9B.4 UNDERSTANDING THE GENESIS OF HURRICANE VINCE THROUGH THE SURFACE PRESSURE TENDENCY EQUATION

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1. INTRODUCTION

Hurricane Vince was one of the many extraordinary hurricanes that formed in the record-breaking 2005 Atlantic hurricane season. Unlike Katrina, Rita, and Wilma, Vince was remarkable not because of intensity, nor the destruction it inflicted, but because of its defiance to our current understandings of hurricane formation. Vince formed in early October of 2005 in the far North Atlantic Ocean and acquired characteristics of a hurricane southeast of the Azores, an area previously unknown to hurricane formation. Figure 1 shows a visible image taken at 14:10 UTC on 9 October 2005 when Vince was near its peak intensity. There is little doubt that a hurricane with an eye surrounded by convection is located near 34°N, 19°W. A buoy located under the northern eyewall of the hurricane indicated a sea-surface temperature (SST) of 22.9°C, far below what is considered to be the minimum value of 26°C for hurricane formation (see insert of Fig. 3f). In March of 2004, a first-documented hurricane in the South Atlantic Ocean also formed over SST below this 26°C threshold off the coast of Brazil. In addition, cyclones in the Mediterranean and polar lows in sub-arctic seas had been observed to acquire hurricane characteristics. These cyclones, like typical tropical cyclones, are apparently warm core in structure, and appeared to be energized by convection. The formation of these cyclones over anomalously low SST motivates us to re-examine our basic understandings of hurricane genesis and intensity change.

2. WHAT WE KNOW ABOUT HURRICANE FORMATION

2.1 *Our basic understandings*

To a large degree, our basic understandings on hurricane formation are still primarily based on deduction from long-term observations. The following statements summarize what we confidently know about hurricanes and their intensity changes.

- Hurricanes are warm-core cyclones that form and develop over warm ocean waters. No hurricanes have ever formed and intensified over land away from large bodies of water.
- Hurricanes and their link with moist convection are inseparable. They appear to intensify in response to development of moist convection near or around their center of circulation.
- Synoptic environmental factors are recognized to greatly influence hurricane formation, intensity, and motion. For example, vertical wind shear is recognized as a strong modulator of hurricane intensity, whereas the upper-air synoptic flow serves to “steer” the forward motion of hurricanes.

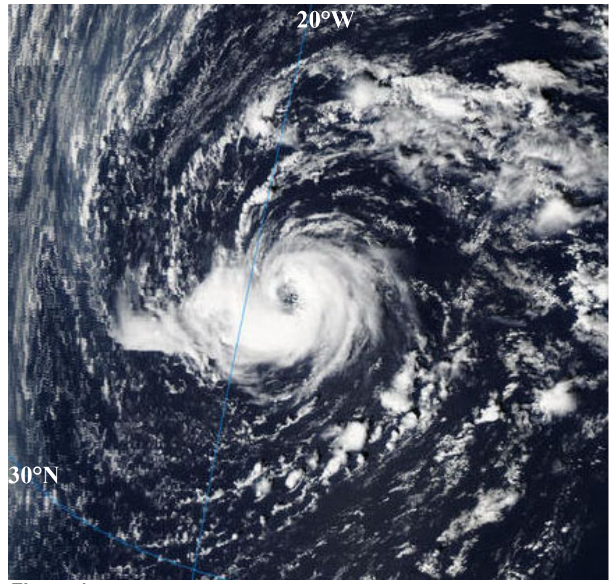

Figure 1 Color visible image taken at 14:10 UTC 9 October 2005 by *Aqua*.

Note that the first statement does not include the well-accepted criterion of 26°C SST as a pre-condition for hurricane formation. This has become a criterion in doubt in light of Vince forming over water at 23°C, and the Brazilian hurricane that formed over 24°C water.

Our basic understandings on hurricanes stated above are admittedly rather sketchy. What we are uncertain about is regarding the details of the above statements, specifically, their importance and relation with one another, and whether their importance differs in different situations. This is largely due to the fact that there has not been a proven theoretical framework of hurricane formation and intensification with which we can confidently rely on as a method of diagnosing hurricane intensity change. This is demonstrated by the fact that meteorological computer models have been unable to handle hurricanes despite their relative success in simulating and forecasting higher latitude weather systems. However, recent advances in numerical methods and computing power appear to be overcoming this difficulty. For the first time, they appear capable of simulating hurricane structures in realistic details. Nevertheless, even if computer models can simulate hurricanes perfectly, they function like a black box from which no information about the fundamental processes governing hurricane intensity is offered. There remains the necessity to formulate a theoretical framework for the purpose of understanding and diagnosing hurricane formation and intensification.

