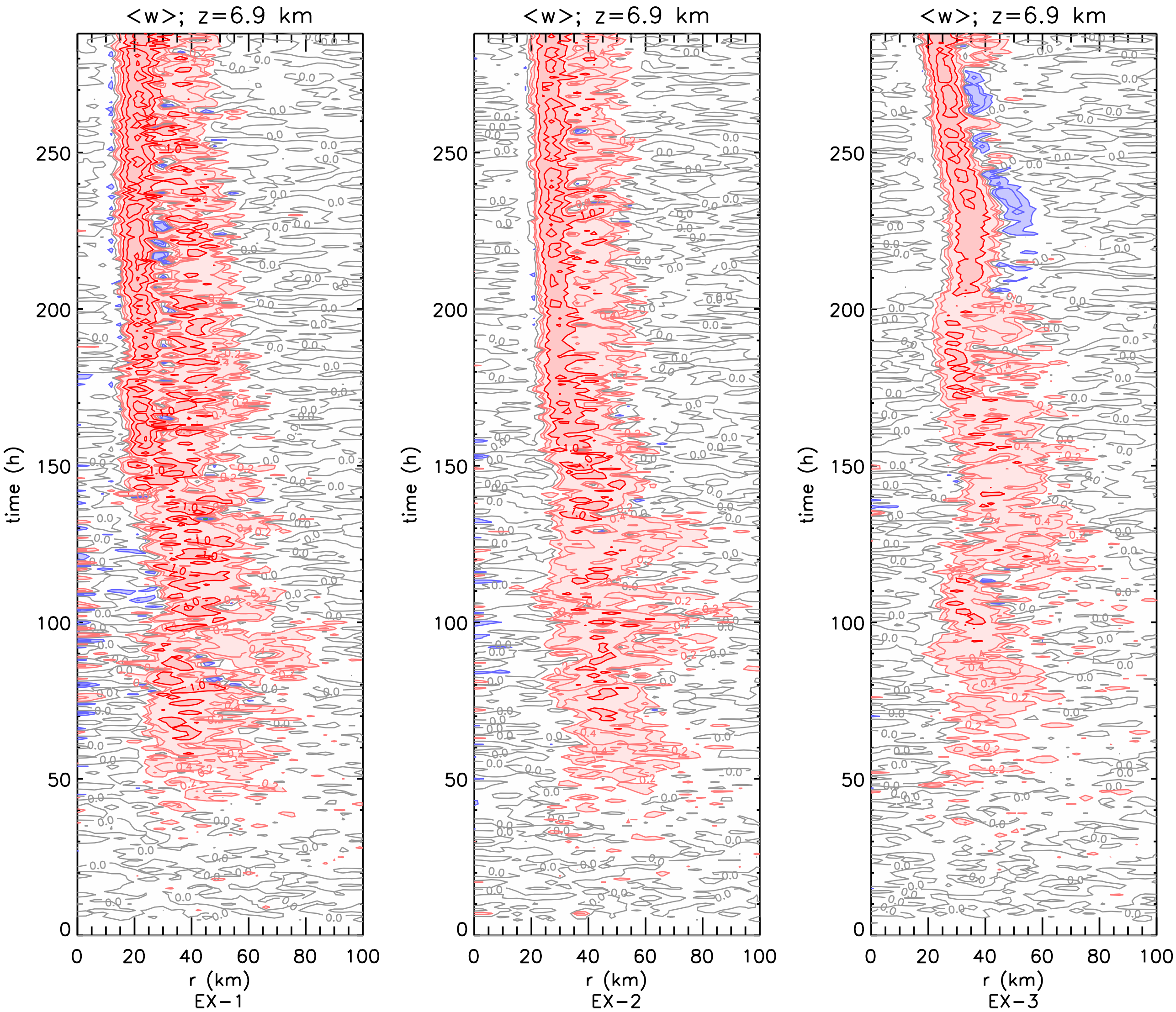

Figure 5. Radius versus time contours of azimuthally-averaged vertical velocity <w> at the height of typical maximum mean updraft $z=7$ km from (left) the control EX-1, (middle) EX-2 and (right) EX-3. Contours (m s^{-1}) shown are -0.4 and -0.2 (blue), 0 (gray), 0.2 and 0.4 (pink), 1, 2 and 3 (red).

