Letter Editors' Suggestion

Birth of a cold core in tropical cyclones past landfall

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A tropical cyclone (TC) over ocean functions as a heat engine fueled by ocean moisture. By contrast, its decay past landfall is thought to be akin to a dry vortex spinning-down due to friction with the land, an intrinsically nonthermodynamic process. We study the evolution of TCs past landfall using computational simulations where we explicitly account for thermodynamics. Doing so allows us to uncover that past landfall the TC's dynamical heart—the warm core—does not simply wither away. Instead, thermodynamic processes modulated by the moisture stored in the TC invariably engender a cold core that grows underneath and at the expense of the warm core. Our findings underscore the key role of moist thermodynamics in the postlandfall evolution of TCs. Additionally, they have direct implications on the prevailing weather forecasting methods which invoke the birth of a cold core as a telltale signature of an extratropical transition.

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I. INTRODUCTION

On 24 September 2005, tropical cyclone (TC) Rita [1] made landfall on the coast of Texas with an intensity of ~51 m/s [Figs. 1(a) and 1(b)]. As it headed northeast, its intensity decayed rapidly. A day past landfall, the intensity plummeted to ~15 m/s, and by the next day, the cyclone had dissipated. Three years later, a similar sequence of events seemed set to unfold. On 13 September 2008, TC Ike [2] made landfall on the coast of Texas with an intensity of ~49 m/s [Figs. 1(c) and 1(d)]. It headed northeast, and its intensity decayed rapidly—but only over the first day. On the second day, Ike transitioned into an extratropical cyclone. Its intensity soared, from ~18 m/s to ~26 m/s, and so did the attendant rainfall. Over the course of the second day, when Ike was about 2000 km inland, it caused widespread flooding, power outages, and other damage totaling a loss of over $1 billion [2]. By the third day, Ike's trail of destruction continued onto Canada, where it finally dissipated.

The disparate fates of TCs Rita and Ike highlight two distinct modes of the evolution of TCs past landfall, which we discuss in turn. Prior to landfall, over ocean, a TC functions as a heat engine [3]. Moisture from the ocean fuels [3,4] its signature warm core, which resides in and around the eye of the TC [Fig. 2(a)]. The warm core creates a region of low pressure in the eye and the resulting pressure gradient drives the intense winds of the TC. Landfall cuts off the moisture supply [4–6], and the heat engine is active no longer. But the TC must contend with friction with the land underneath. Its dynamics is modeled as a dry, incompressible vortex (whose initial condition is set by the wind