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2.2 *Recent researches on tropical cyclone transitions*

The intriguing subject of tropical cyclone transitions has attracted attention in recent years. Tropical cyclones, being inherently warm-core and vertically stacked, often transform into vertically tilted cold-core extratropical cyclones after encountering higher-latitude baroclinity. The reverse process—extratropical cyclones transforming into tropical cyclones—is seen less frequently. But in the years 2000 to 2003, nearly half of the Atlantic tropical cyclones were baroclinically initiated, according to NOAA's Tropical Prediction Center. Davis and Bosart (2004) classified the tropical transitioning cyclones into two main groups—strong extratropical pre-cursors (SEC) and weak extratropical pre-cursors (WEC). The occlusion of an old frontal cyclone is recognized as the main characteristics of SEC cases. This cold-cored, vertically stacked occluded cyclone must persist over warm SST and has surface winds strong enough to induce surface heat exchange (WISHE; Emanuel 1987). The increase of low-level moisture must then trigger the growth of convection close to the cyclone center. This must then trigger a mutual intensification process in which growth of convection leads to intensification of the cyclone. Diabatic heating due to the growth of convection is thought to reduce the vertical shear wherefore the mutual intensification process may be nurtured.

As for WEC cases, Davis and Bosart defined them as either (1) occluding cyclones with weak surface winds that fail to trigger WISHE, or (2) the presence of mid-tropospheric convectively driven mesoscale vortex or vortices. These initial cyclonic disturbances eventually develop into well-defined tropical cyclones.

Regardless of classification, the spin-up of a pre-existing vortex in apparent relation to development of convection is recognized as the most significant characteristic of tropical transitioning cyclones. Hendricks, et al. (2004) called the convectively driven vortices "vortical hot towers". Davis and Bosart (2003) attributed the vortex spin-up to redistribution of potential vorticity, which, Hendricks, et al. understood as the result of vertical diabatic heating gradient. Despite the differences in terminology and ways of relating convection to cyclogenesis, the crucial point that remains largely unexplained is exactly how the initial vortex acquired vorticity and how convection may trigger further vortex spin-up. The answer to this key point not only pertains to tropical transitioning cyclones but also tropical cyclogenesis in general.

3. UNDERSTANDING CYCLOGENESIS BY MEANS OF THE SURFACE PRESSURE TENDENCY

To considering the problem of tropical cyclogenesis, as well as tropical and extratropical cyclone transformations, let us take a step back and consider the problem more broadly as just cyclogenesis. In order to approach the problem theoretically, we must define cyclogenesis by means of a physical quantity. The physical quantity we will use is the surface pressure tendency. This is in contrast to the (potential) vorticity approach, which has become the dominant idea since the 1950s.

A classic method of deriving an equation of surface pressure tendency is by differentiating with respect to time the integrated form of the hydrostatic equation, followed by substitution of the continuity equation to yield the result

$$\frac{\partial p_s}{\partial t} = -g\int_0^\infty (\nabla \cdot \rho\vec{v})\, dz\,. \qquad (0)$$

This result states that the surface pressure tendency is due simply to the integrated mass divergence of the entire depth of the overlying atmospheric column. Although the physical meaning of this result is easy to understand, it does not offer further insights into identifying the thermodynamic processes that undoubtedly affect the surface pressure. Adiabatic cooling and latent heat release are examples of important thermodynamic processes during cyclogenesis, especially tropical cyclogenesis. Using another approach, it will be shown in the next section that it is possible to derive a surface pressure tendency equation that reveals the thermodynamic factors affecting the surface pressure.

3.1 *Derivations*

We begin by considering the hydrostatic equation:

$$\frac{\partial p}{\partial z} = -\rho g\,. \qquad (1)$$

First, we integrate it with respect to z from z_1 to z_2, ($z_2 > z_1$).

$$p_2 - p_1 = -g\int_{z_1}^{z_2} \rho\, dz \qquad (2)$$

where p_1 and p_2 are pressures at z_1 and z_2 respectively. We then differentiate it with respect to t with $x, y,$ z_1 and z_2 held constant.

$$\left.\frac{\partial p_2}{\partial t}\right|_{x,y,z} - \left.\frac{\partial p_1}{\partial t}\right|_{x,y,z} = -g\int_{z_1}^{z_2} \left.\frac{\partial \rho}{\partial t}\right|_{x,y,z} dz \qquad (3)$$

Here $\partial p_2/\partial t$ means the local pressure tendency at (x, y, z_2) and likewise, $\partial p_1/\partial t$ the local pressure tendency at (x, y, z_1). The integral on the right-hand-side (RHS) represents the integrated value of the local density tendency from z_1 to z_2 at point (x, y).

If we divide through this equation by $z_2 - z_1$ and take the limit as $(z_2 - z_1) \to 0$, we find that

$$\frac{\partial}{\partial z}\left(\frac{\partial p}{\partial t}\right)_{x,y,z} = -g\left.\frac{\partial \rho}{\partial t}\right|_{x,y,z} \qquad (4)$$

which is actually the continuity equation in disguise!

