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SEVENTH INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES

Topic 2.1: **Tropical-Cyclone Formation: Theory and Idealized modelling**

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Abstract

This report summarizes work completed since IWTC-VI that contributes to an improved understanding of tropical-cyclone formation and a potentially useful perspective for forecasters and researchers. The topic of tropical cyclone formation has been the subject of considerable active research in the past four years. Much of the recent research reviewed here points to a unified view of the genesis and intensification process. It provides also a basis for some new tools to aid in forecasting tropical-cyclone formation.

2.1.1. Introduction

The most up-to-date review of the topic is that given by Tory and Frank (2010), which forms a chapter of the recent WMO-sponsored update on "Tropical Cyclones: From Science to Mitigation" (2010, Kepert and Chan, Eds.). Much of the work described below has been published since their review went to press.

Before embarking on this review, it is appropriate to discuss some relevant terminology. The glossary on the Hurricane Research Division's website[1] uses "tropical cyclone as the generic term for a non-frontal synoptic-scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and a definite cyclonic surface wind circulation (Holland 1993)." Notably, this definition does not invoke any wind threshold. The same glossary defines a tropical depression as a tropical cyclone with maximum sustained surface winds of less than 17 m s^{-1} (34 kt, 39 mph) and, in the Atlantic and Eastern Pacific Basins, a "tropical storm" as a tropical cyclone with surface winds between 17 m s^{-1} and 33 m s^{-1}.

[1] http://www.aoml.noaa.gov/hrd/tcfaq/A1.html

In contrast, a universally accepted definition of tropical cyclogenesis does not exist. For example, Ritchie and Holland (1999) define genesis as: " … the series of physical processes by which a warm-core, tropical-cyclone-scale vortex with maximum amplitude near the surface forms[2]". In a more recent paper, Nolan et al. (2007) use a wind speed threshold of 20 m s$^{\square\mathrm{m}}$ to define the *time of genesis*. For the purpose of this report we will define genesis as the formation of a tropical depression as defined above and, like Ritchie and Holland, but unlike Nolan, we impose no formal threshold on wind speed. We refer to "intensification" as the amplification of the surface wind speed beyond the stage of tropical depression. Another issue, recognized long ago by Ooyama (1982), is the usage of the words "formation" and "genesis". For the purposes of this report we will use these terms interchangeably. Moreover, we argue later that, from the point of view of understanding the formation and intensification process, a precise definition of cyclogenesis is unnecessary.

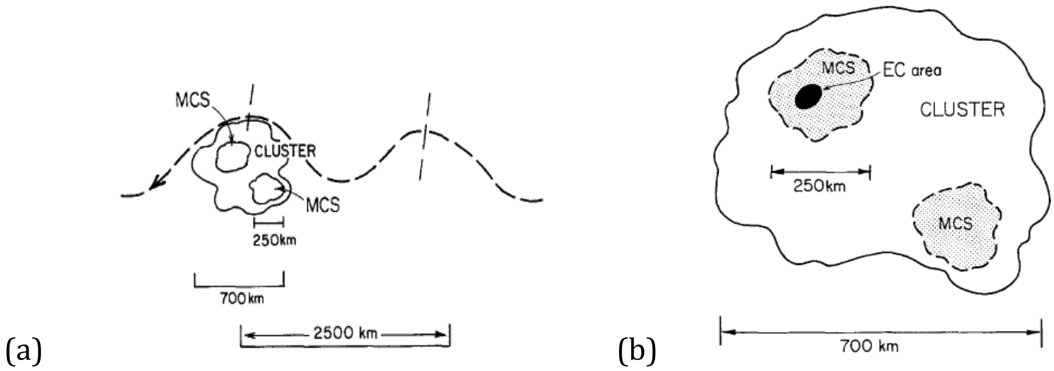

Figure 1. (a) Schematic of synoptic-scale flow through an easterly waves (dashed) with an embedded cluster of convection in the wave trough. In (b) the cluster is shown to contain mesoscale convective systems (MCSs) and extreme convection (EC, black oval) within one of the MCSs. From Gray (1998).

As outlined by Dunkerton et al. (2009, hereafter DMW09), the problem of tropical cyclogenesis in the real atmosphere is a formidable one and goes well beyond semantics. They wrote: "The genesis of tropical cyclones, hurricanes and typhoons is one of the most important unsolved problems in dynamical meteorology (Emanuel 2005) and climate Gore (2006)." One reason why the problem remains unresolved after decades of research is because in situ observations of genesis are mostly lacking over remote tropical oceans. Until recently, field campaigns have been too few and operational efforts have generally targeted mature storms. As a result, critically important processes and their multi-scale interactions thought to be involved in cyclogenesis have been a challenge to model and observe. DMW09 wrote further: "Nature in some cases provides little advance warning of these storms and prediction of genesis beyond 48 h is generally too uncertain to be useful. Funding and technological resources are needed to remedy these deficiencies, to the extent they can be remedied, but … it is unlikely that fundamental progress will be made without a quantum leap in theoretical understanding as well. … the available observations on the synoptic scale need to be analyzed in a manner that is consistent with the Lagrangian nature[3] of tropical cyclogenesis. ... In the earliest stage of genesis, the fluid motion is mostly horizontal and quasi-conservative, punctuated by intermittent deep convection, a strongly diabatic and turbulent process. In order to fully appreciate the transport of vorticity and moist entropy by the flow, their interaction with one another, the impacts of deep convective transport and protection of the proto-vortex from hostile influences requires, among other things, an understanding of material surfaces or "Lagrangian boundaries" in the horizontal plane. This viewpoint, although used subconsciously by forecasters, is invisible to researchers working with standard meteorological products in an Eulerian or Earth-relative framework."

[2] They do not say what the scale is, nor do they explain to what "amplitude" refers.
[3] In a broad sense, Lagrangian refers to the practice of following an air parcel or a flow feature. Here we are following a tropical wave disturbance. For the present purposes we are invoking a wave-relative viewpoint following the trough axis of the wave.

Since the last IWTC report, this new Lagrangian perspective has been applied largely to tropical-cyclone formation in the Atlantic and eastern Pacific basins. As a result, most of this report will focus on the advances made in understanding the formation of tropical depressions in the Atlantic basin. The formation of tropical depressions in other basins, such as the western North Pacific, will be discussed as it relates to this new Lagrangian perspective. In particular, we will discuss controversial aspects of these new ideas and relate them to other theories that have emerged since the last IWTC report.

2.1.2. The formation of tropical depressions: science issues

The development of tropical depressions is inextricably linked to synoptic-scale disturbances that come in a variety of forms. The most prominent synoptic-scale disturbances in the Atlantic basin are African easterly waves. Typically, they have periods of 3-5 days and wavelengths of 2000-3000 km (e.g. Reed et al. 1977).

The multi-scale nature of tropical cyclogenesis within tropical waves is well-known and substantial progress in further understanding the genesis sequence has been made since the last IWTC report. The processes are illustrated schematically in Figure 1 (Gray 1998). There, two length scales are illustrated, with a cluster of deep, moist convection confined to the trough of the synoptic-scale wave. Within these clusters are individual mesoscale convective systems (MCSs).

The parent easterly waves over Africa and the far eastern Atlantic are relatively well studied, as in the classic GATE[4] campaign in 1974 and more recently in NASA AMMA (2006). Sometimes a vigorous, diabatically-activated wave emerging from Africa generates a tropical depression immediately, but in most instances these waves continue their westward course harmlessly over the open ocean, or blend with new waves excited in the mid-Atlantic ITCZ. In a minority of waves, the vorticity anomalies they contain become seedlings for depression formation in the central and western Atlantic and farther west.

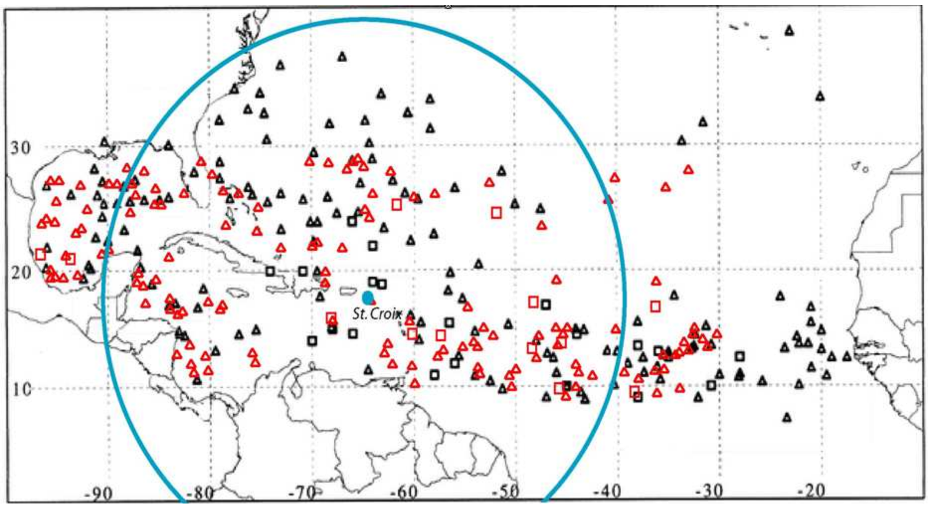

Figure 2. First-detection locations of developing (triangles) and non-developing (squares) tropical depressions from 1975-2005 (1995-2005 in red), adapted from Bracken and Bosart (2000). The blue circle denotes the approximate PREDICT domain.

Figure 2 shows the detection locations of developing and non-developing tropical depressions from 1975-2005 based on the work of Bracken and Bosart (2000). It is apparent that there are relatively few Atlantic tropical depressions that fail to become tropical cyclones. It is well known also that most (approximately 80%) tropical waves do not become tropical depressions. This fact is supported by

[4] Global Atmospheric Research Programme, Atlantic Tropical Experiment

numerous studies (e.g., Frank, 1970; DMW09, their footnote 3). The key questions would appear to be:

- Which tropical waves (or other disturbances) will evolve into a tropical depression?
- What is different about developing waves?
- Can this difference be identified, and on what time scale?
- Why do so few disturbances develop?