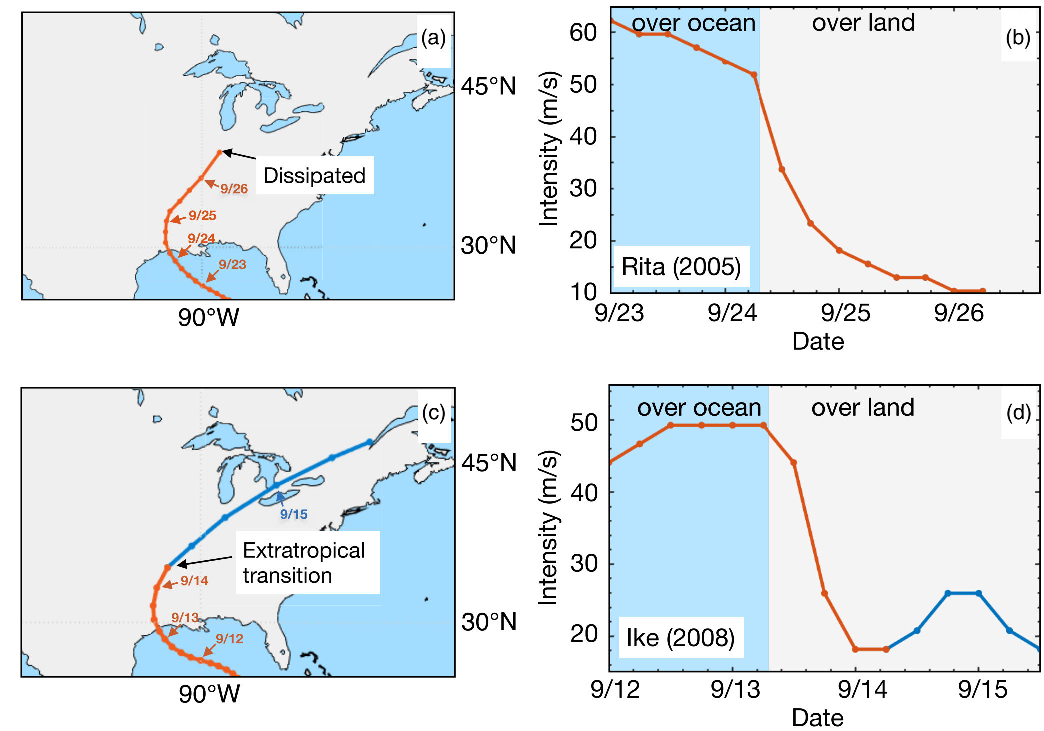

FIG. 1. Fates of two TCs past landfall. Red represents TC and blue represents extratropical cyclone. Track and intensity data are from the "Atlantic HURDAT2" database [10]. [(a) and (b)] TC Rita (2005): track and intensity vs. date. Past landfall, Rita's intensity decayed rapidly; in two days, the storm lost its organized convection and dissipated. [(c) and (d)] TC Ike (2008): track and intensity vs. date. Past landfall, Ike's intensity decayed rapidly, but only initially. On the second day, Ike underwent an extratropical transition and reintensified. Although both Rita and Ike made landfall at similar intensities, at similar locations, and even followed similar tracks, their intensity evolution differed notably, as did the swath and magnitude of the attendant destruction.

field and pressure field of the TC at landfall) that decays due to bottom friction [7–9]. In essence, the postlandfall TC dynamics is simply that of a mature TC withering away.

Unlike the postlandfall evolution discussed above where thermodynamics plays no role, thermodynamics is of central import in the transition to an extratropical cyclone [11–13]—not the thermodynamics intrinsic to the TC but that of the external environment. A typical scenario is when a decaying TC past landfall hits a front (a large horizontal temperature gradient in the environment) and destabilizes this baroclinically unstable environment. The front splits into two: a cold front and a warm front. As these fronts distort and wrap around the cyclone's eye, the cold air upstream of the cold front plunges to occupy the lower reaches of the eye. The cold core is born, and the potential energy released during this process powers the extratropical cyclone's winds [Fig. 2(b)]. Counterpart of the warm core in a TC, the cold core is the cardinal attribute of an extratropical cyclone.

What fate awaits a TC past landfall? Though there are weighty implications, an accurate forecast is a difficult task. In particular, forecasting the transition to an extratropical cyclone presents a formidable challenge as it involves a complex set of structural changes in the cyclone [11,15]. It used to be that a forecaster would subjectively evaluate the many structural changes in a TC past landfall and predict if the TC would transition to an extratropical cyclone [11]. That state of affairs changed with the remarkable work of Evans and Hart [13], which provides an objective framework for forecasting an extratropical transition (ET) [11]. This widely used framework identifies an ET

