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Tropical cyclogenesis in a tropical wave critical layer: easterly waves

T. J. Dunkerton[1,2], **M. T. Montgomery**[2], **and Z. Wang**[2]

[1]NorthWest Research Associates, Bellevue WA, USA
[2]Naval Postgraduate School, Monterey CA, USA

Abstract. The development of tropical depressions within tropical waves over the Atlantic and eastern Pacific is usually preceded by a "surface low along the wave" as if to suggest a hybrid wave-vortex structure in which flow streamlines not only undulate with the waves, but form a closed circulation in the lower troposphere surrounding the low. This structure, equatorward of the easterly jet axis, is identified herein as the familiar critical layer of waves in shear flow, a flow configuration which arguably provides the simplest conceptual framework for tropical cyclogenesis resulting from tropical waves, their interaction with the mean flow, and with diabatic processes associated with deep moist convection. The recirculating Kelvin cat's eye within the critical layer represents a sweet spot for tropical cyclogenesis in which a proto-vortex may form and grow within its parent wave. A common location for storm development is given by the intersection of the wave's critical latitude and trough axis at the center of the cat's eye, with analyzed vorticity centroid nearby. The wave and vortex live together for a time, and initially propagate at approximately the same speed. In most cases this coupled propagation continues for a few days after a tropical depression is identified. For easterly waves, as the name suggests, the propagation is westward. It is shown that in order to visualize optimally the associated Lagrangian motions, one should view the flow streamlines, or stream function, in a frame of reference translating horizontally with the phase propagation of the parent wave. In this co-moving frame, streamlines are approximately equivalent to particle trajectories. The closed circulation is quasi-stationary, and a dividing streamline separates air within the cat's eye from air outside. The critical layer equatorward of the easterly jet axis is important to tropical cyclogenesis because its cat's eye provides (i) a region of cyclonic vorticity and weak deformation by

the resolved flow, (ii) containment of moisture entrained by the developing gyre and/or lofted by deep convection therein, (iii) confinement of mesoscale vortex aggregation, (iv) a predominantly convective type of heating profile, and (v) maintenance or enhancement of the parent wave until the vortex becomes a self-sustaining entity and emerges from the wave as a tropical depression. The entire sequence is likened to the development of a marsupial infant in its mother's pouch. These ideas are formulated in three new hypotheses describing the flow kinematics and dynamics, moist thermodynamics and wave/vortex interactions comprising the "marsupial paradigm". A survey of 55 named tropical storms in 1998–2001 reveals that actual critical layers sometimes resemble the ideal east-west train of cat's eyes, but are usually less regular, with one or more recirculation regions in the co-moving frame. It is shown that the kinematics of isolated proto-vortices carried by the wave also can be visualized in a frame of reference translating at or near the phase speed of the parent wave. The proper translation speeds for wave and vortex may vary with height owing to vertical shear and wave-vortex interaction. Some implications for entrainment/containment of vorticity and moisture in the cat's eye are discussed from this perspective, based on the observational survey.

1 Introduction

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). As for why the problem remains unsolved, after decades of research, it is unfortunately true that in situ observations of genesis are mostly lacking over remote tropical oceans, that field campaigns are too few while operational efforts generally target mature storms, that critically important processes and their multi-scale interactions are challenging to model and observe. Nature in some cases provides little advance

Correspondence to: T. J. Dunkerton
(tim@nwra.com)

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 – to be honest – it is unlikely that fundamental progress will be made without a quantum leap in theoretical understanding as well. As will be demonstrated in this paper and the sequels, available observations on the synoptic scale need to be analyzed in a manner that is consistent with the Lagrangian nature of tropical cyclogenesis. As a moist diabatic vortex, the tropical cyclone, through its lifecycle from genesis to intensification, represents a coherent interaction between potential vorticity (P□) and moist entropy, both of which are adiabatic invariants, i.e., material properties of a conservative flow. 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 P□ 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[1], is invisible to researchers working with standard meteorological products in an Eulerian or Earth-relative framework. For tropical cyclogenesis it is necessary to understand the morphology of Lagrangian transport, and it is desirable to know whether, and how, suitable information for this purpose can be obtained from an intelligent manipulation of Eulerian data.

Compounding the problem is that multiple pathways to genesis exist. Four plausible pathways identify one or more of the following as key ingredients: (i) tropical waves, (ii) monsoon troughs, (iii) extratropical disturbances and (iv) topographic flows[2]. For each pathway we can imagine a theoretical paradigm that provides conceptual stepping stones along the path. In tropical waves, a sweet spot for development evidently exists along the wave, associated with a region of low pressure in the lower troposphere. □aving such a sweet spot does not guarantee genesis, of course, because other environmental factors also play an important role in deciding whether or not a storm may form. Many individual wave-troughs occur in a single hurricane season but only a fraction – approximately 20□ in the eastern and central Atlantic[3] (Frank, 1970) – contribute to the formation of a tropical depression-strength vortex (defined hereafter as "genesis"). Among those disturbances that produce depressions almost all have a "surface low along the wave" in the forecaster's familiar parlance. Few are thought to have a mid-level cyclonic vortex without the surface signature, a negligible fraction of the original wave count. Mid-level vortices without a discernable surface circulation are indeed observed in the tropics, increasingly so as satellite remote sensing improves (e.g., shortwave IR) in regions of frequent deep convection, such as the ITC□. Some have suggested that tropical mesoscale convective systems produce mesoscale convective

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[1] The elusive but sometimes exposed "low cloud swirls" and other stratiform cloud or water vapor anomalies represent *Lagrangian entities* to the extent that they are passively advected by the flow. Feature-tracking provides instantaneous Eulerian winds (e.g., □elden et al., 1997, 2005), while animation of the accumulated horizontal displacement of cloud or water vapor anomalies (away from their sources and sinks: viz., deep convection and other regions of moist ascent) effectively provides a Lagrangian view. So the geostationary imagery are helpful in this respect, whereas standard meteorological charts in the Earth-relative frame and infrequent snapshots from polar orbiting satellites are not. Surface winds from scatterometry are indisputably valuable, but it is unnecessary for such images (as from □uikSCAT or ASCAT) to display a closed circulation in order for a closed circulation to exist in a Lagrangian sense (see Appendix D). A morphed animation of total precipitable water from microwave imagery (beginning in 2006) is proving very helpful for analysis and prediction of moist tropical waves in the lower troposphere (http://cimss.ssec.wisc.edu/tropic2). Forecasters are now using this product to detect, locate and extrapolate the position of wave troughs. By viewing the sequence of frames, the viewer obtains a sense of Lagrangian horizontal motions weighted by the vertical profile of moisture, together with the impacts of convective moistening and horizontal entrainment. Extraction of quantitative Lagrangian information from sequential imagery is far from trivial, but a worthwhile goal. When it comes to closed circulations in propagating waves, the difference between Eulerian and Lagrangian flow is critically important, as will become clear in this paper. Forecasters deal simultaneously with both viewpoints in their arsenal of observations, yet (to our knowledge) without a clear differentiation between them.

[2] The third and fourth pathways do not represent tropical cyclogenesis genesis in the pure sense of the term. The third pathway is not entirely tropical, and the fourth pathway is not entirely oceanic. Therefore if one is interested in pure TC genesis, the problem reduces to (i) a *tropical-wave* pathway and (ii) a *geophysical turbulence* pathway. The latter may be subdivided into quasi-2-D and *rotating 3-D-convective* pathways to highlight the role of horizontal circulations and deep moist convection in a rotating environment, respectively. □ne can then appreciate the fuzzy nature of the classification scheme, as waves and turbulence generally coexist (Lilly, 1983□McWilliams, 1984□McIntyre, 2003). □ur subdivision of pathways becomes counter-productive if applied too rigidly□Genesis is not a question about which of these mechanisms is acting in a particular situation, but rather, how much of each, and how they interact across disparate scales.

[3] The percentage estimate is non-trivial: viz., to evaluate the percentage of parent African easterly waves that generate named or unnamed storms anywhere in the Atlantic sector. It's not a question of where TDs were born□rather, about where their precursor waves, if any, came from. A typical season has 60 waves and 17 named or unnamed storms. This yields an upper limit of 28□ for the average, noting that in some years the percentage may be much smaller, or in few years, much larger (e.g., 2005). Arbitrarily allowing 5 storms from non-AEW (e.g., baroclinic) sources brings the average count down to 12, or 20□. This number matches Frank's (1970) derived from 3 seasons.

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vortices initially without a cyclonic circulation near the surface (Bister and Emanuel, 1997 Ritchie and olland, 1997) and that this may be a reason why only a small fraction of disturbances become tropical depressions (E. ipser, personal communication arr and Elsberry, 1996). It will be shown here that for storms originating in tropical waves, the synoptic wave itself plays a vital role in the near-surface circulation. In our proposed tropical-wave scenario the relevant theoretical paradigm is the formation of a closed proto-vortex within the wave in the lower troposphere and subsequent eddy shedding whereby the vortex, energized further by deep convective heating, becomes detached from the wave and begins to control its own destiny. In what follows we refer to this sequence of events as the marsupial paradigm. Central to our presentation of the marsupial paradigm is a rudimentary understanding of the Lagrangian flow and its dynamical and thermodynamical properties in the neighborhood of the developing storm.

ur series on TC genesis, of which this paper is the first, addresses the tropical wave pathway and variations thereof (easterly wave propagation, tropical depression disturbances, instability of the ITC , and trapped equatorial modes) and the ability of these disturbances to create a closed gyre or "pouch" and subsequently within the pouch, a proto-vortex or "embryo" favorable for hurricane formation[4]. We are concerned also with the monsoon trough pathway (e.g., arr and Elsberry, 1996 Simpson et al., 1997). But for TC genesis, environmental conditions in the monsoon trough (McBride and ehr, 1981) appear favorable over a larger area, providing a diverse set of flow configurations in the lower troposphere (shear line, confluence, gyre Ritchie and olland, 1999) and making the role of tropical waves (with their sweet spot) more challenging to ascertain – although precursor waves can be seen in many of these cases. Genesis by spontaneous aggregation (now a popular subject of research: e.g., Emanuel and Nolan, 2004 Nolan et al., 2006 eld, 2007 Borth, 2007 Schecter and Dunkerton, 2009) may be

regarded as a limiting case of the monsoon trough pathway in which no particular region is favored, but conditions are rendered more favorable, e.g., by cranking up the underlying SST. In the real world, spontaneous aggregation is likely nature's last resort[5]. En route to storm formation, the tropical atmosphere almost always provides a sweet spot or more extensive region favorable to genesis. We believe this fact has important implications for the study of tropical cyclogenesis in climate change. Whereas an increase of SST is expected naively to increase the intensity of mature tropical cyclones, the effects of climate change on tropical cyclogenesis will be felt more immediately by modulation of *local environments that are already favorable for genesis in the current climate* effects that will be manifested, for instance, in a changed morphology of tropical waves, monsoon troughs and their favorable regions, as well as changes of large-scale circulation and ITC that affect storm tracks and environment (Frank and oung, 2007 ecchi and Soden, 2007 entham and Wang, 2007 imont and Kossin, 2007 Wing et al., 2007) possibly directing storms into regions of warmer SST[6].

In the study by Montgomery et al. (2006b hereafter M06) the TC genesis problem was posed as the metamorphosis of a mid-level mesoscale convective vortex (MC) with weak cyclonic circulation at the ocean surface into a self sustaining warm-core tropical depression vortex. The initial MC embryo was assumed to be a by-product (e.g., Emanuel, 1993 Bister and Emanuel, 1997 Raymond et al., 1998) of one or more mesoscale convective systems (MCSs) that form and evolve within the trough region of an African easterly wave in the Atlantic basin, or monsoon trough in the western Pacific basin. The problem was examined using a non-hydrostatic full physics cloud model (RAMS) at 2 km and 3 km horizontal grid spacing for realistic sea surface temperatures (SSTs) and thermodynamic vertical profiles of moist static energy within the low pressure region of

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[4]The "embryo" is borrowed from other authors (Emanuel, 1993, 2007 M06) so to be consistent with the marsupial paradigm we might refer to the proto-vortex as a "joey". Extending the analogy, a female joey provides a second "baby pouch" for convective organization at smaller scales. Little is known about the hierarchy of clouds and vortices in the pouch, and how they interact, but such details are crucial for understanding. bservations sometimes suggest multiple low-level circulation centers in systems that are still becoming organized. Forecasters and scientists alike want to know more about these proto-structures e.g., their role in Ekman pumping and convective triggering. For now and the foreseeable future, the LT in developing environments remains a mysterious realm often obscured by patches of deep convective cloud and stratiform anvils. Exposed low-cloud swirls are marvelous to behold, but they were likely hidden by deeper cloud when generated, and will be hidden again when new convection erupts. Geostationary microwave technology, needed to penetrate this environment continuously, is ~20 years away.

[5]In the "real world" of 3-km simulations performed on Earth Simulator (Matsuno 2006, 2007) tropical easterly waves play a crucial role in TC genesis, for present-day climate conditions.

[6]Genesis depends on the spatial pattern as well as the amplitude of the underlying SST, and most SST variations are contained in coupled patterns of atmosphere-ocean variability that oscillate with time. Even if one could somehow isolate a simple-pattern/secular-trend of SST variation and study its effect on the general circulation (as done by Magnusdottir, 2001 for the N winter season) the effect on genesis is non-trivial. Consider the following: a horizontally uniform change in underlying SST, e.g., the simplest of all changes in an altered world, would be superposed on the existing distribution that is a strong function of latitude. This distribution is responsible, inter alia, for the latitude of the ITC. The impact of a uniform change is therefore also a function of latitude owing to the strong nonlinearity of the Clausius-Clapeyron relation. With changes in SST and ITC come changes in the tropical waves and instabilities (hence, hurricanes) that depend, directly or indirectly, on the structure and stability of circulations associated with the ITC. Such changes impact the hydrological cycle on a global scale, with regional consequences (IPCC, 2007).

a tropical disturbance. M06 obtained new insight on convective and mesoscale processes operating within such an idealized pre-genesis environment. In the absence of hostile influences, such as strong vertical wind shear or dry air intrusions, M06's high-resolution simulations demonstrated an upscale cloud/mesoscale mechanism for building the incipient tropical storm vortex. This mechanism was shown to operate on realistic time scales and, equally important, to precede the wind-speed/evaporation feedback believed to govern the intensification of an already formed tropical depression strength surface vortex (Rotunno and Emanuel, 1987; Emanuel, 1989).

Within the convectively unstable and cyclonic-vorticity rich environment of the initial MCS embryo, horizontally small-scale warm-core updrafts possessing intense cyclonic vorticity in their cores ("vortical hot towers" VHTs) emerged spontaneously as the dominant coherent structures. As often observed in real developing storms, the most prominent VHTs were triggered at a finite radius from the proto-circulation center, consistent with the expected radial dependence of Ekman-like pumping in a geophysical vortex boundary layer (Smith, 1968; Eliassen and Lystad, 1977). Concurrent with this low-level vortex spin-up process are localized downdrafts and spreading gust front boundaries. Minima in equivalent potential temperature occur in association with localized downdrafts that import low equivalent potential temperature from the middle troposphere into the surface boundary layer. Unlike warm season continental or maritime mesoscale convection that often favors linear propagating structures (squall lines), the spreading gust front boundaries were confined laterally, to some extent, by the near-surface cyclonic circulation and the low-level inflow generated by the mean latent heating in the vortex towers. M06 showed that this low level inflow was reasonably well captured by the axisymmetric Eliassen balanced circulation (Shapiro and Willoughby, 1982; Wirth and Dunkerton, 2006) driven primarily by the mean (temporally and azimuthally averaged) heating rate of the vortex towers. The rotational confinement of these gust front boundaries appears important for sustained deep convective activity within the MCS embryo and surface spin-up. Even when gravity waves and gust fronts are not fully contained, they can be expected to play an important role in convective triggering along developing vortical boundaries in the proto-storm.

The numerical experiments of M06 demonstrated a plausible vortex assembly process that can occur within a favorable environment possessing a small but finite cyclonic surface circulation. Yet to be answered, however, is how this "embryo" and its surrounding circulation are created in the first place and whether the initial proto-vortex can survive long enough in realistic environments (e.g., with vertical shear or dry air intrusions) to enable the transition to a self-sustaining warm-core vortex. The numerical problem, as posed by M06 and others, specifies environmental conditions and a seedling disturbance according to their observed relationship (Gray, 1998) but explains neither of them, nor their association. What is special about a tropical wave trough? What latitude along the trough axis is favorable for storm development? What characteristics of a monsoon trough are important for genesis? Where do storms form in relation to the monsoon trough, and why? These questions transcend the local processes considered by M06, and require a connection to be drawn between the proto-vortex environment and synoptic-scale flow. Because of the strongly helical nature of the VHTs, another aspect not yet investigated concerns the role of helicity (Moffat, 1969) in stabilizing the upscale cascade (Lilly, 1986a,b; Herring and McWilliams, 1989; Weisman and Rotunno, 2000; Kurgansky, 2006), a process that occurs generically within the MCS, parent synoptic wave, or monsoon trough. A major objective of our research is to explain the generation and maintenance of the hurricane embryo within its parent synoptic-scale wave or monsoon trough environment. Another is to advance beyond M06 and understand more completely the role of moist convective (helical) turbulence that operates within the embryo.

The tropical wave pathway to genesis involves

1. the familiar easterly waves of the Atlantic (e.g., Carlson, 1969; Burpee, 1974; Reed et al., 1977; Shapiro, 1977, 1980; Thorncroft and Hodges, 2001) and Pacific basins (Chang et al., 1970; Molinari et al., 1997; Raymond et al., 1998; Molinari and Vallaro, 2000; Molinari et al., 2000);

2. the less familiar (mixed) Rossby-gravity waves of the central and far eastern Pacific Oceans (Hendon and Liebmann, 1991; Dunkerton, 1993; Dunkerton and Baldwin, 1995; Dickinson and Molinari, 2002; Molinari 2004); and

3. the so-called "tropical depression" disturbances of the western tropical Pacific (Liebmann and Hendon, 1990; Lau and Lau, 1990; Takayabu and Nitta, 1993; Dunkerton, 1993; Dunkerton and Baldwin, 1995; Wheeler and Kiladis, 1999; Sobel and Bretherton, 1999; Wheeler et al., 2000).

These wave types comprise a range of ground-based periods from 2.5–9 days. Slower waves such as moist Kelvin waves (Dunkerton and Crum, 1995; Wheeler et al., 2000), equatorial Rossby waves (Molinari et al., 2006) and Madden-Julian oscillation (Maloney and Hartmann, 2000) also modulate tropical waves and tropical cyclogenesis (Maloney and Dickinson, 2003; Aiyyer and Molinari, 2003, 2008). Tropical waves in the 2.5–9 day band may originate from convective coupling (Hayashi, 1970; Lindzen, 1974), lateral forcing (Wilson and Mak, 1984; Randel, 1992; Zhang and Webster, 1992), hydrodynamic instability of the ITCZ (Mack et al., 1989; Schubert et al., 1991; Wang and Magnusdottir, 2005, 2006) or fully developed TCs and their associated "Rossby wave wakes" (McWilliams and Flierl, 1979; Montgomery et

al., 1999 Ritchie and olland, 1999). The role of equatori-
ally trapped waves in tropical cyclogenesis requires knowl-
edge of their latitudinal structure and cross-equatorial sym-
metry, while that of TD disturbances requires that we ac-
count for a significant meridional component of propagation.
These wave types are examined separately. Excluded from
consideration in our first three papers are

4. tropical storms originating from extratropical upper-
level P anomalies in a moist baroclinic environment
(Montgomery and Farrell, 1993) and/or stalled frontal
zones in the subtropics (the so-called "tropical transi-
tion" pathway: e.g., Davis and Bosart, 2004) and to-
pographic effects (ehnder et al., 1999 Chang et al.,
2003).

Neither of these pathways (TT or topography) are purely
tropical and oceanic. A key ingredient of TC genesis – for-
mation of a closed recirculation region – pertains, nonethe-
less, to many examples of subtropical development in the
central and western Pacific that we have encountered in our
preliminary survey. A fourth paper will examine these cases.

Local instability of the ITC as a pathway to genesis
is possible, although more commonly, the waves produced
thereby propagate downstream into regions more favorable
to genesis: e.g., with warmer water or larger absolute vor-
ticity. Storms generally do not originate within the locus of
ITC convection, but cause poleward distortion or obliter-
ation of the ambient ITC (Dunkerton, 2006). Significant
storms in the historical record affecting coastal regions of
the southeastern US and Gulf states originated from tropical
waves in the eastern and central Atlantic (the "main devel-
opment region" or MDR) notwithstanding a few spectacu-
lar storms originating in the western Atlantic and the Gulf
of Mexico. wing to their quasi-monochromatic nature and
relative simplicity, we begin our genesis study in the context
of Atlantic easterly waves (Kiladis et al., 2006 all et al.,
2006) and their eastern Pacific extension. The papers to fol-
low will extend this line of research to other types of tropical
waves and instabilities relevant to other ocean basins (Bessafi
and Wheeler, 2006 Frank and Roundy, 2006 Molinari et al.,
2006). To isolate key elements of the various sub-types of
tropical-wave cyclogenesis cited above, we begin our dis-
cussion in Sect. 2 with a conceptually simple scenario in
which hydrodynamically neutral waves emerge from an un-
stable source region upstream, propagate westward into the
domain of interest, and create regions favorable for genesis
regions which may, in turn, maintain or enhance the neu-
tral waves via convective heating against dissipation while
propagating across the basin. This scenario is most rele-
vant to the Atlantic sector, wherein easterly waves generated
by moist hydrodynamic instability over Africa (that is, over
land, where TCs cannot form owing to surface friction and
absence of sustained latent heat fluxes) or by other means
propagate westward into a warm ocean, providing seedlings
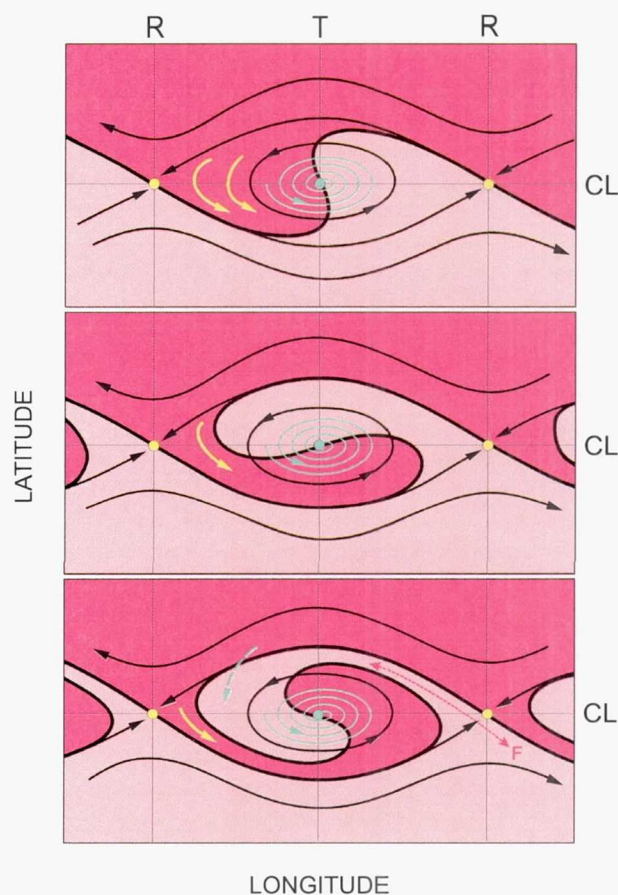for possible genesis. It is also relevant to other basins, such

Fig. 1. Critical layer for waves in latitudinal shear, showing stream-
lines (solid), bounding streamline (thick solid) and Trough/Ridge
axes (thin solid). If the deeper shade of pink represents higher ab-
solute vorticity, the wave acts on a *stable* meridional gradient of
zonal mean PV, with initial vorticity maximum poleward of the crit-
ical latitude (CL). In an unstable configuration, with higher vortic-
ity represented by the lighter shade, the first cycle of overturning
entrains higher vorticity from equatorward of the CL axis. The lat-
itudinal shear is negative in either case. Adapted from Andrews et
al. (1987).

as the eastern tropical Pacific or mid-Atlantic, but we recog-
nize that in such regions (over ocean, where surface friction
is relatively small and latent heat is plentiful), instability of
the ITCZ may sometimes lead directly to genesis (Hack et al.,
1989; Schubert et al., 1991; Wang and Magnusdottir, 2005,
2006). Some of the events occurring in our time period of
interest may belong to this category; they are more akin to
instability than the neutral wave propagation imagined in our
ideal scenario. Hydrodynamically unstable waves have dis-
tinct topological characteristics for a time, but once reaching
finite amplitude they are equally good candidates for genesis,
occurring within a critical layer, as neutral waves.

What follows is primarily an observational study preceded
by formulation and presentation of three new hypotheses

for tropical cyclogenesis in tropical waves. Three independent datasets are used for meteorological analysis (▯RA-40), satellite-derived precipitation (TRMM) and storm history (▯HC best-track data). Section 2 outlines the basic theoretical concepts underlying our analysis. Section ▯illustrates the morphology of waves and convection in relation to the mean ▯ow and embedded critical layers, in two representative cases, and summarizes key properties of all storms examined, while Sect. 4 affords a closer look at the ▯+▯ structure and evolution of the critical layer, closed material contours, and diabatic vortices in one of these cases. ▯etails of our analysis method, additional cases, streamline topology and the view from scatterometry are discussed in Appendices A–▯, respectively. Two contemporary viewpoints of TC genesis and climate change, contrasting the roles of off-equatorial circulation and moisture supply, are noted in Appendix ▯. The time period of interest encompasses the peak hurricane seasons of 1998–2001 when the two primary datasets used in our study (▯RA-40 and TRMM) overlap.

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Whether hydrodynamic instability plays an immediate role in TC genesis (as sometimes observed in the eastern Pacific and mid-Atlantic) or excites waves that later become instrumental in genesis downstream (as in the African/Atlantic sector) there is a ▯uid dynamical situation arising in both scenarios that is relevant to genesis for reasons to be enumerated below. This situation involves the familiar critical layer of waves in shear ▯ow, wherein parcels experience irreversible displacements and trapping about the wave▯s critical level, viz., the location where mean ▯ow and wave phase speeds are equal[7]. In the so-called ▯cat▯s-eye▯of the critical layer where trapping of parcels takes place, the ▯uid becomes isolated from its surroundings on either side of the critical layer as parcels outside the cat▯s eye are advected in opposite directions. The Lagrangian mean ▯ow is asymptotically discontinuous on the edges of the critical layer and its horizontal profile consists of three components▯two are in opposite directions on either side, while the middle is stationary with respect to the cat▯s-eye pattern (Andrews and McIntyre, 1978). The latter is equivalent to a statement that the Lagrangian mean ▯ow in the critical layer is zero in a frame of reference moving with the critical layer itself▯i.e., at the phase speed of the wave[8]. Here we take the Lagrangian mean to be a spatial average in the direction of the ▯ulerian mean ▯ow, which we also as-

Fig. ▯ Idealized profile of an easterly ▯et U north of the equator, on which stable easterly waves propagate westward having their critical latitudes ▯ust outside the ▯et▯s in▯ection points where the gradient of absolute vorticity η or ▯effective β▯is zero. ▯nstable waves may be imagined to have their critical latitudes ▯ust inside the latitude of in▯ection points.

sume to be the direction of wave propagation, as shown in ▯ig. 1. This simplifying assumption will motivate our discussion of the role of the critical layer in TC genesis, but it should be borne in mind we are always concerned with the actual direction of wave propagation in relation to the mean ▯ow, regardless of their azimuthal directions, and will define the critical level generally in terms of the locus of points where the wave intrinsic frequency goes to zero.

▯.1 ▯▯i▯▯▯▯i▯▯▯ ▯▯▯▯▯▯▯ ▯▯▯

To fix ideas, consider a zonally uniform easterly ▯et at tropical latitudes off the equator. ▯or simplicity, assume a barotropic ▯et structure as depicted in ▯ig. 2. There is cyclonic shear equatorward of the easterly ▯et maximum, and anticyclonic shear poleward of the maximum. ▯quatorward of the ▯et core the cyclonic shear vorticity is enhanced by the planetary vorticity, while poleward of the ▯et core, the anticyclonic shear vorticity and the planetary vorticity tend to compensate. The absolute vorticity poleward of the ▯et core is therefore weakly negative or close to zero. Since the meridional gradient of the absolute vorticity changes sign both poleward and equatorward of the ▯et core, the mean ▯ow satisfies one of the necessary (Rayleigh) conditions for barotropic instability. It has been long recognized in the literature that the African easterly ▯et (A▯▯) is unstable to disturbances which might be described as a moist barotropic instability or mixed barotropic/baroclinic instability[9]. More

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[7]The critical level is generally a *surface* in three dimensions, but the word *level* or *line* has been used in the literature to represent any of these dimensions, e.g., latitude or altitude.

[8]In latitudinal shear, the cat▯s eye of the critical layer is uniquely where a wave-centric view is Lagrangian, in the sense described in our response to an Interactive Comment. In the marsupial paradigm, a storm-centric view is approximately equivalent to a wave-centric view, for as long as proto-storm and parent wave move together.
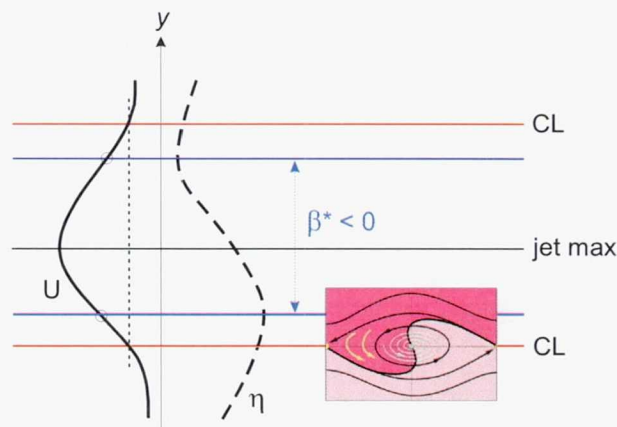
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[9]The critical level plays a central role in such instabilities, enabling phase-locking of counter-propagating Rossby waves in ad▯acent regions of opposite meridional PV gradient (Hoskins et al., 1985; Heifetz et al., 1999) or, in linear ray theory, as the locus

recently it has been suggested that synoptic-scale instability by itself may be too slow to explain easterly wave disturbances in the African sector (Hall et al., 2006). In either event, if we assume that the locus of wave instability or excitation lies upstream, i.e., that the region of interest is stable with respect to exponential growth, it may be inferred that the phase speed of waves generated upstream lies outside the range of mean flow speeds in the region of reversed PV gradient, as depicted in Fig. 2. The alternative – a critical level within the zone of reversed gradient – would likely cause unstable growth. For an easterly jet north of the equator, the critical level (hereafter, critical latitude) therefore resides a bit south of the southernmost latitude where the effective beta is zero.