The traditional derivation approach from this point onward is to substitute the continuity equation in place of the local density tendency, integrate, and yield a surface pressure tendency equation in terms of mass divergence, i.e. equation (0). But instead, we will proceed by expressing local density tendency in terms of total density tendency and advections.

Before doing so, we need to express the partial derivative of density on the RHS in Cartesian-pressure coordinates (x, y, p) as

$$\frac{\partial}{\partial z}\left(\frac{\partial p}{\partial t}\right)_{x,y,z} = -g\left(\frac{\partial \rho}{\partial t}_{x,y,p} + \frac{\partial p}{\partial t}_{x,y,z}\frac{\partial \rho}{\partial p}_{x,y,t}\right). \tag{5}$$

Next, local density tendency is expressed in terms of total and partial derivatives in (x, y, p) coordinates as

$$\frac{\partial}{\partial z}\left(\frac{\partial p}{\partial t}\right) + g\frac{\partial \rho}{\partial p}\frac{\partial p}{\partial t} = g\left(\vec{v}\cdot\nabla_p \rho + \omega\frac{\partial \rho}{\partial p} - \frac{d\rho}{dt}\right). \tag{6}$$

Note that $\omega \equiv \frac{dp}{dt}$ is the vertical velocity in pressure coordinates. Note also that all pressure tendency terms have been brought to the left-hand-side (LHS). Inspecting the LHS, we can realize that equation (6) is actually a first order differential equation with respect to $\partial p/\partial t$! An integrating factor exists for equation (6), and can be determined as follows.

$$e^{g\int\frac{\partial \rho}{\partial p}dz} = e^{-\int\frac{1}{\rho}\frac{\partial \rho}{\partial p}dp} = e^{-\int d\ln\rho} = e^{-\ln\rho} = \frac{1}{\rho}$$

After multiplying by the integrating factor, equation (6) can be expressed as follows.

$$\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial p}{\partial t}\right) = \frac{g}{\rho}\left(\vec{v}\cdot\nabla_p \rho + \omega\frac{\partial \rho}{\partial p} - \frac{d\rho}{dt}\right) \tag{7}$$

Next, we will substitute the thermodynamic equation for an ideal gas in place of the total density tendency. When combined with the Ideal Gas Law ($p = \rho R T_v$), the First Law of Thermodynamics can be expressed in two alternative forms for a finite volume of air. The form that we will use is $\frac{1}{\rho}\frac{d\rho}{dt} = \frac{c_v}{c_p}\frac{1}{p}\frac{dp}{dt} - \frac{\dot{Q}}{c_p T}$ where $\dot{Q}$ represents the diabatic heating rate such as latent heat and radiation. Hence,

$$\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial p}{\partial t}\right) = g\left[\vec{v}\cdot\nabla_p \ln\rho + \left(\frac{p}{\rho}\frac{\partial \rho}{\partial p} - \frac{c_v}{c_p}\right)\frac{\omega}{p} + \frac{\dot{Q}}{c_p T}\right]. \tag{8}$$

Next, we will express $\partial\rho/\partial p$ in terms of temperature lapse rate by differentiating $p = \rho R T_v$ with respect to p to yield $\frac{p}{\rho}\frac{\partial \rho}{\partial p} = 1 + \frac{R}{g}\frac{\partial T_v}{\partial z}$. Substitute this into equation (8), re-arrange terms and note that $c_p - c_v = R$, and the fact that $\nabla_p \ln\rho = -\nabla_p \ln T_v$, we get

$$\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial p}{\partial t}\right) = g\left[-\vec{v}\cdot\nabla_p \ln T_v + \frac{R}{g}\left(\frac{g}{c_p} + \frac{\partial T_v}{\partial z}\right)\frac{\omega}{p} + \frac{\dot{Q}}{c_p T}\right]. \tag{9}$$

This equation is now integrated with respect to z from z_1 to z_2.

$$\int_{z_1}^{z_2}\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial p}{\partial t}\right)dz = \frac{1}{\rho_2}\frac{\partial p_2}{\partial t} - \frac{1}{\rho_1}\frac{\partial p_1}{\partial t} = g\int_{z_1}^{z_2}\left[-\vec{v}\cdot\nabla_p \ln T_v + \frac{R}{g}\left(\frac{g}{c_p} + \frac{\partial T_v}{\partial z}\right)\frac{\omega}{p} + \frac{\dot{Q}}{c_p T}\right]dz\,.$$

Solving for $\partial p_1/\partial t$, we get this result.

$$\boxed{\frac{\partial p_1}{\partial t} = \frac{\rho_1}{\rho_2}\frac{\partial p_2}{\partial t} - \rho_1 g\int_{z_1}^{z_2}\left[-\vec{v}\cdot\nabla_p \ln T_v + \frac{R}{g}\left(\frac{g}{c_p} + \frac{\partial T_v}{\partial z}\right)\frac{\omega}{p} + \frac{\dot{Q}}{c_p T}\right]dz} \tag{10a}$$