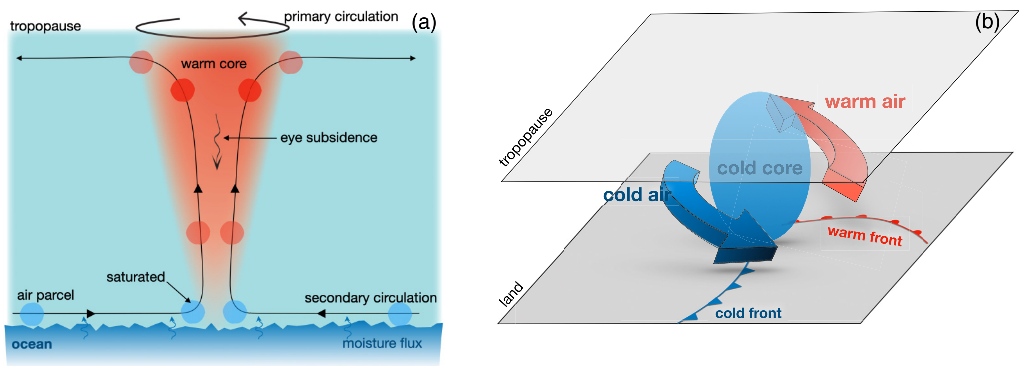

FIG. 2. Tropical cyclones vs. extratropical cyclones. (a) Schematic of a mature TC (cross-sectional view). Its warm core, which is fueled by air parcels laden with moisture from the ocean underneath and further warmed by subsidence heating in the eye, is associated with the TC's intense winds. (b) Schematic of an extratropical cyclone (three-dimensional view). An extratropical cyclone can form when a TC past landfall hits a front. This destabilizes the front, a process is known as baroclinic instability [14]—the cold (and thus, dense) air plunges and the warm (and thus, light) air raises. (Baroclinicity is a measure of the misalignment between the gradient of pressure and the gradient of density.) A cold core forms where the eye of the TC was located, and the environmental potential energy released via the baroclinic instability powers the extratropical cyclone's winds. The warm core in a TC and the cold core in an extratropical cyclone embody the cardinal attributes of their respective cyclones.

by invoking a telltale signature [13]: the birth of a cold core in the lower troposphere (the 900- to 600-hPa layer); see the supplemental material (SM) [16] for further discussion. In this study, we closely examine this defining event, the birth of a cold core.

II. SIMULATIONS

We study TCs past landfall using computational simulations. We use Cloud Model 1, a well-known computational tool that has been extensively used to study the dynamics of idealized TCs over ocean [17–19], and, recently, over land [20,21]. (See Table S-1 in the SM [16] for a list of the simulation parameters.) First, using the default settings for the simulation parameters, we develop a mature TC over a warm ocean (sea-surface temperature = 301 K). Then we subject it to a complete landfall by instantaneously cutting off the supply of moisture and sensible heat from throughout the bottom boundary [4–6,22]. (We do this by setting the coefficient of enthalpy, C_e, equal to zero [21].) Further, because the surface drag affects the TC dynamics [20,22] and because the surface drag over land is typically higher than that over ocean, we use a higher surface drag past landfall by setting the coefficient of momentum, C_D, equal to 0.006. (Over ocean, C_D varies, as a function of the cyclone intensity, between 0.001 and 0.0024.) To keep the simulation setup simple, we keep all other simulation parameters for the landfalling cyclone the same as for the cyclone over ocean.

Two aspects of our simulations bear emphasis. First, we employ a baroclinically stable environmental sounding. This precludes any ET. Second, we account for thermodynamic processes not only when the TC is over ocean but also past landfall. This might seem unnecessary. After all, because an ET is precluded, we expect thermodynamics to exercise no effect on the TC decay. In this scenario, we expect the warm core to simply fade into the ambient and the corresponding temperature difference (relative to the sounding temperature) to disappear. But that is not what transpires.