Research since IWTC-VI has led to a new understanding into how locally-favourable recirculation regions are generated *within these disturbances* in the lower troposphere, and has gone a long way to providing answers to the foregoing questions. On the one hand, these circulation regions help protect seedling vortices from the detrimental effects of vertical and horizontal shearing deformation and from the lateral entrainment of dry air. On the other hand, they favour sustained column moistening and low-level vorticity enhancement by vortex-tube stretching in association with deep cumulus convection.

2.1.3. The marsupial paradigm

DMW09 proposed a new model for tropical cyclogenesis that recognizes the intrinsic multi-scale nature of the problem from synoptic, sub-synoptic, mesoscale and cloud scales. Using three independent datasets, ECMWF[5] Reanalysis data, TRMM[6] 3B42 3-hourly precipitation and the best track data from the National Hurricane Center (NHC), the Kelvin cat's eye within the critical layer[7] of a tropical easterly wave, or the wave "pouch", was hypothesized to be important to tropical storm formation because:

1) wave breaking or roll-up of cyclonic vorticity and lower-tropospheric moisture near the critical surface in the lower troposphere provides a favourable environment for the aggregation of vorticity seedlings for tropical-cyclone formation;

2) the cat's eye is a region of approximately closed circulation, where air is repeatedly moistened by deep moist convection and protected to some degree from dry air intrusion; and

3) the parent wave is maintained and possibly enhanced by diabatically-amplified mesoscale vortices within the wave.

This genesis sequence and the overarching framework for describing how such hybrid wave-vortex structures become tropical depressions is likened to the development of a marsupial infant in its mother's pouch wherein the juvenile proto-vortex is carried along by the mother parent wave until it is strengthened into a self-sustaining entity. A survey of 55 named storms in the Atlantic and eastern Pacific sectors during August–September 1998–2001 was shown to support this so-called "marsupial paradigm". Tropical cyclogenesis tended to occur near the intersection of the trough axis and the critical surface of the wave, the nominal centre of the cat's eye. The marsupial paradigm provides a useful road map for exploration of synoptic-mesoscale linkages essential to tropical cyclogenesis.

The marsupial model subsumes many of the current ideas regarding tropical cyclone formation. Nevertheless, it is useful to call attention to the distinctions between the various theories for explaining the formation of the surface vortex, which in turn is capable of self-amplification within the favorable "pouch" of the parent disturbance. Theories on how a surface vortex forms generally fall into two categories: (i) "top-down" thinking wherein a vortex in the mid-troposphere (that presumably forms within the stratiform region of an MCS) somehow engenders a surface circulation by "building downwards"[8] and (ii) "bottom-up" thinking, in which cyclonic relative vorticity anomalies are generated at low altitudes (~ 1 km) through condensational heating in relatively downdraft-free convection. Mesoscale vortex formation in pathway (ii) may occur more rapidly than in pathway (i) due to the larger low-level vertical velocities involved. Needless to say, lower tropospheric processes favourable to development provide a significant head start in the genesis sequence, relative to

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[5] ECMWF = European Centre for Medium Range Weather Forecasts
[6] TRMM = Tropical Rainfall Measuring Mission
[7] For a complete definition of all technical terms used herein please consult the Glossary at the end of this report.
[8] We know of no convincing argument explaining how the surface spin up occurs in the "top-down" pathway.

processes initially confined to the middle troposphere. The contrast between these two pathways was discussed in the last IWTC report on the topic of tropical cyclogenesis.

2.1.3.1. A real world example: The formation of hurricane Felix (2007)

The recent study by Wang et al. (2010a,b) examining the formation of Hurricane Felix (2007) provides a useful illustration of some of the Lagrangian concepts introduced above. According to the National Hurricane Center summary, Hurricane Felix (2007) formed from an easterly wave that emerged off the coast of Africa on August 24 that year. The wave signal is shown in the 2.5-day low-pass filtered 850 hPa flow field from ECMWF analyses (Figure 3). In the Earth-relative frame of reference, the wave propagated westward with an inverted-V pattern. Sustained convection, as indicated by TRMM 3B42 3-hourly accumulated precipitation data, occurred around the northern tip of the inverted-V pattern, and a tropical depression formed in the area of sustained convection at 21Z 31 August. However, there was no closed circulation in the filtered data at 850 hPa in the Earth-relative frame, even at genesis time. Although this may be partly due to the inaccuracy of the global model analyses, the flow pattern in the Earth-relative frame does not provide an immediate explanation for the preferred location of sustained convection and storm genesis.

Recall that, for a stationary flow, streamlines are equivalent to the flow trajectories (e.g., Holton, 2004). DMW09 showed that in the frame of reference moving zonally at the same speed of the easterly wave (hereafter the "translated" or "co-moving" frame), the flow is quasi-stationary and the translated streamlines are a good approximation of the flow trajectories. To view the Lagrangian nature of the storm evolution, the streamlines are displayed in the co-moving frame. In this event, the zonal wave speed is estimated about -7.7 m s^{-1} based on the Hovmöller diagram of 700 hPa meridional wind from ECMWF analysis (not shown). As shown in Figure 4, a quasi-closed circulation (the *wave pouch*) is present at 850 hPa in the translated frame 2.5 days prior to genesis. Compared to the Earth-

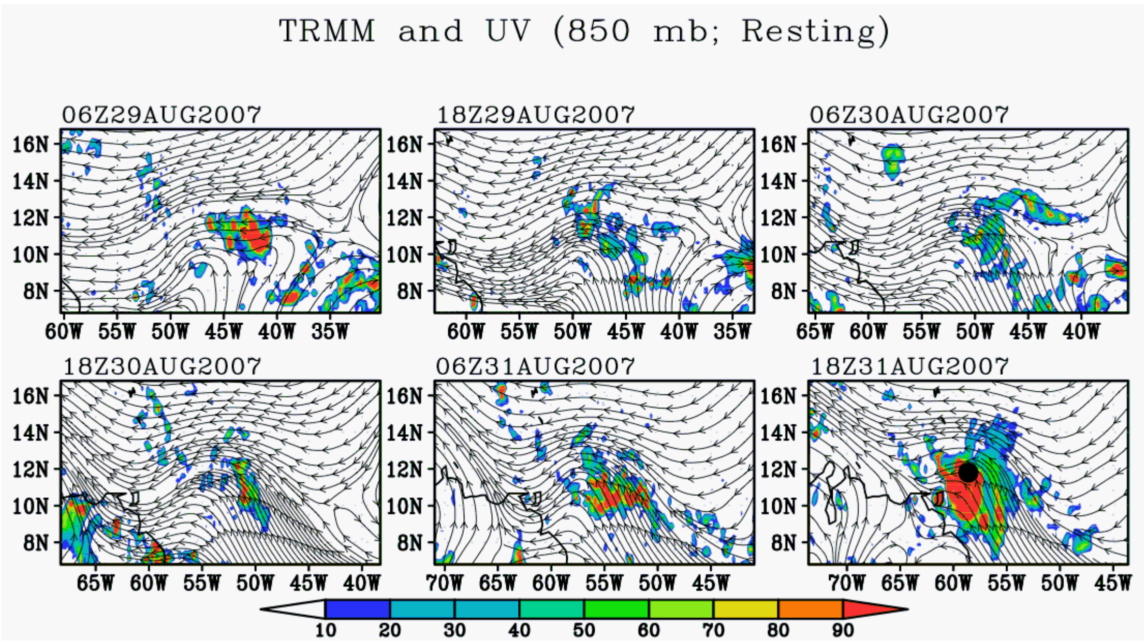

Figure 3. Streamlines of the 2.5-day low-pass filtered 850-hPa flow from ECMWF analyses in the Earth-relative frame of reference from 0600 UTC 29 Aug to 1800 UTC 31 Aug. Shading indicates TRMM 3-h accumulated precipitation (mm day^{-1}). The genesis location is indicated by the black dot in the final panel.

relative frame, the circulation centre in the translated frame shifts northwards, and sustained convection is largely confined within the pouch. Genesis occurred close to the pouch centre, which can be defined more precisely as the intersection of the wave critical latitude and the trough axis. The pre-genesis evolution of Felix supports the hypotheses and observational findings of DMW09 that the pouch centre is the preferred location for tropical-cyclone formation.

The structure of the pre-Felix disturbance as shown in Figures 3 and 4 is typical for easterly waves and can be summarized in a schematic (Figure 5). Often, a wave in the Earth-relative frame of reference appears to be open, having an inverted-V pattern, but such an inference is misleading. Convection tends to occur around the northern tip of the inverted-V pattern along the wave trough. However, in