A second critical latitude exists north of the jet axis, north of the northernmost latitude where the effective beta is zero again, on the opposite side of the jet. As already noted, however, the shear vorticity of the mean flow is cyclonic south of the jet and anticyclonic to the north. If a critical layer of finite width were to form at the location of either critical latitude as a result of wave propagation into the region of interest, the sense of rotation in the cat's eye would be the same as that of the mean relative vorticity. For TC genesis we are obviously interested in cyclonic rather than anticyclonic vorticity in the lower troposphere and therefore regard the southern, not northern, critical layer as a possible locus of TC formation. Moreover, we should not imagine that actual wave disturbances and the critical layers they generate are exactly symmetric or antisymmetric about the jet axis[10]. For the case of an idealized unstable easterly jet, Thorncroft and Hoskins (1994a) showed that the most unstable wave disturbance south of the jet is centered equatorward of the southernmost latitude where the effective beta changes sign. Their maximum amplitude is near the critical latitude, in accord with our propagating-wave scenario (as might be expected from consideration of linear parcel displacements, which maximize at the critical latitude or level). This asymmetry of wave amplitude about the axis of the jet, favoring the southern or equatorward side, also emphasizes the cyclonic critical layer at the expense of the anticyclonic one. For the case of an exponentially stable jet flow, discrete neutral or slowly decaying "quasi-mode" wave packets (Reasor

and Montgomery, 2001; Schecter et al., 2002) – stimulated, perhaps, by mesoscale processes within the trough region of the wave envelope (Berry and Thorncroft, 2005; Hall et al., 2006) – should possess similar phase speed and wave maxima characteristics as their unstable counterparts. Our immediate concern is not with wave sources, which lie outside the scope of this paper, but with downstream propagation of neutral waves on an easterly jet as depicted in Fig. 2.

2.4 Role of the critical layer in convective organization

The formation of a tropical depression in a tropical wave critical layer is plausible only in a cyclonic Kelvin cat's eye, not an anticyclonic one. Therefore we selected the southern, not northern, critical layer as the locus of interest. Formation of a tropical cyclone also requires convective heating in order to achieve the desired levels of potential vorticity and concentration of PV substance (~100 times ambient values, in a mature storm. In the ideal critical layer of Fig. 1, PV anomalies within the cat's eye are symmetrically distributed (i) in physical space about the centerline and (ii) in a statistical distribution about the mean value, which is cyclonic here, because we have chosen the southern CL on the AEJ. Passive roll-up of cyclonic mean vorticity in the southern critical layer does not lead directly to genesis, because local extrema of PV anomalies are preserved by a dry adiabatic rearrangement, in ideal and real-life wave scenarios. It does so indirectly, in the sense that this "coherent structure" of cyclonic vorticity (created at meso-α scale by a synoptic[11] wave) provides one or more seedlings for amplification by mesoscale convective processes (M06) which, as we now argue, might occur preferentially in the critical layer. As shown in Fig. 1, the longitudinal center of the cat's eye corresponds to the trough of the wave, a region favorable for deep moist convection in observations. (i) Formation of a Kelvin cat's eye by critical layer development at meso-α or synoptic scales, and (ii) convective enhancement and up-scale aggregation of cyclonic vorticity from meso-γ to meso-β scales, is a plausible outcome of the neutral wave propagation depicted in Fig. 2. The order of enumeration is important: the cat's eye is a result of wave propagation into the region of interest, while convective amplification and aggregation is aided subsequently by formation of the cat's eye. Causality is determined, in part, by the arrow of time: what follows temporally (item ii) cannot be a cause of what came before (item i). This idea was expressed clearly in theories of the ideal dry Rossby-wave critical layer (Killworth and McIntyre, 1985, and references therein) wherein the cat's eye precedes (logically and chronologically) the redistribution of PV within,

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of wave overreflection (Lindzen and Tung, 1978; Lindzen et al., 1980). Either of these mechanisms leads to wave growth if certain conditions are met. In barotropic instability, one of these conditions is the existence of a critical level within the zone of reversed PV gradient. The latter requirement is not universal, however. When $\beta=0$ the "varicose mode" for a symmetric jet has a critical level at the inflection point. More generally, when the interior PV is everywhere uniform, as in the popular Eady model, the reversal of interior PV gradient is moot.

[10] North-south symmetry of the basic state about the jet axis is broken by mean absolute vorticity, which is asymmetric, and a meridional gradient of moisture, if one exists. Further asymmetry may arise from wave sources upstream.

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[11] Following convention, 2.5–9 day moist tropical waves relevant to TC genesis occur on *synoptic* spatial scales (2000–8000 km or so) while cat's eyes and closed recirculation regions develop at meso-α (200–2000 km). Proto-vortex development occurs at meso-β (20–200 km) involving deep moist convection at meso-γ (2–20 km).

and the advecting □ow does not depend to leading order on the redistribution itself. The reader may consult our □inal Response at the ACP□ website for further discussion, citations and quotations regarding this point. These considerations do not exclude the possibility that upscale mechanisms may have created the easterly wave in the first place (as seen over the African Highlands) or that new Rossby waves may be excited in the wake of a mature storm (as seen in western Pacific T□ disturbances) as noted in the Introduction. □or do they preclude thermal forcing of the parent wave by the developing proto-vortex within. The proper sequence is appreciated most clearly in our neutral wave scenario on a parallel shear □ow, without the clutter introduced by secondary phenomena.

Important to this sequence of events is that the easterly □et is located in the lower, not middle, troposphere and that lower tropospheric vorticity is organized by the □elvin cat□s eye in this layer, and subsequently amplified by convective processes in the cat□s eye. In real life the waves and their effects are more complicated than in our ideal scenario; actual waves are local, episodic, and vary from one trough to the next. This variability, in fact, is so important to genesis that □HC/TPC forecasters (for better or worse) in their online discussion regard each individual trough as a □tropical wave□. We do not expect a uniform train of cyclonic cat□s eyes but rather a zonally nonuniform pattern of cyclonic eddies – eddies which, in some sense, are □shed□from the A□□ as a result of the wave propagation and interaction with the mean □ow at the critical latitude. □ur first hypothesis concerning the role of the tropical wave critical layer in TC genesis is therefore

> □1. Proto-vortex cyclonic eddies instrumental in TC formation are intimately associated with the parent wave□s critical latitude in the *lower troposphere*. The critical layer and □elvin cat□s eye within, formed as a result of the wave□s finite-amplitude interaction with its own critical latitude, contain a region of cyclonic rotation and weak straining/shearing deformation in which synoptic waves and mesoscale vorticity anomalies, moving westward together, amplify and aggregate on a nearly zero relative mean □ow. This multi-scale interaction provides a dynamical pathway to □bottom-up□ development of the proto-vortex from below.

The notion of bottom-up development (Halverson et al., 2007) is advanced as a counterpart to the more familiar □top-down□scenario advocated by □ister and □manuel (1997) and Ritchie and Holland (1997), respectively; see also Ritchie et al. (200□). (This perspective was in vogue when M06 was written. The two scenarios are not mutually exclusive, as emphasized by Halverson et al.; see □lossary.) The top-down pathway begins with a recognition of the □top-heavy□nature of moist convective heating profiles in the presence of combined convective and stratiform precipitation processes. A top-heavy heating profile in a rotating environment necessar-

ily leads to the conclusion that cyclonic vorticity is first concentrated in the middle troposphere by the induced vertical profile of convergence and must therefore find a way subsequently to burrow downward into the lower troposphere in order to provide the surface development needed for warm-core TC genesis. This pathway is inefficient (Tory and Montgomery, 2006) and invites a more direct route to genesis if one could be found, particularly in sectors where development is marginal to begin with. □bservational findings of the top-down school were biased to the western Pacific warm pool, but in light of forecaster□s experience we are inclined to regard this pathway as largely irrelevant to the Atlantic and eastern Pacific sectors outside the ITCZ[12]. The genesis of depressions in this region of the world is almost always associated with a surface low along the wave (see Reasor et al., 2005, for a case study); examples of mid-level cyclonic vortices in developing tropical systems, without a corresponding cyclonic signature near the surface, are evidently rare. □ottom-up development is inextricably linked to column moistening, which favors convective over stratiform heating as the leading contribution to the vertical heating profile. Column moistening, in turn, is naturally favored in a cyclonic critical layer. □ur next hypothesis expands on this theme□

> □□ The critical-layer cat□s eye of the parent wave provides a set of quasi-closed material contours inside of which air is repeatedly moistened by convection, protected to some degree from lateral intrusion of dry air and impinging vertical shear, and (thanks to its location near the critical latitude) able to keep pace with the parent wave until the proto-vortex has strengthened into a self-maintaining entity.

This hypothesis is a □coin with two sides,□combining the notion of repeated column moistening with the equally important notion that the □elvin cat□s eye is protected from lateral entrainment of air – air which, in the case of the A□□ is often dry and dusty if associated with the Saharan Air Layer in the lower free troposphere (Thorncroft et al., 200□; □union and Velden, 2004; Wong and □essler, 2005). Hypothesis 2 also adds the notion of rapid vertical transport by convection to what otherwise has been, in our discussion thus far, a description of moist barotropic or shallow-water disturbances superposed on an easterly off-equatorial □et. These quasi-2-□ disturbances organize the □ow laterally via parcel displacement and create kinematic boundaries to lateral mixing; they also organize moist convection that lofts moisture into the free troposphere. Such convection, of course, is ubiquitous in the tropics and represents the primary mechanism of vertical transport that is rapid in comparison to other vertical motions such as isentropic up-glide along frontal zones

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[12]Although the single developing system (□uillermo) observed during T□□M□□ was originally thought to contain a low-level anticyclone in its earliest stage, subsequent analysis revealed a cyclonic circulation all the way to the surface (Raymond et al., 1998).

and diabatic subsidence in the Hadley circulation caused by radiative cooling. In cases where the ambient cyclonic vorticity and moisture are positively correlated above the boundary layer, gyre formation is accompanied by horizontal entrainment of moisture, shortening the time required to approach column saturation. The "quasi" closure of streamlines or trajectories in H2 conveys two important caveats that will apply in all of the discussion to follow: (i) there is always a temporal development of the closure, as local wave amplitude grows and parcels become irreversibly entrained in the gyre, and (ii) there is often a nonzero divergent component of motion across the outer edge of a "closed" gyre as defined by the bounding contour of (nondivergent) stream function. We have greater confidence in the rotational component of motion than the divergent part, quantitatively speaking, and therefore attach greater significance to the appearance of a closed gyre in stream function. This is not to say that the analyzed divergent wind is unreliable; its sign usually agrees with the expected inflow (outflow) of mass in the lower (upper) troposphere in the neighborhood of a developing storm. At lower levels the divergent component of motion therefore contributes to the entrainment of vorticity and moisture as does the temporal development of the rotational component.

We do not limit deep convection to the critical layer (!) but advance the notion that convection within the Kelvin cat's eye is likely to create a vertical profile of diabatic heating with a lower- to mid-tropospheric maximum (Tory et al., 2006a, b, 2007) instead of the more widely observed "top-heavy" heating profile of canonical mesoscale convective systems (Houze, 1989; Mapes and Houze, 1995). The canonical profile represents a combination of convective and stratiform effects in which evaporative cooling in adjacent stratiform anvil regions offsets the low-level heating in deep convective cores. These two components superpose constructively in the mid- to upper troposphere. A top-heavy profile is important to the tropical general circulation (Hartmann et al., 1984), the mature phase of MJO (Lin et al., 2004) and generation of stratospheric gravity waves (D. Ortland, personal communication) but inimical to tropical cyclogenesis. The argument favoring a convective heating profile in TC genesis rests on an inference by Tory et al. (2007) that simulated storms initialized in actual environments (real-life examples) are accompanied by such a profile when development ensues, and vice versa. This profile also can be inferred indirectly from the observed divergent circulation response (Sect. 4.?) or "directly" from TRMM retrievals in the recirculating gyre (Dunkerton et al., 2009a). The heating profile is coupled to column moistening, and vice versa. As a region of re-circulating quasi-horizontal flow, the Kelvin cat's eye is bounded by closed material contours – a Lagrangian concept that provides a more general definition of the TC "pouch" in cases where a critical layer is not well defined or consists of a solitary shed vortex (as illustrated in Fig. ?; for further commentary on this figure see Appendix A5). The cat's eye is expected to trap, that is, to contain moisture or

moist entropy lofted by convection. The net heating and its vertical profile depends, in turn, on the amount of moisture lofted. Lower tropospheric air close to saturation is less likely to experience evaporative cooling, and the cat's eye (for purely kinematic reasons) favors maintenance of nearly saturated conditions, especially if there exists a concentrated and sustained population of shallower "congestus"-type convection in such a region, as suggested by some recent observations. For low-level mass convergence and vorticity amplification, a convective type of heating profile in the lower troposphere (LT) critical layer – without significant stratiform heating/cooling, or with less stratiform component than typical elsewhere – favors bottom-up development (M06) and concentration of upward mass flux in the lower troposphere (Raymond and Sessions, 2007). This is not to say that mid-level spin-up might not also occur in such cases, but to suggest that a low-level scenario is plausible in which the mid-level spin-up is unnecessary or of secondary importance to TC genesis[1]. This theoretical notion and its implications agree with the common observation by forecasters of a "surface low along the wave" in the development of a tropical depression.

Routine inspection of satellite water vapor imagery suggests that genesis is always associated with a relatively moist free troposphere as observed in the 6.7 micron band. There are many mechanisms governing the distribution of moisture; formation of a closed gyre in a tropical wave critical layer is but one of these. Quasi-stationary tropical features and extratropical disturbances also play a role. A developing gyre entrains whatever moisture exists nearby and experiences self-moistening via deep convection within. Once moistened, it is desirable that the gyre (or some portion of it) remain so in order to facilitate TC formation. A key property of the proto-vortex required for subsequent development is its resilience to lateral intrusions of dry air which are common throughout the Atlantic during the hurricane season and at other times and places. The proto-vortex of a nascent TC, however, lacks a strong transport barrier (cf. McIntyre, 1989, 199?; Montgomery and Kallenbach, 1997; Bassom and Gilbert, 1999; Moulin and Flor, 2005) and is vulnerable to dry-air intrusion and vertical shear (e.g., Reasor et al., 2004). It therefore needs help from the parent wave. The protective kinematics of the Kelvin cat's eye (moving with the wave at its critical latitude) implies a reduction of dry air intrusions from outside (Tuleya and Kurihara, 1981) and a tendency for the heat released by cumulus convection to be retained in the co-moving frame (Krishnamurti et al., 1994). The observation by Krishnamurti et al. is incorporated in a third hypothesis below.

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[1] ERA-40 data examined here suggest, for what it is worth, that mid-level convergence resolved by the analyses occurs in developing systems but is secondary to low-level convergence chronologically as the proto-vortex develops upward.
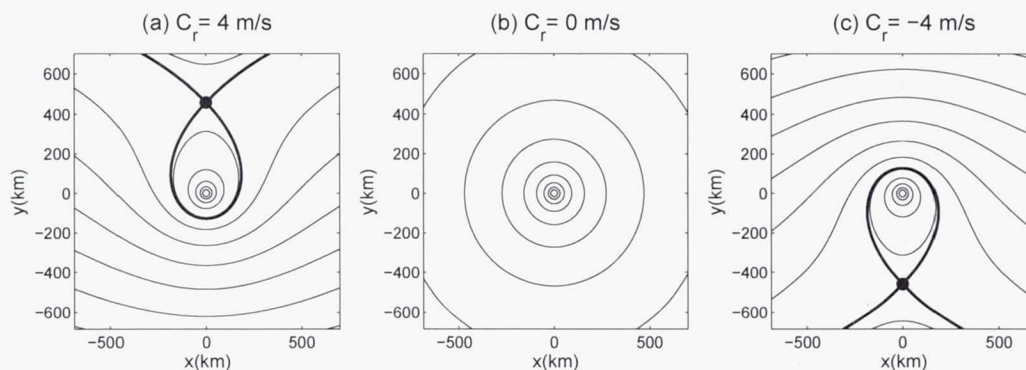
(a) C_r = 4 m/s   (b) C_r = 0 m/s   (c) C_r = -4 m/s

Fig. □ Total streamline structure of a point vortex with cyclonic circulation Γ immersed in a constant mean zonal □ow U_b. In the frame of reference displayed here (with zonal translation speed equal to zero) the vortex is spatially and temporally fixed at the origin. The total □ow is given by the superposition of a constant background zonal wind and a circularly symmetric □ow induced by the point vortex. This □ow is an exact steady solution of the 2-□ □uler equations. As noted in the text, identical streamline patterns are obtained in a *resting* basic state when the vortex translates zonally at speed $C_p = -U_b$. The numerical value of Γ is based on the gyre circulation analyzed for pre-□ebby in August 2000. Three cases are sketched□ □□U_b□4 ms^{-1} (moderate westerly □ow over the vortex), □□□U_b□0 (zero background □ow) and □□□U_b□−4 ms^{-1} (moderate easterly □ow). Light solid curves denote streamlines. The black dot denotes the stagnation point located at (X_c, Y_c)□$(0, \Gamma/2\pi U_b)$; the □uid velocity vanishes there. The thick solid curve denotes the dividing streamline that divides the □ow into three distinct regions□a core region near the vortex, upper outside region and lower outside region. As the magnitude of the imposed □ow increases, the distance from the vortex center to the separatrix decreases and the amount of □uid isolated within the core region decreases.

According to the marsupial paradigm, the critical layer guarantees some measure of protection from intrusion. □ut actual □ow fields are transient and contain mesoscale finestructure, 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[14]. 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 MCSs 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 □□□ aspect is perhaps the most fascinating and daunting of TC genesis; one that has not yet been fully explored (owing to limitations of horizontal resolution in observations or models) but may be advanced as a framework for understanding the multi-scale nature of the problem. □f relevance to H2 are the following considera-

tions□(i) A group of *cloud-system vortices* at meso-γ may delay saturation of the column by a single master VHT, by mixing drier area within the pouch with moister air lofted by the VHT. (ii) A group of *mesoscale vortices* (resulting either from dry or moist processes at meso-β) may entrain drier air from outside the pouch via chaotic advection, partially offsetting the cumulative moistening of this area by persistent deep convection. Requirements for horizontal resolution differ depending on which of these mechanisms is more relevant; they are less stringent for chaotic advection than for upscale aggregation.

A third hypothesis is motivated by the fact that the □elvin cat□s eye of a critical layer is where local sources or sinks of momentum and entropy are amplified owing to the fact that parcels spend a considerably longer time in such regions compared to those well outside the critical layer. In linear theory the net effect of fixed sources and sinks is inversely proportional to intrinsic frequency. This response, as noted by Held and Ting (1990), contrasts sharply with topographic wave excitation in which the response is proportional to the mean □ow speed relative to the obstacle. It exists for purely kinematic reasons and is entirely independent of any presumed relationship between the wave and induced sources or sinks. In fact, since the wave trough is a preferred region for diabatic heating in tropical waves (or close to such; see □iladis et al., 2006) and its longitude is at the center of the cat□s eye (□ig. 1) the effect of diabatic heating due to deep moist convection is doubly amplified in this region of the critical layer. (i) The heating is stronger here (owing primarily to mesoscale processes that favor convection in the trough) and (ii) its rectified effect on the wave is also stronger owing to

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[14]Relevant to this discussion are two studies outside the atmospheric literature. The effects of entrainment on the buoyancy of rotating □énard convection were discussed by □ulien et al. (1999). □rganization of deep ocean convection by mesoscale eddies was examined by Legg et al. (1998).

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the kinematics of parcel motion in the critical layer. Hence we propose that

> □□ The parent wave is maintained and possibly enhanced by diabatically amplified eddies within the wave (proto-vortices on the mesoscale), a process favored in regions of small intrinsic phase speed.

This hypothesis, incidentally, agrees with the common observation that a tropical wave is weakened or eliminated when the diabatic vortex leaves the pouch, having acquired its own identify and propagation characteristics independent of the parent wave. A typical scenario[15] is that a westward propagating wave carries its proto-vortex for a time, and if a depression ensues, the strengthened and enlarged vortex acquires a poleward component of propagation while its zonal component begins to slow relative to the phase speed of the parent wave. The parent wave continues its westward motion at more or less the same speed it originally had, but with severely diminished amplitude. In the Atlantic sector the wave speed is typically 4–6° per day westward, while the vortex speed is ∼2° per day west-northwestward. Individual cases may resemble this scenario or differ considerably; nevertheless, the basic description is robust.

The observed combination of westward moving tropical wave and proto-vortex within evokes a □marsupial□paradigm for TC genesis, as charmingly illustrated in the popular on-line encyclopedia[16]. In contemporary □argon the marsupial paradigm combines elements of a *diabatic Rossby wave* (Wernli and □enzelmann, 2006) with those of a *diabatic Rossby vortex* (Moore and Montgomery, 2004, 2005, 2006). We suggest that the diabatically activated easterly wave is a hybrid wave/vortex structure, particularly in cases leading to formation of a tropical depression[17].

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A mysterious and sometimes counter-intuitive element of the marsupial paradigm is the role of mean vertical shear in TC

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[15]Sometimes two or more visible proto-vortices are involved, a scenario that may be more common in the western Pacific monsoon trough environment (□dson and Lander, 2006).

[16]http□//en.wikipedia.org/wiki/Marsupial

[17]It is noteworthy that most tropical depressions become named storms, although the reasons are unclear. The cumulative experience of forecasters is evidently important in assigning depression status and in knowing at what formative level further development is virtually assured. This property of tropical depressions suggests a finite-amplitude instability for cyclogenesis above a certain threshold amplitude (e.g., □manuel, 1989). As to what the relevant criteria are, they likely include some measure of tangential circulation strength, persistence of deep convection near the center, and a (possibly sub□ective) sense of closed circulation. Such criteria, in any case, must be invariant under a □alilean transformation, that is, Lagrangian properties of the □ow. A coordinate-dependent □ulerian measure (e.g., westerlies south of center, in the resting frame) is inadequate.

genesis. It is widely appreciated, especially by forecasters, that strong vertical shear is inimical to genesis. This fact is thought to account for the reduction of Atlantic hurricanes in warm □□S□ events, as the eastern Pacific □warm pool□forces upper-level westerlies over the Caribbean (□ray, 1984a, b; □oldenberg and Shapiro, 1996). Although reasons suggest themselves, none are entirely convincing. Vertical shear in the upper troposphere (□T) is sometimes imagined to □ventilate□deep convection, but since the water content is very small at these altitudes, thermodynamic consequences arising from the phase change of water in the □T are likely to be very small as well. Similarly, the clear-sky radiative impacts of water vapor redistribution in the □T are probably too slow to affect genesis on time scales of 1–2 days, although their effects on longer time scales (e.g., M□□) may be significant. An indirect effect of vertical shear, if westerly, is an implied wave duct for quasi-stationary waves of midlatitude origin in the tropical upper troposphere. This dynamical opening between tropics and extratropics (Webster and Holton, 1982) is responsible for the appearance of synoptic-scale troughs sometimes observed to penetrate the tropics in the hurricane season. If such □troughy□□ow persists over a substantial part of the season it may ostensibly suppress genesis in some years (e.g., Atlantic 2006). The extratropical disturbances themselves may enhance genesis (TT pathway□ □avis and □osart, 2001; Hendricks et al., 2004; Hidalgo, 2007) or suppress it (via dry air intrusion or cyclonic □ow aloft) so their net effect is not obvious and may be sensitive to the □uxtaposition between upper- and lower-level disturbances (□avis and □osart, 2004; □osart, 2006).

It is well-known that vertical shear can be detrimental to hurricane intensification; the strongest and most circularly symmetric storms have little environmental shear or shear tendency. It is precarious, however, to take whatever mechanisms are responsible for the effects of shear on hurricane-strength vortices and assign them to the pre-depression stage. Whereas in a mature system, vertical shear interacts with a single large vortex, in genesis, the shear is interacting with one or more deep convecting elements, rotating or not (□rank and □ohnson, 1969; □entry et al., 1970; Hendricks et al., 2004; M06; Hendricks and Montgomery 2006). At this stage, the effects of shear are more likely to be felt in *convective organization* rather than via the dynamics of a single large vortex. We speculate that strong shear in the genesis stage (i) may lead to linear rather than circular organization, and that (ii) longitudinally radiating gravity waves or density currents coupled to convection are more likely to be excited when the LT shear is strong (LeMone et al., 1998). Mechanisms of convective organization in vertical shear were studied by Corbosiero and Molinari (2002) and Molinari et al. (2004, 2006). □orecasters□experience notwithstanding, there is no reason to think that genesis is optimized in exactly zero vertical shear. If it were, the fact that easterly-wave amplitudes maximize near the altitude of A□□ maximum (∼600 hPa) would be convenient to the marsupial

paradigm because wave ☐ mean vertical shear is zero at this altitude, by definition. We suspect that the role of vertical shear in the marsupial paradigm is more subtle and may (in some cases) facilitate refraction of the waves, without affecting adversely their embedded deep convection.

☐ ☐ ☐☐☐☐☐g☐ ☐☐☐☐☐ ☐☐☐ ☐☐ g☐☐☐i☐i☐ ☐☐☐☐☐☐☐☐☐ i☐☐ ☐☐☐☐

Sixty-one named storms formed over the Atlantic (including the Caribbean Sea and ☐ulf of Mexico) and eastern Pacific during August and September 1998–2001, almost one-half of the 1☐6 (named or numbered) tropical depressions that formed during all four hurricane seasons within these two ocean basins and their ad☐acent seas. ☐ifty-four (88☐) of the 61 named storms fell into the ☐monochromic easterly wave☐ category based on the criteria described in Appendix A☐. In the remaining (seven) cases, either a multiple-wave interaction was involved, or easterly waves were not well-defined[18]. Among the 54 storms in the monochromatic category, many formed from African easterly waves; others over the eastern Pacific formed from wave disturbances originating in the ITCZ. Although unstable ITCZ disturbances have a different morphology from African easterly waves, as explained in Appendix C, they support the marsupial paradigm; genesis is found once again to occur in the ☐elvin cat☐s eye of the wave☐s critical layer. In addition to the 54 cases from the Atlantic and eastern Pacific, we include a single case from the central Pacific ☐ust east of the ☐ateline (178° ☐), bringing the total number of named storms in the monochromatic easterly wave category to 55. ☐or each event a zonal phase speed was determined as a function of height in the lower troposphere, as described in Appendix A4. ☐ey to the following analysis is our visualization of the horizontal ☐ow (streamlines and stream function) in a frame of reference translating westward with the parent wave, at its speed of zonal phase propagation, as explained in Appendix A5.

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The time of TC genesis, lat/lon location and accompanying wave phase speeds at 850 and 600 hPa for the 55 ☐monochromatic easterly wave☐ cases are summarized in Table 1, together with the uncertainty of the phase speed estimate, and various properties of the ☐ow in which the proto-storm develops, such as (i) the area of the surrounding closed gyre in the co-moving frame, (ii) orientation of the separatrix or dividing streamline that bounds the gyre, as defined by the direc-

tion of its saddle point (☐hyperbolic point☐) relative to gyre center, and (iii) two measures of recirculation time about the proto-storm center, to be discussed in Sect. 4.1. ☐or most of these quantities the median of the distribution is shown at the bottom, together with one-half the inter-quartile range, representing the difference between the 75th and 25th percentiles, divided by two.

Phase speeds are similar at the two levels, though slightly larger in median at 600 hPa. About 60☐ of the members have larger phase speed at 600 hPa, a bias that seems somewhat more prevalent in the eastern Pacific. A physical interpretation is that some of the waves in question are not *modes* with fixed vertical structure, but a sheared disturbance or quasimode with vertical alignment that varies with time. ☐vident in the resting frame is that waves faster than $\sim$7 ms^{-1} westward are found only in the Atlantic sector, although slower waves are found here, too, similar to those of the eastern Pacific. The ratio of 600 to 850 hPa phase speed is generally larger for slower waves than for faster waves.

The uncertainty of phase speed was obtained performing a least-squares fit on the Hovmöller diagram in up to four ways☐ fitting the positive and negative lobes of band-pass meridional velocity anomaly individually, either (i) ☐days prior to genesis, or (ii) (2 days prior) ☐ (1 day after) genesis. The latter contingency allows a reliable estimate in a few cases where a well-defined wave did not exist more that 48 h before genesis. We are naturally reluctant to use wave properties after genesis to estimate gyre kinematics before genesis because the wave morphology and propagation begin to change when a tropical depression is born, and significantly so, once the ☐☐oey☐leaves the ☐pouch☐. ☐or this reason the phase speed estimates and uncertainty thereof were based primarily on the pre-genesis behavior of the waves.

☐yre properties such as size and orientation vary widely among the 55 cases selected for study, whereas the estimates of recirculation time occupy a much narrower range, probably because (as explained in Sect. 4.1) they are derived from dynamical information closer to the center of the gyre. It should be kept in mind that gyre size, as displayed here, is a metric of area☐e.g., the value 25 is approximately equivalent to a 5×5 array of grid points, the side of each grid box equal to $\sim$1.125°. A linear metric would reveal a narrower range, to be sure, but the range of gyre areas is impressive nonetheless (varying by a factor of 200). ☐iven that the Atlantic and eastern Pacific storms are usually modest in extent (unlike western Pacific typhoons of the tropical depression category) relative to the larger gyres observed in these two sectors, a reasonable preliminary conclusion is that, beyond a certain size, a very large gyre area is not relevant to storm development. Regarding separatrix orientation, a pronounced dearth of angles occurs near −90° (due south) – a key observation for identifying the Lagrangian ☐ow around the proto-storm and the air mass from which environmental properties have been entrained. We emphasize this point in the examples to follow.

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[18] ☐ur selection of quasi-monochromatic easterly wave cases highlights the role of incident waves in the lower, not upper, troposphere. Various ☐T phenomena such as midlatitude baroclinic waves, westward subtropical Rossby waves, and erosion of vertical shear by deep moist convection can play an important role in genesis, but are disregarded in the selection criteria which emphasize tropical waves in the LT.