$t>150$ h) the typical maximum values of azimuthally averaged vertical velocity in the control EX-1 are 3 m s^{-1} or more. In EX-2 with capped surface fluxes, the corresponding maximum values are still more than 2 m s^{-1}.

Figure 6 (right column) demonstrates that convection at a time of peak intensification for each simulation remains highly cellular even as a prominent band is organizing into a nascent eyewall. The low-level θ_e presented in Figure 6 (left column) represents the midpoint of a broad-scale ($r<100$ km; Figure 7) warming and moistening at the lowest model levels. The effects of cold-pools, found near deep convection, become less prominent after this time (see also M2). The simulations with capped wind speed in the heat fluxes have smaller values of near-surface θ_e overall, but the convective organization appears to be quite similar. While the vertical motion field is highly localized into cells, the vertical vorticity ζ (Figure 6, middle column) shows a combination of the highly cellular organization associated with recent convection together with a mesoscale core of cyclonic vorticity that reflects the aggregate effect of prior convective events.

7. Conclusions

The multistep evaporative-wind feedback mechanism of tropical cyclone intensification known as "the WISHE mechanism" continues to be the widely accepted explanation of tropical cyclone intensification in

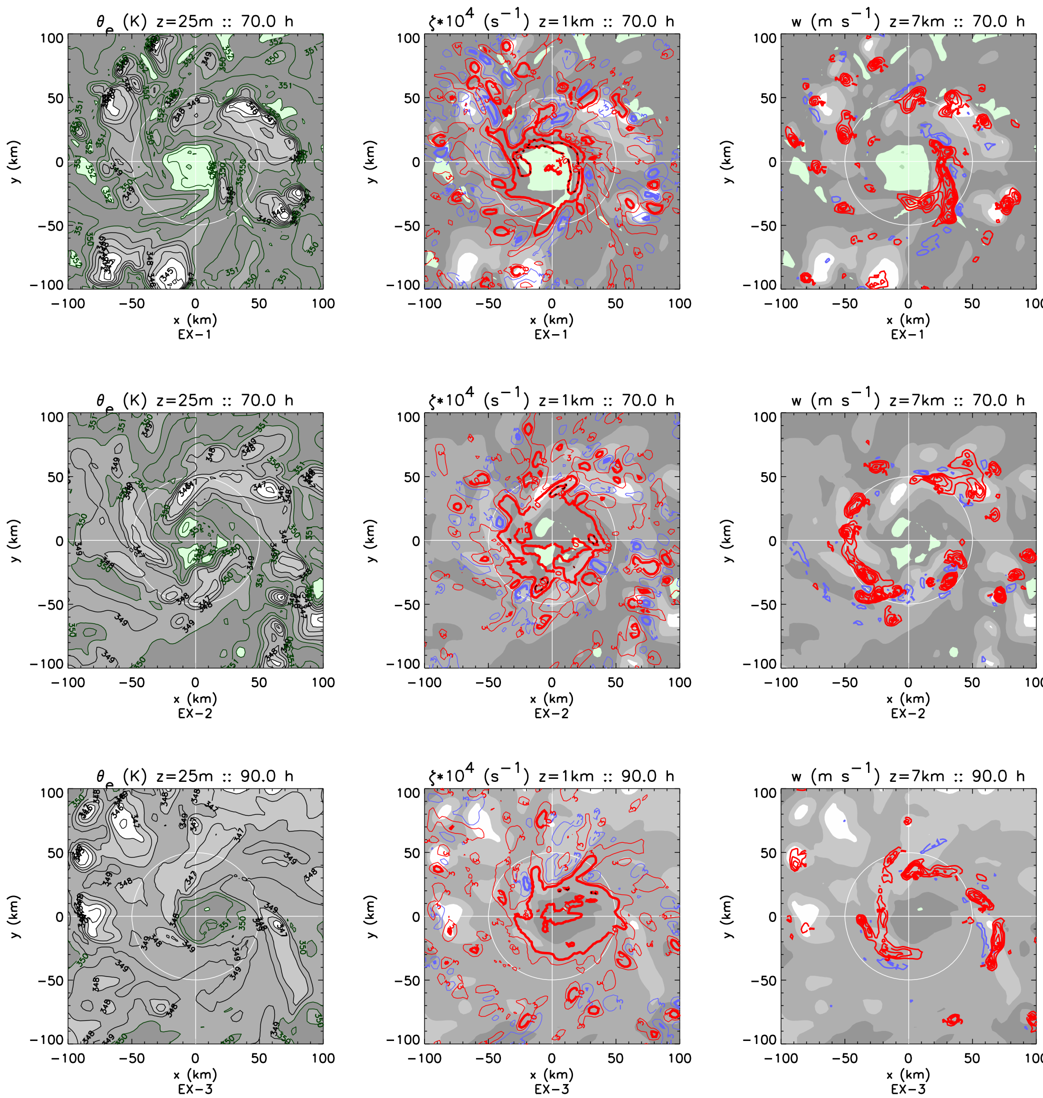

Figure 6. Thermodynamic and dynamic quantities at a moment of rapid intensification from (first row) EX-1, (middle row) EX-2, and (bottom row) EX-3. In the left column, θ_e at the 25-m level is contoured at 1 K intervals with shading (also shown in the middle and right columns) white <346 K, light gray <348 