Note that this pressure tendency equation was derived using the dry adiabatic version of the thermodynamic equation. Therefore, it is more applicable specifically to an unsaturated hydrostatic atmosphere. If the air is saturated, the latent heat associated with the phase change of water may be included. The pressure tendency equation under such condition is found to be

$$\boxed{\frac{\partial p_1}{\partial t} = \frac{\rho_1}{\rho_2}\frac{\partial p_2}{\partial t} - \rho_1 g\int_{z_1}^{z_2}\left[-\vec{v}\cdot\nabla_p \ln T_v + \frac{R}{g}\left(\Gamma_m^* + \frac{\partial T_v}{\partial z}\right)\frac{\omega}{p} + \frac{\dot{Q}}{c_p T}\right]dz} \tag{10b}$$

where Γ_m^* is a variant form of the moist adiabatic lapse rate. $\dot{Q}$ now represents heating rates other than moist adiabatic.

3.2 *Physical meanings of individual terms in the pressure tendency equation*

Equation (10) is a set of solutions for $\partial p_1/\partial t$, the pressure tendency at the bottom of an arbitrary column of air. Equation (10a) is applicable to the part of the air column that is sub-saturated with respect to water, whereas equation (10b) applies to saturated air, especially one that undergoes moist adiabatic ascent. If p_1 is taken to be the pressure at ground level and p_2 to be approaching zero, then $\partial p_1/\partial t$ would represent the surface pressure tendency. The RHS of the equations shows that, aside from the upper boundary condition, the surface pressure tendency is due to the sum of three separate terms integrated through the vertical depth of the air column. The physical interpretations of these terms are given as follows.

The first term on the RHS $-\vec{v}\cdot\nabla_p \ln T_v$ is temperature advection on a constant pressure surface. It shows that a net cold air advection in an atmospheric column would cause its surface pressure to rise. Conversely, a net warm air advection in the column would cause its surface pressure to fall.

The second term on the RHS reveals a direct linkage among vertical motion, static stability, and the surface pressure tendency that does not appear in the classic derivation of the surface pressure tendency. Mathematically, it states that the surface pressure tendency is proportional to the product of vertical velocity and static stability given by $\frac{g}{c_p}+\frac{\partial T_v}{\partial z}$, where $\frac{g}{c_p}$ is the dry adiabatic lapse rate, and $\partial T_v/\partial z$ is the environmental virtual temperature lapse rate. Using conventional lapse rate definition, this stability factor can be denoted as $\Gamma_d-\Gamma_{T_v}$, which is the difference of the environmental lapse rate **from** the dry adiabatic lapse rate. Thus, for a statically stable environmental lapse rate, this stability factor is positive. But for a super-adiabatic environmental lapse rate, it is a negative quantity. If this super-adiabatic lapse rate is coupled with a negative ω, or ascent, it will result in a negative $\partial p_1/\partial t$, or surface pressure fall. In other words, **ascent in an absolutely unstable environment would cause the surface pressure to fall**. This scenario is presumably likely since air parcels are likely to be freely buoyant and therefore acquiring ascending motion in a super-adiabatic environmental lapse rate.

The last term on the RHS is the diabatic term. It states that diabatic heating, such as latent release and radiation, would lead to a decrease of surface pressure.

Lastly, the RHS of equation (10) also contains the upper boundary term: $\frac{\rho_1}{\rho_2}\frac{\partial p_2}{\partial t}$. Its numerical value is assumed to vanish as the pressure approaches zero.

The following table summarizes the different possible situations that can affect the signs of each of the three terms in the integral of equation (10) and how they affect the sign of the surface pressure tendency.

TERMS in the surface pressure tendency equation	**RISE of surface pressure if**	**FALL of surface pressure if**
$\vec{v}\cdot\nabla_p \ln T_v$	There is cold air advection.	There is warm air advection.
$-\left(\frac{g}{c_p}+\frac{\partial T_v}{\partial z}\right)\frac{\omega}{p}$	• Ascent occurs in a statically stable environment.	• Descent occurs in a statically stable environment.
	• Descent occurs in an absolutely unstable environment.	• Ascent occurs in an absolutely unstable environment.
$-\frac{\dot{Q}}{T}$	There is diabatic cooling	There is diabatic heating

In addition, we also note that if the environmental lapse rate is in neutral stability, there is no contribution to the surface pressure tendency.

To get an idea of the magnitude of surface pressure tendency due to the vertical motion term, we will substitute these values: $w = 1\,\mathrm{ms}^{-1}$, $\Delta\Gamma = -1°\mathrm{K\,km}^{-1}$ (i.e. environmental lapse rate is 1° super-adiabatic), p = 80000Pa, $\rho_1 = 1\,\mathrm{kg\,m}^{-3}$, and Δz = 5km.

$$-\rho_1 R\left(\frac{g}{c_p}+\frac{\partial T_v}{\partial z}\right)\frac{\omega}{p}\Delta z \cong -6.5\,\mathrm{mb\,h}^{-1}$$

3.3 *Implications of the surface pressure tendency equation on cyclogenesis*

The pressure tendency equation as derived above consists of three separate integral terms. Having this separation suggests that one or more of the three terms could be the dominant reason(s) of causing the surface pressure to change. Based on their physical meanings, these three terms may be called (a) the temperature advection term, (b) the vertical motion term, and (c) the diabatic term.