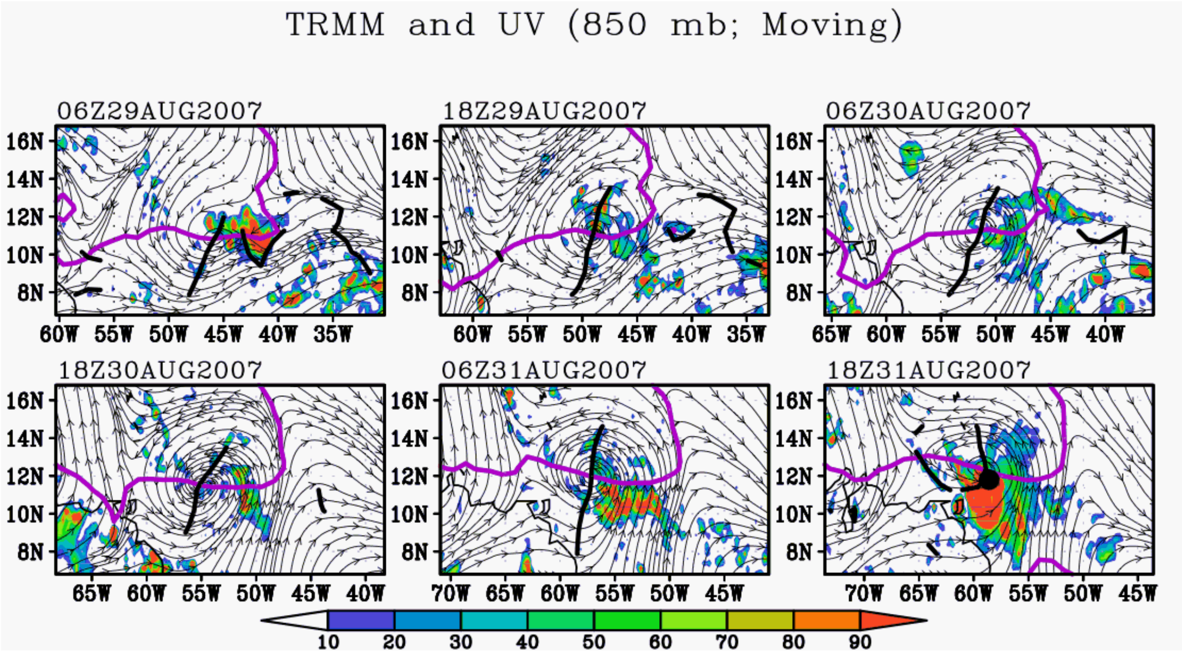

Figure 4: As in Figure 3, but the streamlines are displayed in the frame of reference moving westwards at the zonal propagation speed of the parent wave. Isopleths of zero relative zonal flow are indicated by the purple contours, and the wave's trough axis is shown in black. The genesis location is indicated by the black dot in the final panel.

the co-moving frame of reference a pouch may be present, though not necessarily in all cases. The formation of a wave-pouch requires i) that the phase speed of the wave be within the range of the mean flow in which it is embedded and, ii) that the wave be of sufficient amplitude for the wave to interact with its own critical surface so as to create a recirculation region within the ambient mean shear flow. The formation and extent of a quasi-closed recirculation region depends, inter alia, on wave amplitude, intrinsic phase speed, and mean latitudinal shear. The pouch is a region of quasi-closed Lagrangian circulation with cyclonic rotation and weak strain/shear deformation within the wave critical layer, favouring the creation and preservation of coherent vortex structures at the meso-β scale. Its kinematic structure protects to some extent the convective cells inside the pouch from the hostile exterior environment: e.g., dry air associated with the Saharan air layer. The air within the pouch will be also repeatedly moistened by convection, which in turn provides a favourable environment for deep moist convection. As noted above, the pouch centre is the preferred location for tropical cyclogenesis. Also indicated in Figure 5 is a small opening of the pouch due to the divergent component of the flow, which allows influx of environmental air and vorticity. Entrainment of environmental air and its material properties may be induced also by transient flow (DMW09).

2.1.3.2. Fundamental coherent structures within the pouch

Vortical hot towers (or VHTs) have been identified as fundamental coherent structures in both the tropical cyclone genesis process (Hendricks et al. 2004, Montgomery et al. 2006, Braun et al. 2010, Fang and Zhang. 2010) and the tropical-cyclone intensification process (Nguyen et al. 2008, Shin and Smith 2008, Montgomery et al. 2009). A widely accepted definition for these vortical convective

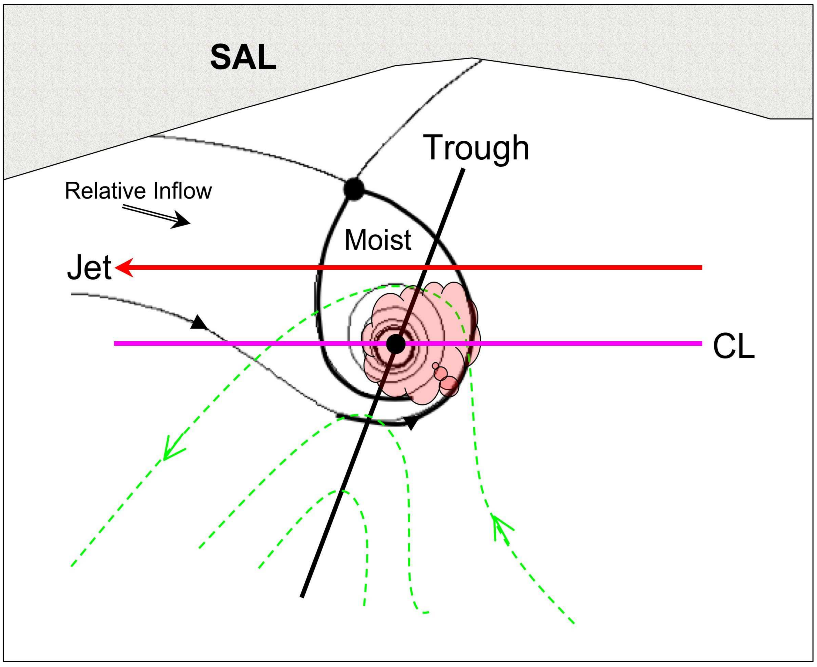

Figure 5: Idealized schematic of the wave-pouch. The dashed green contours represent the wave in the ground-based frame of reference, which is usually open and has an inverted-V pattern. The black contours delineate the wave pouch as viewed in the frame of reference moving at the same speed with the wave. A deep pouch can protect the enhanced vortical structures generated by convection from the hostile tropical environment. Examples of such an environment are the dry air masses associated with the Saharan air layer or environments with strong vertical or horizontal wind shear. The pouch is the preferred region of persistent convection (pink shading). Due to convergent flow, the pouch may have an opening that allows the influx of environmental air and vorticity (relative inflow is represented by a black thick arrow). The thick red line indicates the easterly jet maximum of the eastern and mid Atlantic basin. The thick purple and black curves represent the critical latitude and the trough axis, respectively. The intersection of the these two curves pinpoints the pouch centre (or "sweet spot"), which Montgomery et al. (2010) and Wang et al. (2010) have shown to be the preferred location for vorticity aggregation and tropical cyclogenesis. (Adapted from Wang et al. 2010).

structures does not yet exist, but the definition by DMW09 highlights the essential physical characteristics, namely, "deep moist convective clouds that rotate as an entity and/or contain updraughts that rotate in helical fashion (as in rotating Rayleigh-Bénard convection) …. These locally buoyant vortical plume structures amplify pre-existing cyclonic vorticity by at least an order of magnitude larger than that of the aggregate vortex." Even for background rotation rates as low as that of an undisturbed tropical atmosphere away from the equator, cloud model simulations demonstrate this tendency to amplify planetary vorticity by vortex-tube stretching on time scales of an hour (Saunders and Montgomery, 2004; U. Wissmeier, personal communication). These cloud model simulations indicate also that the induced horizontal circulation by a single updraught is typically no more than a few meters per second with a horizontal scale of around 10 km, and would be barely detectable by normal measurement methods in the presence of an ambient wind field. All of these results together suggest that non-shallow tropical convection away from the equator is vortical to some degree and can amplify the vertical vorticity by between one and two orders of magnitude. It is not hard to imagine, then, that the stretching of vertical vortex tubes by a developing cumulus cloud is a fundamental process. Based on this accumulating evidence, we believe that a precise quantitative definition of a VHT in terms of the degree of vorticity amplification and possibly updraught strength is not required and for this reason a precise definition will not be pursued here.

Wissmeier and Smith (2010) described idealized numerical model experiments using a contemporary cloud model[9] to isolate and quantify the influence of ambient vertical vorticity on the dynamics of deep convection, such as that in the inner-core region of a tropical depression or pre-depression circulation. The vertical vorticity is represented either by a uniform horizontal shear, a uniform solid-body rotation, or a combination of both.

The behaviour of the initial updraught is exemplified by the calculation with uniform solid body rotation and a representation of warm-rain processes only. Experiments that include the ice phase show similar results. Figure 6 shows time-height plots of vertical velocity, vertical mass flux and

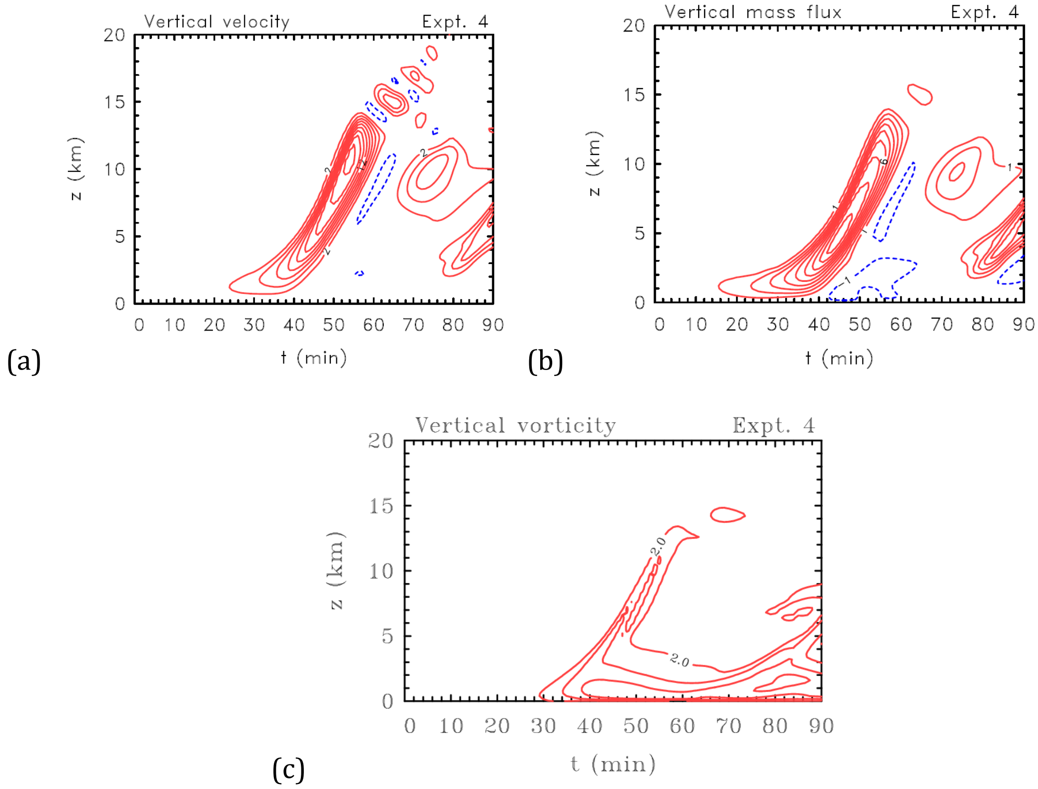

Figure 6. Time-height series of (a) vertical velocity, (b) vertical mass flux, and (c) relative vorticity at the centre of the updraught in the calculation with uniform background rotation with $f = 3 \times 10^{-4}$ s^{-1}. Contour interval 2 m s^{-1}, for vertical velocity, 1 kg m^{-2} s^{-1} for mass flux, and 1×10^{-3} s^{-1} for relative vorticity.