□□□□□**1.** Statistics of the 55 storms during August–September 1998–2001. The left four columns show the storm names (highlighted cases in red), genesis time (□TC-day-month-year), genesis latitude (Lat) and longitude (Lon). □ther columns list the phase speed (C_p) of the easterly waves, its standard deviation (δC_p) based on 2–4 estimates, the gyre size (in terms of grid points in T106 □CMW□data), the angle of the separatrix, and recirculation time τ_1 and τ_2 (units□days) at 850 hPa and 600 hPa. (–) indicates an undefined value. The phase speed and its standard deviation are derived from the Hovmöller diagrams (see Appendix A□for details). The orientation of the separatrix is defined as the angle between the line from the gyre center to the nearest saddle point on the gyre□s bounding streamline and the east direction (90 indicates that the saddle point is due north of the gyre center, 180 indicates due west of the gyre center, and so on). The recirculation time τ_ζ is defined as

$$\tau_\zeta = 4\pi / \zeta_{max}$$

where ζ_{max} is the maximum vorticity within the gyre. The recirculation time τ_{ow} is defined as

$$\tau_{ow} = 4\pi / \sqrt{\overline{OW}}$$

where $\overline{OW}$ is the average of positive □kubo-Weiss in the regions with cyclonic vorticity within the gyre. If a gyre does not exist, ζ_{max} and $\overline{OW}$ are defined as vorticity and □kubo-Weiss at the genesis location, respectively. □or negative ζ_{max} or $\overline{OW}$, the recirculation is undefined. The gyre is based on the □6-h pre-genesis average of stream function in the co-moving frame of reference. (see Sect. 4.1 for details). Values at genesis time are substituted where the □6-h gyre does not exist (magenta). The median and one-half inter-quartile range of phase speed, gyre size and recirculation time are shown in the bottom two rows.

name	genesis time	Lat	Lon	850 hPa Cp (m/s)	dCp (m/s)	gyre size	s trix angle	t_ζ (day)	t_{ow} (day)	600 hPa Cp (m/s)	dCp (m/s)	gyre size	s trix angle	t_ζ (day)	t_{ow} (day)
□eanne	06Z 21 Sep 1998	9.6	−17.4	−4.1	1.7	□□	8	1.4	2.□	−□.5	−	6□	−2	2.1	4.0
Alberto	18Z 0□ Aug 2000	10.8	−18.0	−8.4	1.1	2□	6	6.4	9.4	−11.1	1.0	2□	18	4.7	8.5
Cindy	00Z 19 Aug 1999	1□.5	−18.9	−7.8	1.4	14	−70	5.4	8.9	−6.5	0.6	185	165	2.0	7.□
Isaac	12Z 21 Sep 2000	11.5	−2□.0	−8.7	0.9	9	54	2.4	4.4	−6.□	0.4	109	7	2.9	5.□
□ert	12Z 11 Sep 1999	12.6	−24.2	−8.5	0.6	87	56	2.4	4.4	−8.6	0.5	78	170	□0	5.4
□eorges	12Z 15 Sep 1998	9.7	−25.1	−6.2	0.2	25	55	4.□	6.8	−6.□	1.4	□9	−55	5.2	8.9
Ivan	00Z 19 Sep 1998	1□4	−26.6	−4.4	2.1	21	57	2.1	□4	−4.6	0.7	□8	−□	□0	6.□
□elix	18Z 07 Sep 2001	1□9	−28.4	−5.5	0.8	22	170	1.5	□0	−6.6	1.□	75	158	2.9	5.4
□oyce	12Z 25 Sep 2000	11.2	−29.6	−6.6	0.9	−	−	10.1	−	−6.6	0.7	−	−	1□1	1□7
□anielle	06Z 24 Aug 1998	1□4	−□4.□	−8.□	1.0	9	56	5.2	7.6	−8.5	0.4	115	98	□8	8.2
□rin	18Z 01 Sep 2001	12.5	−□4.□	−10.7	0.9	−	−	5.4	6.4	−11.1	0.5	15	1□4	4.4	6.9
Chantal	18Z 14 Sep 2001	12.8	−□7.0	−7.5	4.1	1	−5	2.6	□0	−10.2	0.65	−7	4.5	8.2	
□ebby	18Z 19 Aug 2000	12.0	−44.5	−10.0	0.6	□□	□6	□8	6.6	−9.1	0.□	120	56	4.0	7.4
□rnesto	12Z 01 Sep 2000	14.8	−45.2	−8.□	0.14	29		5.4	8.0	−6.1	−	□5	14	7.2	11.9
□loyd	18Z 07 Sep 1999	14.6	−45.6	−7.□	0.4	65	70	□□	5.□	−6.9	0.1	60	−4	□1	5.7
□onnie	12Z 19 Aug 1998	14.7	−48.1	−8.0	0.7	114	9	2.9	5.2	−8.□	0.2	79	124	□6	6.□
Chris	12Z 17 Aug 2000	14.2	−51.9	−9.1	1.1	−	−	5.9	7.8	−8.5	0.5	□	7□	4.8	7.5
Helene	12Z 15 Sep 2000	14.9	−52.2	−10.2	0.2	−	−	9.0	12.1	−8.7	0.1	1	−6□	12.2	15.6
□mily	06Z 24 Aug 1999	11.5	−5□.6	−4.□	0.1	9	□7	□2	6.7	−4.1	0.5	9	□□	□4	6.8
Humberto	12Z 21 Sep 2001	25.1	−64.2	−4.5	1.0	12	125	4.2	6.6	−□.□	0.2	□	81	5.□	7.2
□ean	12Z 22 Aug 2001	17.9	−64.□	−5.0	0.2	−	−	25.6	−	−8.4	1.6	−	−	−	−
□ennis	00Z 24 Aug 1999	21.5	−67.7	−□.7	0.9	9	−119	□.2	4.9	−4.5	1.4	15	−1□2	□.1	4.7
□lorence	18Z 10 Sep 2000	□0.9	−70.9	−1.9	0.6	4□	−1□4	2.7	4.8	−□.0	0.0	6	45	2.4	4.0
□arry	12Z 02 Aug 2001	25.7	−84.8	−2.4	0.2	5	−96	□.1	□1	−7.7	4.4	19	94	4.0	□8
□ordon	12Z 14 Sep 2000	19.8	−87.□	−2.5	1.2	7	−171	4.8	7.8	−□.8	0.0	16	−174	7.0	7.□
Hermine	12Z 17 Sep 1998	26.9	−90.□	−2.8	0.6	14	180	□0	4.2	−□.9	0.1	71	147	2.9	5.4
□uliette	06Z 21 Sep 2001	12.6	−91.1	−7.0	1.0	76	98	4.5	10.6	−7.9	0.8	78	−17□	□.□	6.7
Charley	06Z 21 Aug 1998	25.□	−92.□	−4.1	0.5	66	−□9	4.1	6.□	−6.5	1.0	10□	68	4.5	7.7
□eryl	18Z 1□ Aug 2000	22.5	−9□.5	−□.8	2.8	10	50	□7	4.6	−□.1	0.8	25	62	4.2	5.1
□arl	12Z □1 Aug 1998	21.6	−9□.5	−2.5	0.9	68	−177	1.9	□.1	−5.6	1.0	42	155	2.7	4.□
□rd	18Z 18 Aug 1999	19.5	−94.4	−	−	1	58	14.0	−	−□.□	1.0	17	−1□7	4.□	7.4
□rances	18Z 08 Sep 1998	25.5	−94.5	−5.5	−	47	151	2.9	4.6	−□.2	1.0	211	119	2.2	5.□
Ivo	12Z 10 Sep 2001	14.8	−98.9	−6.6	0.5	−	−	8.6	−	−6.9	2.2	7	162	□5	7.8
□ora	00Z 06 Aug 1999	12.1	−100.9	−2.9	0.□	22	5	1.9	□0	−4.5	1.0	6□	160	□7	8.1
Lane	00Z 05 Sep 2000	15.4	−102.2	−4.0	1.1	24	1□8	1.2	1.8	−□.□	0.5	24	155	1.6	2.6
Ileana	18Z 1□ Aug 2000	17.1	−104.0	−4.9	0.5	11	105	□2	4.7	−4.7	0.1	25	−174	1.9	□.6
□reg	12Z 05 Sep 1999	18.6	−105.1	−2.8	0.2	□5	90	1.5	2.7	−□.□	0.6	142	15□	1.9	4.4
□ilma	00Z 05 Aug 2000	15.0	−105.2	−□.7	0.8	18	157	1.9	□1	−4.1	0.7	□8	15□	1.9	□□
Hector	18Z 10 Aug 2000	17.8	−106.6	−5.1	0.□	15	105	6.5	6.8	−6.1	0.9	216	156	□4	7.7
□avier	12Z 06 Sep 1998	17.8	−106.8	−□.0	0.□	47	102	2.5	4.5	−5.0	0.4	□7	172	2.2	4.6
Hilary	06Z 17 Sep 1999	15.2	−107.1	−2.6	0.4	2□	171	1.0	1.8	−2.8	0.□	54	−11	1.8	□□
Miriam	18Z 15 Sep 2000	19.2	−107.4	−□.2	0.0	□6	85	5.0	8.0	−□.9	0.7	99	□1	□8	6.7
□lossie	06Z 26 Aug 2001	19.1	−108.5	−	−	1	157	−	14.8	−5.□	0.6	22□	66	□0	5.4
Henriette	12Z 04 Sep 2001	16.9	−108.8	−2.8	0.5	88	1□6	1.1	2.1	−4.□	1.□	20	−176	1.9	□.0
□eorgette	00Z 11 Aug 1998	11.0	−108.9	−5.8	1.4	□6	125	1.9	□6	−7.1	0.2	6	2□	□9	6.2
Isis	00Z 01Sep 1998	18.□	−109.2	−□.2	1.1	79	91	1.6	2.5	−□.9	1.6	88	−172	1.8	□.4
□rank	12Z 06 Aug 1998	16.7	−111.5	−4.2	0.□	89	82	□□	7.□	−5.8	1.6	120	164	□1	5.8
□ernanda	06Z 17 Aug 1999	12.4	−11□.1	−5.1	0.7	47	154	□1	4.5	−5.□	0.2	76	−10□	2.9	5.1
□abio	12Z 0□ Aug 2000	16.4	−11□.6	−□.7	0.5	78	65	1.5	2.8	−□.8	0.6	64	−8	1.4	2.9
□iko	18Z 21 Sep 2001	15.6	−116.1	−5.8	0.7	80	1□9	1.5	□1	−5.□	0.6	85	−20	2.1	4.0
□ugene	06Z 06 Aug 1999	12.2	−119.9	−□.5	0.4	18	97	□0	5.4	−5.8	1.2	6□	92	□□	6.6
□il	06Z 04 Sep 2001	15.4	−122.6	−□.1	0.9	41	176	2.6	5.6	−2.4	0.8	5	4	□2	□7
□risty	00Z □1 Aug 2000	1□0	−1□1.4	−□.2	1.0	25	−9	2.1	□8	−2.1	0.9	11	6	2.6	4.4
□ohn	06Z 28 Aug 2000	14.9	−1□7.4	−□.1	0.□	27	−167	1.7	□.8	−2.7	0.□	26	178	2.4	4.□
Shanshan	18Z 15 Sep 2000	15.1	−182.0	−2.8	0.□	70	−171	2.6	4.9	−5.7	2.8	16	152	□0	4.9
median		−4.4		25		□.1	4.7	−5.□		□9		□.1	5.6		
I□R/2		1.9		18		1.4	1.8	1.5		□2		0.8	1.5		

□oting a wide range of sizes at both levels, the 600 hPa gyres are systematically larger, but with a proportionately larger range. There are several examples of late-developing gyres (magenta). Allowing for inclusion of these cases to fill gaps left by the □6-h statistics, all but two of the storms have closed translating gyres at 600 hPa. This number is reduced to one (□ean) for reasons explained in Sect. □□and footnote 24. There are several storms with no apparent gyre at 850 hPa – still a small fraction of the total – which seems consistent, at least, with the tendency for gyres to be smaller at this level and therefore more vulnerable to fall below the finite horizontal resolution of the analyses. A few gyres (mostly at 850 hPa) contain only one grid point; for these cases a □×□grid box was substituted for the purpose of calculating gyre averages as described in Sect. 4.□

The time and longitude of events provides an important clue regarding the possible role of hydrodynamic instability in tropical cyclogenesis which may be expected to give birth to paired systems within a short time interval (□erreira and Schubert, 1997). There are 4 paired events in Table 1 (1 in the mid-Atlantic, □in the eastern Pacific) where both depressions were declared within 24 h, and 15 paired events where both were declared within 6 days – all such events occurring within 20° longitude of each other. Amazingly these events (whether combined or segregated by basin) can be modeled by a linear regression of longitude vs time separation with slope (phase speed) of −4.2 to −4.6 ms^{-1} and y-intercept (zonal wavelength) of 17.1 to 17.6° longitude, with extremely high R^2 values (0.88 to 0.91). □ut whereas this model seems to explain the paired systems of the eastern Pacific quite well, most of the Atlantic waves in the paired group have phase speeds about twice as fast as the model estimate. Pairing does not suffice to prove instability; it simply indicates that a wave packet had two ad□acent gyre-troughs favorable to genesis. In theoretical terms the question is whether the ITCZ supports □absolute□instability that may occur in situ without an upstream stimulus (Pierrehumbert, 1984). We cannot answer this question here. □evertheless, the observed pairing of genesis events strengthens the marsupial paradigm by showing that large-scale organization of rotating convection spans more than a single wavelength of incident waves.

All 55 wave/genesis events have been examined, and our conclusion is that in most cases (i) persistent convective precipitation occurs in a quasi-closed recirculating gyre in the co-moving frame, and (ii) the tropical storm develops near the intersection of the critical latitude and the trough axis. To illustrate our basic results, five representative storms during August 2000 were selected; the evolution of easterly waves and convection (as measured by TRMM accumulated precipitation) before TC genesis are discussed in detail for these cases.

□.□ □□□□□□i□□□□□□□□ □□g□□□□□□□ □□□□□□

Hovmöller diagrams of 2.5–9 day bandpass meridional velocity at the best-track genesis latitude for each of the five highlighted cases are shown in □ig. 4 at the 850 and 600 hPa levels. The large dot near the center of each panel indicates the longitude and time of genesis according to the best-track data, while filled squares trace the storm□s longitude subsequent to genesis, at 6-h intervals. (The latitude of the storm is not shown here; it is listed in Table 1 and shown in the maps to follow.) □ach storm originated between a negative and positive meridional velocity anomaly to the west and east, respectively, a region of anomalous cyclonic vorticity. In the first four examples, easterly waves at the two levels were aligned almost perfectly in the vertical, while in the remaining case (Shanshan) an eastward phase tilt with height can be detected. The tilt diminishes approaching genesis time as the 600 hPa wave (with approximately twice the phase speed□Table 1) catches up with the 850 hPa wave. In such cases an improving vertical alignment of the wave is part of the pre-genesis sequence. Characteristic of these examples and almost all of the events in Table 1 is that easterly wave anomalies (i) are present prior to genesis time, (ii) are reasonably monochromatic for at least the two preceding days, and (iii) become well aligned vertically in the lower troposphere below 500 hPa before genesis occurs. The fact that wave anomalies appear vertically aligned does not imply, however, that the □ow kinematics are identical at 850 and 650 hPa, as will be evident in some of the cases highlighted.

□f the ten panels shown in □ig. 4, only the first two display a reasonably uniform pattern of wave amplitude and zonal phase propagation across the entire longitude range and time period spanned by the figure. It turns out that pictures like □ig. 4a, b are the exception and not the rule. Most often we find one or more of the following in the Hovmöller plots of meridional velocity anomaly□(i) a group of wave phases originating to the west (east) of the genesis location, followed by eastward (westward) apparent group propagation across the diagram (the eastward scenario is preferred and nicely illustrated in □abio and Shanshan); (ii) abrupt amplification of the wave packet near the genesis point (as in □eryl); (iii) diminution of wave amplitude towards the end of the storm track (in all panels except Shanshan 850 hPa) and (iv) a pronounced wave packet in the upper right quadrant of the Hovmöller diagram (in all cases highlighted) indicating either that the incident wave is maintained for a time by diabatic processes operating within the proto-vortex (note that the vortex remains in the trough of the wave for a few days in each of the examples shown) or that new waves are excited by the vortex as it develops into a full-□edged tropical storm, and these waves subsequently propagate as a group to the east. In order to understand the last feature it proves necessary to examine the wave/vortex structure in four dimensions. Most aspects of the subsequent □wave radiation□ – if this is the correct way to think of it – are not relevant to
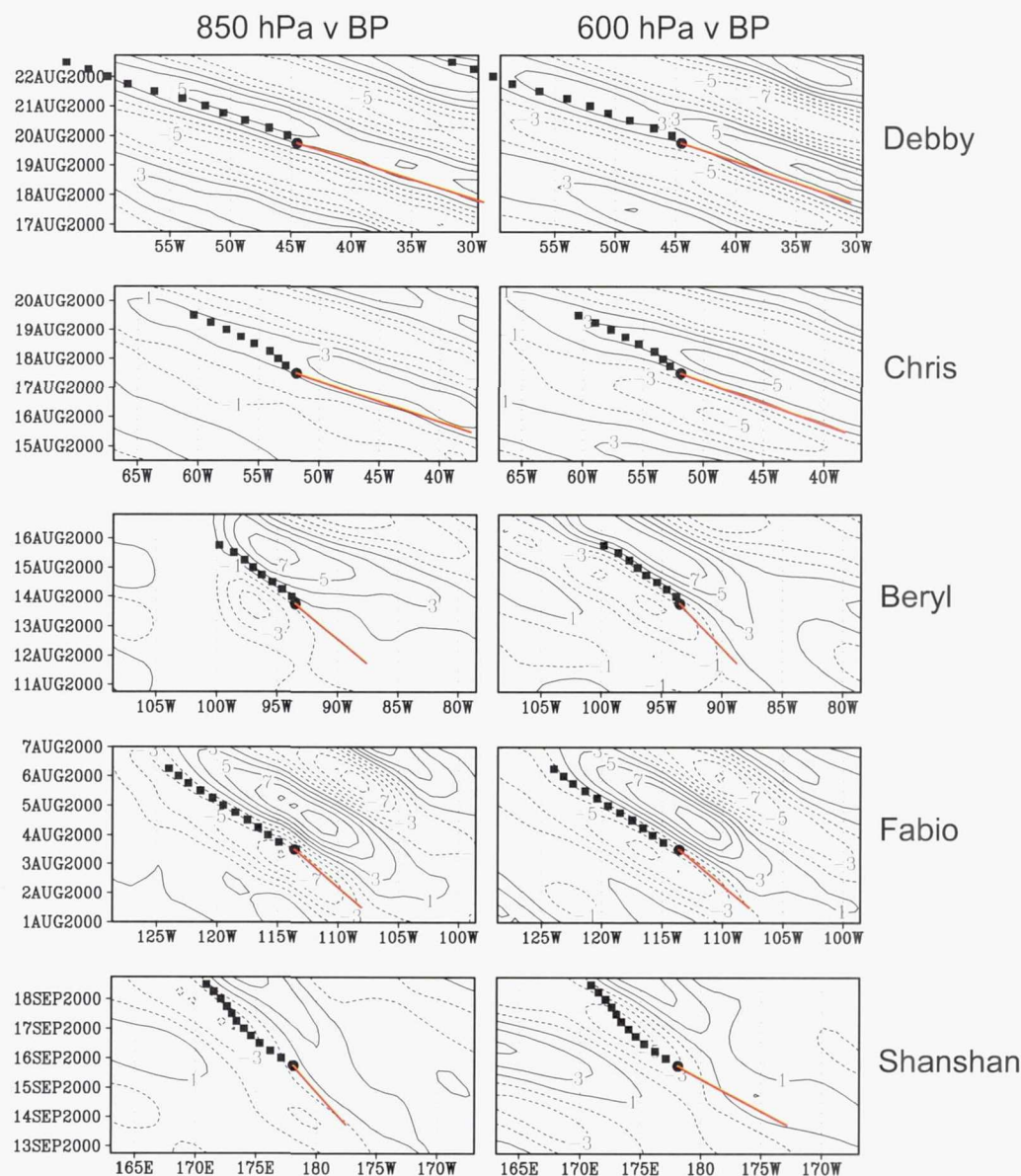
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850 hPa v BP   600 hPa v BP

Fig. ⬚ Hovmöller plots of band-pass meridional velocity component at 850 hPa (left column) and 600 hPa (right column) in a longitude-time plane for the five cases of summer 2000 highlighted in the text⬚⬚ ⬚Hurricane ⬚ebby; ⬚⬚⬚Tropical Storm Chris; ⬚⬚⬚Tropical Storm ⬚eryl; ⬚⬚⬚Tropical Storm ⬚abio; ⬚⬚⬚Super Typhoon Shanshan. ⬚lack circles indicate the best-track longitude and time of genesis, while black squares indicate subsequent best track locations at 6-h intervals. Red line denotes the Hovmöller estimate of zonal translation speed C_p.

genesis and will be discussed elsewhere. ⬚n the other hand, the transition of wave structure from equivalent barotropic in the LT to a deep quadrupole[19] or ⬚first baroclinic mode⬚pattern spanning the depth of the troposphere in the longitude-height plane (along the genesis latitude, at nearby longitudes)

represents a key signature of genesis process insofar as this structural transition indicates deep convective mass transport coupled to the incident wave and generally precedes the best-track genesis time by a day or more. This transition will be discussed further in Sect. 4.⬚ A first baroclinic mode structure was found to be dominant in the western Pacific during boreal summer (⬚unkerton, 199⬚) and probably characterizes the tropical depression disturbances that populate this region. It is noteworthy that a similar structure appears in basins marginal for development (e.g., Atlantic and eastern

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[19]A quadrupole structure describes the appearance of meridional velocity anomalies in a longitude-height plane intersecting the vertical axis through a developing storm, with cyclonic (anticyclonic) ⬚ow at lower (upper) levels.

Pacific) □ust prior to TC genesis. The quadrupole pattern is apparently responsible for the subsequent radiation of a Rossby-like wave which, to our knowledge, has not been discussed previously in the literature but may have important consequences for the □T/LS.

A monochromatic wave, with discrete ground-based frequency and zonal wavenumber, would necessarily look like □ig. 4a, b... from which it is obvious that most incident waves are *not* perfectly monochromatic and therefore contain a modest spread of wavenumbers and frequencies in spectral space. The zonal-wavenumber bandwidth (Δk) of incident waves can be estimated from Heisenberg□s □ncertainty Principle $\Delta k \Delta x \sim 2\pi$ or equivalently $\Delta k / k \sim 1/N$ where N is the number of full cycles observed in the wave packet in the x-direction. A similar estimate applies to frequency bandwidth using the number of full cycles in the t direction. □udging from □ig. 4 one might infer a typical value $N \sim 1 - □$. □asterly waves, like most tropical waves, are local and episodic in physical space (□unkerton, 1991). The term □intermittency□ (Mandelbrot, 1974) has been used in recent years to describe (i) waves that come and go, having peak quadratic □uxes (of momentum, heat or constituents) much larger than their time-averaged value (Alexander and □unkerton, 1999); or (ii) turbulence that is inhomogeneous in space or time, containing coherent structures that disrupt the self-similar character of the inertial subrange (□risch, 1996). As noted in the Introduction, we believe it is necessary to invoke wave and turbulence concepts in order to understand tropical cyclogenesis. In the real world, nonetheless, there is usually a natural order to genesis such that *waves precede turbulence* in a logical and chronological sense. Since we are considering many wave/vortex events as individual events, not as part of a time-averaged spectrum of geophysical turbulence, it would be better to say that □waves precede vortices.□ □ne could then regard the proto-vortex and resulting storm as a coherent structure arising from the wave and interacting with it for a time before acquiring a separate life of its own. The typical sequence of events will become evident in the examples highlighted.

□.□.1 □□□□□□ □□□□i□□□□□i□□□□ □□□□

The sloping lines in □ig. 4 represent the mean phase speed derived from the linear regressions of the southerly (solid lines) and northerly (dashed lines) meridional wind anomalies, as described in Appendix A□ The Hovmöller diagrams for □ebby, shown in □ig. 4a, b, suggest that the wave has an equivalent barotropic structure in the lower troposphere, as noted in the preceding discussion; the difference of the phase speeds at 850 hPa and 600 hPa is less than 1 ms^{-1}. The similarity of phase speeds is consistent with the barotropic structure evident over the entire diagram.

□igures 5 and 6 show the relative vorticity (representing time scales longer than $\sim$2.5 days) at the 850 and 600 hPa levels at 6 h intervals, before the genesis of □ebby, from

12□00 Z 18 August to 18□00 Z 19 August 2000. As discussed in Sect. 2, the Lagrangian mean □ow in the critical layer is zero in a frame of reference moving at the phase speed of the wave (□ig. 1). Alternatively, the streamlines of a steady vortex are advected by the basic □ow (□ig. □). To illustrate motions relative to the wave and its associated proto-vortex, the streamlines of 2.5-day low pass □ow in a □wave-centric□ co-moving frame of reference are also shown.

At 850 hPa, the best-track genesis location for □ebby coincides almost perfectly with the center of a closed gyre in the co-moving frame. The thick curve passing through the center of the gyre denotes the isopleth of zero zonal velocity in the co-moving frame. Along this curve the translating streamlines are oriented meridionally by definition. The thick curve is bracketed by two ad□acent curves representing the uncertainty in our phase speed estimate. Ad□acent to the center of the gyre, approximately 800 km to the □□□, is a saddle point or □hyperbolic point□ of the translating streamlines. A dividing streamline intersecting the saddle point can be imagined to surround the genesis point, spanning a distance of about 700 km north to south. Streamlines passing near the saddle point are shown in red. □wing to a small but nonzero divergent component of horizontal motion, the dividing streamline is not exactly closed, but converges towards the center of the gyre in the latter part of the sequence. Significant cyclonic vorticity exists not only within the closed gyre but in a wider area to the south. This additional region of vorticity is less associated with the gyre (as curvature vorticity) than with the □et itself (as shear vorticity). We return to this point in the next example when discussing an alternative measure of vortical □ow, the so-called □kubo-Weiss parameter.

At 600 hPa, the best-track genesis location likewise coincides with the center of a closed gyre which is much larger in horizontal extent than the gyre at 850 hPa. □nce again the principal saddle point is located about 800 km to the east. A secondary saddle point is seen at both levels about 1400 km to the □W. Three gyres arrayed along an approximately zonal axis from W□W to □S□ can be imagined to comprise a series of cat□s eyes along the critical latitude for this wave. Strictly speaking, the thick curve in both figures denotes the effective center of the critical layer, not the critical latitude of the wave itself. Supposing that a mean □ow as seen by the wave should be represented by a modified low-pass filter (periods >9 days) excluding the period of the wave itself (□–4 days), we find that a critical latitude – defined as the locus of points where this low-frequency zonal wind matches the zonal phase speed of the wave – again intersects each of the gyres arrayed zonally in □igs. 5 and 6 (last panel of each). In other words, the critical layer has formed more or less at the critical latitude of the incident wave, as expected from linear theory. This is useful knowledge for wave dynamics but we caution that what actually matters for mesoscale developments is the critical layer with its □elvin cat□s eye, and their subsequent role in TC genesis.
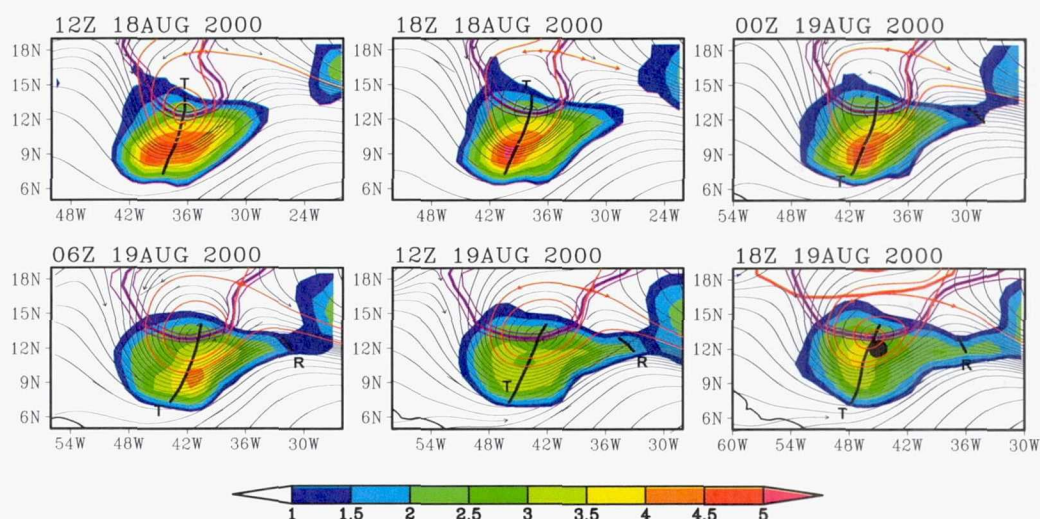
Debby: Zeta (2.5-day LP)

Fig. 5. Streamlines of horizontal (rotational + divergent) flow at 850 hPa, as seen in ERA-40 data, for six consecutive analyses leading up to the best-track genesis time of Hurricane Debby (2000). Shading indicates relative vorticity (units: $10^{-5}\,\mathrm{s}^{-1}$). The sequence of frames translates westward at the zonal propagation speed of the parent wave at 850 hPa as estimated from the Hovmöller method ($-10.0\pm0.6\,\mathrm{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame; note that relative vorticity itself is invariant with respect to the translation. Isopleths of zero relative zonal flow are shown (purple) together with their uncertainty. In the final panel of the sequence the critical latitude of the parent wave is also indicated (red) corresponding to isopleths of zero relative zonal flow in low-frequency data with periods longer than 9 days. The wave's trough axis is shown for reference (black). The genesis location is indicated by the black dot in the final panel.

Debby: Zeta (2.5-day LP)
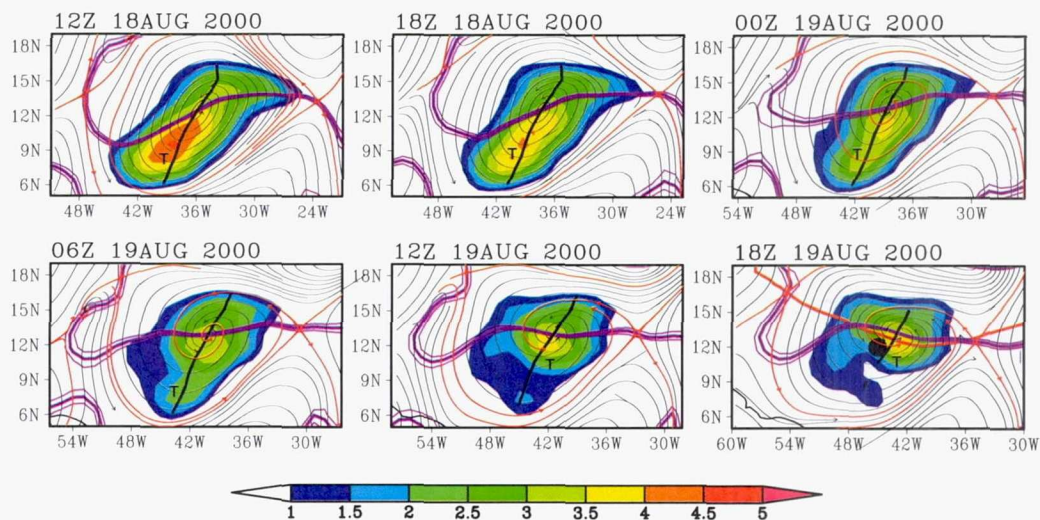
Fig. 6. Streamlines of horizontal flow for the genesis sequence of Hurricane Debby as in Fig. 5, but at 600 hPa. Shading indicates relative vorticity (units: $10^{-5}\,\mathrm{s}^{-1}$). The sequence of frames translates westward at the zonal propagation speed of the parent wave at 600 hPa ($-9.1\pm0.8\,\mathrm{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.