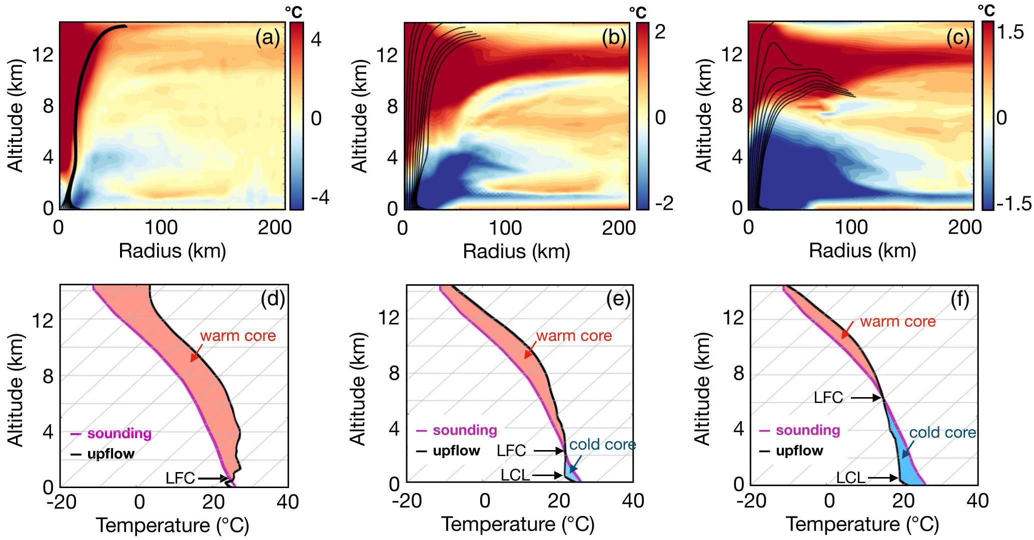

FIG. 3. Birth of a cold core in simulated landfall of an axisymmetric TC. [(a)–(c)] Contours of temperature difference (relative to the sounding temperature) at 0 h (a), 15 h (b), and 30 h (c) past landfall. We also plot representative streamlines (black lines) to visualize the secondary circulation (for which we seed the flow at the altitude of 0.1 km and at 10 radial positions spaced 2 km apart, starting at radius = 1 km). [(d)–(f)] Temperature profiles of the sounding and upflow corresponding, respectively, to panels (a)–(c). Note that the temperature coordinate is skewed (the slanted gray lines correspond to constant temperature) to clearly show the warm core and the cold core. Past landfall, the lessening of moisture in the upflow causes the altitude of the LFC to increase. As a result, the cold core grows at the expense of the warm core.

III. RESULTS

In Fig. 3(a), we plot contours of the temperature difference for the simulated mature TC over ocean. In its central region, resides a prominent warm core, the height of which spans the whole troposphere. A day past landfall, the warm core notably shrinks in size and diminishes in strength [Fig. 3(b)]. That is what we expect. But, on closer inspection, we note a surprising phenomenon: Underneath the warm core appears a cold core that spans the lower troposphere and grows at the expense of the warm core [Fig. 3(c)]. If the birth of this cold core is construed as the signal for an ET, then we would conclude that the TC is transitioning to an extratropical cyclone. And yet, because the environment is baroclinically stable, an ET is not possible. Clearly, baroclinic instability of the external environment is not a necessary condition for engendering a cold core. Further, the birth of the cold core is not tied to a specific choice of simulation parameters—it occurs even when we vary the surface drag, sea-surface temperature, and geometry (axisymmetric vs. three dimensional); see Figs. S-1, S-2, and S-3 in the SM [16]. It is a robust phenomenon that stems not from the external environment but from mechanisms that are intrinsic to a TC past landfall, as we discuss next.

To understand these mechanisms, consider a TC's secondary circulation. In Figs. 3(a)–3(c), we plot a few representative streamlines illustrating the secondary circulation. Of particular interest for our considerations is the vertical segment of the secondary circulation, the upflow in the eyewall (the annular region of intense flow around the eye). As a moist air parcel ascends in the upflow, it expands and cools. The rate of cooling depends on the saturation level of the parcel [14]. For an unsaturated parcel, the cooling follows the dry adiabat, with a typical lapse rate of $\sim 9.8\,^{\circ}\mathrm{C/km}$. For a saturated parcel, the cooling follows the moist adiabat, with a typical lapse rate of $\sim 5\,^{\circ}\mathrm{C/km}$, which is smaller than that of the dry adiabat because of the latent heat of condensation released from the condensing moisture in the parcel.