vertical vorticity at the centre of the updraught. As in all the experiments conducted, the updraught develops slowly at first, but increases rapidly in vertical extent and strength as buoyancy is generated by the latent heat release of condensation. Cloud water produced by condensation is carried aloft in the updraught and much of the rain water that develops falls to the ground. The maximum vertical velocity is attained in the upper troposphere after about 45-55 minutes. Thereafter, the initial updraught decays as a result of water loading and a downdraught forms. Note that the maximum vertical mass flux occurs much lower than the maximum vertical velocity on account of the exponential decrease in density with height. A striking result of all the calculations is the exceedingly large amplification of the vertical component of relative vorticity, which is a maximum at low levels and which persists long after the initial updraught has decayed. This enhanced cyclonic vorticity is a result of the stretching of ambient vorticity associated with the vertical gradient of the mass flux. This gradient is largest and most prolonged at low levels.

The presence of ambient vertical vorticity *reduces* the updraught strength, more so when the vorticity is associated with horizontal shear, than when it is associated with solid-body rotation. Despite the

[9] The model used was the cloud model of Bryan an Fritsch (2002).

significant amplification of vorticity, the corresponding azimuthal winds are small, typically on the order of 1-2 m s^{-1}, and would be barely detectable in observations. As a result, the sum of the centrifugal and Coriolis forces is mostly small compared with the lateral pressure gradient. Thus, at the level of background rotation studied, the Rossby elasticity effects for inhibiting cloud entrainment postulated by Montgomery et al. (2006) are not large in the initial cell, although they may become important for higher levels of background rotation. The reduction of updraught strength can be attributed to the reduction of the lateral inflow by the centrifugal and Coriolis forces. While the simulations ignore several processes that are likely to be important in reality, such as ambient vertical shear and surface friction, they provide important benchmark calculations for interpreting the additional complexity arising from the inclusion of these effects. In particular they help dispel a popular myth that because the maximum vertical velocity occurs high in the troposphere, this elevated maximum will tend to induce spin up in the middle troposphere and not at low levels.

2.1.3.3. Observational evidence for vortical convection in pre-storms

The discovery of VHTs in three-dimensional numerical model simulations of tropical cyclogenesis and tropical-cyclone intensification has motivated efforts to document such structures in observations. Two early studies were those of Reasor et al. (2005), who used airborne Doppler radar data to show that VHTs were present in the genesis phase of Hurricane Dolly (1996), and Sippel et al. (2006), who found evidence for VHTs during the development of Tropical Storm Alison (2001). It was not until very recently that Houze et al. (2009) presented the first detailed observational evidence of VHTs in a depression that was intensifying and which subsequently became Hurricane Ophelia (2005). The specific updraught that they documented was 10 km wide and had vertical velocities reaching 10-25 m s^{-1} in the upper portion of the updraught, the radar echo of which reached to a height of 17 km. The peak vertical velocity within this updraught exceeded 30 m s^{-1}. This updraught was contiguous with an extensive stratiform region on the order of 200 km in extent. Maximum values of vertical relative vorticity averaged over the convective region during different fly-bys of the convective region were on the order of 5-10 $\times$ 10^{-4} s^{-1} (see Houze et al. 2009, Figure 20).

Bell and Montgomery (2010) analyzed airborne Doppler radar observations from the recent Tropical Cyclone Structure 2008 field campaign in the western North Pacific and found the presence of deep, buoyant and vortical convective features within a vertically-sheared, westward-moving pre-depression disturbance that later developed into Typhoon Hagupit. Raymond et al. (2010) carried out a similar analysis of data from the same field experiment, in their case for different stages during the formation and development of Typhoon Nuri and provided further observational evidence for the existence of VHT-like structures.

2.1.3.4. Vertical Mass Flux Profiles in VHTs (Contributed by D. Raymond)

One issue as yet unresolved about VHTs is the factors that determine the vertical mass flux profile in these convective systems. Montgomery et al. (2006) performed a cloud-resolving simulation of the evolution of VHTs and the overall circulation in an initial mesoscale convective vortex. In the control experiment in the first 24~h, there was significant spin up of the tangential wind in two regions, one in the lower troposphere with a maximum at the surface and the other in the mid-to-upper troposphere with a maximum near 9 km (see their Fig. 16e). There was persistent radial inflow at these levels (see their Fig. 5a) and a corresponding influx of the vertical component of absolute vorticity occurred at these levels (see their Fig. 16a). By mass continuity, this has to be associated with a vertical mass flux profile which increases strongly with height in the lowest 2 km and in the 8-10 km range.

Shallow inflow is particularly important in the spin up of a tropical cyclone (e.g. Smith et al. 2009). However, strong low-level inflow is not a universal property of moist convection. As Mapes and Houze (1995) show, the mass inflow profile of much western tropical Pacific convection is maximal at middle levels and weak at the surface. One notable exception in their work occurred in the rainbands of a tropical cyclone. Strong low-level inflow existed in this case.

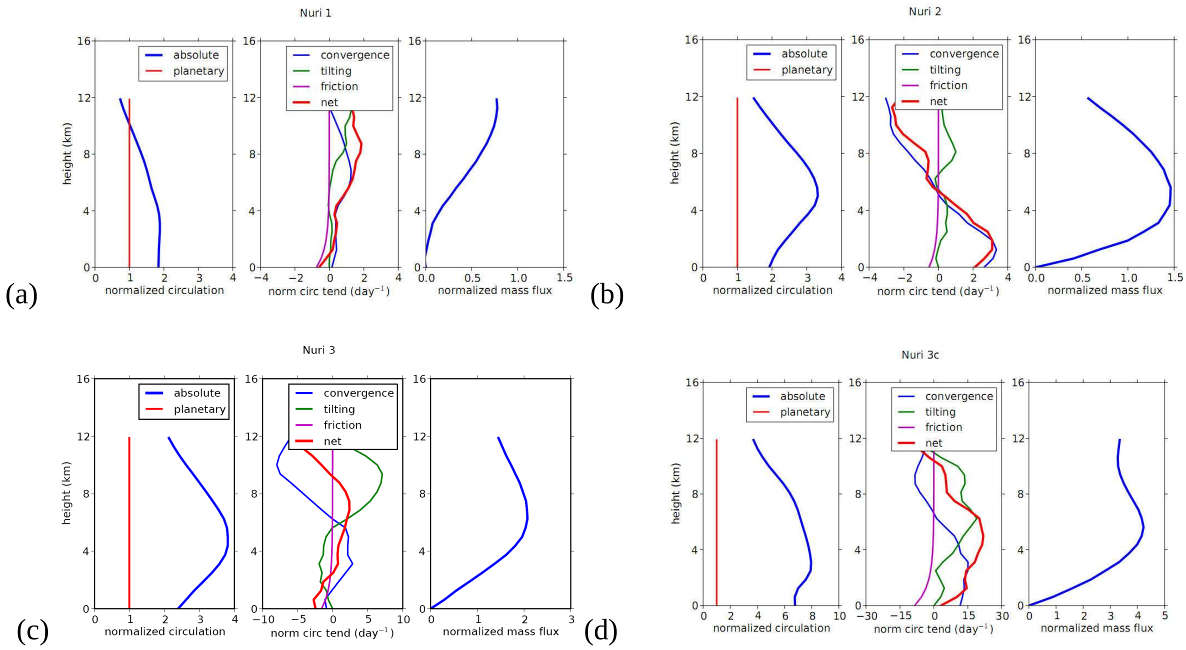

Figure 7 (a) Nuri 1: Nuri as a tropical wave, 15-16 August 2008: Vertical profiles integrated over the central, analyzed region. Left panel: Planetary (red) and absolute (blue) circulations. Middle panel: Contributions to the total circulation tendency (red) due to vorticity convergence (blue), vortex tilting (green), and surface friction (magenta). These curves were computed using the flux form of the vorticity equation. Right panel: Vertical mass flux profile. All curves are divided by the planetary circulation for normalization purposes. (b) Nuri 2: as in (a) except Nuri as a tropical depression, 16-17 August. Nuri 3: (c) as in (a) except as a tropical storm on 17-18 August. Integration over the full observed domain. Nuri 3c: (d) as in (c) except over the central region of Nuri. Integration over a central 2 degree square domain. (From Raymond and López 2010)

Raymond et al. (1998) demonstrated that developing tropical cyclones show a systematic lowering of the level of maximum vertical mass flux as they intensify. Similar behavior occurred as the precursor to typhoon Nuri (2008) developed from a tropical wave to a tropical storm, as is shown in Figure 7. This figure demonstrates that, as the vertical mass flux maximum drops in elevation, the level of the maximum in the circulation tendency inferred from the vorticity equation drops also. These tendencies are confirmed by the corresponding day-to-day changes in the vertical profile of circulation, with spin up first at mid-levels and then near the surface. In particular, in Nuri 1 the strongest convergence occurred at middle levels, resulting in the greatest increase in circulation between Nuri 1 and Nuri 2 at these levels. In contrast, Nuri 2 exhibited the strongest convergence at low levels, resulting in a strong increase of the surface circulation in Nuri 3 (illustrated in panels (c) and (d)). This intensification was stronger in a 2 degree square region around the center of Nuri 3 (panel (d)) than over the larger observed domain (panel (c)).