The importance of the co-moving frame and its specification of gauge for flow potentials (Appendix A6) becomes clear when comparing the translating streamlines to those of a resting frame. Figures 7a, b illustrate the latter at genesis time only. At 850 hPa there is a closed gyre with principal saddle point misplaced to the SW of the genesis point by

Debby: Zeta (2.5-day LP, resting)
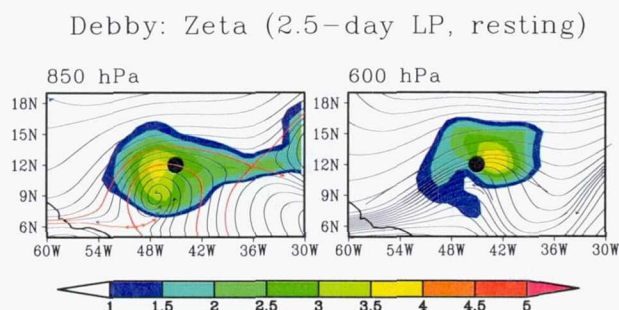
Fig. ▢ Streamlines of horizontal ▢ow at ▢ ▢850 hPa and ▢▢600 hPa at the genesis time of Hurricane ▢ebby, in the *resting* frame. Shading indicates relative vorticity (units▢ 10^{-5} s^{-1}) which is invariant with respect to translation, therefore identical in co-moving and resting frames (cp. final panels of ▢igs. 5, 6).

about 700 km. This pattern seems to have little relation to the distribution of vorticity, even though the choice of gauge in this instance (zero everywhere) is – like any other choice – completely consistent with the vorticity itself. In the ▢arth-relative frame a substantial part of the motion exists simply to translate the vorticity pattern westward without changing its shape, thereby obscuring the distributive effect of motions within the critical layer. In the translating frame streamlines and isopleths of vorticity are approximately parallel while curving around the southern boundary of the gyre (not unlike the ideal nonlinear critical layer of ▢ig. 1). At 600 hPa in the resting frame there is no closed gyre at all. Although we do not claim that the choice of translation speed and resulting streamlines in ▢igs. 5, 6 provide an exact picture of the ▢ow kinematics in this case, the translating frame is clearly superior to the resting frame from a vorticity advection point of view[20]. The near perfect coincidence of a closed gyre in the translating frame with the actual location of TC genesis is also striking. In the resting frame they are far apart. ▢ebby is by no means unique in this respect. We find an actual or probable closed gyre in the translating frame surrounding the genesis point in almost all of the cases in Table 1 (see Sect. ▢▢). ▢ote that an optimum overlap of streamlines and vorticity isopleths maximizes ▢elvin▢s circulation around the translating gyre as calculated along the bounding streamline.

Streamlines in the co-moving frame plausibly explain the distribution of moisture in the free troposphere above the

boundary layer (as represented by the saturation fraction[21] averaged from the surface to 500 hPa, shown in ▢ig. 8) and of deep moist convection (as represented by the TRMM ▢-hourly accumulated precipitation, shown in ▢ig. 9). Their role is ▢plausible▢in the sense that moisture and persistent deep moist convection are located within the translating gyre; a specific role for entrainment of moisture into the developing gyre is less certain (in this case, at least). It is clear from the evolution of saturation fraction that horizontal advection alone cannot explain its distribution. While advection might account, in part, for the wrapping of moist air around the northern side of the gyre, and its transport eastward out of the domain, the entire moistened area in the southern half of the gyre creeps steadily westward against the prevailing ▢ow (with the wave) as if to suggest that the precipitation cells in this region (▢ig. 9) are supplying moisture to the gyre. A symbiotic relation between convective moistening and closed gyre circulation evidently exists in this sequence. Convection moistens the free troposphere, the moisture is subsequently contained by the gyre, which favors further deep convection in the gyre. Seeing how some of this moisture is able to escape to the east, we regard the closed circulation as critically important to depression development to the same extent that moist thermodynamic processes are important in the gyre. Progressive saturation of the column (in a single-column point of view) is arguably important to genesis (Raymond and Sessions, 2007; ▢manuel, 2007). ▢ur description of the approximately two-dimensional, equivalent barotropic ▢ow kinematics and dynamics in the co-moving frame adds a critical (no pun intended) dimension to the single-column model (SCM) viewpoint while preserving the essential element of deep convective moistening and its consequences. Without the quasi-2-▢ kinematics and dynamics, the SCM viewpoint has no context within which to explain tropical cyclogenesis.

▢.▢.▢ ▢ ▢ ▢▢▢i▢▢▢▢i▢▢▢▢▢ F▢▢i▢

The evolution of vorticity and translating streamlines in the development of ▢abio is shown in ▢ig. 10 at 850 hPa, while ▢ig. 11 shows the corresponding pattern at 600 hPa. In the latter, an alternative measure of vortical ▢ow is provided by the ▢kubo-Weiss parameter[22]

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[20] ▢or nondivergent barotropic ▢ow the horizontal advection of vertical vorticity is described by the ▢acobian of stream function and its Laplacian (all quantities and operators defined in a horizontal plane); translation of the coordinate system with the wave minimizes this quantity by eliminating unsteadiness due to wave propagation. Vorticity advection as viewed in the resting frame primarily causes the pattern to propagate in the direction of the wave. It is desirable to eliminate (via translation) this dominant contribution to the tendency in order to expose more clearly the evolution of the synoptic ▢ow pattern and mesoscale features embedded therein.

[21] Saturation fraction represents how much water vapor is in the column relative to the maximum that the column might hold, given the observed temperature as a function of pressure (Raymond et al., 2006). A similar quantity was defined by ▢retherton et al. (2004). It is equivalent to the vertical integral of relative humidity weighted by saturation mixing ratio.

[22] In geosciences the ▢kubo-Weiss parameter is used frequently in physical oceanography and two-dimensional turbulence; a few atmospheric applications have been reported (Lukovich and Shepherd, 2005; Rozoff et al., 2006). An improved definition of the parameter for transient ▢ow was developed by Patrice ▢lein and co-workers (Lapeyre, 2000).
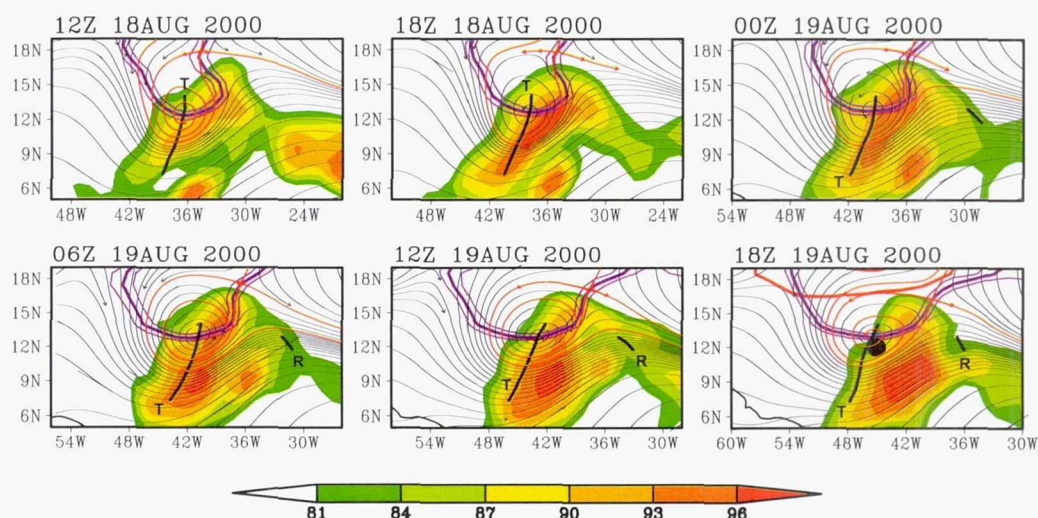
Debby: SF (2.5−day LP)

Fig. ☐ Streamlines of horizontal ☐ow at 850 hPa for the genesis sequence of Hurricane ☐ebby as in ☐ig. 5, with high values of ☐RA-40 saturation fraction indicated by shading (units☐percent). The sequence of frames translates westward at the zonal propagation speed of the parent wave at 850 hPa ($-10.0\pm0.6\,\mathrm{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.
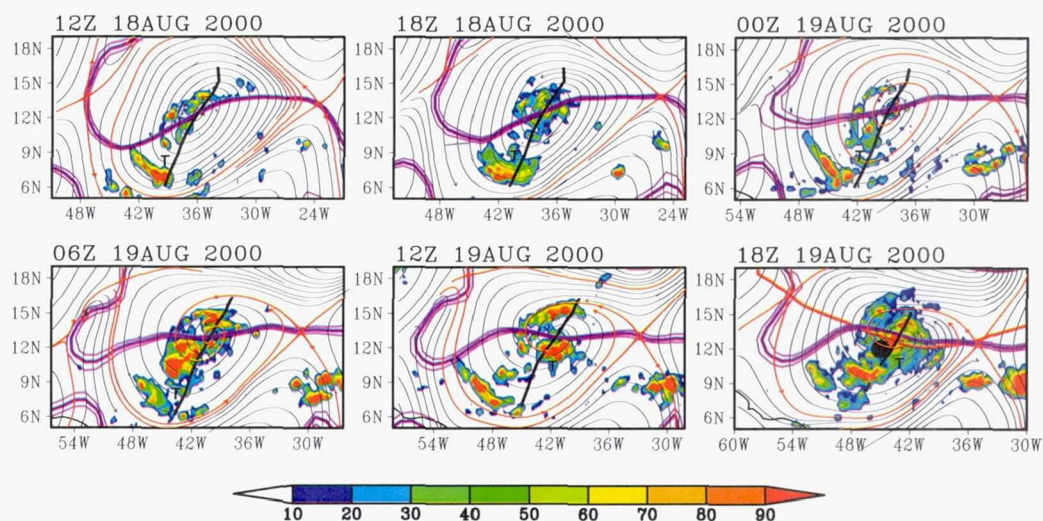
Debby: TRMM (2.5−day LP)

Fig. ☐ Streamlines of horizontal ☐ow at 600 hPa for the genesis sequence of Hurricane ☐ebby as in ☐ig. 6, with high values of TRMM ☐+h accumulated precipitation indicated by shading (units☐mm/day). The sequence of frames translates westward at the zonal propagation speed of the parent wave at 600 hPa ($-9.1\pm0.☐\mathrm{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.

$$O\,W = \varsigma^2 - S_1^2 - S_2^2 = (V_x - U_y)^2 - (U_x - V_y)^2 - (V_x + U_y)^2 \quad (1)$$

Patterns of saturation fraction, precipitation and vertical shear in the lower and upper troposphere for this event are shown in ☐igs. 12–15, respectively. At both levels, closed streamlines formed near the intersection of the critical latitude and the trough axis, delineating a critical layer of fi-nite width. Strong cyclonic/rotational vorticity, high satura-tion fraction and weak vertical shear coincide simultaneously within the critical layer and provide a favorable sub-synoptic scale environment for tropical storm formation. TRMM data suggests that convective activity is present near the critical latitude ☐0 h before genesis was declared by the forecast-ers. ☐ear the critical latitude the convective activity becomes

Fabio: Zeta (2.5−day LP)
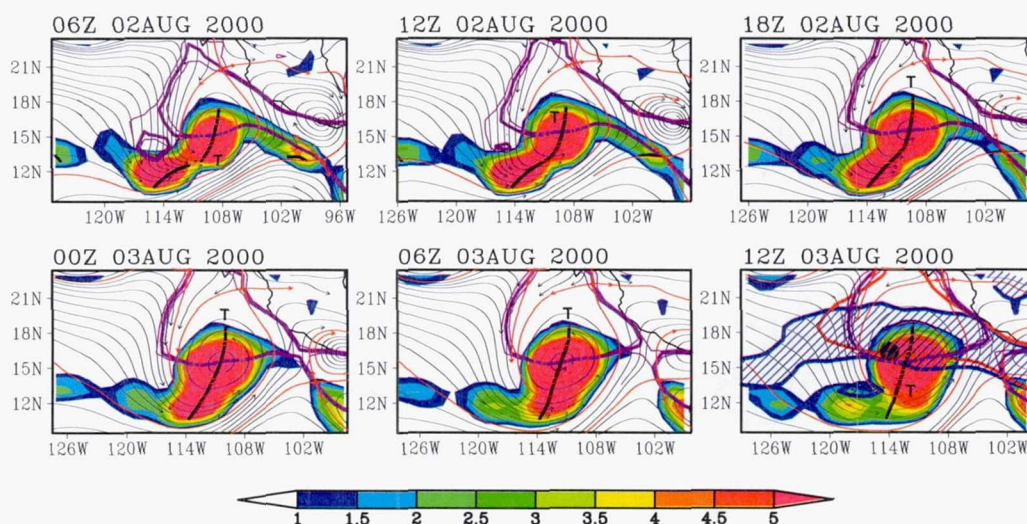
Fig. 10. Streamlines of horizontal (rotational + divergent) flow at 850 hPa, as seen in ERA-40 data, for six consecutive analyses leading up to the best-track genesis time of Tropical Storm Fabio (2000). Shading indicates relative vorticity (units: 10^{-5} s^{-1}). The sequence of frames translates westward at the zonal propagation speed of the parent wave at 850 hPa as estimated from the Hovmöller method (-9.7 ± 0.5 m s^{-1}) and streamlines are calculated and displayed in the co-moving frame; note that relative vorticity itself is invariant with respect to the translation. Isopleths of zero relative zonal flow are shown (purple) together with their uncertainty. In the final panel of the sequence the critical latitude of the parent wave is also indicated (red) corresponding to isopleths of zero relative zonal flow in low-frequency data with periods longer than 9 days. These data were also used to estimate the zero contour of absolute vorticity gradient or "effective β" (blue). This quantity is negative in the zone just north of the genesis latitude, bracketed by the blue curves (diagonal hatching). The wave's trough axis is shown for reference (black). The genesis location is indicated by the black dot in the final panel.

Fabio: OW (2.5−day LP)
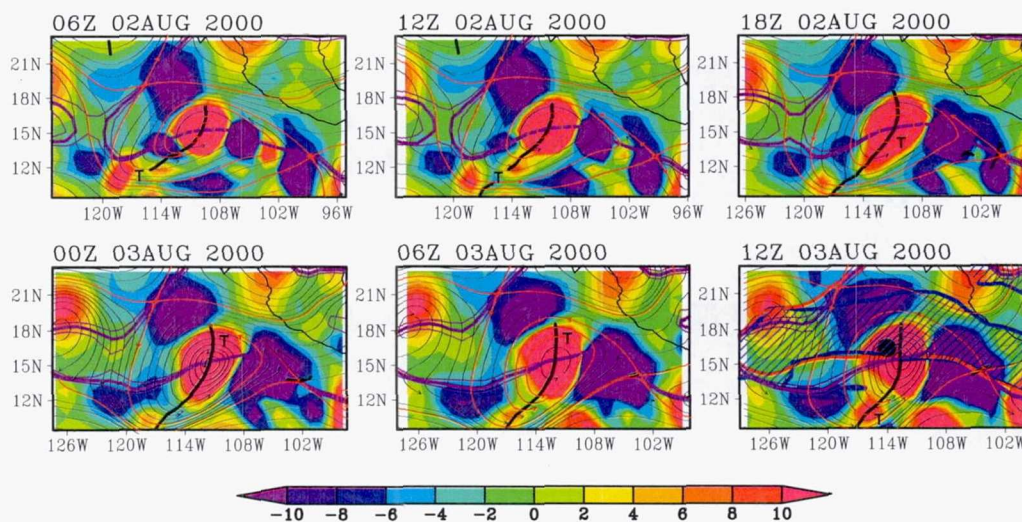
Fig. 11. Stream function of horizontal flow for the genesis sequence of Tropical Storm Fabio as in Fig. 10, but at 600 hPa. Shading indicates the Okubo-Weiss parameter (units: 10^{-10} s^{-2}) as defined in Eq. (2). This quantity, like vorticity, is invariant with respect to translation, therefore identical in co-moving and resting frames. The sequence of frames translates westward at the zonal propagation speed of the parent wave at 600 hPa (-9.1 ± 0.8 m s^{-1}) and stream function is calculated and displayed in the co-moving frame. Red and blue lines in the final panel show the wave's critical latitude and isopleth of zero effective β as estimated from low-frequency data with periods longer than 9 days.
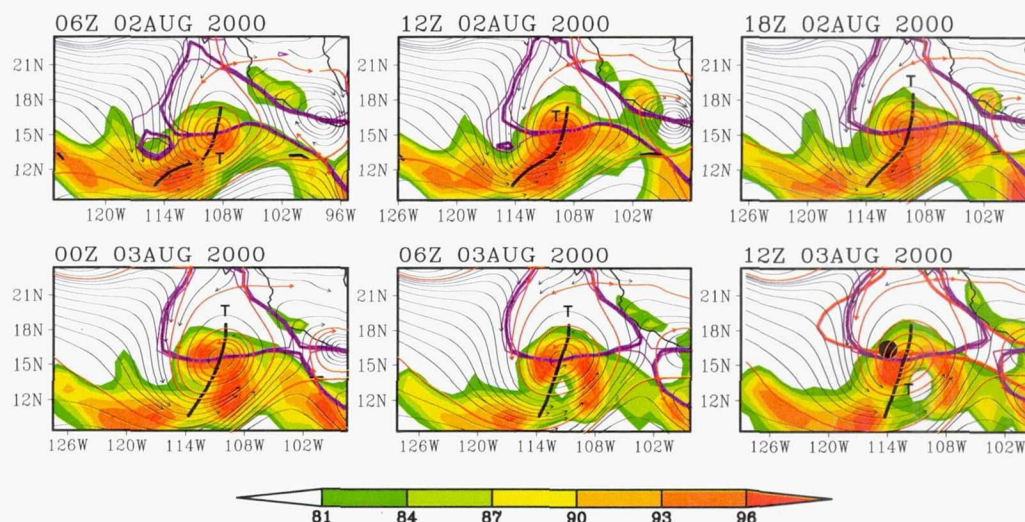
Fabio: SF (2.5−day LP)

Fig. 1☐ Streamlines of horizontal ☐ow at 850 hPa for the genesis sequence of Tropical Storm ☐abio as in ☐ig. 10, with high values of ☐RA-40 saturation fraction indicated by shading (units☐percent).The sequence of frames translates westward at the zonal propagation speed of the parent wave at 850 hPa ($-$☐.7±0.5 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame.
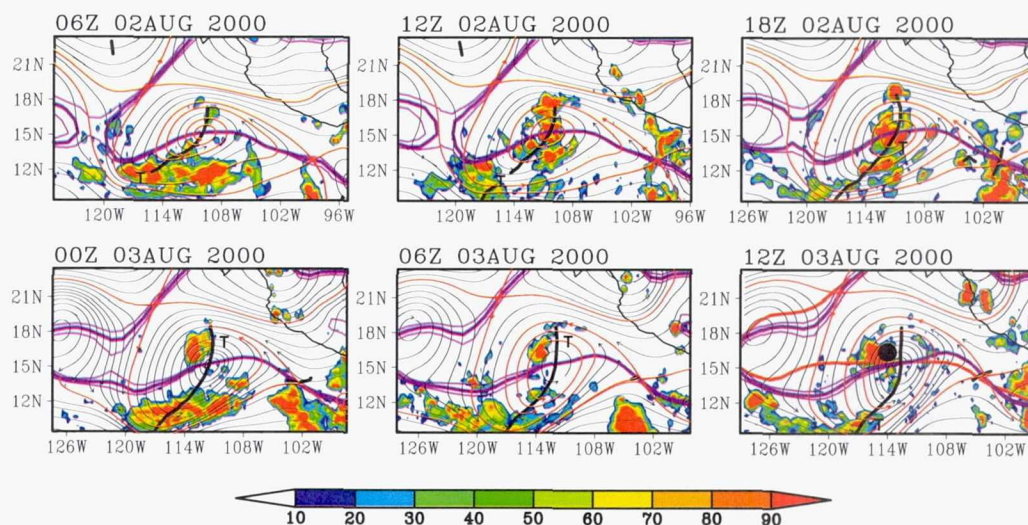
Fabio: TRMM (2.5−day LP)

Fig. 1☐ Streamlines of horizontal ☐ow at 600 hPa for the genesis sequence of Tropical Storm ☐abio as in ☐ig. 11, with high values of TRMM ☐-haccumulated precipitation indicated by shading (units☐mm/day). The sequence of frames translates westward at the zonal propagation speed of the parent wave at 600 hPa ($-$☐.↓±0.8 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame.

sustained, and more focused, while the convective activity away from the local critical latitude dies out. It is striking that genesis eventually occurs very close to the intersection of the trough axis and the critical latitude (as true for the other cases highlighted). Also striking is that the eventual location of TC genesis lies ☐ust within a wet zone delineated by a strong north-south gradient of moisture, as depicted by the color shading in ☐ig. 12. This configuration is expected in cases where genesis occurs poleward of, but close to, the ITCZ. ☐xpansion of the closed gyre during the pre-genesis sequence exaggerates the weak undulation of moisture ribbon that was present at the start. With a fully developed

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hurricane nearby, the amplified pattern indicates a severe deformation or demise of the original ITCZ (Dunkerton, 2006) although this is not yet apparent in the final panel of Fig. 12. By this time, however, deep convection has become notably absent in the diffluent region (lower right corner) in the final panel of Fig. 1 . Farther east, deep convection has become invigorated in a second closed gyre.

The genesis of Fabio, over the eastern Pacific, may be more closely related to the ITCZ than the other storms highlighted thus far in the sense that cyclonic vorticity, convection and high humidity all have a zonally elongated pattern prior to genesis. The actual storm, however, is located north of the ITCZ, and is associated with a break in the zonally elongated pattern. As noted by Dunkerton (2006), it is common for tropical storms to displace poleward or to obliterate the ambient ITCZ. The role of the ITCZ in such cases is not obvious. Although hydrodynamic instability yields a similar outcome, as instabilities become nonlinear and detached from their source (viz., an unstable strip of PV along the original ITCZ: see, e.g., Fig. 5 of Wang and Magnusdottir, 2005) it is plausible that neutral easterly waves propagating parallel to the ITCZ have a similar effect in cases where genesis ensues. In Fabio, the easterly wave exists ahead of time (as shown by the Hovmöller plots) and the original critical latitude and isopleth of zero PV gradient (blue curve) were nearly coincident. It appears that the wave prior to genesis was nearly neutral (according to the Rayleigh criterion) or at most, marginally unstable[25].

A final point is that the best-track genesis location does not coincide with the minimum vertical shear as measured by either of our two metrics (lower to mid- or upper troposphere, as shown in Figs. 14–15, respectively). It is clear from this case and others, and from our modeling study, that the horizontal distribution of vertical shear is not the deciding factor in where a storm will form. As will be shown later, shears of this magnitude do not prevent development, so it is not surprising that Fabio's origin does not coincide with the location of minimum shear. Of more importance is that vertical shears in the neighborhood of the genesis point are not extremely large (much greater than $10\,\mathrm{ms}^{-1}$). It should be noted that vertical shear over the depth of the troposphere is influenced by deep moist convection and unrelated synoptic activity in the UT, as discussed in Sect. 4, not by easterly waves alone.

Maps for the three additional highlighted cases are described in Appendix B: Chris (noted for early detection of closed streamlines in the co-moving frame prior to genesis), Beryl (noted for interaction of easterly wave and frontal boundary) and Shanshan (noted for its evolving vertical wave phase tilt).

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[25] The marsupial paradigm embraces the hydrodynamically unstable pathway insofar as the critical layer (relevant to TC formation) is an essential part of the synoptic-scale instability itself, as noted above.

6.2 Summary and hypothesis 1 revisited

Our diagnoses of the 55 named storms in Table 1 and the five cases highlighted herein support the hypotheses (H1–H2) that the critical layer containing the surface low of the parent wave, and Kelvin cat's eye within, is a preferred region or sweet spot for TC genesis. The intersection of (east-west) critical latitude and (north-south) wave trough corresponds to the center of the Kelvin cat's eye of nonlinear critical layer theory (Fig. 1). Such features correspond to regions of closed Lagrangian circulation which, on the southern side of the A-B axis, have cyclonic vorticity and abundant moisture.

An obvious closed gyre in ERA-40 data is found at 600 hPa in the translating frame within −0 h prior to genesis in 53 of the 55 cases; in one of the remaining cases (Boyce) the gyre is probable and in another (Dean) possible[26]. At 850 hPa the statistics are almost as good: 50 of 55 are obvious, 1 probable, 3 possible, and 1 unlikely. A closed gyre implies one or more saddle points in the vicinity. Inspection of the 55 selected cases reveals a remarkable result that, whereas this point is usually located to the south of the gyre center in the resting frame, it is almost never located directly to the south in the co-moving frame (Table 1). Meteorological charts displaying Earth-relative streamlines are a standard tool in the forecasting industry, but generally provide a misleading picture of actual flow kinematics, or Lagrangian displacement of air, in propagating tropical waves. These maps typically display an upright omega pattern in the lower troposphere straddling the wave's trough axis. In fact the omega pattern is often upside-down in the translating frame, with separatrix orientation to the north. In other cases, the separatrix is oriented to the east or west (or both). To the extent that horizontal advection explains the topology of streamlines, and therefore indicates where air in the closed gyre has detached from, it is firmly established in our 55 cases that air at 600 hPa is not derived from or being exchanged (by resolvable motions) with distant points to the south. For the most part, this is also true at 850 hPa. Rather, it is coming from (or previously associated with) air to the east, north or west of the gyre center. This result is probably the most important take-home message for operational purposes and weather briefings.

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[26] In Boyce, the estimate of zonal translation speed in Table 1 is exaggerated owing to a northward component of wave propagation that is not accounted for by this analysis; a closed gyre at 850 hPa is found at slower translation speed (−4 to $-5\,\mathrm{ms}^{-1}$; not shown). In Dean, storm formation occurred at the separatrix of a cutoff anticyclone on the SW side of the Bermuda High, a narrow trough whose kinematic features are partially attenuated by the ERA-40 reanalysis and possibly by our 2.5-day low-pass filter. A northward component of propagation is evident in this event also. All of these challenges (and others not mentioned) make the identification of Lagrangian boundaries more difficult in such cases.

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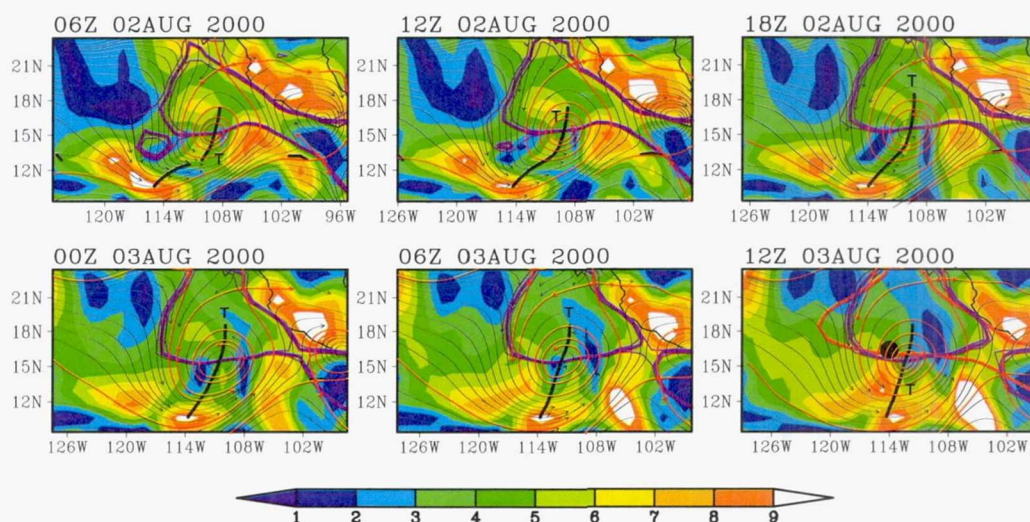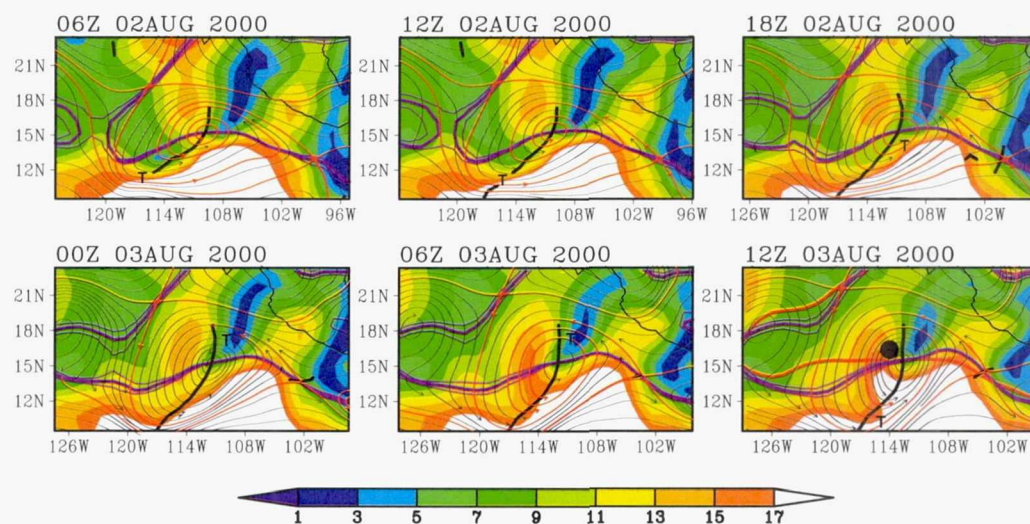
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Fabio: UV500−UV850 (2.5−day LP)

Fig. 1⬚ Streamlines of horizontal ⬚ow at 850 hPa for the genesis sequence of Tropical Storm ⬚abio as in ⬚ig. 10, with ⬚RA-40 850–500 hPa vertical shear (magnitude of shear vector, units⬚ms⁻¹) indicated by shading. The sequence of frames translates westward at the zonal propagation speed of the parent wave at 850 hPa ($-⬚.7±0.5\,\text{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.

Fabio: UV200−UV850 (2.5−day LP)

Fig. 1⬚ Streamlines of horizontal ⬚ow at 600 hPa for the genesis sequence of Tropical Storm ⬚abio as in ⬚ig. 11, with ⬚RA-40 850–200 hPa vertical shear (magnitude of shear vector, units⬚ms⁻¹) indicated by shading. The sequence of frames translates westward at the zonal propagation speed of the parent wave at 600 hPa ($-⬚.⬚±0.8\,\text{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.