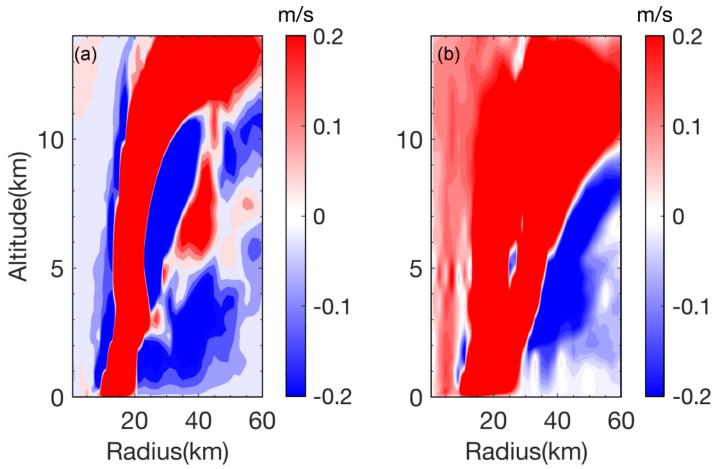

FIG. 4. Eye subsidence before and after landfall. Contours of vertical velocity: (a) averaged over the 15-h period before landfall and (b) averaged over the 15-h period after landfall. The data correspond to the simulation shown in Fig. 3. Before landfall (a), in the eye of the TC (of radius ≈10–20 km), there is a noticeable downdraft (and in the eyewall, a noticeable updraft). This subsidence makes the eye warmer than the warm eyewall. After landfall (b), the subsidence disappears, suggesting that it plays no role in controlling the thermal structure of the core.

In a mature TC over ocean, the parcels, laden with the moisture from the ocean, arrive at the base of the upflow nearly saturated and at a temperature close to the ambient [23]. They follow the moist adiabat and turn warmer, and thus lighter, than the ambient. These buoyant, warm parcels scale the height of the cyclone along the eyewall and the eyewall turns warm. The warm eyewall surrounds an eye that is even warmer [Fig. 3(a)]. This is because of "subsidence heating," which stems from the downflow of dry air in the eye [Fig. 4(a)], where the air parcels are compressed and adiabatically heated [24–26]. (The eye is cloud free because of the eye subsidence.) The downflow is driven by the flow in the eyewall [24,27], its velocity increasing with the TC intensity. Thus, the more intense a TC, the more manifestly warm its eye. Together, the warm eye and eyewall constitute the prominent warm core of a mature TC [Fig. 2(a) and Fig. 3(a) and 3(d)].

After landfall, the TC intensity decays exponentially [28]. The weakened flow in the eyewall can no longer drive the subsidence in the eye [Fig. 4(b)]. In turn, the upflow segment of the secondary circulation invades the eye [Figs. 3(b) and 3(c)]. The distinctive cloud-free eye of a mature TC now ceases to exist. The dynamics of the upflow in this central region plays a critical role in the birth of the cold core, as we discuss next.

On landfall, the active supply of moisture disappears [4–6]. The TC, however, still contains moisture from its passage over ocean prior to landfall [21]. Laden with moisture from this unreplenished, dwindling source, the parcels now arrive at the base of the upflow moist but unsaturated and at a temperature colder than the ambient (because these unsaturated parcels expand as they move radially inward). They first follow the dry adiabat and continue to cool. On reaching the altitude of the "lifting condensation level" (LCL), the cooling parcels turn saturated [14]. Hereafter, they follow the moist adiabat. At the "level of free convection" (LFC), the temperature of the ascending parcel equals that of the ambient [14]. From the base of the upflow to the LFC, the parcels are colder than the ambient. They engender a cold core [Figs. 3(b) and 3(e) and Fig. 5]. Above the LFC, the parcels are warmer than the ambient. They engender a warm core atop the cold core [Figs. 3(b) and 3(e) and Fig. 5]. As the landfall progresses, the specific humidity and temperature of the parcels at the base of the upflow lessens, which, in turn, causes the altitudes of the LCL and LFC to increase. Consequently, the cold core grows and the warm core shrinks [Figs. 3(c) and 3(f)].