Bister and Emanuel (1997) suggest that moisturization and stabilization of the environment lead to convection which is able to spin up a warm core vortex, presumably via the effects of low-level inflow. Numerical simulations by Raymond and Sessions (2007) support the idea that (non-vortical) convection in this thermodynamic environment produces such low-level inflow. However, Hendricks et al. (2004) suggest that the vortical nature of VHTs may also have something to do with the entrainment profile. The reasons for this change in the behavior of the deep convection need to be explained and we recommend that resources be put into understanding what governs the vertical mass flux profile in VHTs.

2.1.3.4. A mesoscale view of tropical cyclogenesis within an easterly wave

Having discussed the fundamental coherent structures of the surface spin up process, we now move back up in scale to gain a new perspective into how the large scale and small-scale processes operate together on the mesoscale. Figure 8 illustrates the evolution of vertical vorticity and saturation fraction (column relative humidity from the surface to 500 hPa) that occurs within the pouch of an easterly wave during its transition to a tropical storm in an idealized numerical modelling study (Montgomery et al. 2010)[3]. Figure 8a summarizes the evolution of the maximum relative vorticity along each latitude near and within the wave's cyclonic critical layer, and shows cyclonic vorticity with values larger than

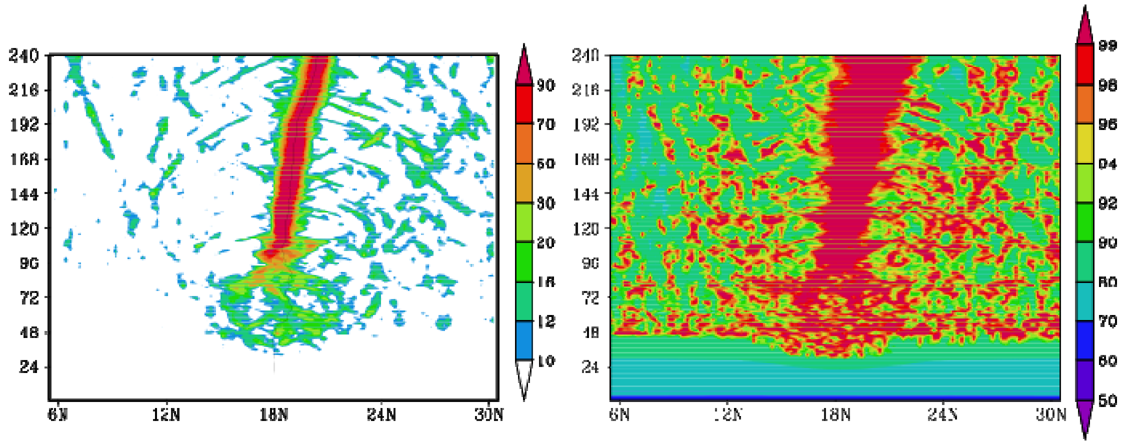

Figure 8: “Fujita Diagram”: (a) depicts the time evolution of the maximum relative vorticity along each latitude. The x-axis indicates the latitude of the vorticity maximum and the y-axis is time (from day 0 to day 10); (b) depicts the time evolution of the maximum saturation fraction from the surface to 500 hPa. The ordinate is time (h).

1.5×10^{-4} s^{-1} only. A concentrated and intense mesoscale vortex appears around 96 h (Day 4) near the original critical latitude of the parent wave (18^{o}N). After this time the vorticity intensifies primarily in a highly localized spatial region near the critical latitude, and the emergent vortex starts a slow northwestward drift away from the original critical latitude. The chaotic swarming of vorticity maxima about the critical latitude (prior to 96 h) followed by the highly focused vorticity concentration is a striking feature. Figure 8b shows a similar diagram of the analyzed saturation fraction (column relative humidity from the surface to 500 hPa). The emergent vortex, which develops into a tropical storm, forms in a region with high saturation fraction. Before storm formation the horizontal scale of the region of high saturation fraction is comparable to that of the region of large cyclonic vorticity. After consolidation to a single master vortex there is a broader ``funnel" of saturation fraction.

Based on the suite of idealized numerical experiments analyzed in Montgomery et al. (2010), and in a companion study examining the cyclogenesis of pre-Hurricane Felix (2007) by Wang et al. (2010a, b), this attractor-like behavior appears to be a ubiquitous property of the simulated wave-to-storm transition process. The focal point is the nominal centre or sweet spot of the critical layer of the finite-amplitude tropical easterly wave (or the centre of the wave pouch). The sweet spot of the pouch is thus the preferred location for tropical cyclogenesis and the findings herein support this novel prediction of the marsupial paradigm. The attractor-like property is reminiscent of Ooyama’s penetrating view of the linkage between the stochastic nature of the small-scale features and the more deterministic nature of the synoptic and sub-synoptic scale flow (Ooyama 1982, p372): “… we now perceive the question of tropical cyclogenesis to be that of placing probabilistic mesoscale convective systems under the control of a deterministic environment.”

[3] The data plotted are from a coarse resolution simulation (28 km horizontal grid spacing) using a Betts-Miller cumulus parameterization. However, the principal features discussed here are essentially unchanged with an explicit representation of cumulus convection and a 3 km horizontal grid spacing (not shown, see Montgomery et al. 2010 for details). For the sake of brevity, we focus here on the coarse-resolution simulation.

2.1.3.5 Relative contributions of convective versus stratiform clouds

The idealized experiment summarized in section 2.1.3.4 was conducted without a representation of ice microphysics. In this section we summarize a related idealized experiment in which ice processes were included. This experiment was designed to determine the relative importance of convective versus stratiform processes in the proposed genesis sequence. To be sure, the use of rain-only physics provides an incomplete picture of the mesoscale processes occurring within the pouch. We employ the same nested grid configuration used in section 2.1.3.4 and the same boundary layer and cumulus parameterization on the coarsest mesh (28 km). The only difference between the present experiment and the previous one is the replacement of the Kessler warm- rain microphysics scheme by the WRF[10]-model single-moment, 6-class microphysics scheme (Hong and Lim, 2006) which includes ice, snow and graupel processes. As in the warm rain experiment, the fine grid is activated at 44 h. The ensuing development is significantly delayed relative to the warm rain experiment. It is not until approximately 180 h that the ice microphysics simulation surpasses the intensity of the warm rain experiment, presumably because of the stronger downdrafts associated with ice processes (Srivastava, 1987).

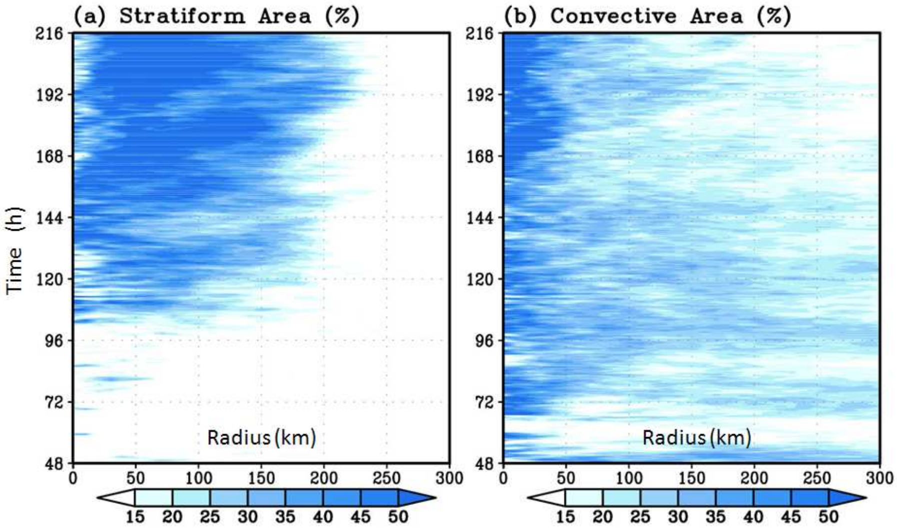

Figure 9: Time-radius evolution of the stratiform (left) and convective (right) precipitation. The figures show the area coverage by each rain type in percentage (%). The ordinate is time (h) and the abscissa is radius with respect to the moving pouch centre (km). (Adapted from Montgomery et al. 2010b)

To investigate the relative role of the convective and stratiform processes in the genesis sequence, a simple and physically-based method for identifying (deep) convection and stratiform precipitation was employed. Details of this procedure are given in Montgomery et al. (2010b), following the work of Tao et al. (1993) and Braun et al. (2010). Figure 9 shows a time-radius plot of the area percentage that is stratiform and convective within the wave's pouch. The radius is defined relative to the centre of the pouch and spans a domain of 300 km in extent. It is evident that the convective population is active throughout the pouch after 48 h. The stratiform population on the other hand does not make a significant contribution until approximately 100 h. In time, however, the convective population occupies a more substantial fraction of the area near the centre of the pouch. This conclusion is confirmed by examining the precipitation rate for the convective and stratiform clouds, which shows that the convective precipitation is maximized near the centre of the pouch and progressively dominates the stratiform component (not shown). The heaviest rain rate is associated with the convective precipitation and it is spatially concentrated near the centre of the pouch. These rain plus ice results point to a containment of persistent deep convection near the centre of the pouch. This

[10] WRF-model: Weather Research and Forecasting model.

containment has a very important effect in the aggregate by producing mesoscale convergence at low-levels, which leads to low-level spin up. This behavior is unlike that of stratiform convection that selectively spins up the middle levels and spins down the low-levels (Tory and Montgomery, 2006; cf. Houze, 2004).