⬚sing the concept of ⬚translating closed gyre⬚the statistical properties of dynamical fields (e.g., vorticity, ⬚kubo-Weiss parameter and vertical shears) and thermodynamical fields (e.g., saturation fraction, deep convective precipitation) relevant to TC genesis can be evaluated within the observed gyres – fields that were illustrated for representative cases in the preceding figures. Rather than display these statistics in obscure tabular form, we summarize the results pictorially in ⬚igs. 16–17 for the 850 and 600 hPa levels, respectively. We focus here on the simplest of all statistics⬚the mean. Various spatio-temporal averages were constructed by selecting from two choices of spatial average (horizontal expanse of
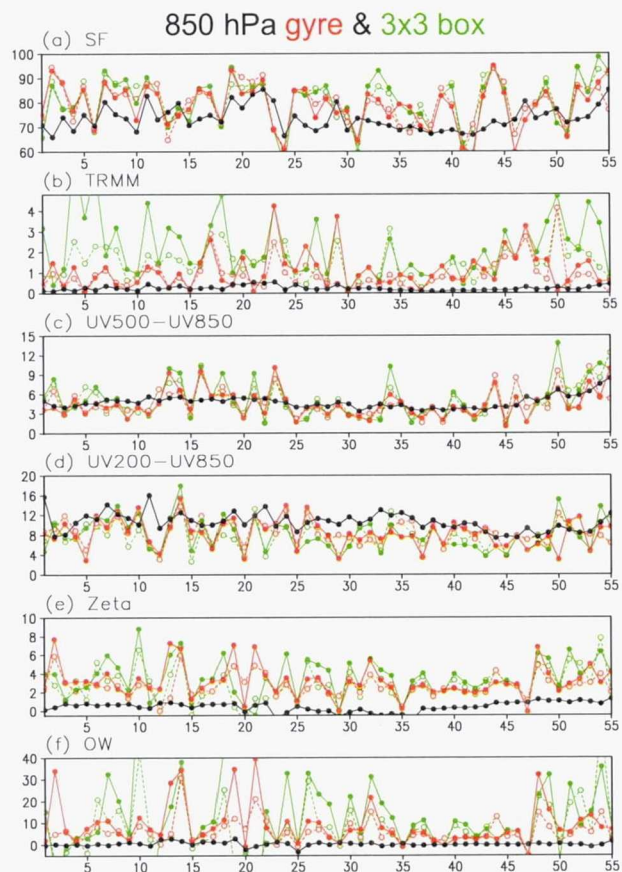
Fig. 1 Spatio-temporal average of dynamical and thermodynamical fields in the neighborhood of the best-track genesis location and time immediately preceding. The storms are arrayed west to east, from left to right, in the reverse of Table 1. The *spatial average* corresponds either to that of (i) the translating gyre (red) or (ii) a × matrix of RA-40 grid points surrounding the point $x(t) = x_0 - C_p \cdot (t - t_0)$ where x is longitude, t is time, C_p is the speed of translation and the subscript 0 refers to the location and time of genesis (green). The *temporal average* corresponds either to (i) the genesis time (single analysis, filled circles) or (ii) the 6-h interval preceding and slightly overlapping genesis time (average of six consecutive 6-hourly analyses ending at genesis time, open circles). lack circles denote climatological values for August–September 1998–2001 at the various gyre or grid box locations. The data shown in the figure were derived using gyre properties and translation speeds at 850 hPa   saturation fraction averaged from 1000–500 hPa (units percent),   TRMM deep convective precipitation (units mm/day),   vertical shear from lower to mid-troposphere (850 to 500 hPa, units ms^{-1}),   vertical shear from lower to upper troposphere (850 to 200 hPa, units ms^{-1}),   relative vorticity at 850 hPa (units 10^{-5} s^{-1}),   kubo-Weiss parameter at 850 hPa (units 10^{-10} s^{-2}). Please refer to footnote 25 for important information regarding the climatology of vertical shear and kubo-Weiss.

the translating gyre versus a × matrix of RA-40 grid points moving at the wave phase speed and ending at the genesis location) and two choices of temporal average (genesis time versus a 6-h average preceding and slightly overlapping genesis time). To put these average values in context, they are compared to climatological values defined simply as the August-September 1998–2001 average at the location of each gyre or × array. The climatological values are independent of time by definition, but depend on spatial position; the variety of observed gyres effectively samples the climatology in many different ways, depending on gyre location and extent, and optimum translation speed C_p. It is important to note that what distinguishes this analysis from all previously published studies of the genesis environment is that we include in our menu of averaging operators a *zonal translation* of the array of selected points; that is, a spatial array that is a function of *time*, owing to wave propagation.

Space precludes a detailed discussion of each storm. Apart from a small number of oddballs, the message is clear the observed storms formed in relatively moist, precipitating environments with large values of vorticity and kubo-Weiss parameter. This is true for gyre and local averages alike, but the local average contains some exceptionally large values of precipitation and kubo-Weiss parameter, suggesting that (i) the TRMM satellite has observed enhanced precipitation associated with the developing storm, concentrated at the best-track location rather than distributed throughout the gyre, and (ii) CMW analyses have pinpointed the location of the developing vortex within the gyre and identified its vorticity as predominantly rotational rather than deformational, i.e., not deformed by strain or shear. The *persistence* of TRMM precipitation in the 0 h preceding genesis is evident – the translation of coordinate system is crucial for proper alignment – and the same can be said for relative vorticity and kubo-Weiss. A null hypothesis for oddball cases (exceptions to the pattern) is that they represent a failure of the analysis to capture the actual circulation or moisture, not a freak development.

Although vertical shear is not necessarily small in developing environments prior to genesis, values are either comparable to (at 850–500 hPa) or somewhat less than (at 850–200 hPa) the climatological shears[25]. The local shear is often smaller than the gyre-wide shear, especially for 600 hPa gyres which can be expansive. This suggests that the center

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[25]Climatological shears were obtained by first calculating the modulus of the shear vector, then averaging together to form the climatology. In storm development regions, vertical shear of the climatological wind velocity is small ($\sim$ ms^{-1}, not shown). eveloping systems generally form in shear that exceeds the shear of the climatology but is comparable to or less than the climatology of the shear The climatology of kubo-Weiss parameter was obtained in a similar way, by first calculating the quadratic products and then averaging. eveloping systems generally form in environments with kubo-Weiss parameter well above its climatological range.

of the gyre (or proto-storm location) is already a favorable spot for genesis, relative to the gyre as whole. □ote that the average shear as defined here represents the average of a positive definite quantity (modulus of the shear vector at each point within the gyre) and therefore disallows any cancellation of opposing shears in different parts of the gyre. The average indicates, rather, a typical vertical shear that might be seen by convective elements in each grid-box column, regardless of shear vector orientation. Storms are evidently able to form in environments containing a wide range of shear values from □±12 ms^{-1}. These values admittedly are not huge, and as forecasters are aware, local shears in hostile environments can be much larger, exceeding 20 ms^{-1}. □or developing storms, as displayed in □igs. 16–17, vertical shears *in the Eulerian frame* are comparable to the differences in optimum phase speed C_p between the lower and upper troposphere (Sect. 4.□). □either of these quantities exceed 10 ms^{-1}, except on rare occasions, so it is likely that the *Lagrangian shear* seen by the developing vortex is small as well. The last remark is intended to expose a point easily overlooked□if a pouch were tilted against a modest shear initially, but made erect by the shear over several days (requiring wave phase speed to vary with height), deep moist convection reaching the upper troposphere in an hour or less could then occur in upright fashion throughout the depth of the pouch, favoring storm development. Larger vertical shear, on the other hand, might sti□e vortical organization by shearing the clouds themselves, favoring linear organization.

□nce formed, the storm may help to maintain small shear, to the extent that it can. □ivergent out□ow originating above the storm center ensures that modest vertical shear will continue to exist off-center (even when the environmental shear is negligible) while remaining small on-center. Hendricks and Montgomery (2006) suggested that deep convection associated with vortical hot towers can erode vertical shear, as suggested by Molinari et al. (1995). This mechanism is important in tropical transition, where vertical shear owing to the □T cyclone upstream (to the □W of the developing low-level center) is unfavorable for further development and must be kept at bay (□avis and □osart, 2004). Similar vulnerability to adverse shear may exist for storms originating in the M□R when □troughy□conditions prevail aloft. In the next section the vertical structure and evolution of waves and their associated critical layer is described in more detail for Hurricane □ebby (2000). In this case the divergent out□ow becomes visible prior to genesis, and is weakly anticyclonic.

The relation of □wave□ (as defined by the band-pass meridional velocity anomaly) and □vortex□ (as defined by the best-track location following genesis) in the 55 storms is summarized compactly in Table 2. After genesis, the average best-track location moves from its initial location near the trough axis (zero phase) to a somewhat negative phase; i.e., east of the westward-moving axis. The drift is much larger in cases where the best track drifts eastward in the □arth-relative frame later in the sequence (□eastward-also□). In
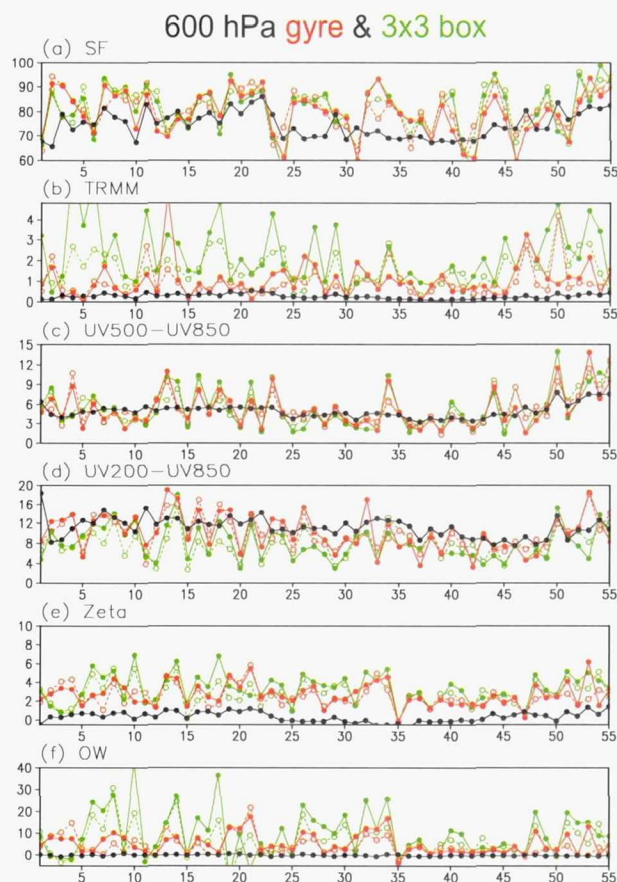

Fig. 17. Spatio-temporal average of dynamical and thermodynamical fields as in Fig. 16, but for 600 hPa gyres and translation speeds. Vorticity and Okubo-Weiss parameter from the 600, rather than 850 hPa level are shown in panels **(e, f)**.

each category, the relative drift or lack thereof is statistically significant. Average wave amplitude declines following genesis, but the variability among cases is large. A longer time interval following genesis is evidently required in order to witness a significant amplitude decline. Conversely, one could argue that maintenance of wave amplitude during the time period shown supports H3, although quantitative proof of the hypothesis is beyond the scope of this paper.

4 Three-dimensional structure and evolution of a tropical wave critical layer

Two observations are evident from the historical record of TC genesis and early intensification over the Atlantic and eastern Pacific for events having a clear signature of tropical waves prior to genesis. (i) A "surface low along the wave" is a necessary, but not sufficient, condition for genesis of a tropical depression. (ii) In all but a few cases, genesis of a tropical depression is a sufficient condition for further intensification

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Table 1. Peak-to-peak wave amplitude (band-pass meridional velocity anomaly, ms^{-1}) from genesis time to the end of the Hovmöller sequence (±3 days) and variation of vortex phase relative to wave trough (degrees) over this time interval. Negative relative phase is located to the east of the trough. The normalized distance from trough to ridge is 180° by definition. For wave amplitude (vortex phase) the average (median) and standard deviation (one-half inter-quartile range) of initial and final values are displayed in the first and second rows of each pair, respectively.

	850 hPa wave amplitude			600 hPa wave amplitude			850 hPa vortex phase			600 hPa vortex phase		
	initial	final	change	initial	final	change	initial	final	change	initial	final	change
all events [55]	4.3	3.8	−0.5	3.9	3.5	−0.4	8	−8	−16	21	−21	−42
	2.0	2.0	−	1.7	1.5	−	25	37	−	26	39	−
all events, Atlantic [31]	4.3	3.8	−0.5	3.8	3.4	−0.5	3	−30	−33	8	−26	−35
	1.8	1.8	−	1.5	1.5	−	20	27	−	21	27	−
all events, Pacific [23]	4.5	3.8	−0.7	4.0	3.7	−0.4	35	21	−14	30	−15	−45
	2.2	2.3	−	1.9	1.6	−	29	38	−	29	62	−
wwd only [40]	4.7	4.1	−0.7	4.1	3.8	−0.3	0	0	0	0	−15	−15
	2.1	1.9	−	1.8	1.5	−	26	33	−	23	39	−
wwd only, Atlantic [22]	4.8	4.0	−0.7	4.0	3.6	−0.4	0	−10	−10	−4	−18	−14
	1.8	2.0	−	1.6	1.5	−	21	26	−	19	28	−
wwd only, Pacific [17]	4.8	3.9	−0.9	4.2	3.9	−0.3	23	21	−2	23	−7	−29
	2.4	1.9	−	2.0	1.7	−	27	25	−	31	53	−
ewd also [15]	3.3	3.3	−0.1	3.4	2.7	−0.7	25	−45	−70	36	−50	−86
	1.2	2.2	−	1.4	1.3	−	29	26	−	20	41	−
ewd also, Atlantic [9]	3.2	3.1	−0.1	3.3	2.7	−0.7	18	−51	−69	36	−50	−86
	1.4	1.2	−	1.3	1.4	−	20	16	−	17	41	−
ewd also, Pacific [6]	3.5	3.5	0.0	3.5	2.8	−0.7	45	15	−30	47	−65	−112
	0.8	3.3	−	1.5	1.2	−	35	43	−	34	59	−

to named storm (tropical storm and possibly hurricane). Our definition of "genesis" in Sect. 1 is equivalent to the development of a depression-strength vortex, not to any subsequent intensification. From the results reported above, the development of a critical layer in the lower troposphere is evidently a *necessary* condition for genesis (and further intensification) by statistical association (Table 1) and by physical reasoning as outlined in the three hypotheses of Sect. 2.2. It is obviously desirable to find conditions, in addition to the existence of a critical layer, that would be *sufficient* for a tropical depression. Here "sufficient" could mean either that (i) in an ensemble of realizations, a tropical depression forms in most cases, or (ii) in a single realization, such development is guaranteed. The latter definition is more strict and arguably impractical for the chaotic dynamics of geophysical turbulence as it would require observations on all relevant scales, accurate and fine enough to overcome (with predictive capability, too) the uncertainties of vortex aggregation and triggering of deep moist convection (D06; Van Sang et al., 2008; Schecter and Dunkerton, 2007). The related definition of sufficiency opts instead for a statistical measure, e.g. of variances or co-variances of mesoscale fields, when considering possible conditions for up-scale development and formation of a tropical depression.

Unfortunately even a statistical measure is difficult to obtain, as it is impossible to calculate mesoscale (co-)variances either from analysis data, which are too coarse in horizontal

resolution, or from field campaigns, which are too brief to provide good statistics. It seems that modeling studies are needed for this purpose (Montgomery et al., 2009). We can, however, dig a little deeper into the available observations to define conditions that come closer to sufficiency for tropical depression formation. In this section we provide additional details that may be relevant for this purpose as well as for quantitative evaluation of the three hypotheses outlined in Sect. 2.2. We provide a partial but incomplete evaluation, for the fundamental reason mentioned above. Our analysis will focus on the kinematics of parcel motions, the vertical structure of the hurricane embryo, and the vertical structure of waves that create its environment. For this purpose our discussion will highlight aspects of Debby (Atlantic 2000) that are broadly typical of the cases listed in Table 1.

4.1 Comparison of streamlines and trajectories, 1–5 Sep.

In Sect. 3, streamlines in the co-moving frame were used as a surrogate for parcel trajectories to delineate the critical layer. Although trajectories and streamlines generally differ for unsteady flow, we demonstrate in this section that the translating streamlines so constructed serve as a reasonable first approximation within a few days of genesis. Only the horizontal (isobaric) component of motion is considered here. For a circular vortex moving at a constant speed C_p, the
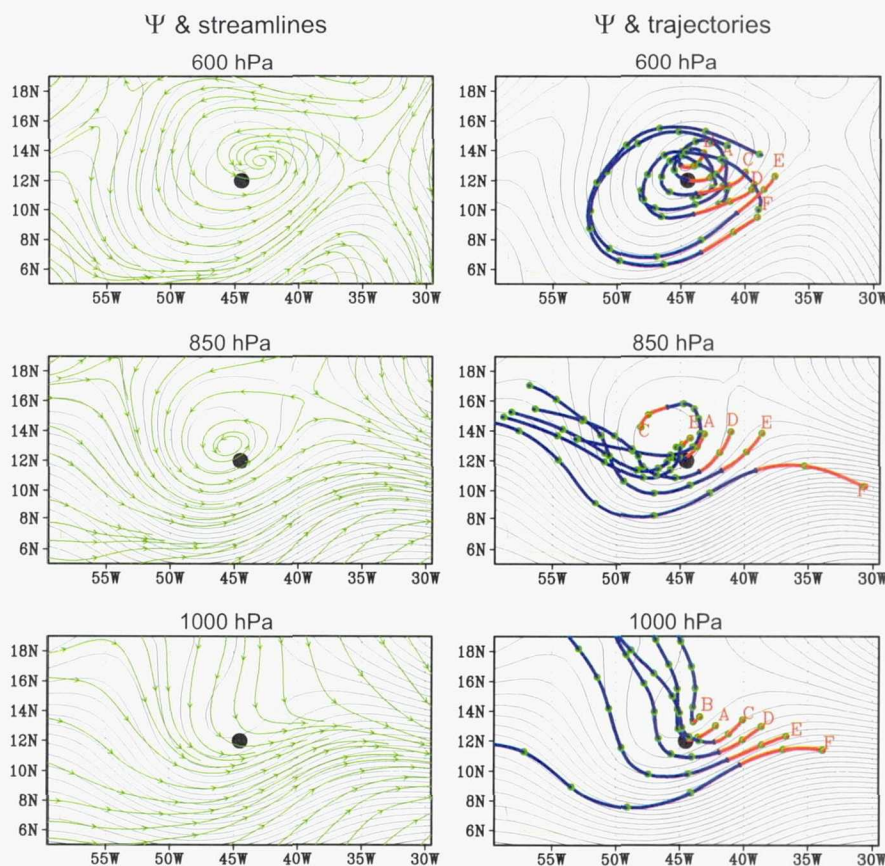
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Ψ & streamlines

600 hPa

850 hPa

1000 hPa

Ψ & trajectories

600 hPa

850 hPa

1000 hPa

Fig. 1□ Streamlines and tra□ectories of hori□ontal (rotational □divergent) □ow at **(a, □)** 600 hPa, **(c, d)** 850 hPa, and **(e, f)** 1000 hPa as seen in □□A-40 data, for the average of si□consecutive leading up to the best-track genesis time of Hurricane □ebby (2000). As in Fig. 5, the streamlines (shown in panels a, c, e) are calculated and displayed in a frame of reference moving westward with the parent wave. Translation speeds estimated from the Hovmöller method at the three levels are $-9.1 \pm 0.3\,\mathrm{m\,s^{-1}}$ (600 hPa), $-10.0 \pm 0.6\,\mathrm{m\,s^{-1}}$ (850 hPa) and $-10.1 \pm 0.6\,\mathrm{m\,s^{-1}}$ (1000 hPa). □ikewise the stream function of non-divergent □ow (thin solid) and tra□ectories (shown in panels b, d, f) are calculated and is displayed in the co-moving frame. The contour interval for stream function is $0.5 \times 10^6\,\mathrm{m^2\,s^{-1}}$. The genesis location is indicated by the black dot in each panel. □ote that owing to the translation of sequential frames used to construct the time average when $C_p \neq 0$, the longitude labels on the □+a□ is pertain to the final analysis time only.

relationship between the local curvature of the streamlines (r_s) and the local curvature of the tra□ectories (r_t) is

$$r_s = r_t \left(1 - \frac{C_p \cos \gamma}{V}\right) \qquad (2)$$

(Holton, 2004) where V is the hori□ontal wind speed in a natural coordinate (not □ust the □onal component), and γ is the angle between the streamlines and the direction of the vorte□translation. For a cyclonic vorte□moving westward (eastward), the curvature of the tra□ectories is stronger (weaker) than that of the streamlines south of the center of the vorte□and weaker (stronger) north of the center. For a vorte□embedded in and advected by a constant mean □ow, the tra□ectories are corkscrew in shape due to rotation and translation of the vorte□ In a frame of reference moving at the hori□ontal speed C_r, $X_L = (x_L, y_L)^T = X - X_c$ represent the cardinal coordinates moving with the vorte□ and

$X_c = (x_c, 0) = (C_r(t - t_0), 0)$ is the center of the vorte□ Particle tra□ectories in this frame of reference satisfy the following equations

$$\begin{cases} \frac{dx_L}{dt} = \frac{dx}{dt} - \frac{dx_c}{dt} = u - C_r \\ \frac{du_L}{dt} = \frac{dy}{dt} = v \end{cases} \qquad (3)$$

As illustrated in Fig. 3, if $C_r = C_p$ streamlines in the co-moving frame are stationary and coincide e□actly with hori□ontal tra□ectories. If the westward phase speed is underestimated (overestimated) the curvature of tra□ectories is stronger (weaker) than that of streamlines south of the center of the vorte□and weaker (stronger) north of the center. Here we will use the formation of Hurricane □ebby to e□amine the three-dimensional structure and evolution of the critical layer.

Figure 18, left column, shows streamlines at 600, 850 and 1000 hPa in a co-moving frame averaged over the 36-h period leading up the genesis time of Hurricane Debby. Also shown is the stream function obtained from the horizontal velocity components by a Helmholtz decomposition. Streamlines and stream function contours are nearly parallel at 850 hPa, indicating a non-divergent flow, except near South America where air flows into the gyre from the west. The 600 hPa flow is almost non-divergent as well. The Helmholtz decomposition is linear, so that transient divergent flows are eliminated by time averaging, or if they are small to begin with (as true at these two levels for the individual analyses used in the time average) the divergence remains small when averaged in time. The exact location of flow separatrix and its hyperbolic point(s) is evidently sensitive to the small divergent component, because the horizontal wind speed vanishes at this point (by definition) whereas for stream function alone, the critical point is located where the *nondivergent component* of horizontal wind speed is zero. Note that, despite this error, the separatrix inferred from stream function is within 100–300 km of the separatrix inferred from streamlines. Unlike the first two levels, the 1000 hPa level displays significant convergence into the gyre from the north and west, and into a zonally elongated ITCZ in the eastern half of the figure, from north and south. This feature is described in Sect. 4.3. The flow entering the gyre from the north makes little effort, as it were, to avoid the center of the gyre by turning to the west, as at the other two levels. Although the genesis location (black dot) is ∼100 km south of the gyre center at all three levels, the exact latitude of center is sensitive to our choice of C_p, moving ∼80 km southward for each 1 ms^{-1} increase of C_p towards zero (generally this depends on vorticity or circulation. A weaker circulation implies a stronger sensitivity to C_p). Values of C_p = −8 to −9 ms^{-1} place the 1000 hPa closed gyre precisely over the genesis location. These values are outside the range of uncertainty based on the Hovmöller method, but are optimum for steadiness of flow in the translating frame, as described in Sect. 4.2. Steadiness in the translating frame implies that streamlines and trajectories should be similar in this frame. To settle the question of which translation speed is best, streamlines and trajectories can be compared.

Figure 18, right column, shows 2-D parcel trajectories superimposed on the stream function averaged over the same time interval. The trajectories are calculated in the co-moving frame, as shown in Eq. (3). The red curves are one-day forward trajectories from day 0 to day 1, and the blue curves are four-day backward trajectories from day 0 to day −4. (Trajectories are not shown outside of the domain.) The gyre at 600 hPa, indicated by closed stream function contours, is quite expansive. Six particles are picked, five of them (A–E) inside the gyre at the genesis time, the other one (F) just outside of the gyre. The particles moved counterclockwise around the gyre center, and their trajectories are nearly parallel to the stream function contours from day −2 to day −1. Since the flow is non-stationary, the trajectories are different from the stream function contours or streamlines from day −4 to day −2, but it nevertheless confirms our hypothesis that *particles inside the critical-layer cat's eye tend to stay inside.* Compared to 600 hPa, the gyre at 850 hPa is less expansive. The evolution of the streamlines (not shown) showed that the wave at 850 hPa propagated on the northern flank of the AEW over West Africa. It turned southward and merged with the wave on the southern flank (maximum at 600 hPa) off the west coast, and meanwhile the closed circulation extended to the surface. A tropical depression formed within the wave about two days later. Six particles are picked at 850 hPa; particles A–C are inside the gyre and D–F outside the gyre. Particles D–F moved from west to east in the co-moving frame, and stayed outside of the gyre. Particles A–C also came from the west. They took a small loop, and entered the gyre around day −2. This is consistent with the formation of the gyre at 850 hPa around day −2, as shown by the evolution of the streamlines. The trajectories of all the six particles are nearly parallel to the stream function contours from day −2 to day −1. At 1000 hPa, the gyre is much more confined. Particle A is picked near the genesis location, D close to the gyre center, and C–F outside of the gyre. Particles A–D came from the north, and particle F, which is far from the gyre center, moved from the west, which suggests that the closed circulation near the surface is directly related to the northern wave.

To test the robustness of this result, we increased the sample size by examining the trajectories of 40 particles inside or just outside of the gyre at each of the three vertical levels (not shown). Similar to what is shown in Fig. 18, the particles inside of the gyre tend to stay inside from day −2 to day −1, and all the trajectories are nearly parallel to the stream function contours during this time interval. This suggests that the stream function in the frame of reference moving with the wave serve as a reasonable first approximation within about 2 days of genesis. From the trajectories, we can also estimate the recirculation time of a parcel inside the CL or the eddy turnaround time, which is about 2–3 days and close to the tropical storm development time scale. This is also the length of time that streamlines, stream function and trajectories are roughly equivalent near the gyre center. Table 1 includes two estimates of gyre recirculation time, one derived from the maximum vorticity in the gyre, the other from the average Okubo-Weiss parameter in the cyclonic vorticity region only. The maximum vorticity estimate (typically 2–5 days) is shorter than the O-W estimate (typically 3–8 days) because the latter pertains to a broader region of the pouch, and subtracts the contributions from straining and shearing deformation. Actual recirculation times probably fall between these two extremes. Note, however, that horizontal convergence in the boundary layer shortens the recirculation time as the effective radius of trajectory curvature contracts while parcels begin their ascent near the proto-storm center.

4. Vertical structure and evolution of the mother pouch

The need to translate the coordinate system zonally for an optimum view of Lagrangian flow kinematics has been stressed throughout the paper. Towards this end, a method for determining the optimum translation speed was devised using bandpass meridional velocity anomalies in time-longitude Hovmöller diagrams just prior to genesis. The purpose of the translation is to render flow streamlines approximately equivalent to trajectories, as demonstrated in the preceding subsection. If one were to instead measure explicitly the temporal variance of the flow in a coordinate system translating zonally at an arbitrary speed, it would be found that temporal variance in the vicinity of the developing storm is indeed minimized at a phase speed close to that selected by the Hovmöller method. The reason is that when one chooses an incorrect phase speed for translation, the wave's phase propagation contributes significantly to the temporal variance in the incorrectly translating frame. When the proper translation speed is selected, this temporal variance is mostly eliminated. The proper speed pertains to that of the "co-moving" frame as defined herein. We have applied the alternative method to stream *function* (as opposed to stream*line*) which represents a field, that is, function of space and time (unlike *particles* whose location is simply a function of time). Because the flow is dominated by the rotational[26] component, stream function in the co-moving frame nicely illustrates the structure and evolution of the parent wave's "pouch". Representative examples of stream function for the mother pouch of Debby were shown in Fig. 18. The definition of Lagrangian boundary in steady flow can be made precise by locating the saddle point nearest (in psi) to the gyre center and equating the gyre boundary with the value of stream function intersecting that point.

In regard to the vertical structure of Debby's pouch, two salient features emerge with other interesting details. (i) A closed gyre is found at all levels from 1000–500 hPa for at least 30 h prior to genesis, for westward translation speeds in the range −8 to −10 ms⁻¹. The signature of this disturbance decreases abruptly in amplitude above 500 hPa. (ii) Above the mid-troposphere is a second closed *anticyclonic* gyre having somewhat larger spatial extent and located slightly to the east of center, but a significantly slower range of possible westward translation speeds in the range −3 to −7 ms⁻¹. Close inspection of gyre properties, such as the steadiness of pattern, stationary center location and minimum temporal variance near the center (all evaluated in the translating frame) establishes a pair of optimum westward translation
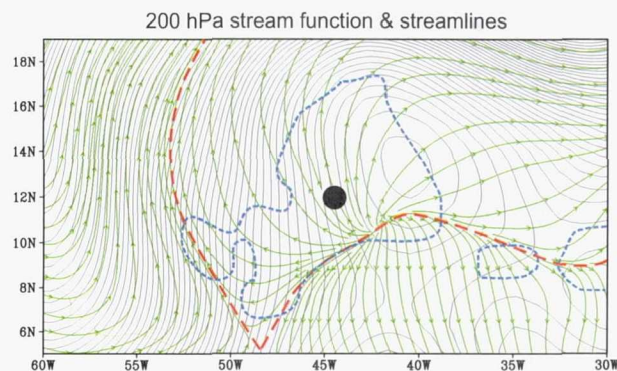
Fig. 19. Streamlines of horizontal flow and stream function of nondivergent flow at 200 hPa calculated and displayed in a frame of reference moving 5 ms⁻¹ westward, at the genesis time of Hurricane Debby. Divergence contributing to anticyclonic outflow can be seen by comparing streamlines with stream function. The genesis location is indicated by the black dot. TRMM precipitation is outlined in blue.

speeds: −9 ms⁻¹ in the lower troposphere and −5 ms⁻¹ in the upper troposphere. Streamlines and stream function at 200 hPa in the −5 ms⁻¹ gauge at genesis time are shown in Fig. 19. The two signals (−5 and −9 ms⁻¹) are found to have a common origin in the convective flare-up at 36–38° W at 30 h before genesis (Fig. 9a) explaining why the upper tropospheric signal is located to the east of the storm center at genesis time. The UT wave continues its westward propagation near −9 ms⁻¹, reaching the genesis location 30 h later, while the UT anticyclone drifts westward about half as fast, reaching 40–42° W as shown in Fig. 19. Stream function is a reasonably good proxy for streamlines over the left and upper halves of the figure, but misses completely the strongly divergent outflow above the proto-storm center as well as the local Hadley circulation outflow (along the ITCZ to the east) directed back to the Equator.

Mean vertical shear over the troposphere is relatively light in this case. The flow speed in the upper troposphere near 300 hPa is about −4 ms⁻¹, so that when the coordinate system translates westward near this speed, most of the jet structure disappears, leaving an anticyclonic gyre slightly to the east of the genesis location, with other meridional meanderings elsewhere. As a result, weak southerly flow (3 ms⁻¹) occurs over the depression at genesis time, in the co-moving frame as shown in Fig. 19. (The meridional component, of course, does not depend on the choice of translation speed, or gauge, when the translation is zonal. It is the vanishing of zonal component in the co-moving frame that makes the flow appear southerly in this frame, rather than westsouthwesterly as in the resting frame.) The UT gyre may be significant for development by providing favorably light winds above the proto-storm. The developing storm itself may have had a role to play in carving out the UT anticyclone

[26]The rotational component is larger in most places except, e.g., the upper branch of the local Hadley circulation, where the divergent component is comparable in a relatively shallow layer near 200 hPa (Dunkerton, 1995) and in the lower branch of this circulation, or boundary layer.