The noted separation of terms happens to be just suitable to the inherent dynamical differences in the weather systems that develop on the Earth's two broadest climate regimes—namely the tropics and the extra-tropics. In the extra-tropics, horizontal temperature gradient is prevalent. Thus, one would expect that at least the temperature advection term would dominate. Previous synoptic studies have shown that the horizontal advection and the vertical motion terms are frequently nearly equal but opposite in signs. Thus, the resulting surface pressure tendency is often the residue of these two large but opposing terms.

But for the tropics, temperature is much more uniform than at higher latitudes. Therefore, we do not expect the temperature advection term to be a significant contributor of surface pressure tendency in the tropics. This leaves the vertical motion and the diabatic terms to be the potential significant factors in changing the tropical surface pressure. As has been analyzed in the previous sub-section, the scenarios that give rise to the decrease of surface pressure include (1)—sinking air in a highly stable environment (e.g. an inversion), (2)—vigorous ascent in an absolutely unstable environment. **This implies that in a tropical environment where temperature gradient is weak, the only plausible surface pressure reducing mechanism is through either a) sinking of stable air, b) ascent in absolutely unstable air, or c) diabatic heating.**

3.4 *Implications of the surface pressure tendency equation on tropical cyclogenesis*

The above analyses have significant implications to the understanding of cyclogenesis in the tropics; the most prominent example is, of course, the hurricane. The most impressive characteristics in a mature hurricane are undoubtedly the high surface winds, the extremely low central pressure, the overwhelming dominance of moist convection in its inner core, and last but not least, the eye at its very center. The most baffling problem in tropical meteorology has been to explain how a usually tranquil tropical atmosphere turns into one of the Earth's most violent tempest. Many insights to this inquiry may be realized by analyzing the vertical motion term in the surface pressure tendency equation in light of the known observed structures of hurricanes. To put the theoretical analyses into perspectives, the following questions are posed for pondering.

- *How does the surface pressure drop so low in hurricanes?*
- *What role does moist convection play in hurricanes?*
- *Does the eye have anything to do with hurricane intensity?*
- *Is a warm SST the only determining factor in tropical cyclogenesis? If yes, how warm? If not, what other factors are necessary for tropical cyclogenesis?*
- *Why do hurricanes have to form over ocean and not over land?*

To tackle these questions, we begin by realizing that since a hurricane environment is highly saturated in moisture, equation (10b) would be more suitable than equation (10a). In equation (10b), the vertical motion term suggests that a large decrease in surface pressure occurs when (1)—air sinks in a highly stable environment (e.g. an inversion), and (2)—air rises vigorously in a "moist super-adiabatic" lapse rate. Here, moist super-adiabatic lapse rate means that the lapse rate of the environment is larger than the moist adiabatic lapse rate and the air is saturated with moisture. Bryan and Fritsch (2000) called this a moist absolutely unstable layer (MAUL). MAULs have been observed in mesoscale convective complexes. It was Bryan and Fritsch who recognized them as important structures and brought them to our attention as the atmospheric sixth static stability state. More recently, Ross et al. (2004) studied high-resolution simulations of Hurricane Isabel and found that MAULs as deep as 4 km are prevalent in the inner core as well as the rainbands of the hurricane. Thus, they hypothesized that MAULs are a potentially important ingredient for hurricane intensification. However, their exact dynamical linkage to hurricane intensity is unclear.

Given what the Isabel simulation shows, it is desirable to see whether MAULs are actually observed in hurricanes. Inspections of rawinsonde soundings taken prior to the landfalls of Hurricane Floyd (1999), sub-tropical storm Allison (2001), and Hurricane Isabel (2004) reveals that nearly-saturated MAULs are indeed found from the surface up to about 700 hPa (Kong, 2001). Figure 2 shows a dropsonde sounding taken just inside the western eyewall of Hurricane Ivan. The super moist-adiabatic lapse rate with nearly-saturated condition is evident.