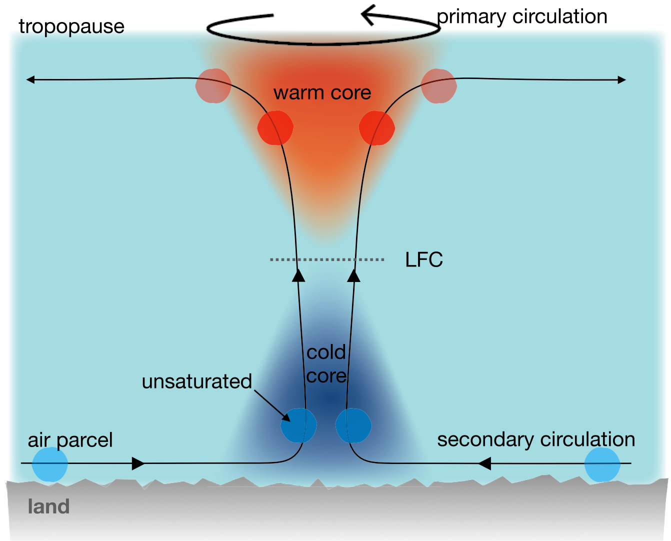

FIG. 5. Schematic of a postlandfall TC (cross-sectional view). Compared with a mature TC [Fig. 2(a)], the warm core has shrunk and a cold core occupies the lower troposphere. The LFC separates the warm core and the cold core.

The thermal structure in a TC is closely linked to the TC's flow structure. Specifically, the temperature field sets the pressure field, which, in turn, determines the wind field; see SM for further discussion [16]. That is, using the temperature field we can predict the wind field. To illustrate this approach, in Fig. S-4, we plot, for different times past landfall, the predicted wind profiles atop the boundary layer and compare them against the corresponding wind profiles from the simulation. The close correspondence between them corroborates that in a TC the thermal structure and the flow structure are closely linked.

IV. DISCUSSION

Our study makes it evident that thermodynamic processes modulated by the moisture stored in the TC play a key role in shaping the evolution of TCs past landfall. Owing to these processes, the birth of a cold core in the lower troposphere is simply a natural consequence. This finding has a direct bearing on a foundational element of the prevailing forecasting methods of an ET: The birth of a cold core in the lower troposphere should not be construed as a telltale signature of an ET. That feature is shared by both ETs and TCs past landfall.

To distinguish between the two, our results suggest a simple way—whereas a shallow cold core (which spans the lower troposphere; see Fig. 5) forms in a TC past landfall, an extratropical cyclone has a deep cold core [which spans the whole troposphere; see Fig. 2(b)]. We submit that to identify an ET unambiguously, the requirement of a cold core in the lower troposphere must be changed to a deep cold core. Indeed, recent studies [29,30] have shown that by including an upper cold core (that spans 600–300 hPa) in addition to the shallow cold core, ETs are identified more reliably. One reason, we conjecture, may be that including this additional metric rooted out the postlandfall TCs with a shallow cold core.

Last, we note that while we have focused on landfall, similar considerations may also hold for a TC traversing from warmer to colder ocean. A decrease in the sea-surface temperature by a few $^{\circ}$C can reverse the air-ocean thermodynamic disequilibrium [31] and therefore cut off the moisture supply to the TC, analogous to the case of a landfall. One difference with the landfall case is the timescale of the development of the cold core. Whereas landfall typically corresponds to a higher frictional drag at the bottom of the TC [20], the frictional drag remains the same for the case of a colder ocean. This yields a slowly growing cold core (Fig. S-1). Whether over land or over colder oceans, we submit that the birth and growth of a cold core are but the natural stages in the evolution of a moisture-deprived TC.

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