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as a result of a convective event at 36–38° W (ne□t sub-section). Averaged over the 36 h (6 consecutive analyses) prior to genesis, the structure of relative wind speed (modulus of vector □ minus C_p □ for two values of C_p (−9 and −5 ms^{-1} for □T and □T, respectively) is shown in Fig. 20a, b. The temporal standard deviation of wind speed over the same time interval is also shown (c, d). Contours indicate a □onal-temporal average over a 30° longitude interval eventually centered at the genesis point and translating □onally prior to this time for 30 h at speed C_p. These wave-centric views illustrate in appro□imate fashion the structure of the mother pouch in a latitude-height cross section. Superposed as shaded pi□els are wind speed and its temporal standard deviation *within the boundaries of the translating closed gyres* in each frame, as defined by their ma□imum e□tent in this longitude/time interval. As already noted, the purpose of the translation is to minimi□e the temporal variation of streamlines in the translating frame, rendering streamlines appro□imately equivalent to tra□ectories. Comparison of Fig. 20c, d indicates that the temporal variation of wind speed *within the gyre* over 36 h is considerably smaller in the □T when the translation speed is set at −9 ms^{-1} (0.3–0.7 ms^{-1}) than at −5 ms^{-1} (0.7–1.6 ms^{-1}) whereas a value of −5 ms^{-1} is superior for steadiness of the □T anticyclone (a closed a/c gyre at these altitudes does not appear at all at −9 ms^{-1}). When the translation speed is set at −9 ms^{-1}, relative wind speeds in the □T are *smaller* inside the gyre (1.4–3.4 ms^{-1}) than over all longitudes (4–6 ms^{-1}), whereas at −5 ms^{-1}, these values (4–6 ms^{-1}) are *comparable*. The moral of the story□ the slower translation speed is inappropriate in the lower troposphere, and its effect in reducing the relative □ow or variation thereof inside the □T gyre is inconsequential. It is easy to understand why the *temporal variation* is minimi□ed at −9 ms^{-1}, because the wave□s phase propagation has been accounted for. This translation speed closely appro□imates that of the □T wave, while the slower speed does not. The reason why the gyre□s *relative flow* is reduced is more subtle. □ike the hyperbolic point on the separatri□, the gyre center is a *stagnation point* where the relative □ow is weak, albeit rotating cyclonically in such a way as to make a complete revolution about gyre center in a few days or less. □oth choices of translation speed yield a closed translating gyre, implying a stagnation point either way, so why is the faster translation speed ostensibly superior in the metrics of Fig. 20□ The "secret of success" at −9 ms^{-1} is that the gyre keeps perfect step with the wave *and* is not too large in hori□ontal e□tent. In the −5 ms^{-1} gauge the gyre is much larger and includes a peripheral region of stronger relative □ow. This peripheral □ow is so strong, in fact, that the gyre-average relative □ow (shaded pi□els in Fig. 20c) is stronger than that of all longitudes (contours)□ We emphasi□e, however, that small relative □ow per se is not necessarily significant. It will be noted (Fig. 20b) that a small relative □ow (1–2 ms^{-1}) is also observed at 400 hPa near the genesis latitude when the translation speed is set at −5 ms^{-1}. There is no closed gyre at this

level□rather, the selected translation speed is similar to the □onal □ow speed here. Translation eliminates the □onal component of relative □ow at 400 hPa, leaving weak meridional meanderings at this level which have little, if any, importance dynamically – other than to ensure weak relative □ow above the proto-storm.

In regard to temporal evolution, a closed □T gyre in the co-moving frame can be found all the way back to 54 h before genesis time. The traveling gyre emerges from a quasi-stationary gyre near the west coast of Africa, presumably a monsoonal feature. The e□act time of gyre closure is a function of altitude and translation speed C_p. A closed surface circulation e□ists at least 60 h prior to genesis in the −5 ms^{-1} gauge, but as already noted, this speed is inappropriate for the □T wave[27]. In the properly co-moving frame (−9 ms^{-1}) the surface circulation closes at 18□00 □ on 17 August, 48 h prior to best-track genesis. There is an implied delay (albeit short) between the formation of a closed circulation in the lower free troposphere relative to the surface. It remains to be determined whether downward burrowing of a closed gyre to the surface from above is a universal behavior in all 55 cases□the largest and/or earliest translating gyres can be found at *any* of the analy□ed □T levels (1000–600 hPa) depending on the storm. A closed surface circulation, nonetheless, is present in most cases together with a modest vertical shear e□tending to the □T and other environmental stimulants as identified in Figs. 16–17. These observations confirm H1, establishing that the locus of gyre formation and organi□ation of deep convection is in the lower half of the troposphere, while leaving some important details (e.g., communication between the lower free troposphere and boundary layer) for future study. On balance, conditions throughout the depth of the troposphere in this event seem very favorable for tropical cyclogenesis via the tropical wave pathway. □ut as already noted, □ebby was not unique in this respect. Similar conditions are found in most of the cases selected for the "quasi-monochromatic easterly wave" category.

4.□ □ignatures of wave and dia□atic vorte□prior to genesis

A distinct *signature* of the parent wave and diabatic proto-vorte□□ust prior to genesis can be seen in □ebby and in other cases e□amined, that is, a set of defining characteristics that help to discriminate these two entities. □ecognition of how these characteristics evolve in the day or two immediately preceding genesis may prove useful for diagnosis and prediction of incipient storm development. The vertical structure of

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[27] □onsoon circulations (tied to stationary land surfaces) □uctuate slowly in time, implying a non-□ero bandwidth in frequency. Closed monsoon gyres are therefore e□pected in a modest spread of translation speeds, as observed in this case. □onsoons do not give birth to tropical depressions, but tropical waves and monsoon depressions do. For genesis it is not the translation speed of monsoon circulations that is important, but that of waves.
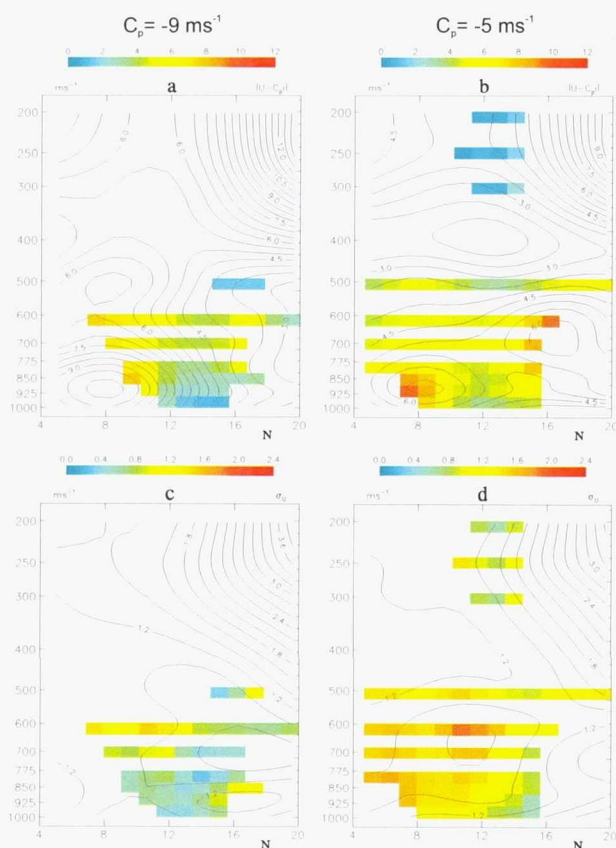
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Fig. ⬚⬚ Hori⬚ontal wind speed in two co-moving frames averaged over the si⬚consecutive analyses leading up to the genesis time of Hurricane ⬚ebby. The range of longitudes x used to construct the average is given by the speed of translation beginning at the genesis longitude ($x_0 = 44.5°$ W) and going eastward (backward) in longitude (time) from the genesis point according to the formula $x(t) = x_0 - C_p \cdot (t - t_0)$ where t_0 is the best-track genesis time. The hori⬚ontal wind speed in each co-moving frame is given by $|⬚ - C_p⬚|$ where $⬚$ is the hori⬚ontal vector wind, C_p is translation speed and $⬚$is the unit vector in the x-direction. The quantity contoured represents a ⬚onal average within $\pm 15°$ longitude of the center longitude as given above, including regions inside *and* outside the gyre. **(a, c)** $C_p ⬚-9$ ms^{-1} ⬚(⬚, **d)** $C_p ⬚-5$ ms^{-1} (negative values are westward). These values correspond appro⬚imately to the ⬚onal component of disturbance propagation in the lower and upper troposphere, respectively. The ma⬚imum e⬚tent of closed stream function gyre in each frame of reference is also shown by superposing (as shaded pi⬚els) the gyre-average values of $|⬚ - C_p⬚|$ where they e⬚ist. Here, "gyre average" refers to a ⬚onal average over longitudes within a closed gyre as delimited by a bounding contour of stream function ψ intersecting the nearest (in ψ) separatri⬚. The lower panels show the temporal standard deviation of hori⬚ontal wind speed in each co-moving frame. The quantity contoured once again represents a ⬚onal average over the entire domain, while shaded pi⬚els indicate gyre-average values. For modulus and standard deviation, their ⬚onal average was obtained by first summing the squares and then taking the square root of the sum.

wave and vorte⬚seem especially important in this regard. As noted in the preceding subsection, the parent wave of ⬚ebby translates westward at about 8–10 ms^{-1}, with little vertical phase tilt up to the mid-troposphere and abrupt decrease of amplitude above. ⬚eanwhile, an e⬚tensive anticyclonic gyre develops in the upper troposphere and propagates west, but with slower phase speed than the wave, about 5–6 ms^{-1} westward. It is thought that the ⬚T anticyclone may have originated from diabatic forcing by deep moist convection at 36–38° W about 30 h prior to genesis time. Figure 9 indicates that persistent convection was seen by T⬚⬚⬚ during this sequence, aligned well with the translating gyre, especially at the beginning. ⬚emarkably, the ⬚⬚A-40 stream function and velocity potential, when e⬚amined together, seem to confirm these two signatures – noting the important caveat that the analy⬚ed divergence is driven in part by the model⬚s cumulus parameteri⬚ation and is therefore uncertain. Velocity potential in the upper troposphere indicates a strong divergence anomaly in the upper troposphere propagating westward during the 30-h sequence from 36–38° W to the e⬚act location of genesis at genesis time, accompanied by a convergence anomaly in the lower troposphere propagating westward in parallel, 1 or 2° south of this track as shown in Fig. 21a–d . The vertical alignment of these anomalies of opposite sign is similar to the "first baroclinic mode" structure of tropical depression disturbances in the western Pacific (⬚unkerton, 1993) but very different from the vertically trapped, ∼equivalent barotropic structure typical of Atlantic easterly waves that are not diabatically activated. We con⬚ecture that a vertical dipole of velocity potential (accompanied by a ⬚T anticyclone and vertical quadrupole of meridional velocity anomaly) indicates activation by one or more diabatic vortices and their associated deep moist convection within the mother pouch of the wave. In ⬚ebby and in other cases, e⬚citation of a divergent ⬚T anticyclone above the ⬚T disturbance provides a spectacular early warning signal in the dynamical fields that seems to corroborate well with convective precipitation retrieved from T⬚⬚ ⬚ measurements.

Forecasters consider in advance various signatures of T⬚ genesis⬚ for some of them, the upper tropospheric ⬚ow plays a role, as in vertical shear, upper-level dif⬚uence or divergence, and of course, deep convective cloud-top temperature. It is often impossible to distinguish cause and effect, since one could ⬚ust as well interpret their presence as indicating that a tropical depression already e⬚ists, but has not been officially recogni⬚ed. The main hurdle in identifying a T⬚-stage disturbance is the inability to see a closed rotational ⬚ow in the lower troposphere in visible or infrared imagery when obscured by clouds aloft. In this respect it is worthwhile to recogni⬚e the often crucial role played by the upper tropospheric ⬚ow in identifying conditions which either are favorable to development or indicate that development is already in progress. Owing to improvement in the assimilation of cloud and water-vapor winds in operational analyses over the last two decades (e.g., Velden, 1997, 2005) the free
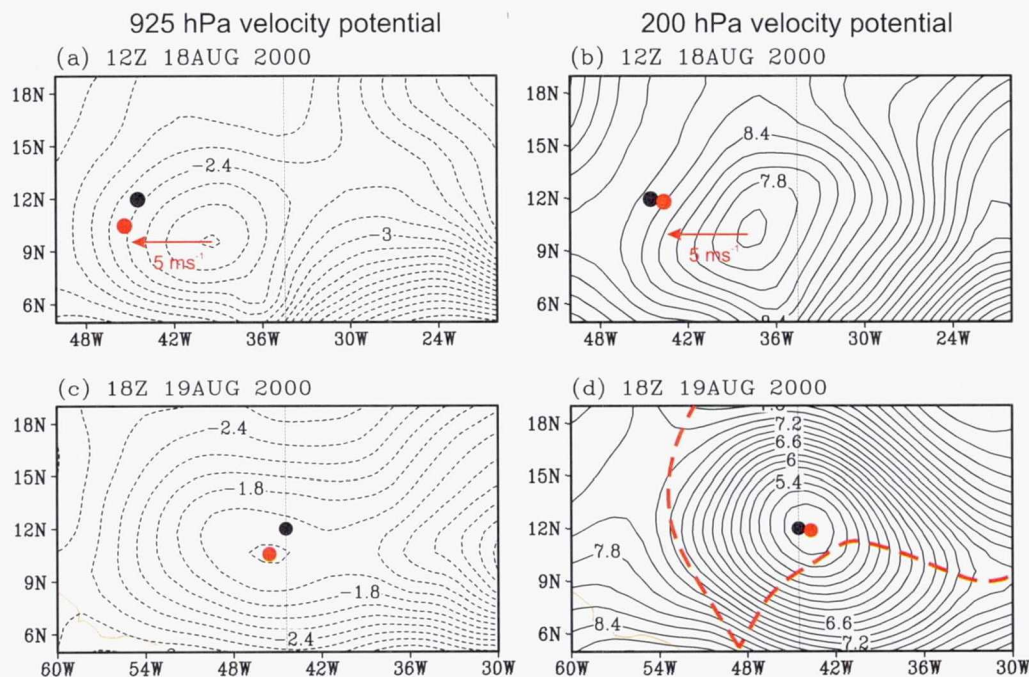
Fig. ☐1. Velocity potential of divergent ☐ow, as seen in ☐☐A-40 data, at **(a, c)** 925 hPa and **(☐, d)** 200 hPa leading up to the genesis time of Hurricane ☐ebby, at (a, b) 30 h before genesis and (c, d) genesis.

troposphere ☐ow is well-represented on the synoptic scale (a compliment that e☐cludes the tropical tropopause layer or TT☐, and the lower stratosphere, due to insufficient cloud coverage or water vapor content, and lower troposphere in regions where thick clouds obscure). To the e☐tent that both lower *and* upper troposphere hori☐ontal winds are captured faithfully by the analyses on the synoptic scale, it is possible to identify T☐-like conditions in the parent wave from the vertical structure of wind anomalies☐specifically, a "first baroclinic mode" structure or stacked arrangement of ☐T cyclone and ☐T anticyclone.

Such features – as one might e☐pect us to say – are best revealed in a frame of reference translating with the parent wave. ☐ut in the case of ☐ebby and more generally, *there is no need for the optimum translation speeds to be identical throughout the depth of the troposphere*. One reason (noted in Sect. 3 and quantified in Table 1) is that the phase speed of the parent wave may vary with height, from lower to mid-troposphere. Another (noted here) is that the proto-vorte☐ may translate slowly with respect to its parent wave while its deep convective signature e☐tends to the upper troposphere[28]. The definition of "properly co-moving frame" therefore depends precisely on what the "co" refers to. In-

deed, it is likely that a trapped ☐T disturbance propagates at a slightly different speed than a diabatically activated ☐T-☐T dipole. There are multiple reasons, the simplest being that gross moist stability is reduced by the latent heating associated with deep moist convective precipitation, causing wave phase speed of moister waves to be slower than that of drier waves. In the language of tidal theory it could be said that the equivalent depth of the proto-vorte☐and its induced ☐ow is smaller than that of the original parent wave, which sees a larger area and more dilute distribution of precipitation than the proto-vorte☐ itself and its upper tropospheric signature. We therefore e☐pect a diabatic ☐ossby wave and diabatic ☐ossby vorte☐to propagate at slightly different speeds, the speed of the wave depending, among other things, on the degree of convective heating seen by the wave, via the gross moist stability. Also possible is that the two entities respond differently to vertical shear. An isolated vorte☐is e☐pected to propagate at the speed of the local mean ☐ow (e☐cluding the effects of unbalanced motions, if any) which, as noted in Sect. 2, matches the phase speed of the wave at the critical latitude. There are kinematic reasons for the parent wave and proto-vorte☐to remain together, at least within some ma☐imum distance as determined by the dimensions of the translating gyre. ☐ut they do not necessarily walk in lock step. The marsupial paradigm evidently allows some "slop" in the e☐act position of the vorte☐relative to the wave trough, i.e., slightly different propagation speeds which (as in ☐ebby and other cases) are *measurably* different. ☐ey to the success

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[28] ☐ffects of the diabatic proto-vorte☐ on the upper troposphere may be separated into a *near-field* response with anticyclonic out-☐ow aloft (relevant to TC genesis within) and a *far-field* response communicated by secondary ☐ossby waves (relevant to ad☐acent troughs and TC genesis therein).

of the marsupial mechanism is that the respective horizontal velocities not differ too much either in speed or azimuthal direction.

Broadly speaking, for diagnostic purposes and short-term prognosis, we conclude that (i) stream function in the lower to mid-troposphere suitably illustrates the incident wave structure, along with velocity potential in the lower free troposphere above the boundary layer, while (ii) velocity potential in the boundary layer and upper troposphere, along with stream function in the upper troposphere, depicts the diabatic vortex and/or modification of wave structure once diabatic activation has occurred.

8 Conclusions, new visions and directions

The genesis of tropical cyclones was described by Emanuel (2005) as one of the remaining "great mysteries of the tropical atmosphere." The persistence of the mystery over many decades underscores the difficulty of the problem—like the conquest of Mount Everest, a formidable "ascent" from observational, numerical *and* theoretical directions. Some of the processes involved in genesis occur at horizontal scales which are very small and unresolved by analyses such as ERA-40 on a ~1 degree grid. Numerical models need much finer resolution than this in order to capture the mesoscale construction of the incipient PV monolith in a realistic manner (e.g., M06). But the mystery also exists owing to imperfect theoretical understanding and visualization of fluid dynamics and thermodynamics that comes from working in an Eulerian or Earth-relative framework. We have produced and advocated in this paper a Lagrangian or wave-centric view for the study of tropical cyclogenesis and have chosen the simplest of all scenarios to present the fundamental concepts of genesis in a tropical wave critical layer. These events were associated with quasi-monochromatic easterly wave disturbances which account for the majority of tropical cyclones in the Atlantic and eastern Pacific sectors (if we allow in some cases for hydrodynamic instability to account for the waves themselves). To the extent that the phase speed of waves is reasonably constant over their life cycle, the coordinate system may be translated westward to match the phase speed of the incident wave. By examining streamlines in the co-moving frame a wave-centric picture of the flow is obtained in which trajectories and streamlines are nearly equivalent over a time span of a few days. Because the divergent component of horizontal flow is small relative to the rotating component, with certain exceptions, streamlines in the translating frame are closely approximated by a stream function with the appropriate "gauge" (in this case, a scalar harmonic function) added corresponding to the speed of translation. This device enables us to identify approximate Lagrangian boundaries in the flow in lieu of performing trajectory calculations. To confirm inferences from streamlines

in the co-moving frame we calculated back-trajectories from within the closed gyre (Sect. 4.1).

The marsupial paradigm provides a convenient and self-consistent framework for the coupled dynamical/thermodynamical processes that are essential to tropical cyclogenesis. Our analysis has highlighted the role of tropical wave critical layers as preferred loci for the formation and aggregation of diabatic vortices which represent moist coherent structures on the mesoscale. The critical layer is where the mean flow (in the direction of wave propagation) and wave phase speed are similar, implying that cutoff vortices will be able to travel with the wave (in this case, westward) for a time. The coherent relationship that exists between the wave and vortex serves to preserve both. It preserves the vortex because the Lagrangian boundaries formed by the wave at its critical layer remain in the same phase of the wave. These boundaries appear stationary or slowly varying in the co-moving frame. Also, diabatic heating associated with the spawned vortices acts coherently to maintain the wave to the extent that these vortices are able or inclined to keep step with the wave, as implied by the preceding argument. This phase locking, however, does not persist indefinitely, and when a vortex becomes sufficiently strong[29] it may acquire its own propagation characteristics which usually involves some degree of meridional propagation that the wave did not have originally as well as a slower horizontal speed. The vortex is then no longer propagating with its parent wave. This sequence of events we have described as the marsupial paradigm because the wave is providing a pouch or sweet spot for cyclonic vortex development, up-scale aggregation, convective moistening and diabatic amplification. This process has a finite gestation period. Once the vortex leaves, the wave is often observed to weaken or die when viewed in NHC/TPC surface analyses. Multi-dimensional visualization of ERA-40 data suggests also a subsequent radiation of waves, either from the genesis region itself or from the new translating vortex, that introduces new variance in the upper troposphere.

Our third hypothesis (H3) is consistent with these observations; quantitative proof is outside the scope of this paper. Phase-locking of wave and proto-vortex for ±3 days about the best-track genesis time is more prominent in stronger waves than in weaker waves, the latter seeming to exert less influence on the direction of vortex propagation. As for the effect of vortex on wave, there are numerous instances in which the speed of zonal phase propagation is reduced after genesis, although this behavior is not universal. Model results (to be reported separately) confirm that a diabatically activated easterly wave is slowed, by about 20%, relative to its initial speed prior to vortex development. Observations from ERA-40 indicate a prominent signature of

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[29] Our modeling study establishes that vortex merger and convective amplification play equally important roles in the selection of a dominant vortex in the pouch (Montgomery et al., 2009).

diabatic activation in the upper troposphere above the developing storm, as seen by a quadrupole structure of meridional velocity anomaly in the longitude-height plane. Similar structure comprised the leading mode of meridional velocity variance in the western Pacific during boreal summer (⬚unkerton, 1993). Its occasional presence in Atlantic and eastern Pacific sectors, uniquely associated with TC genesis in these regions, may prove important in diagnosis and short-term prediction. Forecasters show keen interest in anticyclonic out⬚ow in the ⬚T when it e⬚ists prior to intensification. ⬚ivergence and anticyclonic rotation above the proto-storm adds a piece of information to the marsupial paradigm and supports the notion that the mother gyre and child vorte⬚have different personalities, i.e., contrasting vertical structures and slightly different hori⬚ontal propagation speed and/or direction.

These ideas provide a road map for e⬚ploration of synoptic-mesoscale linkages essential to tropical cyclogenesis, an e⬚citing area of research in the years ahead. For tropical cyclogenesis in tropical waves, our analysis begins to close the gap between observationally resolvable scales (synoptic, meso-α) and cloud scales (meso-γ) that require numerical models. To recap⬚the formation, aggregation and amplification of preferentially cyclonic anomalies by convective heating in the ⬚elvin cat⬚s eye of a critical layer comprise the principal pathway for tropical cyclogenesis in tropical waves (H1). A key concept derived from theories of the nonlinear critical layer is that the cat⬚s eye e⬚ists prior to organi⬚ation and does not depend, structurally or otherwise, on the details of organi⬚ation until TC intensification begins. The formation of closed streamlines implies that the air within the materially closed space is protected, to some degree, from lateral entrainment of dry air (H2). Therefore the closure serves not only to concentrate vorticity by the aforementioned mechanism but may also account for the accumulation of moist entropy and saturation of the tropospheric column by persistent deep moist convection in the pouch – the same convection that facilitates growth of cyclonic anomalies. This containment has a very important effect in allowing a convective type of heating profile to dominate the closed region with a relatively lesser contribution from stratiform precipitation that is otherwise common in meso-scale convective systems (Tory and ⬚ontgomery, 2006). The ma⬚imum heating in the immediate region of interest occurs at a lower altitude than normal for organi⬚ed tropical convection, favoring surface convergence and rapid spin-up of one or more low-level vortices. We con⬚ecture that this process, representing a "non-advective" transport of PV (Haynes and ⬚cIntyre, 1987) by hot towers in an environment of large saturation fraction (e⬚ceeding $\sim$80⬚) provides a direct "bottom-up" pathway to tropical cyclogenesis more or less independent of the mid-level transport of PV by typical mesoscale convective systems in the tropics.

Persistent deep convection in the gyre and its signature in the upper troposphere observed prior to official T⬚ declaration suggests that anomalous diabatic processes are already operating in this region⬚anomalous with respect to temporal duration, vertical profile of heating and the resulting profiles of vorticity and divergence. How these anomalies translate into TC formation remains something of a mystery because the mesoscale processes most relevant to storm development are uncertain, while available observations lack sufficient resolution. For this reason, we cannot establish that gyre formation in the co-moving frame is completely sufficient for tropical depression formation. ⬚onetheless, a critical role for a closed surface gyre is supported by these observations. We have associated (i) gyre depth (equivalently, vertical alignment) and (ii) anomalous dynamical and thermodynamical properties within the gyre, with developing systems, and have used contemporary meteorological analyses and satellite data for this purpose, notwithstanding their limitations. Further insight into mesoscale processes that link gyre formation to ensuing developments will help to establish how far the forward enstrophy cascade penetrates the mesoscale before cloud-system processes trigger the inverse cascade and ultimately dominate the intensification phase via upscale aggregation. ⬚umerical models will be brought to bear on this aspect of the problem. With a ⬚agrangian framework for ⬚ow kinematics (relevant to the forward cascade) and a cloud-system resolving model (needed for the inverse cascade) a direct assault on mesoscale processes leading to tropical cyclogenesis at meso-β is now feasible. We have brought the necessary materials to base camp, so to speak, and the summit of the mountain is within reach.

The multi-scale problem ⬚ust described would be complicated enough if confined to a hori⬚ontal plane, but nature provides a vertical dimension, or degree of freedom, absent from the 2-⬚ model. We have attempted to draw some preliminary conclusions from the vertical structure of waves, proto-vorte⬚and mean ⬚ow (Sect. 4) but most of the work on this aspect of the problem remains to be done. Identification of a gyre boundary in the co-moving frame enables a quantitative estimate of vertical shear seen by the developing storm, in addition to its intrinsic properties (vorticity, moisture, deep convection and recirculation time⬚Table 1, Figs. 16–17). It seems that genesis is favored in regions of weak vertical shear when measured over the depth of the troposphere. The shear need not be identically ⬚ero, nor as small as the "shear of the climatology", but the typical 850–200 hPa shear at the genesis point observed in our survey of events is modest ($<12\,\mathrm{ms}^{-1}$) in agreement with previous studies. ⬚ero shear throughout the gyre would imply that the ⬚ow kinematics at any two levels are the same. Of course this is never e⬚actly so. Hori⬚ontal transports of cyclonic vorticity and moisture are therefore somewhat different in all cases, but they are seldom radically different. ⬚or would it be correct to regard TC genesis in these basins as resulting from little more than "stratified turbulence" in which hori⬚ontal ⬚ows at different levels overlap randomly. Incident waves are usually observed at both levels (600 ⬚ 850 hPa)

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with similar amplitude and phase. In regard to the vertical structure of horizontal transport (of vorticity and moisture) the *marsupial paradigm*, with its approximately equivalent barotropic structure of lower-tropospheric waves, provides a much more realistic picture of tropical cyclogenesis than the *stratified turbulence paradigm*. The latter may describe better the relation of upper and lower troposphere, the upper levels often influenced by intrusion of extratropical anomalies uncorrelated with the lower tropical troposphere.

Vertical alignment of the marsupial pouch as a favorable condition for TC genesis helps to mitigate the deleterious effect of vertical shear on the nascent storm:

"A major inhibitor of genesis is the presence of vertical wind shear, defined as the change in direction and/or speed of the wind with altitude... If there is no wind shear, a nascent tropical system just moves along with the wind (which, in the absence of shear, has the same speed and direction at all altitudes). No air flows through the storm. But if wind shear is present, the storm tries to move along at an average wind speed, and at some altitudes wind must blow through the storm. This storm-relative flow can import dry air from outside the cloud cluster, destroying the humid column of air that is needed for genesis. For this reason, wind shear is inimical to genesis" (from *Divine Wind: The History and Science of Hurricanes* by Kerry Emanuel, 2005, p. 97).

Although additional reasons were noted in Sect. 2, concerning effects of vertical shear on convective organization, two aspects of the marsupial paradigm were anticipated in Emanuel's reasoning: the need for weak storm-relative flow and some protection from dry-air intrusion. The role of the critical-layer cat's eye in helping to provide these conditions was formulated in our second hypothesis (H2). Later in the same chapter, the author describes the transition from a subtle surface signature of easterly-wave passage, to a more robust closed surface circulation:

"We observe that occasionally, especially in late summer and early fall, the amount of convection associated with a particular wave increases, and winds near the surface evolve from a typical wavy pattern of an easterly wave into a closed circulation. A tropical depression is born." (ibid., p. 99).

We would go, of course, a step further and identify a closed cyclonic circulation *in the co-moving frame* as the critical ingredient for depression formation (see Appendix). The author, nonetheless, recognizes the apparent need for a closed gyre at or close to the surface, a feature which by no means is present in all waves, but clearly exists in the developing cases considered in this paper. As to why the surface gyre forms, and why it is important to genesis, we are left to speculate that (i) diabatic activation[30] of the wave by deep moist convection is needed to amplify the effect of an otherwise "dry"

critical layer[31] (H3) while (ii) Ekman pumping from the tropical boundary layer is needed (or desirable, at least) to organize convection in a ring-like pattern about the proto-vortex (Eliassen and Lystad, 1977; Van Sang et al., 2008). In a rotating environment such pumping is sensitive to the radial gradient of absolute vorticity (Ooyama, 1969; Hack and Schubert, 1986). The role of boundary-layer forcing in a co-moving frame was studied in the classic paper by Shapiro (1983) for mature hurricanes. Wind speeds in the proto-vortex are considerably less, but (as in a mature system) surface drag varies quadratically with wind speed for speeds greater than a few ms^{-1} but less than 25 knots. Therefore, azimuthal asymmetries of BL forcing are relevant to tropical depression formation.