2.1.3.6. A multiscale view of tropical cyclogenesis

The paper by DMW09 (p5596) offers a multiscale perspective of tropical cyclogenesis associated with tropical easterly waves:"the critical layers guarantees some measure of protection from intrusion. However, actual flow fields are transient and contain mesoscale fine structure, making the Lagrangian kinematics rather messy. A group of smaller vortices, e.g., will entrain the surrounding air more readily than a single larger vortex. As for how these smaller vortices are created in the first place, there are essentially two possibilities: (i) *upscale aggregation* of mesoscale convective vortices associated with mesoscale convective systems and/or VHTs, and (ii) eddy shedding that works its way to smaller scales via a *forward enstrophy cascade*, such as might be associated with wave breaking at the critical layer. Tropical cyclogenesis evidently represents a kind of process in which the inverse energy and forward enstrophy cascades (originating respectively from cloud system and synoptic scales) collide in "spectral" space at some intermediate scale to form a diabatic vortex larger in horizontal scale than the vortices associated with individual cloud systems but substantially smaller in scale than the mother pouch created by the synoptic wave. This geophysical fluid dynamics aspect is perhaps the most fascinating and daunting of tropical cyclogenesis; one that has not yet been fully explored (owing to limitations of horizontal resolution in observations or models), but to be advanced as a framework for understanding the multi-scale nature of the problem."

Figure 10 presents an idealized schematic of this multi-scale view of the problem. Plotted on the abscissa is the natural logarithm of horizontal wavenumber with various motion systems indicated and

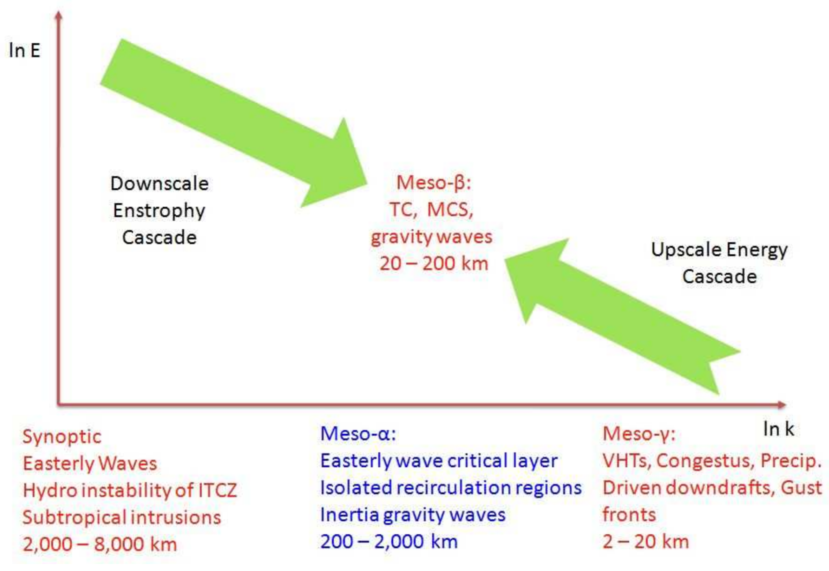

Figure 10. A spectral view of the tropical cyclogenesis problem. The figure depicts a downscale cascade of enstrophy from the synoptic scale to the meso-α scale and an upscale cascade of energy from the cloud scale (meso-γ) to the meso-β scale. The tropical cyclone resides at the meso-β scale.

whose horizontal wavenumber increases from left to right. Plotted on the ordinate is the natural logarithm of kinetic energy of the various motion systems. The arrows denote the direction of the two cascades. The downscale cascade from the synoptic to sub-synoptic (meso-α) scale resembles broadly the forward enstrophy cascade of quasi-two-dimensional turbulence theory in which strong jets and eddies irreversibly deform weaker eddies into filaments on progressively smaller scales. In the case of easterly waves, the forward enstrophy cascade in the figure is intended to include `eddy shedding events from the mean easterly jet' that create a sub-synoptic scale nonlinear critical layer, i.e., cat's eye, or pouch[11] . The pouch circulation resides at meso-α. The upscale cascade from the cloud (meso-γ) scale to the larger (meso-β) scale of a tropical depression vortex is associated with the aggregation of the vortical convective elements in a region of high saturation fraction as described in the foregoing section. The latter cascade resembles also the inverse energy cascade of quasi-two-dimensional turbulence in which small vortical features merge to form progressively larger features, such as large eddies, Rossby waves and zonal jets (e.g., McWilliams 2006, Vallis 2007). An important difference between the simple two-dimensional inverse cascade model and the moist inverse cascade model sketched in Fig. 10 lies with the strong vortex-tube stretching and low-level spin up that is associated with vortical convection and the corresponding secondary circulation of individual elements and also the aggregate. For such a cascade to be maintained, energy input at small scales is necessary.

2.1.3.7. Tropical cyclogenesis in diabatic Ekman turbulence

A recent study by Schecter and Dunkerton (2009) explores the formation of model hurricanes from a perspective of rotating, convective turbulence. Specifically, the paper uses an idealized, three-level numerical model with a parameterization of deep cumulus convection and surface friction. The goal is to examine how deep convection may counter frictional spin down and spontaneously generate hurricanes from a turbulent sea of small-amplitude relative vorticity of either sign. To this end the experiments are initialized everywhere with a chaotic small-scale flow. They found, inter alia, that: "The initial stage of self-organization resembles ordinary two-dimensional turbulence, in which like-sign vortices coalesce and filaments are chaotically stirred. Convection gradually develops, and the flow skews toward cyclonic dominance. Over time, a distinguished region of cyclonic vorticity engulfs lesser cyclones in the immediate vicinity, and erupts into a dominant hurricane." Schecter and Dunkerton define a "primary genesis timescale" as the time when the maximum wind speed in the boundary layer reaches[12] $10\ \mathrm{m\ s^{-1}}$. Their finding that " … subtle changes to the initial conditions can prevent the development of tropical cyclones from turbulence" is potentially troubling because then the detailed structure of turbulence would have to be routinely observed. Fortunately, this sensitivity does not appear to be a feature of the behavior of global forecasting models. In fact, the marsupial paradigm discussed in section 2.1.3 highlights the role of tropical-wave critical layers as preferred locations for the formation and aggregation of vortical convection on the mesoscale and these waves are much more predictable than the small-scale turbulent structure of the tropical atmosphere.

2.1.3.8. Multi-scale methods applied to tropical cyclogenesis

Majda et al. (2010) applied multi-scale methods of applied mathematics to explore basic aspects of tropical cyclogenesis. Three multi-scale sub-models emerge in the analysis: one model captures the VHT dynamics without gravity waves; another captures mesoscale vortex dynamics without gravity waves; and the third model represents mesoscale fluctuations as well as forced linear hydrostatic waves. These models are designed to retain the essential coupling with each other. Idealized simulations within this multi-scale framework illustrate the development of intense low-level cyclonic vorticity associated with the VHTs and the tendency for the flow to skew towards cyclonic dominance. Majda et al. conclude that the sub-models capture several of the features observed in the numerical simulations of tropical cyclogenesis by Hendricks et al. (2004) and Montgomery et al. (2006). They suggest that the sub-models may have use as diagnostic and predictive tools for clarifying key mechanisms for tropical cyclogenesis.

[11] Technically speaking, the creation of the cat's eye flow or pouch can result from either a finite-time or exponential instability of the mean easterly jet. More frequently, the pouch results from the finite amplitude evolution of a quasi-neutral easterly wave that is excited by an instability farther upstream or an episodic convective event over the Ethiopian highlands, etc. (DMW09 and refs. therein).

[12] Strictly speaking, this definition does not distinguish between gust fronts, squall lines or emergent tropical cyclone vortices in their numerical simulations or reality.

2.1.4. Thermodynamical theories of tropical cyclogenesis

2.1.4.1 Nolan (2007)

Using idealized, high-resolution cloud-representing numerical-model simulations, Nolan (2007) undertook an examination of the question: "what is the trigger for tropical cyclogenesis"? The paper focuses primarily on the "genesis" of a tropical cyclone from an initially warm-core mesoscale vortex of moderate intensity (maximum wind 10 m s^{-1}). Despite the favourable environmental conditions used in the model set up, there is an incubation period of one to three days before the surface wind speed increases rapidly. During the incubation period, the inner-core of the initial mesoscale vortex is gradually moistened by intermittent deep convection. Once the air column achieves near saturation, a much smaller-scale intense vortex forms near the surface within this initial mesoscale vortex. This event is accompanied by a rapid increase of the local surface wind and a rapid drop of the minimum surface pressure. Nolan identifies this moment with the beginning of the intensification process for the system-scale tangential wind. This small-scale, low-level vortex is argued to become "the central core of the developing cyclone." On the basis of these numerical simulations and diagnostic analyses, Nolan suggests that the appearance of this small-scale vortex in conjunction with a saturated middle troposphere is the trigger for tropical cyclogenesis.

In particular Nolan states on p248 that "In this and all the subsequent simulations, the appearance of this smaller-scale, low-level vortex is closely correlated with an increase in the rate of pressure fall and substantial increases in deep convection near the vortex centre. In each case, we saw that rapid intensification …proceeded immediately after the formation of this smaller vortex, and it is this vortex that grows and intensifies into the primary circulation … . The mid-level wind maximum is superceded as the low-level vortex strengthens and expands. Since the formation of the low-level vortex so clearly marks the time when intensification begins, we use this moment to define the time of tropical cyclogenesis."

We have several questions about the interpretation of the dynamical processes of spin up described above. Based on the evidence shown "this amazingly small vortex" (p248) has all the characteristics of a strong and persistent VHT, which fortuitously develops near the centre of the computational domain. The processes by which the small-scale vortex grows and intensifies into the primary circulation are not explained. Since the term 'primary circulation' is never defined, it is unclear what its role might be in the genesis process. The process by which the system-scale rotation amplifies is not explained either. In this study the primary process that intensifies the low-level, system-scale wind field appears to be similar to that discussed by Montgomery et al. (2006), Nguyen et al. (2008), Smith et al. (2009), and Bui et al. (2009), namely, the vortical convective elements contribute to a system-scale convergence of absolute angular momentum in the lower-troposphere.