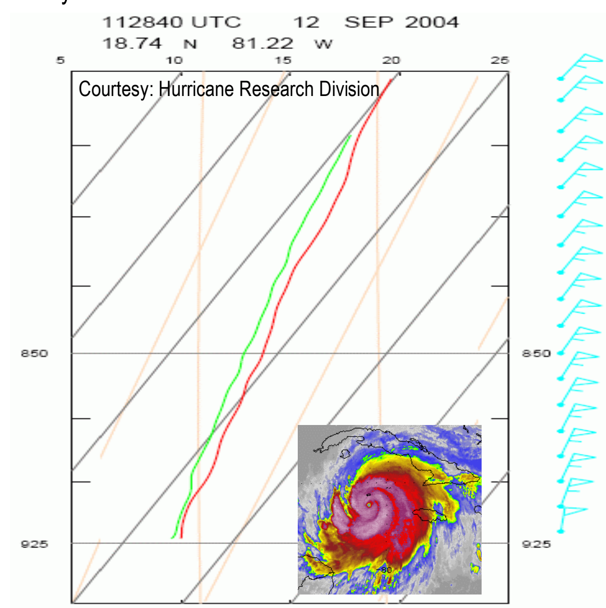

Figure 1 Skew-T log-P diagram of a dropsonde launched at 11:29 UTC on 12 September 2004 just inside the western eyewall of Hurricane Ivan. Insert shows GOES-12 infrared image at 11:45 UTC 12 September 2004.

The existence of MAULs in hurricanes confirms the necessity of static instability to drive the moist convection that is so prevalent in hurricanes. Based on principles of parcel theory, this implies that air parcels are freely buoyant and thus have a tendency to rise in a statically unstable environment. Thus, a physical link between moist convection and ascent in hurricanes is established.

While long-term observation of hurricanes has established that vertical depth of moist convection is directly related to hurricane intensity (i.e. the Dvorak technique), the connection between moist convection and hurricane intensity change is not as obvious. On the other hand, forecasters have looked for convective bursts that occur close to the center of tropical cyclones as a first sign of intensification since their central pressure appears to drop after seeing these convective bursts. Although theoretical considerations such as upper-level divergence, latent heat release, ascent, and potential vorticity can offer physically consistent explanations to the observed intensification, they are mostly qualitative in nature and do not yield more tangible quantities such as a "deepening rate" in terms of surface pressure tendency.

The vertical motion term in the moist adiabatic version of the pressure tendency equation (10b) provides the missing theoretical link between moist convection, ascent, static instability, and hurricane intensity change. It confirms that ascent within moist super-adiabatic layers is a mechanism that leads to the reduction of surface pressure. In addition, descent of stable air also contributes to surface pressure reduction. Thus, based on the analyses of the vertical motion term in equation (10b), the likely formation and intensification mechanisms of hurricanes are concluded and stated as follows.

An initial vortex that may eventually evolve into a hurricane is created by <u>ascent of moist super-adiabatic air</u> in a developing cumulus convection coupled with compensating sinking motion in the adjacent stable air. Continued development of the initial vortex is dependent on the ability of the MAULs to be sustained at and around the vortex center. These MAULs act to sustain ascent in moist convection which, in turn, sustain the reduction of surface pressure. In addition, the sinking of dry stable air inside the eye also reduces the surface pressure.

4. TROPICAL CYCLOGENSIS AND SST

The above theoretical analyses have provided answers to the first three questions posed earlier. The importance of moist super-adiabatic layers to hurricane formation and intensification reminds us yet another important condition regarded as necessary for hurricane formation, that is—a warm SST above 26°C. If ascent in moist super-adiabatic layers is the cause of hurricane intensification, then a warm SST is indeed favorable for hurricane intensification since the warm sea-surface tends to destabilize the near-surface air layer. Hurricanes have been observed to rapidly intensify as they pass over a warm pool of SST. An example is Hurricane Opal of 1995. However, the destabilization is possible only if the temperature above the surface is cold enough to support a super moist-adiabatic lapse rate. In other words, a warm SST must occur in conjunction with a cold upper troposphere.

The presence of a cold upper troposphere together with a warm SST is exactly what was found prior to the transition of a frontal cyclone into Hurricane Diana in 1984. In an observational study, Bosart and Bartlo (1991) found that a cold dome associated with a fractured upper-level trough moved over the warm waters of the Gulf Stream east of Florida. This cold dome eventually collapsed as the frontal cyclone transformed into a warm-core tropical cyclone. Although Davis and Bosart (2004) classified Diana as a WEC, the presence of a fracturing upper-level cold trough that developed into a cut-off low was similar to many of the SEC cases where an "occlusion-like" synoptic upper-level cut-off low developed. Convection was able to develop around the pre-existing occluded surface cyclone. As convection completely wrapped around the cyclone center, the structure of the system appeared to be no different from a hurricane.