K, medium gray <350 K, dark gray <352 K, light green <354 K, medium green <356 K, dark green >358 K. In the middle column, $\zeta \times 10^4$ is contoured with contours (s^{-1}) -10 (thick blue), -3 (blue), 3 (red), 10 (thick red), and 30 (spotted red). In the right column, w is contoured with contours (m s^{-1}) -2 and -1 (blue) and 1, 2, 3, 4, and 5 (red).

textbooks, didactic material, and the peer-reviewed literature. We acknowledge the importance of Emanuel's work in highlighting the necessity of surface moisture fluxes in tropical cyclone intensification, which we do not dispute, but we have found many shortcomings in the linkages proposed by others between these fluxes and other elements of the intensification process. Indeed, a careful examination of some of the interpretations of Emanuel's theory exposes ambiguities or contradictions regarding the pertinent physical processes of WISHE.

The current work was motivated by extant descriptions of the intensification process in the open literature and the linkages proposed by the study of *Miyamoto and Takemi* [2013]. The latter authors attempted to understand the transition between their slow intensification phase (phase 1) and the rapid intensification phase (phase 2) of their simulated hurricanes as illustrated in their Figure 3. The crux of their argument for the importance of the nearly-axisymmetric WISHE mechanism during the rapid intensification phase of their experiments was based on the implied link between the amplifying tangential winds and the increase of surface enthalpy fluxes during the rapid intensification phase of the simulated vortex. However, as is well known, the association of one effect with another does not necessarily imply that the two effects are