We have two additional concerns with this study. First, the paper presumes that there is a trigger for tropical cyclogenesis. Echoing Ooyama (1982), we will argue in the summary that there is no need to invoke a trigger. While the numerical simulations clearly develop a mid-level cyclonic vortex (as found also by Montgomery et al. (2006, their Figures 4c, 16e), the formation of this mid-level vortex is not explained in Nolan (2007) and its relevance to the formation process is unclear to us.

In the Introduction we intimated that a precise definition of genesis is unnecessary. Nolan's definition of genesis time discussed above merely highlights a particular time in his numerical calculations. This definition is employed without ever defining what genesis is. The time of genesis is not part of the forecaster checklist.

2.1.4.2. Nolan, Rappin and Emanuel (2007)

In a subsequent paper, Nolan et al. (2007) examined the sensitivity of tropical cyclogenesis to environmental parameters in conditions of radiative-convective equilibrium. They showed, inter alia, that, under such conditions, tropical cyclogenesis can occur on an *f*-plane even in the absence of a pre-existing [cyclonic] circulation. They argue on p2101 that "spontaneous tropical cyclogenesis in this simulation is a process with two stages. The first stage appears equivalent to the aggregation phenomenon … , which involves a radiative-convective feedback, whereby the more moist regions … generate enhanced convection due to low-level moisture and mean ascent due to decreased radiative cooling. The second process is more like the tropical cyclogenesis [described earlier in the paper], whereby a pre-existing circulation with embedded convection contracts into a tropical cyclone."

In the first stage of development, what the authors describe as "aggregation" is a thermodynamic process following earlier work of Bretherton et al. (2005) examining convective aggregation in the complete absence of background rotation. Nolan et al. (2007) do not discuss the influence of the rotational dynamics during the aggregation stage as discussed in sections 2.1.3.2-2.1.3.4. Moreover, no interpretation of the surface spin up mechanism during this first stage is offered. Our interpretation of their results is simply that the amplification of the low-level circulation proceeds by the VHT pathway as described above.

The second stage of development is described on p2105 as follows: "… in the second stage of development, the broad circulation contracts into a tropical cyclone in the manner similar to the [their] simulations with initial vortices, due to a WISHE feedback and the enhanced trapping of heat and energy (*sic*) released by convection as the local inertial stability increases…". Rather than explaining a stage of genesis, this description appears more like an explanation for intensification.

2.1.4.3. Raymond and Sessions (2007)

The starting point of recent work by Raymond and Sessions (2007) is based on some earlier work based on the TEXMEX[13] experiment conducted in 1991. Bister and Emanuel (1997) argued that the development of a cool, moist environment resulting from stratiform rain serves as the incubation region for the formation of a low-level, warm-core vortex. Cloud-representing numerical simulations in the absence of planetary rotation by Raymond and Sessions (2007) offer support for this idea. Environments cooler at low levels and warmer at upper levels on the order 1 K lower the level of maximum vertical mass flux from 10 km to approximately 5 km in their calculation; such environments increase the precipitation rate as well. These effects intensify the inflow into the convection. The suggestion is that if realistic values of ambient rotation associated with a tropical wave or monsoon trough were included, this inflow would cause a stronger vorticity convergence at lower levels and thus contribute to the spin up of the system. This effect is argued to be an explanation for why tropical-wave-scale mid-level vortices foster tropical storm formation; their horizontal scale is large enough for them to exhibit significant vertical Rossby penetration depths.

Without ambient rotation these experiments cannot offer insight into the rotational dynamics of vorticity aggregation as discussed in the foregoing section. It is yet to be demonstrated whether the envisaged process is essential in a rotational environment.

2.1.5. New tools for forecasters

We draw attention now to several aspects of the new cyclogenesis model discussed in sections 2.1.3.1-2.1.3.5 that may be of use to forecasters. Using the marsupial framework, Wang et al. (2010) developed a real-time forecast methodology for predicting the tropical cyclogenesis location using global model operational data. These authors showed that a wave-pouch region of approximately closed Lagrangian circulation is characterized by a distinct moisture gradient ahead of the wave trough effectively separating the relatively moist air within from the relatively dry air outside the pouch. The propagation speed of the pouch can be estimated based on a Hovmöller diagram of the moisture front or meridional wind.

Wang et al. (2010) showed that the genesis location of a tropical storm can be predicted using global model forecast data up to three days in advance with less than one degree error. A similar method was applied also to easterly waves over the western North Pacific to provide flight-planning guidance during the Tropical Cyclone Structure 2008 (TCS-08) field experiment (Montgomery et al. 2010). The 'pouch' diagnostics have been updated and applied to real-time wave tracking during the 2010 NSF-

[13] TEXMEX = Tropical Experiment in MEXico

PREDICT/NASA-GRIP/NOAA-IFEX experiments[14]. Using ECMWF, GFS, NOGAPS and UKMET 5-day forecasts[15], the pouch tracks were predicted, and pertinent dynamical and thermodynamical fields within the prospective pouches were analyzed following the wave-pouch. Satellite products were examined also in the marsupial framework together with the model analysis data. Several examples may be obtained at the address below[16]. Another quantity that has proven useful in real-time wave tracking applications is the Okubo-Weiss (*OW*) parameter. The Okubo-Weiss parameter is defined as "vorticity squared minus strain rate squared" ($OW = \zeta^2 - S_1^2 - S_2^2 = (V_x - U_y)^2 - (U_x - V_y)^2 - (V_x + U_y)^2$). Significantly positive *OW* values indicate strongly curved (cyclonic or anticyclonic) flow with minimal shearing deformation. The wave pouch is characterized by significantly positive *OW* and cyclonic rotation, and provides a favourable environment for vortical convection and vorticity aggregation.

There are other lessons learned from the marsupial paradigm that can offer guidance to forecasters in interpreting the observations. It has been shown in the numerical experiments that simulate the transformation of an easterly wave to a tropical cyclone, summarized in sections 2.1.3.1, 2.1.3.2 and 2.1.3.5, that there is no 'trigger' for cyclogenesis (cf. section 2.1.4.1). The development of low-level vorticity and mid-level moisture proceeds monotonically in tandem over a time period on the order of a few days. In the summary we will explain why no trigger is necessary. From a system-scale viewpoint, that results after areally-integrating the vertical vorticity budget over a 2°× 2° horizontal domain centred on the sweet spot, the spin up of near-surface vorticity occurs primarily in association with near-surface convergence of absolute vorticity (Montgomery et al. 2010; Wang et al. 2010a). There is no systematic contribution from downward advection of absolute vorticity from the middle levels (Haynes and McIntyre 1987), and the contribution from vortex tilting is second order. An alternative way of viewing these latter processes in an axisymmetric framework is in terms of the convergence of absolute angular momentum (e.g., Smith et al. 2009).

2.1.6. Summary

On the basis of the evidence summarized here, we believe that a unified view of tropical cyclogenesis and intensification is emerging. In this unified view, the separate stages proposed in previous significant studies and reviews (e.g. Frank, 1987; Emanuel 1989; McBride 1995; Karyampudi and Pierce 2002; Tory and Frank, 2010) are unnecessary. The idea that tropical cyclones in the current climate are a manifestation of a finite amplitude instability or that they are the result of some "trigger" mechanism is challenged by a new way of thinking about the basic processes of vortex spin up by vortical convection in a favourable tropical environment. The basis for this unified view is that deep convection developing in the presence of vertical vorticity amplifies the vorticity locally by vortex tube stretching, irrespective of the strength of the updraught and the depth of convection (Wissmeier, 2010, personal communication), and that the vortical remnants outlive the convection that produced them in the first place. The vortical remnants tend to aggregate in a quasi two-dimensional manner with a corresponding upscale energy cascade and some of these remnants will be intensified further by subsequent convective episodes. The amplification and aggregation of vorticity represents an increase in the relative circulation within a fixed circuit encompassing the convective area. As the circulation progressively increases in strength, there is some increase in the surface moisture fluxes. However, it is not necessary that the moisture fluxes continue to increase with surface wind speed. The boundary layer pseudo-equivalent potential temperature, θ_e, will continue to rise as long as the air adjacent to the surface remains unsaturated relative to saturation at the sea-surface temperature and the positive entropy flux from the ocean surface

[14] NSF = United States National Science Foundation; PREDICT = PRE-Depression Intensification of Cloud systems in the Tropics; NASA = (United States) National Astronautical and Space Administration; GRIP = Genesis and Rapid Intensification Processes; NOAA = (United States) National Oceanic and Atmospheric Administration; IFEX = Intensity Forecasting Experiment.

[15] GFS = NOAA Global Forecasting System; NOGAPS = Navy Operational Global Atmospheric Prediction System; UKMET = United Kingdom Meteorological Office.

[16] http://www.met.nps.edu/~mtmontgo/storms2010.html

overcomes downward import of low θ_e from above the boundary layer (Montgomery et al. 2009, Montgomery and Smith, 2010). The upshot is that the boundary layer θ_e will continue to increase towards the saturation value, providing air parcels acquire the needed boost in θ_e necessary for them to ascend the warmed troposphere created by prior convective events.

This unified view is consistent with the insights articulated long ago by Ooyama (1982), who wrote: “It is unrealistic to assume that the formation of an incipient vortex is triggered by a special mechanism or mechanisms, or that genesis is a discontinuous change in the normal course of atmospheric processes”. For the reason discussed below, it is far more natural to assume that genesis is a series of events, arising by chance from quantitative fluctuations of the normal disturbances, with the probability of further evolution gradually increasing as it [the process] proceeds. According to this view, the climatological and synoptic conditions do not directly determine the process of genesis, but may certainly affect the probability of its happening. With a better understanding of the mesoscale dynamics of organized convection, the range of statistical uncertainty can be narrowed down. Nevertheless, the probabilistic nature of tropical cyclogenesis is not simply due to lack of adequate data, but is rooted in the scale-dependent dynamics of the atmosphere.”