5. THE GENESIS OF HURRICANE VINCE—*is warm SST necessary?*

The aforementioned "occlusion-like" synoptic development appears to be similar to what had occurred during the formative stage of Hurricane Vince. Figure 3 shows a sequence of GOES-12 infrared images taken at 11:45 UTC from October 4th through 9th, 2005. This sequence shows that the cyclonic disturbance that eventually develops into Hurricane Vince (Fig. 3f) can be tracked back to an initial disturbance near 43°N, 28°W on the 5th midway between a remnant polar low near the Azores and a sub-tropical low to the northeast (Fig. 3b). This disturbance is identified by a cyclonic twist that develops on the eastern edge of a convective burst. The polar low then pivots cyclonically around the southern flank of the vortical convective disturbance and appears to be absorbed by the disturbance later on the 5th. During the next four days, scattered moist convection develops around and near the cyclonic center and becomes more concentrated. Ships and buoys indicate that the cyclone is traveling across SSTs generally from 25°C to under 23°C during this period. Initially, the pre-Vince disturbance appears to have a westward vertical tilt (as judged by a cold cloud top marked as "V" being located west of a surface low center in Fig. 3b). By the 6th and 7th, the vertical tilt has been eliminated (as judged by the near co-location of the surface low center and the cyclonic motion of the cold cloud tops in figs. 2c and d). On the 8th, some outflow motion of the cold cloud tops is seen. By the 9th, cyclonic outflow motion is established on the cloud top of the ring of eyewall convection. The satellite presentation appears no different from a hurricane, and the cyclone was declared Hurricane Vince by the National Hurricane Center. Overall, this sequence of events depicts the transformation of a cold-core occluded cyclone to a warm-cored hurricane. The synoptic settings in which tropical transition of Vince occur are similar to the SEC cases as classified by Davis and Bosart (2004).

The formation of Vince over 23°C SST demonstrates that the warmth of the water is not the only determining factor in hurricane formation. This point is supported by the fact that polar lows, as well as some intense extratropical cyclones, have been observed to develop eye-like feature over relatively cold SSTs as moist convection envelops the cyclone center. The transformation of Vince from a cold-core occluded cyclone adds another tally to the growing SEC cases in Davis and Bosart's classification of tropical transitioning cyclones. In fact, the last three named-storms in the 2005 Atlantic Hurricane Season—Delta, Epsilon, and Zeta—all appear to have transformed from a cold-core occluded cyclone. Based on these observations, it appears that a cold-core occluded cyclone moving over warmer SST is the most favorable synoptic settings for tropical transition to occur, since the presence of upper-level cold air tends to destabilize the air column, promoting development of convection which erodes the upper-level cold dome and eventually transforms the cyclone into warm-cored. Since a warm-core cyclone is vertical stacked, it acts to provide a low wind shear environment favorable for hurricanes. The ascent of super moist-adiabatic air in the convection reduces the surface pressure, as affirmed by the vertical motion term in the surface pressure tendency equation. The cyclone would continue to intensify as long as the ascent and super moist-adiabatic layers are maintained.

The analyses of synoptic settings of tropical transitioning cyclones as presented above, together with the vertical motion term in the pressure tendency equation, actually raise an important conclusion—the moist static instability, rather than a high SST, should be viewed as the determining factor for hurricane formation and intensification. This answers the fourth question posed in section 3.4.

The vertical motion term in the surface pressure tendency equation asserts that ascent in a super-adiabatic lapse rate would lead to reduction of surface pressure. Given that this is the case, why do hurricanes form over the ocean but not over land? After all, if ascent in a moist super-adiabatic lapse rate is the cause of hurricane formation, why do mesoscale convective complexes (MCC) that form in late-spring in the Mid-West not develop into "land hurricanes"? Nevertheless, a warm-cored mid-level cyclone has indeed been observed to associate with the remnants of an MCC (Bluestein, p. 532). The circulation does not extend to the surface, however. The pressure tendency equation does not offer answer to this inquiry directly, since it does not impose restrictions on where super-adiabatic layers may exist. The key point in explaining this disparity between land and water may hinge on the ability of the surface layer to transport moisture upward from the surface interface into the air. Let us imagine that an unsaturated layer with lapse rate less than dry adiabatic exists above the surface interface. If moisture were to be supplied constantly from the surface interface into the unsaturated layer, the increase in moisture would eventually saturate the air layer. Once saturation occurs, the entire layer would become super moist-adiabatic! This mechanism of creating a super moist-adiabatic layer out of unsaturated air is quite plausible, and is more likely to occur over the ocean surface than on land. This last point emphasizes the important role of air-sea interaction (specifically sea-to-air moisture flux) in the creation of super moist-adiabatic surface layer, and its implications on hurricane formation and intensification.

6. CONCLUDING SUMMARY

The unusual formation of Hurricane Vince in the northeast North Atlantic in October of 2005 prompted the undertaking of this study. Observations showed that Vince developed from a cold-core occluded type cyclone that formed to the north of the Azores on the 5th of October. This cyclone moved southeastward and transformed into a tropical cyclone during the next four days while staying over sea-surface temperature as low as 23°C.

In order to understand the dynamics of cyclogenesis in general, a pressure tendency equation has been derived. This new equation reveals the link between temperature advection, static stability, vertical motion, diabatic heating, and their effects on the surface pressure tendency. Analysis of the vertical motion term reveals that ascent in a super-adiabatic lapse rate and descent in a stable lapse rate lead to reduction of surface pressure. When applied to a hurricane, the ascent in a super moist-adiabatic lapse rate in moist convection and descent in adjacent stable air are identified as the likely causes of hurricane formation and intensification. Super moist-adiabatic lapse rate has been directly observed and shown to be quite prevalent in a modeling study by Ross et al (2004).