Perhaps the most impressive and humbling aspect of these observations is the great variety of flow configurations seen in the 55 cases selected for study. Although generally similar and tending to support the marsupial paradigm, no two events are exactly alike. Their similarities prevent us from labeling TC genesis as an entirely turbulent process, thanks to the underlying synoptic wave structure and its implications for flow kinematics when superposed on the adjacent easterly jet. In the co-moving frame, the region of closed circulation displays a preferred, non-random orientation with respect to the jet axis and its associated gradients of vorticity and moisture. The basic state represents a "coherent structure" in the lingo of contemporary GFD, just as the tropical depressions that form on it, and grow for a time within their parent waves. So the real world of TC genesis is not a story about quasi-2-D turbulence nor a moist generalization thereof – not exclusively, at least. Nonetheless, differences from one event to the next compel us to recognize the disordered and variable nature of the sub-synoptic dynamics, a characteristic partly attributable to quasi-2-D turbulence but magnified by rotating 3-D-convective turbulence, as contained in the ubiquitous "vortical hot towers" (Frank and Johnson, 1969; 2006). One can hardly imagine a more fascinating interactive, multiscale system in nature than this.

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[30]It is clear from Berry and Thorncroft (2005) that the amplitude of waves emerging from West Africa is not a good indicator of future development, except near the coast.
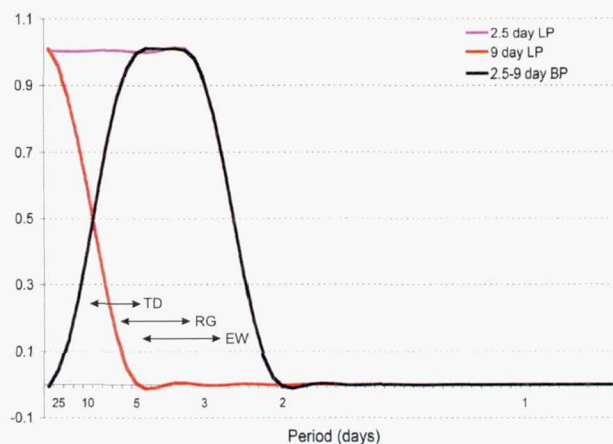
[31]Tropical waves display moist propagation speed even when not coupled to convection if background convection is present (Dunkerton and Baldwin, 1995) so we may regard the incident easterly waves as linearly moist waves prior to their diabatic activation by a proto-vortex in the critical layer. Subsequent to activation, organization of convection by the wave-vortex hybrid implies a "conditional" or phase-dependent diabatic heating (Crum and Dunkerton, 1992, 1993).

Fig. □1. Frequency response of temporal filters used in this study. A low-pass filter (purple□periods longer than ∼2.5 days) describes the total □ow evolution sans high-frequency component. A band-pass filter (black□periods between ∼2.5 and 9 days) captures tropical waves in this frequency range for the purpose of estimating their propagation speed in Hovmöller diagrams. A low-frequency filter (red□periods longer than 9 days) provides an informal estimate of critical latitudes as seen by the waves.

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The time period of interest encompasses a substantial fraction of the hurricane seasons of 1998–2001, the years when the two primary datasets used in our study overlap□ (i) □□A-40 6-hourly re-analyses were used to analy□e tropical waves and nearby circulation. The data are available from □CA□ at multiple pressure levels in T106 spectral resolution (∼1.125×1.125°). Properties of □□A-40 and other analyses (e.g., circulations and physical □u□es) were recently evaluated and compared by □rot□ahn (2007). A 2.5–9 day band-pass filter (□oblas-□eyes and □eque, 1998) was applied to the original data to e□tract wave propagation signals, while a 2.5-day low-pass filtered wind field was used to define the total □ow (i.e., wave □mean fields) in the vicinity of the wave. The response functions of the filters are shown in Fig. A1. It is important to note that the *band-pass* data supply information on wave packet structure and propagation, while the *total* □ow (e□cept for its high-frequency component) defines critical *layers*, stream function or streamlines, □agrangian boundaries, and so forth. *Low-frequency* data (periods longer than 9 days) were used casually to estimate the mean □ow and its critical *latitudes* as seen by the waves, not by individual parcels, which respond instead to the total □ow sans high frequency component. (Parcel displacements are relatively insensitive to high frequency oscillations because they are inversely proportional to intrinsic frequency in linear the-

ory.) (ii) □ainfall data from T□□ □ 3□42[32], available every 3 h and having a spatial resolution of 0.25×0.25°, were used in the study as a pro□y for deep moist convection. The level 3 gridded data are convenient for this purpose but occasionally suffer gaps in coverage owing to the satellite orbit. □□A-40 re-analyses and T□□ □ rainfall are independent data. The time period of □□A-40 used in this study (1998–2001) derives from Stream 1 (1987–2002) which incorporates satellite data from ATOVS, SS□/I and □□S, in addition to satellite data from VTP□, TOVS and cloud motion winds used in Stream 3 (1972–1988). □□A-15 analyses for tropical waves were validated against rawinsonde data by □unkerton and □aldwin (1995). We consider the □C□ WF product to be optimum for synoptic-scale waves, particularly for the rotational component of hori□ontal winds in the lower and upper troposphere and (presumably) for the associated hori□ontal transports of moisture in the lower troposphere as analy□ed in Stream 1. The divergent component is problematic in global analyses, whether from □C□ WF or elsewhere, particularly when associated with deep convection. Vertical motions are not observed directly, but are obtained from a cumulus parameteri□ation. □egions of deep convection, moreover, tend to concentrate vertical motions at the grid scale, making the resulting ma□imum upward velocities resolution-dependent (in such a way as to conserve appro□imately the total vertical *flux* of mass, which is driven by the cumulus scheme). Convective precipitation from T□□ □ is a derived product which we employ here, not for quantitative precipitation, but for geolocation of convecting features relative to the □C□ WF product. It was shown by □ulian (1984) that a deep cloud pro□y (O□□) is correlated with upper tropospheric divergence. □eedless to say, the T□□ □ geolocation (∼25 km) is accurate enough for the purpose at hand. We therefore regard the □u□taposition of □□A-40 and T□□ □ data to be a useful way of relating actual convection (an indicator of T□ development) to actual waves, in the discussion to follow. Forecaster□s best-track data provide a third independent source for genesis location and storm track although as we will argue, their identification of genesis *time* is sometimes delayed, perhaps owing to a conservative mindset[33]. Storm geolocation based on geostationary imagery is accurate to within the nominal 4 km pi□el resolution at the sub-satellite point, superior to any of the other products used in our analysis. August and September were chosen because they represent the peak of the Atlantic hurricane season (□imball and □ulekar, 2004).

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[32]http□//disc.sci.gsfc.nasa.gov/T□□ □/precipitation/trmm_intro. shtml

[33]The best-track (retrospective) estimate of genesis time can be earlier than the initial (real-time) estimate by as much as 2 days. Our point is that, in some cases, even the best-track estimate is late, relative to the analy□ed □agrangian criteria. For westward propagating disturbances, the temporal offset implies a longitudinal offset, which can be as large as ∼20° in e□treme cases.

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3.2 Critical latitude definition

At the critical latitude or level, the intrinsic wave frequency goes to zero. Mean flow and wave phase speed in the direction of wave propagation are equal, i.e., $c = U^* \hat{k}$, where U is the mean vector wind, and $\hat{k}$ is the unit wavevector. For zonally propagating waves, this equation can be simplified, and the critical latitude is defined as the location where $c = U$, where U is the zonal component of mean vector wind.

3.3 Wave tracking algorithm

For quasi-monochromic easterly waves, a semi-automated algorithm was developed in order to track the incident waves and to calculate their zonal phase speeds. The tracking algorithm is based on a Hovmöller diagram of 2.5–9 day band-pass meridional wind along the genesis latitude as identified in the best-track data. The exact choice of latitude is relatively unimportant, as nearby grid points give similar results. What is more important is the choice of genesis *time*, as noted below. First, the location of meridional wind anomalies was determined at genesis time within $\sim16.9°$ (15 grid points) on both sides of the genesis longitude (x). Anomalies were then traced backward in time (t) from this point for 72 h. For such an anomaly to be acceptable it was required that the local maximum and minimum wind perturbations last at least 12 h. To identify wind anomalies which are presumably most directly related to genesis, the time series of maximum and minimum perturbations nearest in x surrounding the genesis point were selected, and two phase speeds, c^+ and c^-, derived based on a linear regression (t upon x) of the areas (in the x, t plane) of southerly and northerly wind perturbations, respectively, exceeding $1\,\text{ms}^{-1}$ in absolute value. Two additional estimates of phase speed were likewise obtained for the period from -48 h to $+24$ h. This procedure for quantifying wave characteristics semi-automatically is similar to that shown in Fig. 11 of Dunkerton and Baldwin (1995). The algorithm as described above was found superior to an alternative procedure following only the local maxima and minima of v' instead of the full anomaly area. If the phase speeds as determined by the tracking algorithm were found to represent adequately the observed wave propagation, as indicated by the slopes of meridional wind anomalies in the Hovmöller diagrams, their average (c_m) was used to define the incident wave phase speed at this altitude. Note that we do not mix adjacent altitudes for this purpose.

Our default was to select phase speeds based on a time period 72 h before genesis. It is preferable to exclude data after genesis because parent waves are often changed by the tropical depression, and new waves excited. In some cases the pre-genesis lifespan of a parent wave is exceptionally short. We allow, therefore, and only where necessary, an alternative definition of phase speed based on data extending from 48 h before best-track genesis to 24 h after genesis. This alternative definition was adopted if and only if one or more of the default values of phase speed were unsuitable, as determined by a visual evaluation of the goodness of fit. It should be noted that best-track data do not necessarily indicate the exact moment of genesis because the time chosen for the first advisory is based on a human decision. The subjective nature of the operational procedure will become evident in one of the cases highlighted below (Chris 2000) wherein a depression-strength closed gyre in the co-moving frame ~30 h prior to "genesis" in the Earth-relative frame.

4 Vertical structure

Prior to genesis, easterly waves are generally confined to the lower troposphere at or below ~500 hPa, with equivalent barotropic structure or slight vertical phase tilt. In some cases the phase tilt in the lower troposphere is observed to change with time during the storm development stage. It is instructive therefore to examine their propagation at two representative levels, 850 and 600 hPa. In most cases analyzed, the same wave packet could be identified at both levels with similar propagation characteristics. Their averaged phase speeds on each level (c_m as defined above) generally differ – usually by a small amount, but sometimes significantly – so in order to handle the latter contingency it is preferable to use the phase speed *at a particular level* when analyzing data at that level, rather than a *blend of phase speeds from different levels* to characterize the incident wave propagation. The vertical structure of tropical waves participating in TC genesis is an interesting part of the marsupial story, and its evolution throughout the depth of the troposphere has several typical characteristics. The transition of wave structure from a trapped UT disturbance to deep "first baroclinic mode" structure immediately before genesis, subsequent vortex shedding in the lower troposphere and radiation of new waves (if any) have been identified using multi-dimensional visualization software from Pixotec. Some aspects of vertical structure are highlighted in Sect. 4.

4.1 Translating coordinate system

A key element in the analysis is the depiction of horizontal flow in a co-moving frame of reference, i.e., moving westward with the parent easterly wave. It should be clear from the opening remarks of Sect. 2 that the critical layer of a traveling wave becomes stationary when viewed in a coordinate system moving horizontally at the phase speed of the wave. The simplest case is a single wave with constant phase speed that is uniform in time and space: the translation speed is then a constant, and whatever unsteadiness remains in the wave field is attributable to amplitude evolution or structural change, rather than phase propagation. An interesting extension is to have a modest spread of frequencies about a central frequency, with the possibility of horizontal dispersion, forming a *wave packet* with group propagation differing from the phase propagation (for a general discussion of

waves in fluids see Lighthill, 1978; for examples of group propagation in tropical waves see Liebmann and Hendon, 1990; Dunkerton and Baldwin, 1995). As long as the packet contains multiple phases in physical space, as implied by a *modest* spread in spectral space, it is appropriate to translate the coordinate system at the dominant phase speed, usually resulting in a non-zero zonal group propagation as viewed in the co-moving frame. Cases of TC genesis involving the intersection of two or more waves with substantially different phase speeds, as sometimes observed in the western tropical and subtropical Pacific, are outside the scope of this paper and will be discussed elsewhere in this series.

The purpose of translating to a co-moving frame is to render wave phases approximately stationary, in order to minimize the temporal evolution of the flow pattern. In steady flow, streamlines are equivalent to trajectories (Holton, 2004). If the flow pattern consists of a steady mean flow and quasi-monochromatic wave, streamlines in a coordinate system moving at the phase speed of the wave may then be used as a surrogate for parcel trajectories. Allowing for a modest dispersion or other kind of amplitude evolution, the temporally evolving streamlines still provide a useful, albeit approximate, depiction of particle paths. For example, if a wave packet in the co-moving frame were to creep slowly eastward, forming new phases to the east while old ones decay to the west (resembling surface waves on water), parcel motions near the longitude of interest could be anticipated simply by waiting for the packet to arrive at that longitude.

Similar reasoning applies to an isolated region of enhanced vorticity, as might be found at the peak amplitude of a wave packet, or in a single wave phase where diabatic amplification is exceptionally strong for whatever reason. Figure 3 illustrates streamlines of a point vortex, with cyclonic circulation, translating to the west (panel a), stationary (b) or translating to the east (c) relative to the fluid. For sake of illustration we are not concerned with *why* the vortex translates, other than to assume that some external agent is responsible for the translation (since left to itself, the vortex would be subject to magnus and advective forces). The vortex-induced flow is a function of $x - C_p t$ – assumed steady, that is, in a frame of reference moving with the vortex at its velocity C_p, while the imposed background flow velocity is U_b. The kinematic parcel displacement field is an intrinsic fluid-dynamical property and therefore depends on the difference $C_p - U_b$ and not on the terms individually. The vortex can be imagined to induce parcel displacements which decrease in amplitude with increasing distance from the vortex center. When the vortex translates zonally in one direction or the other, parcels experience either a temporary influence of the passing vortex (far from center) or are permanently trapped in a vortex-induced gyre (close to center). A bounding streamline separates these outer and inner regions, and a stagnation point exists where vortex and ambient flows cancel. The stagnation point defines the dividing streamline; it is also a *saddle point* of stream function in a

horizontally non-divergent flow. This flow configuration is the point-vortex analogue of the discontinuous Lagrangian mean flow associated with a steady wave critical layer described in Section 2a. What is missing[34] from the point-vortex flow in Fig. 3 (panel b in particular) that was present in the critical layer of Fig. 1 is the *latitudinal shear* (for constant shear, a parabolic y-profile of ambient stream function) that suppresses the meridional component of parcel displacement at large distances from the centerline. Owing to latitudinal shear, the cat's eye has a bounding streamline, whereas the stationary vortex in a resting flow does not. (A train of cat's eyes can be formed by placing equally spaced point vortices along an isotach in parallel shear flow, as shown in Fig. 2.10.1 of Pozrikidis, 1997.) Panels (a) and (c) demonstrate that trapping of parcels nevertheless can occur close to vortex center, without shear, because the nearby influence of the vortex (a singular point) is stronger than that of the vortex-relative background flow U_b. The streamline patterns in Fig. 3 are steady in a frame of reference moving with velocity C_p, matching that of the *vortex* in the same way that the streamline pattern of a nonlinear wave critical layer is steady in a frame of reference moving with the *wave* at its phase velocity C_p. In the properly translating frame, streamlines are therefore equivalent to trajectories.

We may also interpret the panels of Fig. 3 as depicting the instantaneous view of streamlines obtained by observers in different reference frames moving at velocity C_r – whether "translating properly" or not. Note that proper translation requires $C_r = C_p$ whereupon the vortex-induced flow becomes a function of $x_r \equiv x - C_r t = x - C_p t$ and the explicit dependence on t is eliminated. For example, the viewpoint of panel (c) is obtained in the Earth-relative frame for a vortex moving westward in this frame. It is important to note that only one of these viewpoints is "proper" for a particular U_b in the sense that streamlines are equivalent to trajectories only in the frame moving with the vortex, because the vortex-induced flow is steady in this frame only[35]. For

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[34] The critical layer and point vortex also differ in their vorticity distributions and the horizontal flows induced (via PV inversion) by the distributions of vorticity. The steady asymptotic critical layer consists of a constant background *vorticity gradient* plus an east-west train of cat's eyes with homogenized PV within; the point vortex consists of an isolated "PV charge" and constant background *velocity* (the constant cannot be obtained by PV inversion). When the vorticity of the point vortex is distributed monotonically over a finite circular area, a dividing streamline exists if and only if the background velocity does not exceed the maximum wind at the edge of the vorticity distribution.

[35] We should therefore qualify Emanuel's (2005, p. 127) recommendation that *streamlines* – owing to their non-uniqueness – not be used to locate a storm center because, as shown in this paper, a translation speed determined by the parent wave provides a uniquely "proper" view of translating (possibly closed) streamlines that agree with parcel trajectories over a time span of a few days and provide an optimum view of the horizontal transport of adiabatic invariants.

a westward-moving vortex, the stationary (Earth-relative) frame gives a misleading picture of flow kinematics. Figure 3 demonstrates, among other things, that the proper choice of reference frame is essential in order to understand flow kinematics in the neighborhood of the vortex (Ide et al., 2002; K. Ide, personal communication). The number of closed contours and the sense in which the vortex "connects" to the exterior flow (i.e., at the nearest saddle point) obviously depend on the choice of frame. The frame of reference is therefore important for an optimal view of horizontal transport as well. In the context of Atlantic easterly waves we infer, for instance, that if environmental air were moist in one direction (e.g., near the ITCZ) but dry in another (e.g., near the equator), the orientation of the connection might significantly affect diabatic processes regulating the subsequent vortex development (H2). Entrainment of absolute vorticity would be affected similarly in the presence of a mean vorticity gradient (H1). Note also that the translating views of a point vortex introduce a north-south asymmetry, reminiscent of actual easterly wave troughs, that was not present in the idealized critical layer of a shear flow in Fig. 1. The asymmetric structure and existence of a separatrix on one or both sides of the cat's eye proves to be a characteristic feature in many observed genesis events, including western Pacific events (Edson and Vander, 2006).

2.2 Horizontal flow potentials and the choice of "gauge"

For synoptic flows, even in the tropics, the horizontally rotational part is much larger than the horizontally divergent part, with certain exceptions, so that streamlines can be approximated by a *stream function* using the Helmholtz decomposition of the horizontal velocity vector **v**. Crucial to our analysis in Sect. 3 is that the stream function and velocity potential, like any other potential, are known only up to a "gauge", i.e., a function whose horizontal Laplacian is zero and therefore makes no contribution to relative vorticity or divergence, which are Galilean invariant, that is, invariant to a uniform horizontal translation of the coordinate system, as contemplated here. Remarkably, there are an infinite number of stream functions (velocity potentials) that are perfectly consistent with the actual vorticity (divergence). For a quasi-monochromatic wave superposed on a steady mean flow, however, only one choice of translation speed, or gauge, makes sense (viz., that corresponding to a uniform horizontal translation at the phase speed of the wave[36]. By viewing

streamlines in a frame of reference moving with the wave (the "co-moving" frame) we are able to visualize the structure of recirculation regions, their formation and subsequent modification by diabatic vortices, together with the evolution of potential vorticity, moist entropy and other adiabatic invariants in such regions. It should be noted that the although the proper gauge for quasi-monochromatic waves is structurally simple, it is not a trivial constant. For zonally propagating waves, the gauge function varies linearly in latitude, and therefore always changes the stream function pattern, unless zero everywhere (i.e., no translation).

Depending on whether the reader has a degree in physics or meteorology (or both), two analogies may be offered for clarification. One is from electromagnetism: the familiar equations of Maxwell, and the introduction of potential functions to calculate the remote influence of charges that evolve in time. The simplest choice of potential, or Coulomb gauge, is not the best choice for this equation set, because it implies (or seems to imply, at first sight) instantaneous action at a distance; given a certain charge at some point in space, the entire space is seemingly affected at once by the charge, and its time variation. This inference violates the theory of special relativity, overlooking the finite speed of electromagnetic wave propagation, on which the theory is based, as implied by the equations themselves[37]. An alternative potential, or *Lorenz* gauge – which is also *Lorentz* invariant[38] – correctly accounts for the finite propagation speed by building a temporal part into the definition of the potential function – the so-called "retarded potential". This choice of gauge is not obvious from the single equation for electric field induced by a charge, but turns out to be the preferred choice for the whole set of equations; in particular, for the radiation of electromagnetic waves from time-varying distributions of charge. In our case, the proper choice of gauge – a function that converts the stream function into something appropriate for visualizing the Lagrangian flow – is not obvious from a Helmholtz decomposition of the Eulerian flow in a resting frame. Its definition is motivated by the inclusion of a quasi-monochromatic wave in the problem, if the phase speed of this wave is known a priori.

This comment applies equally to genesis and mature stages, although in a fully developed storm the time span is considerably shorter.

[36]A more general construction of Lagrangian boundaries from an Eulerian diagnostic is possible in 2-D and 3-D flows; for some recent ideas see Haller and Yuan (2000) and Green et al. (2006) respectively. By contrast, a local "wave gauge" such as ours is designed to be optimum in one region but not in another, depending on the local wave spectrum. It nonetheless works well for the quasi-

monochromatic cases considered here, aided by the fact that we are targeting a single genesis point in space-time.

[37]The inference is incorrect, and with extra effort (Brill and Goodman, 1967) the Coulomb gauge can be shown to be consistent with the theory of special relativity, a result more easily obtained if the Lorenz gauge is adopted in the first place. It is remarkable though overlooked initially that Einstein's theory of special relativity is contained in Maxwell's equations, insofar as the electric and magnetic permittivities, whose inverse product defines the speed of light squared, are constants independent of the choice of coordinate system, whether moving or not. The moral of this story, and the present one, is that the laws of physics do not change with a coordinate transformation, but some pathways to enlightenment are considerably shorter than others!

[38]http://en.wikipedia.org/wiki/Lorenz_gauge_condition

A second and more familiar analogy is the popular "storm relative velocity" used in the depiction and interpretation of ☐oppler radar re☐ectivity from precipitation cells embedded in mesoscale (convective or stratiform) systems that move hori☐ontally with the synoptic-scale ☐ow. ☐y translating to a co-moving frame defined by motion of the storm system as a whole, it is possible to visuali☐e mesocyclones (important for tornado genesis) and other circulation features associated with the system. The ingredients in this situation are analogous to those of our translating tropical wave critical layer and its incipient tropical depression☐a storm system that is steered at more or less constant speed by the environmental ☐ow, evolving slowly in a frame of reference moving with the ☐ow. ☐se of storm relative velocity is a simple way to minimi☐e the translational evolution of the *pattern* of precipitation cells while retaining the evolution of the cells within the translating pattern.

☐ppendi☐☐

☐dditional cases highlighted

☐ap sequences for the remaining storms highlighted in Fig. 4 are discussed in this Appendi☐, e☐tending the marsupial paradigm to the west Atlantic, ☐ulf of ☐e☐ico and central Pacific.

☐1   ☐est ☐tlantic☐tropical storm ☐hris

A similar story as ☐ebby may be told regarding the birth of Chris, but with an odd twist☐closed gyres are evident at both levels 12–30 h prior to the best-track genesis time, as shown in Figs. ☐1 and ☐2, but by the time the first advisory was issued, the streamlines (and stream function contours) opened up. The genesis location is consistent with that e☐pected from westward translation of the closed gyres from the time of their disappearance. A principal separatri☐ e☐isted 12–30 h before genesis (☐ust to the north of the closed gyre at either level) but is either gone or displaced northward out of the picture by the time genesis was officially declared. A secondary saddle point far to the WSW is present throughout the sequence at either level. It seems odd that a closed gyre does not appear around the best-track genesis point, even though it was present a short time before. A possible e☐planation is that ☐☐A-40 data do not fully resolve the hori☐ontal structure of the tropical depression. ☐ote however that the critical latitude seen by the waves (red curve in final panel☐this quantity is based on 9-day low-frequency data and changes little in 30 h) together with the analy☐ed trough a☐is pinpoints the best-track genesis location to within ∼100 km – as observed at one or both levels in each of the five storms highlighted here. The silver lining in this event may be that we are able to detect a depression-strength closed gyre more than a day in advance of the official time, simply by e☐amining streamlines

in the co-moving frame. A key consideration for operational purposes is that for this technique to be useful in real time, the easterly wave must be identifiable sufficiently in advance☐ identifiable, that is, not only before the *official* genesis time (since the depression at this time would be identified anyway without knowledge of the translating streamlines) but before an *earlier* point in time when we wish to issue a forecast in advance of the first. In so many words, the co-moving frame needs to be determined ahead of time. ☐ittle would be gained by issuing a forecast at the genesis time based on wave information accumulated up to *that* point☐such knowledge is needed well in advance of the official time. With this caveat, an earlier identification of tropical depressions seems possible in cases like Chris.

Streamlines in the resting frame once again are almost useless for this system, as there are no closed streamlines anywhere (Fig. ☐3). The best indication of possible development might have been inferred from a trough e☐tending from SW to ☐☐, a tilted version of the "right-side-up" omega pattern of an isolated vorte☐in the resting frame (Fig. 3). As in ☐ebby, the translating but not resting streamlines provide a reasonably consistent picture of the containment of cyclonic vorticity by a closed gyre (e☐cept for its disappearance in the analyses ☐ust prior to genesis time). The Okubo-Weiss parameter is shown in Fig. ☐2 at the 600 hPa level for the genesis sequence. This quantity highlights regions of strong rotational ☐ow (curvature vorticity), while suppressing the display of shear vorticity in regions of strong shearing deformation (third term of Sect. 4.1) ☐anking the ☐et a☐is[39]. At both levels the center of the cyclonic OW anomaly coincides almost perfectly with the best-track genesis location. A disadvantage of this quantity is that anticyclonic regions are highlighted equally. In general, we e☐pect that OW will be useful for pinpointing genesis, in situations where an elongated vorte☐strip rolls up into one or more closed vortices, by isolating the curved regions of ☐ow at the e☐pense of the elongated features (vi☐, the vorte☐strip that caused roll-up in the first place). Perhaps the most important conclusion to draw from the OW parameter inside the translating gyre is that the ☐ow within is relatively free of strain and shear (☐cWilliams, 1984), favoring nominally the formation of smaller proto-vortical structures within.

With regard to saturation fraction (Fig. ☐4) and precipitation (Fig. ☐5) similar conclusions may be inferred as in the previous case☐convective precipitation moistens the column along an a☐is e☐tending SW-ward from the gyre center while advection carries this moisture to the ☐☐, allowing some to escape the domain while the remaining moisture is contained in the northern half of the gyre. It is difficult to evaluate the containment effect since precipitation is rather constant near the genesis location throughout the sequence. The distribution of precipitation in relation to vorticity is interesting☐an

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[39]Curvature vorticity is useful for this purpose if calculated in the co-moving frame, not the resting one.
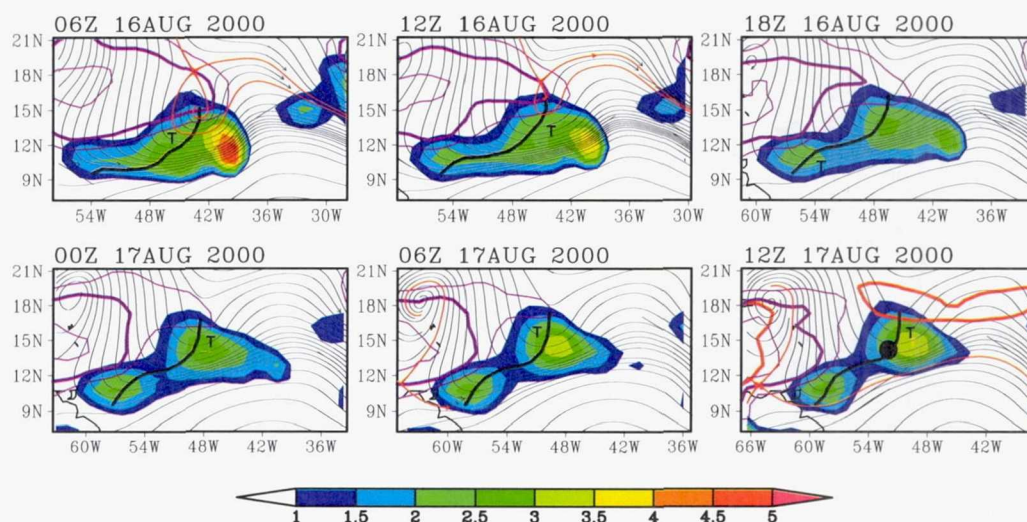
Chris: Zeta (2.5−day LP)

Fig. □1. Streamlines of hori□ontal (rotational □ divergent) □ow at 850 hPa, as seen in □□A-40 data, for si□consecutive analyses leading up to the best-track genesis time of Tropical Storm Chris (2000). Shading indicates relative vorticity (units□ $10^{-5}\,\text{s}^{-1}$). The sequence of frames translates westward at the □onal propagation speed of the parent wave at 850 hPa as estimated from the Hovmöller method ($-9.1\pm1.1\,\text{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame□note that relative vorticity itself is invariant with respect to the translation. Isopleths of □ero relative □onal □ow are shown (purple) together with their uncertainty. In the final panel of the sequence the critical latitude of the parent wave is also indicated (red) corresponding to isopleths of □ero relative □onal □ow in low-frequency data with periods longer than 9 days. The wave□s trough a□is is shown for reference (black). The genesis location is indicated by the black dot in the final panel.

Chris: OW (2.5−day LP)

Fig. □□ Stream function of hori□ontal □ow for the genesis sequence of Tropical Storm Chris as in Fig. 23, but at 600 hPa. Shading indicates the Okubo-Weiss parameter (units□ $10^{-10}\,\text{s}^{-2}$) as defined in □q. (2). This quantity, like vorticity, is invariant with respect to translation, therefore identical in co-moving and resting frames. The sequence of frames translates westward at the □onal propagation speed of the parent wave at 600 hPa ($-8.5\pm0.5\,\text{ms}^{-1}$) and stream function is calculated and displayed in the co-moving frame.
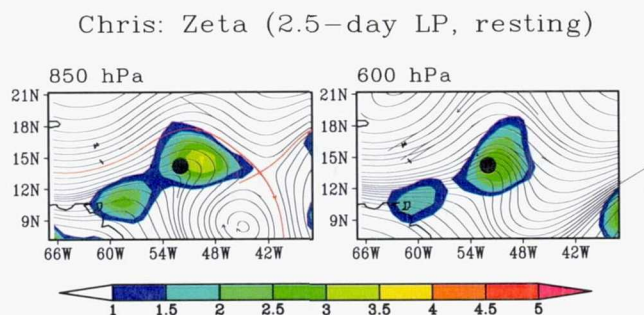
Chris: Zeta (2.5−day LP, resting)

Fig. □□   Streamlines of hori□ontal □ow at **(a)** 850 hPa and (□) 600 hPa at the genesis time of Tropical Storm Chris, in the *resting* frame. Shading indicates relative vorticity (units□ $10^{-5} s^{-1}$) which is invariant with respect to translation, therefore identical in co-moving and resting frames (cp. final panel of Figs. 23, 24).

apparent spatial correlation with shear vorticity (but not OW) early in the sequence, oriented to the SW of center (following the trough a□is□black curve) followed by precipitation at the center only (correlated with OW, but not shear vorticity). There may have been some initial tendency for frontogenesis in the distended □ow along the a□is to the SW, possibly triggering *the deep convection*, but as genesis time approached this convective line was replaced by rotating convection, or convection tied to the rotating □ow near the genesis location.