The unified view is consistent also with the findings of Nolan et al. (2007), who, in a re-assessment of their original hypothesis for the existence of a finite-amplitude wind threshold for genesis to occur, wrote the following on page 2105 of their paper: “We also proposed that environmental parameters consistent with the tropics represent a region of ‘finite amplitude instability’, where disturbances below some threshold intensity will not develop into a tropical-cyclone. However, simulations with extremely weak initial vortices ($v$max = 2.5, 1.25 m s^{-1}) ultimately did arrive at tropical-cyclone genesis. The extremely slow pace of the development (as compared to $v$max = 5 m s^{-1}), and an examination of the evolution leading up to genesis in these cases … indicated that the genesis mechanism was more like the spontaneous genesis mechanism discussed in section 5; the extremely weak initial vortex simply provides the seed location for the aggregation process that leads to genesis.”

The necessity of the marsupial pouch for genesis in the real atmosphere of the tropical Atlantic and eastern Pacific basins as proposed by DMW09 is in part consistent with Ooyama’s view: the pouch provides a favourable environment for the deep convection to persist, thereby enabling the upscale energy cascade process of moist vortical convection to operate unimpeded. The work of Montgomery and Enagonio (1998), Nguyen et al. (2008), Shin and Smith (2008) and Schecter and Dunkerton (2009) supports also the probabilistic nature of vortex amplification, but goes further by highlighting the vortical nature of the convective elements and their interaction with each other and with the mean vortex as part of the upscale growth and amplification process.

In light of this unified view of genesis and intensification, there seems little need to refine the definition of genesis. We believe that the definitions of the stages of tropical cyclone development used in current practice are adequate for forecast purposes.

The recent review of paradigms for tropical-cyclone intensification by Montgomery and Smith (2010) is relevant also to understanding aspects of the genesis process and the emerging unified view of genesis and intensification. Although the foregoing amplification pathway is intrinsically non-axisymmetric, it is insightful to adopt an axisymmetric viewpoint of this process as noted at the end of Section 2.1.5. A schematic for understanding the amplification of the azimuthally-averaged tangential wind field is shown in Figure 11. The idea is that the aggregate effects of diabatic heating associated with the vortical convective elements leads to a system-scale inflow in the lower troposphere. This inflow can be represented approximately using axisymmetric balance dynamics in which the aggregate of diabatic heating, boundary layer friction and related eddy fluxes of heat and momentum force a meridional overturning circulation (Bui et al. 2009). This inflow converges azimuthal-mean absolute angular momentum, a quantity that is approximately conserved above the shallow boundary layer, so that its convergence leads to a spin up of the azimuthal-mean tangential winds. As these winds increase in strength, so does the azimuthal-mean radial inflow within the boundary layer (see e.g. Smith et al. 2009). As described above, this inflow converges moist air that has been enriched by surface fluxes from the ocean surface to ``fuel" the deep convection.

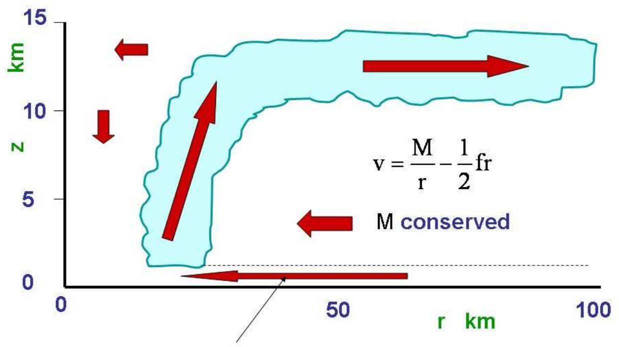

Figure 11. An axisymmetric view of tropical-cyclone amplification. This figure aims to convey the idea that, in an axisymmetric-mean sense, deep convection in the inner-core region induces convergence in the lower troposphere. Above the frictional boundary layer, the inflowing air materially conserves its absolute angular momentum and spins faster. Strong convergence of moist air in the boundary layer provides moisture to ``fuel'' the deep convection. Although the air-parcels converging in the boundary layer lose a fraction of their absolute angular momentum, they undergo much larger inward displacements and acquire a higher tangential wind speed than those converging above the boundary layer. (From Montgomery and Smith 2010).

The above description presumes that the boundary layer of the system-scale circulation has become well established. However, during the genesis phase when there is weak system-scale rotation, the boundary layer inflow associated with this rotation is much weaker than the inflow forced by the aggregate diabatic heating (e.g., Montgomery et al. 2006, p363). As long as there is convergence above the boundary layer the system-scale rotation will amplify because of the convergence of absolute angular momentum. The corresponding boundary layer inflow will increase progressively. Although the air-parcels converging in the boundary layer lose a fraction of their absolute angular momentum, they undergo much larger inward displacements. A point is reached during the evolution at which the highest tangential wind speeds are found to occur in the boundary layer (Smith et al. 2009). Beyond this point, the boundary layer plays also a *dynamical role* in the spin up process because the amplification of the inner-core tangential winds occurs within this layer. In summary, the foregoing discussion indicates that the boundary layer exerts a progressive control on the vortex evolution as the system-scale rotation amplifies.

2.1.7 Recommendations

1. Further analyze recent and current field data documenting the lifecycle of vortical convection, and its contribution to amplification of the system-scale rotation in pre-depression environments. We see a role also for idealized numerical simulations to complement these observational studies.

2. Carefully examine global model forecasts where the model appears to correctly capture observed genesis events several days in advance.

3. Determine the limits of predictability of tropical cyclogenesis.

2.1.8 Appendix: A Recent Controversy

The companion report by Davis and Elsberry (Topic 2.2) on recent Tropical Cyclone Field experiments contains a summary of recent observational analyses of the formation of typhoons Nuri (2008) and Hagupit (2008) that occurred during the Tropical Cyclone Structure 2008 experiment (hereafter TCS08). The genesis of typhoon Nuri is particularly noteworthy because the bulk of the formation process was observed by both C-130J and NRL[20] P3 aircraft on consecutive days and for this reason offers an unprecedented opportunity to test the new cyclogenesis model proposed by DMW09 and other proposed cyclogenesis theories. The Nuri case has become controversial for reasons that are obscure.

As discussed in Section 2.1.1 the DMW09 model emphasizes a Lagrangian viewpoint and the ensuing convective development within the cat's eye circulation of a tropical wave critical layer. Two very

[20] NRL = United States Naval Research Laboratory

different interpretations of this genesis event have been provided in the companion report. Montgomery et al. (2010) presented evidence to suggest that Nuri formed in association with a westward propagating disturbance possessing a cat's eye recirculation region. Evidence was presented to suggest that the cat's eye circulation within the wave was of sufficient magnitude and depth to withstand hostile influences of vertical shear as it propagated towards Guam. The sweet spot, defined as the intersection between the wave trough and critical latitude, was suggested to be the preferred location for vorticity aggregation and low-level spin up. Global Forecast System Final Analyses and IR satellite imagery, showed convective bands wrapping around the sweet spot as genesis neared, and suggest that this sweet spot was the location where Typhoon Nuri's dominant low-level circulation emerged.

Quoting from the companion report: "The differences in interpretation as to the formation of pre-Tropical Depression Nuri arise in part from the analyses of the observations from this first research mission [on 16 August, 2008]. The Montgomery et al. (2010, their Fig. 12) analysis with the 850 hPa dropsonde winds relative to the MTSAT[21] infrared brightness temperatures (Fig. 2.2.3a) would imply a low-level closed circulation in the region of the southern convective burst, and perhaps somewhat south of the circulation centre at 13.3°N, 144°E as analyzed by Cisneros et al. (2010) in Fig. 2.2.1."

Careful inspection of the processed data from TCS08 reveals a misinterpretation of the data presented in Montgomery et al. (2010). In the resting frame of reference, their analysis using the quality-controlled data shows that there is no closed low-level cyclonic circulation in the 850 hPa dropsonde data. Confusion has arisen in interpretation of their Figure 12 because of the two light (< 2 knots magnitude) wind barbs in the southwestern quadrant of the image. Without looking at the raw data, these two wind barbs appear to form a closed circulation in the resting frame. However, an examination of the raw data indicates that the wind at 12.5N, 144.5E is flow from the south-southeast and the wind barb located near 11.8 N, 145 E is indicative of southeasterly flow. In summary, at the 850 hPa level, *the dropsonde data has no indication of a closed circulation in the resting frame and none of the wind barbs have a westerly wind component.* All related interpretations in the companion report that invoke westerly winds at these levels south of Guam are illusory.

The above remarks serve as a useful reminder of what was discussed in Section 2.1 of the pitfalls of analyzing observational data in an earth-relative reference frame, which is not the appropriate reference frame for understanding the tropical cyclogenesis process within an easterly wave critical layer (DMW09).

2.1.9 Glossary

Critical latitude: For a zonally-propagating easterly wave, the critical latitude is the latitude at which the zonal phase speed coincides with the low-pass filtered zonal flow. More generally, since easterly waves have some vertical structure, we often think of a critical surface as the locus of points where the zonal phase speed of the wave coincides with the low-pass filtered zonal flow.

Critical layer: Following DMW09, the critical layer of a tropical easterly wave is the region surrounding the nonlinear wave's critical latitude or level in shear flow. In the enclosed region of recirculating flow, particles are trapped and recirculate, rather than being swept one way of the other by the surrounding shear. Reversible undulations of particles immediately adjacent to the recirculating region on either side are included in the definition.

Cat's eye: The recirculating region within the critical layer of a finite amplitude wave. An example is that which occurs in Kelvin-Helmholtz instability. The streamlines in the recirculation region resemble the eye of a cat.

Diabatic activation: A term introduced in DMW09 to describe how a propagating easterly wave is maintained or amplified by a diabatic vortex within the critical layer region of a tropical wave. Without diabatic activation, such a wave exists as a dynamical feature in the lower troposphere, whose

[21] MTSAT = Multi-functional Transport Satellite

signature may be seen in low cloud or deep-layer water vapour, but with deep moist convection that is either absent or poorly organized.

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