The formation of hurricanes over relatively low SST in recent years warrants re-examination of this accepted hurricane formation criteria. The existence of a cold dome observed in a majority of tropical transitioning cyclones, combined with theoretical analyses of the vertical motion term in the pressure tendency equation, leads to the conclusion that the moist static instability, rather than a high SST, should be viewed as the determining factor for hurricane formation and intensification.

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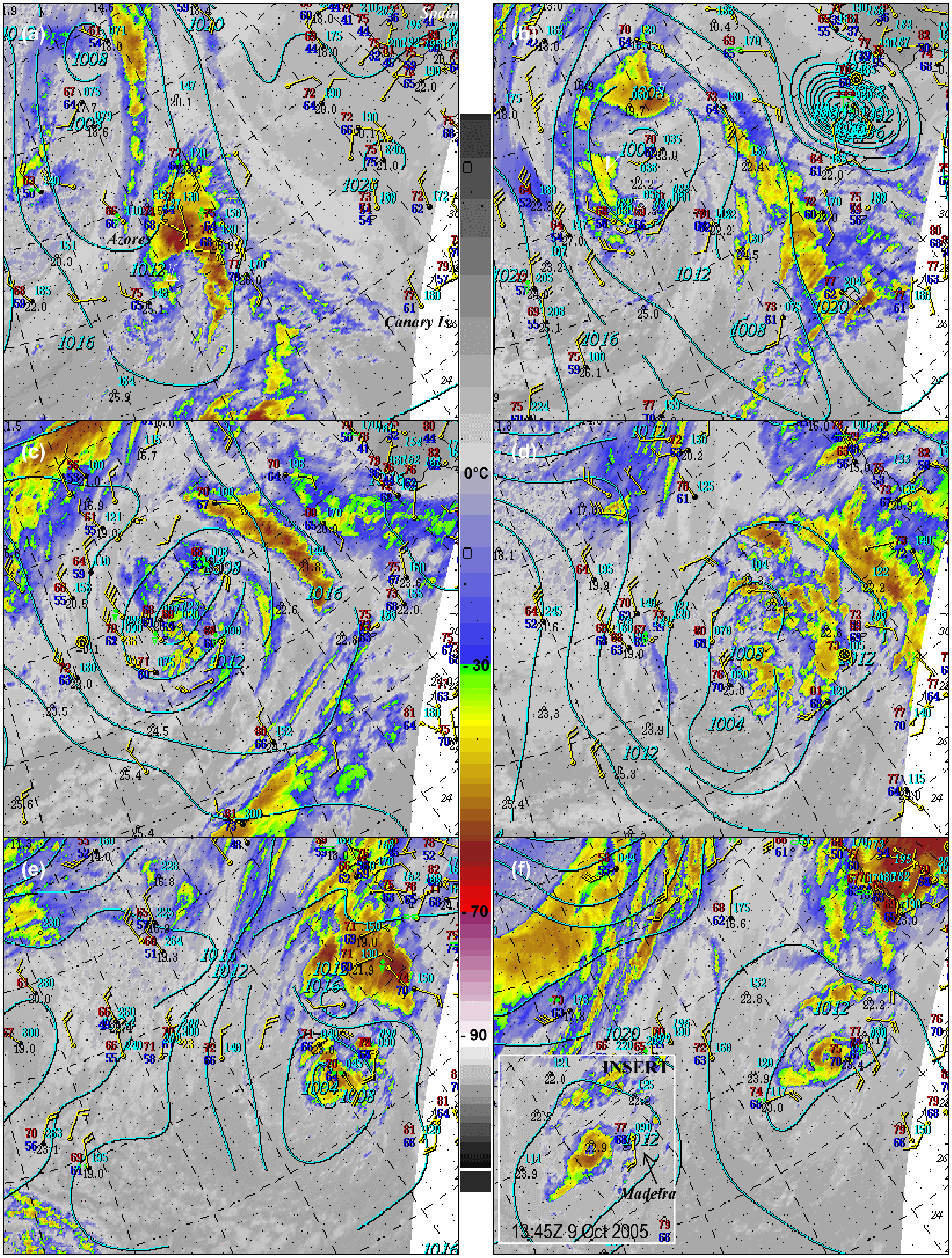

Figure 3 Color-enhanced GOES-12 infrared images at 11:45 UTC on (a) 4, (b) 5, (c) 6, (d) 7, (e) 8, and (f) 9 October 2005. Cyan contours are isobars of sea-level pressure. Surface station models are also overlaid (Red and blue numbers are surface air temperatures in °F; cyan numbers are abbreviated SLP; black numbers are sea-surface temperature in °C). "P", "L", "V" denote locations of a remnant polar low, a sub-tropical low, and the pre-Vince disturbance.