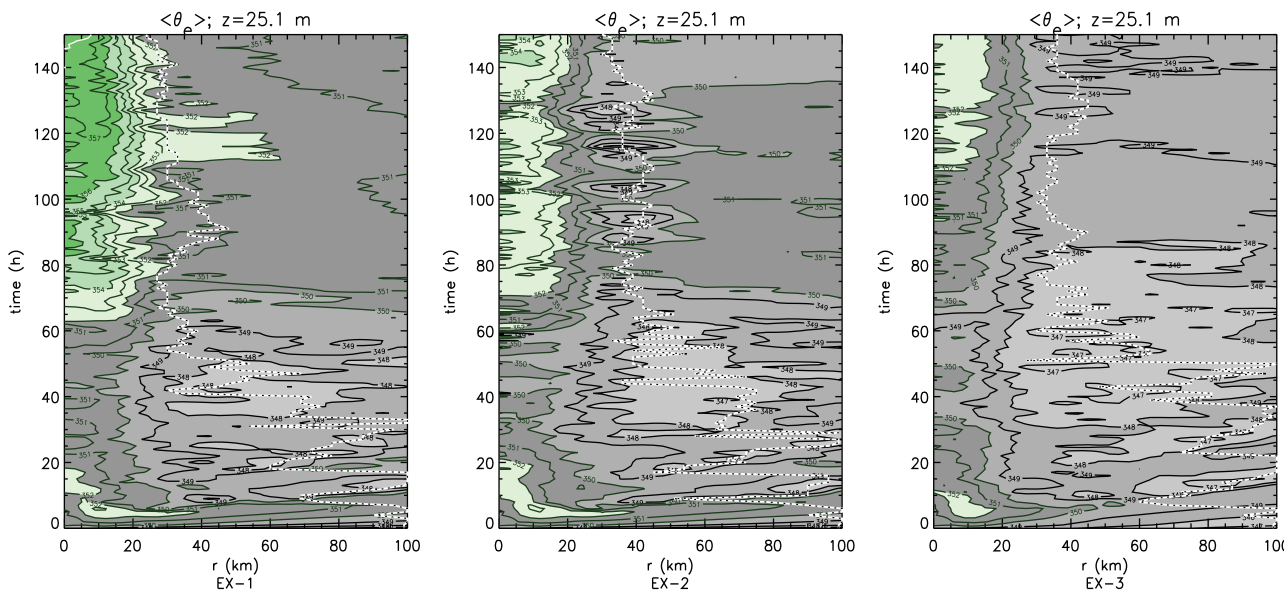

Figure 7. Azimuthally-averaged $<\theta_e>$ at $z=25$ m from (left) EX-1, (middle) EX-2, and (right) EX-3 with contours at 1 K intervals with shading white $<$ 346 K, light gray $<$ 348 K, medium gray $<$ 350 K, dark gray $<$ 352 K, light green $<$ 352 K, medium green $<$ 354 K, dark green $>$ 354 K.

causally linked. To test the *Miyamoto and Takemi* inference, we conducted new idealized three-dimensional numerical experiments using a state-of-the-art cloud model with capped wind speed in the latent and sensible heat fluxes at near trade wind values. The results of the experiments demonstrate that their implied linkage between near-surface wind speed and surface enthalpy fluxes is merely incidental. The results of the new calculations affirm prior work showing that the putative multistep WISHE feedback mechanism is not a dominant pathway of tropical cyclone intensification in the idealized configuration that has been used to underpin the paradigm.

Taken together the calculations presented herein and those in *Montgomery et al*. [2009] refute the prior view that the WISHE mechanism is the essential and dominant mode of tropical cyclone intensification in the prototype problem. For these reasons, we recommend that the hypothesized WISHE feedback mechanism be highly qualified in the classroom and/or discussions. A more complete framework, like that of *Montgomery and Smith* [2014], that includes rotating convection as an element of the intensification mechanism would seem to be necessary to describe and understand the simulated development process in three-dimensional models and the intensification of real storms.

Acknowledgments

Data supporting all figures is available at: https://www.dropbox.com/sh/ptlm2j07133p3dq/AACwCDLILMP1x06ROf-FBAHza?dl=0. This work was supported in part by the National Science Foundation Award AGS 0733380, and AGS-1313948, The Office of Naval Research (ONR), through award N0001411WX20095, National Aeronautics and Space Administration (NASA) grant NNG11PK021 and the U. S. Naval Postgraduate School. M.T.M. wishes to thank JM, JEM, LKP, MPM, and PCM for their support. R.K.S. is grateful for support from the German Research Council (Deutsche Forschungsgemeinschaft) under Grant SM30-23. We also thank Gerard Kilroy for his assistance preparing figures.

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