□□   □ulf of □ e□ico□tropical storm □eryl

Tropical storm □eryl demonstrates that westward propagating anomalies of meridional velocity may in□uence TC genesis as far north as the □ulf of □ e□ico. In this case, however, the incident wave was relatively weak compared to that of the previous e□amples, while propagating into a more comple□ □ow pattern in such a way as to enhance the prevailing vortical □ow, resulting in genesis. The full sequence of events in the translating frame is shown in Figs. □6 and □7 at the 850 and 600 hPa levels, respectively. The viewpoint in the resting frame at genesis time only is shown at these two levels in Fig. □8. Since the translation speed is relatively small in this case, compared to the previous e□amples, either reference frame (translating or resting) is able to capture the closed gyre and correctly anticipate the genesis location and time. Close inspection of Fig. □8, however, once again reveals a slightly misaligned streamline pattern, implying a first-order vorticity advection that does not e□ist in the co-moving frame. As noted in □ebby, the □arth-relative □ow is responsible, in part, for hori□ontal translation of the pattern – a detail that is irrelevant to the internal dynamics and tends to obscure the in situ evolution. One could argue that a proper frame of reference is superior, even in cases with smaller translation speed, like □eryl[40]. In the co-moving frame the

principal saddle point e□ists to the □□ of the closed gyre and a secondary saddle is located to the SW. A second and fairly significant gyre e□ists in the SW corner of the figures, making the entire pattern look like a critical layer aligned from SW to □□, tilted ~45° relative to a latitude circle. The incident wave alone cannot e□plain this pattern. Without further analysis (outside the scope of this paper) it is difficult to say how much of the □ow kinematics should be attributed to the prevailing □ow and to what e□tent this □ow was altered by the incident wave, other than to amplify the "pocket" of cyclonic vorticity that eventually became a closed circulation. The transition from a linear vorticity pattern to a more circular one at the end of the sequence suggests that the incident wave was instrumental not only in enhancing the local vorticity ma□imum but also in altering the □ow topology around this ma□imum in such a way as to produce a much larger region of closed recirculating □ow than was present initially. This contribution is apparent at both levels. The prevailing distributions of saturation fraction (Fig. □9) and precipitation (Fig. □10) display a persistent ribbon, or in □ewell□s terminology (□hu and □ewell, 1999) a "river" of moisture along the same SW-□□ a□is as the prevailing critical layer. As with vorticity, the shape of the moist convecting region is altered from an e□tensive linear pattern (aligned from SW to □□) to a more confined circular patch – all of this *before* best-track genesis. We are evidently dealing with a more comple□ situation than imagined in our simple scenario outlined in Sect. 2 and as illustrated by the preceding e□amples in the central Atlantic. □onetheless, the gyre circulation in this event displays a tantali□ing relationship to the prevailing moisture and convection that was also seen in the simpler cases highlighted above□*the closed gyre evidently forms at, or close to, a boundary between relatively wet and dry air.* □y the end of the sequence (genesis time) the moisture and its associated convection have engulfed most of the enclosed circulation. Is there something about the initial moisture gradient that is instrumental either in the formation of a closed circulation pattern or in the genesis to follow□ The e□ample of Fabio (Sect. 3) from the eastern Pacific, provided another illustration of this *intriguing relationship and piques our curiosity further.*

□□   □entral □aci□c□super typhoon □hanshan

The sequence of events prior to the birth of Shanshan illustrates vorte□roll-up similar to that of Fabio, but more clearly. Also illustrated clearly is a vertical phase tilt of the parent wave that changes in time, towards a vertically aligned arrangement at genesis time. The 850 hPa □ow, shown in Fig. □11, consists of a band of vorticity that acquires a more circular symmetry as time proceeds. It appears from Fig. 4i, □that a weak wave propagating at 850 hPa from the east intersected a stronger wave (or instability□) to the west of

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[40]The □arth-relative frame, however, may be important for evaluation of surface □u□es, as elaborated in our response to an Interactive Comment.

Atmos. Chem. Phys., 9, 5587–5646, 2009   www.atmos-chem-phys.net/9/5587/2009/

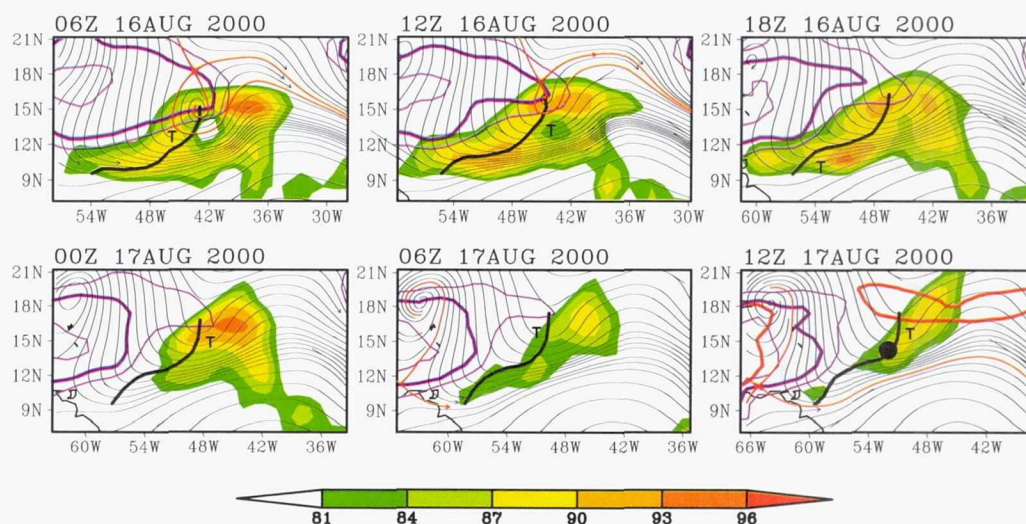48

Chris: SF (2.5−day LP)

Fig. ☐4. Streamlines of hori☐ontal ☐ow at 850 hPa for the genesis sequence of Tropical Storm Chris as in Fig. 23, with high values of ☐☐A-40 saturation fraction indicated by shading (units☐percent).The sequence of frames translates westward at the ☐onal propagation speed of the parent wave at 850 hPa (-9.1 ± 1.1 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame.
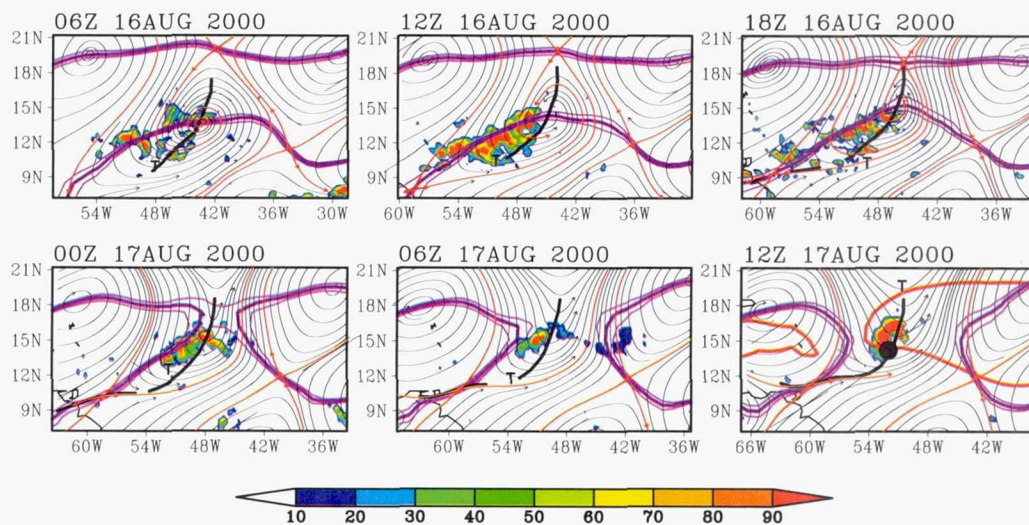
Chris: TRMM (2.5−day LP)

Fig. ☐☐ Streamlines of hori☐ontal ☐ow at 600 hPa for the genesis sequence of Tropical Storm Chris as in Fig. 24, with high values of T☐☐ ☐ 3-h accumulated precipitation indicated by shading (units☐mm/day). The sequence of frames translates westward at the ☐onal propagation speed of the parent wave at 600 hPa (-8.5 ± 0.5 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame.

the genesis location, also with westward phase propagation, but apparent eastward group propagation at 600 hPa. The proper choice of translation speed is more difficult to determine in this case compared to the preceding e☐amples. As e☐pected from a relatively fast westward translation, the pattern of 600 hPa streamlines in the co-moving frame, shown

in Fig. ☐12, looks markedly different than either the corresponding pattern at 850 hPa (with slower translation speed) or those at either level in the resting frame (as shown in Fig. ☐13 for the genesis time only). The translating and resting patterns at 850 hPa are similar because the translation speed is slow – the slowest of any of the e☐amples thus far.
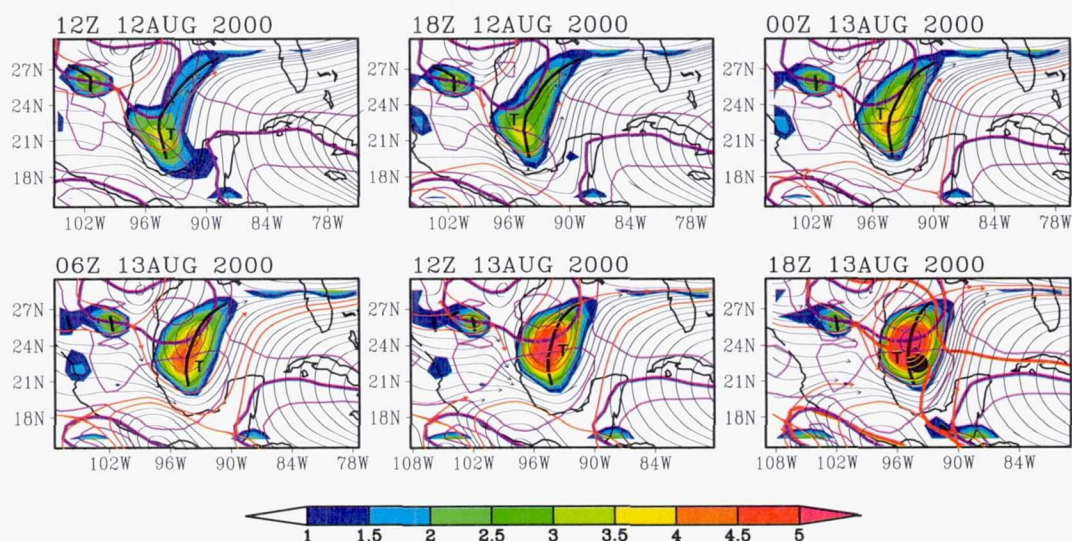
Beryl: Zeta (2.5−day LP)

Fig. ☐☐ Streamlines of hori☐ontal (rotational ☐ divergent) ☐ow at 850 hPa, as seen in ☐☐A-40 data, for si☐consecutive analyses leading up to the best-track genesis time of Tropical Storm ☐eryl (2000). Shading indicates relative vorticity (units☐10^{-5} s^{-1}). The sequence *of frames translates westward at the ☐onal propagation speed of the parent wave at 850 hPa as estimated from the Hovmöller method* (-3.8 ± 2.8 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame☐note that relative vorticity itself is invariant with respect to the translation. Isopleths of ☐ero relative ☐onal ☐ow are shown (purple) together with their uncertainty. In the final panel of the sequence the critical latitude of the parent wave is also indicated (red) corresponding to isopleths of ☐ero relative ☐onal ☐ow in low-frequency data with periods longer than 9 days. The wave☐s trough a☐is is shown for reference (black). The genesis location is indicated by the black dot in the final panel.

Beryl: Zeta (2.5−day LP)

Fig. ☐7. Streamlines of hori☐ontal ☐ow for the genesis sequence of Tropical Storm ☐eryl as in Fig. 28, but at 600 hPa. Shading indicates relative vorticity (units☐10^{-5} s^{-1}). The sequence of frames translates westward at the ☐onal propagation speed of the parent wave at 600 hPa (-3.1 ± 0.8 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame.
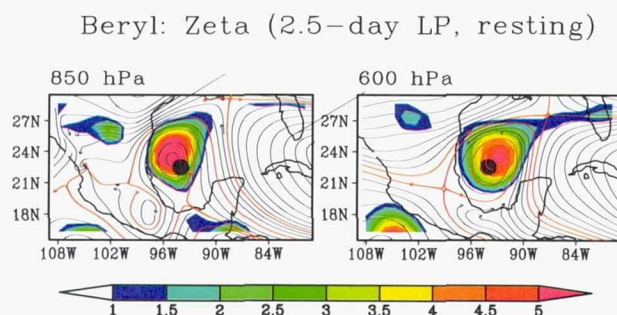
Beryl: Zeta (2.5−day LP, resting)

Fig. □□ Streamlines of hori□ontal □ow at **(a)** 850 hPa and (□) 600 hPa at the genesis time of Tropical Storm □eryl, in the *resting* frame. Shading indicates relative vorticity (units□ 10^{-5} s^{-1}) which is invariant with respect to translation, therefore identical in co-moving and resting frames (cp. final panels of Figs. 28, 29).

□ither choice, translating or resting, yields a closed gyre (although the gyre at 600 hPa is much larger in the co-moving frame) and the relationship of streamlines and vorticity contours is plausible either way. The deciding factor at 600 hPa is the e□istence of a second gyre near 165° □ that is absent in the resting frame. In the left half of Fig. □12f we see the familiar cat□s-eye pattern aligned in the □onal direction, as in the ideal case (Fig. 1). The □□A-40 analyses in this case do not seem able to capture much of the structure in saturation fraction, other than a general moistening along the southern half of the □onally elongated closed gyre at 850 hPa (not shown). The distribution and evolution of T□□□ precipitation in this case is similar, nonetheless, to that of Fabio as shown in Fig. □14, with ITC□ convection gradually replaced by convection predominantly in the closed gyre as visuali□ed in the co-moving frame at 600 hPa. The e□cellent correspondence of convection and closed circulation in the co-moving frame (absent in the resting frame) further supports our preference for the co-moving frame in this instance. It is not uncommon for easterly waves and/or ITC□ to e□tend into the central Pacific from the east, so it is plausible that genesis occurred in a manner similar to the easterly wave cases highlighted above. Whether characteri□ed primarily as "incident waves from upstream" or as "in situ instability of the ITC□" their westward phase propagation plays a key role in the genesis sequence.

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Topological aspects of the marsupial paradigm

The evolution to a tropical depression evidently requires formation of closed streamlines in the co-moving frame, comprising a westward-moving cyclonic gyre at meso-α. In □□A-40 analyses, closed streamlines are observed prior to T□ formation as declared officially, sometimes by 30 h or more. In the quasi-monochromatic cases e□amined here,

we have identified the tropical wave critical layer with these closed streamlines, known in nonlinear critical layer theory as "□elvin cat□s eyes". One or more cat□s eyes aligned □onally are present prior to genesis in virtually all cases. Formation of closed streamlines is also common in quasi-2-□ turbulence and involves, as it were, the creation of new vorte□ coordinate system when a hyperbolic critical point appears in the □ow. It is at this point that the □acobian of the mapping from isentropic PV (or isobaric vorticity) to physical coordinates becomes singular as material contours connecting the vorte□ to its parent □ow are distended into a thin, wispy filament. For practical purposes (as accomplished, e.g., by contour surgery) we end up with a detached vorte□ with its own identity and closed isopleths of PV (vorticity). In the co-moving frame the good agreement between vorticity isopleths and streamlines or stream function contours, and the near-coincidence of gyre center with eventual TC development in most cases, confirms our choice of translation speed or "gauge" and strongly suggests that the □ow kinematics within the critical layer in□uence mesoscale developments subsequent to gyre formation. Our first hypothesis (H1) is confirmed by these observations.

In a nonlinear critical layer the □agrangian mean □onal □ow is asymptotically discontinuous at the edge of the cat□s eyes (Fig. 1□Andrews and □cIntyre, 1978) indicating the creation of three separate air masses. In cyclonic latitudinal shear the cat□s eyes themselves are cyclonic and their isolation effectively separates air within from the e□terior □ow. Thus, even though an *easterly* □et (e.g., A□□) does not afford the same barrier to meridional transport[41] as typical of *westerly* □ets in rotating planetary atmospheres (□unkerton and Scott, 2008) the critical layer south of the □et a□is may protect a proto-storm from dry air to the north, air often associated with the Saharan Air □ayer (SA□). Such protection is available only if persistent waves e□ist on the □et with amplitude that is neither too small (as to be insignificant) nor too large (as to draw air from the SA□ north of the □et a□is)[42].

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[41] Among the reasons cited by □unkerton and Scott for the apparent transport barrier is the fact that a westerly □et core on a stable gradient of PV cannot be the locus of a free □ossby wave critical level/latitude□therefore, isopleths of PV tend to remain elastic at this location (□cIntyre, 2003) and irreversible displacements, if any, are limited in meridional e□tent (e.g., Panetta, 1993). This situation contrasts with an easterly □et core, which can serve as the locus of instability with critical level/latitude near the core (□ind□en et al., 1983) or (if stable) the locus of critical-layer development owing to the weakness of shearing deformation along the □et a□is (□runet and Warn, 1990□□runet and Haynes, 1995). Whatever barriers to meridional transport that might arise on an easterly □et will depend on the *inhomogeneity* of stirring owing to the finite e□tent of the critical layer.

[42] □arge-amplitude easterly waves, that is, with large meridional e□tent, may be ineffective for TC genesis owing to the latter reason. These waves are often observed to precede a new SA□ air mass as it sweeps across the tropical Atlantic.
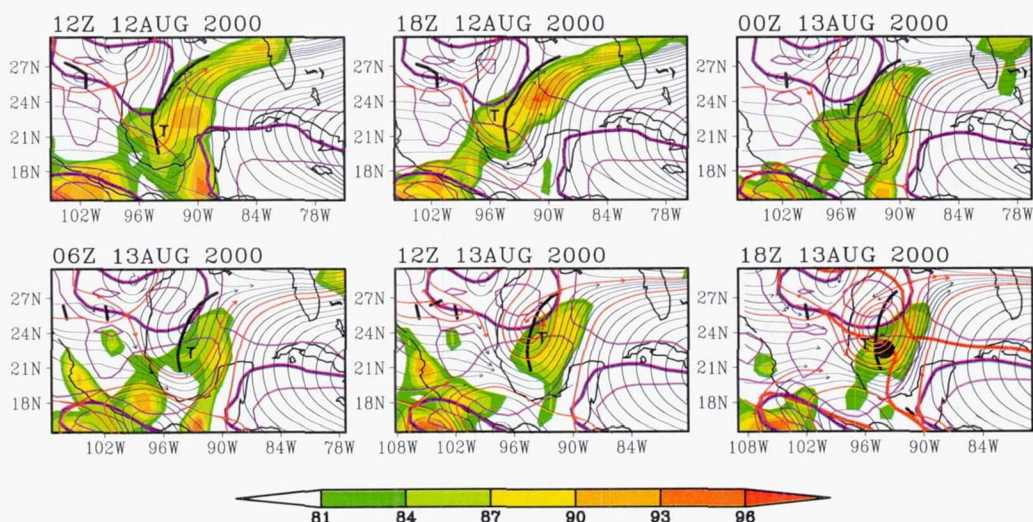
Beryl: SF (2.5−day LP)

Fig. ⬚⬚ Streamlines of hori⬚ontal ⬚ow at 850 hPa for the genesis sequence of Tropical Storm ⬚eryl as in Fig. 28, with high values of ⬚⬚A-40 saturation fraction indicated by shading (units⬚percent).The sequence of frames translates westward at the ⬚onal propagation speed of the parent wave at 850 hPa ($-3.8\pm2.8\,\mathrm{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.
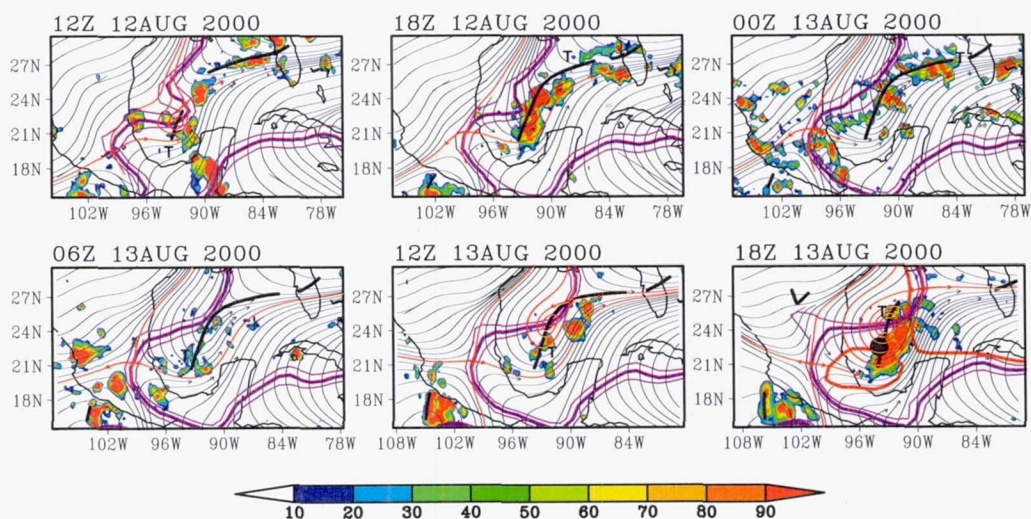
Beryl: TRMM (2.5−day LP)

Fig. ⬚1⬚ Streamlines of hori⬚ontal ⬚ow at 600 hPa for the genesis sequence of Tropical Storm ⬚eryl as in Fig. 29, with high values of T⬚⬚⬚ 3-h accumulated precipitation indicated by shading (units⬚mm/day). The sequence of frames translates westward at the ⬚onal propagation speed of the parent wave at 600 hPa ($-3.1\pm0.8\,\mathrm{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.

In real life the ideal critical layer sometimes appears, with several ⬚elvin cat⬚s eyes in the row, but more often takes the form of an isolated vorte⬚ surrounded by an asymmetric "teardrop". For both types of streamline configuration, the ⬚ow kinematics are very different when viewed in co-moving and resting frames. The orientation of separatri⬚ in the co-moving frame, connecting the proto-vorte⬚ to the e⬚-

terior ⬚ow to the east, north or west, but not south[43] of the

[43]Streamlines of the resting frame are misleading in this respect⬚ an upright omega pattern with separatri⬚ (if any) oriented south of center is usually implied, consistent with Fig. 3c. The similarity of this pattern to the distribution of moisture and low cloud is an unfortunate coincidence, but with careful analysis, a ⬚onal phase lag of $\sim$1/4 wavelength can be detected.

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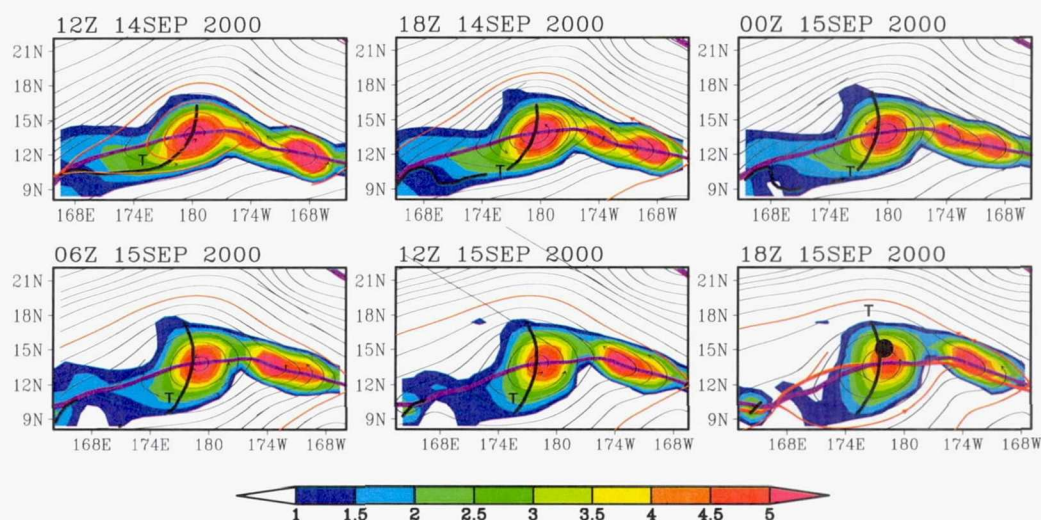
52

Shanshan: Zeta (2.5−day LP)

Fig. □11. Streamlines of hori□ontal (rotational □divergent) □ow at 850 hPa, as seen in □□A-40 data, for si□consecutive analyses leading up to the best-track genesis time of Super Typhoon Shanshan (2000). Shading indicates relative vorticity (units□10^{-5} s^{-1}). The sequence of frames translates westward at the □onal propagation speed of the parent wave at 850 hPa as estimated from the Hovmöller method (-2.8 ± 0.3 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame□note that relative vorticity itself is invariant with respect to the translation. Isopleths of □ero relative □onal □ow are shown (purple) together with their uncertainty. In the final panel of the sequence the critical latitude of the parent wave is also indicated (red) corresponding to isopleths of □ero relative □onal □ow in low-frequency data with periods longer than 9 days. The wave□s trough a□is is shown for reference (black). The genesis location is indicated by the black dot in the final panel.
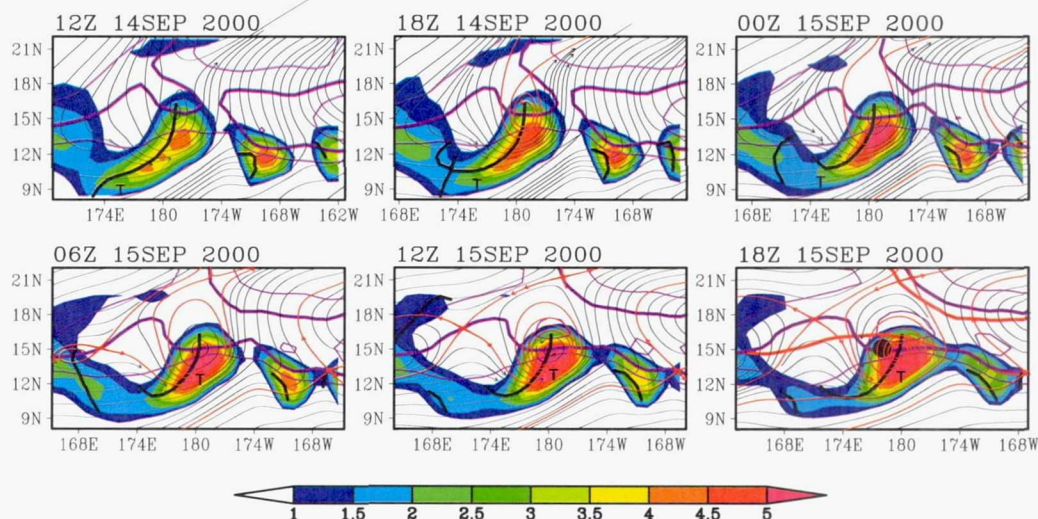
Shanshan: Zeta (2.5−day LP)

Fig. □1□ Streamlines of hori□ontal □ow for the genesis sequence of Super Typhoon Shanshan as in Fig. 33, but at 600 hPa. Shading indicates relative vorticity (units□10^{-5} s^{-1}). The sequence of frames translates westward at the □onal propagation speed of the parent wave at 600 hPa (-5.7 ± 2.8 ms^{-1}) and streamlines are calculated and displayed in the co-moving frame.
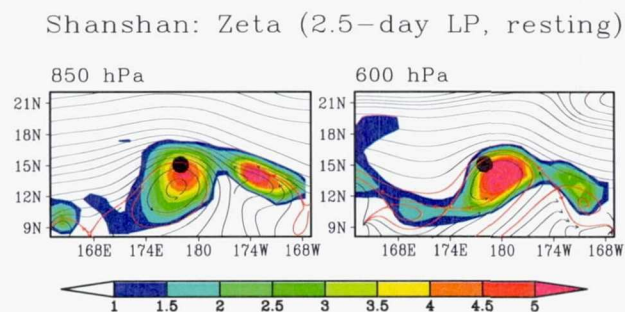
www.atmos-chem-phys.net/9/5587/2009/ Atmos. Chem. Phys., 9, 5587–5646, 2009

53

Shanshan: Zeta (2.5−day LP, resting)

Fig. ⬚1⬚ Streamlines of hori⬚ontal ⬚ow at **(a)** 850 hPa and (⬚) 600 hPa at the genesis time of Super Typhoon Shanshan, in the *resting* frame. Shading indicates relative vorticity (units⬚10^{-5} s^{-1}) which is invariant with respect to translation, therefore identical in co-moving and resting frames (cp. final panels of Figs. 33, 34).

gyre center, has two implications⬚

1. The critical latitude of stable waves lies equatorward of the in⬚ection point where cyclonic vorticity is ma⬚i-mum, therefore the developing gyre is able to tap the relatively high vorticity that e⬚ists near the in⬚ection point closer to the a⬚is of the ⬚et[44].

2. Air entering the gyre, for the most part, is not coming from points far to the south, whether wet (as from a distant ITC⬚) or dry (as from the equator). Instead – consistent with our comparison of the analy⬚ed saturation fraction and observed precipitation – moisture is provided to the gyre by moist convection directly. In some cases lateral entrainment of moisture from a nearby ITC⬚, slightly south of center, also promotes saturation of the gyre.

⬚oisture in⬚ected into the free troposphere above the boundary layer by deep convection is then transported hori⬚ontally, some of it remaining in the gyre, some of it escaping the region of interest. When ambient moisture is also available, it is entrained passively into the cat⬚s eye along with

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[44] A disturbance growing on an unstable meridional gradient of PV would tap mean vorticity at the in⬚ection point *equatorward* of its critical level. The observed distribution of separatri⬚ location does not preclude instability altogether, but seems to argue against this simplest of instability configurations in the conte⬚t of TC genesis. A separatri⬚ slightly south of centerline suggests instability originating from a vorte⬚strip to the south, as in ideal simulations of the breakdown of the ⬚orthern Hemisphere ITC⬚ (Wang and ⬚agnusdottir, 2005, 2006). ⬚ut in most cases there is some ⬚onal variation of the basic state to contend with. A broader definition of "instability" should include (i) eddy shedding *to the west* of a moist vorte⬚strip (as in the African/Atlantic sector) or (ii) unstable interaction between a monsoon gyre and waves incident *from the east* (as in the western Pacific). These scenarios, together with our neutral wave scenario, help to account for separatri⬚orientations to the east, north and west of gyre center.

cyclonic vorticity, from ad⬚acent environments (convergence ⬚one or monsoon gyre to the east or west) in which these two variables are positively correlated above the boundary layer. Whether or not entrainment of pre-e⬚isting moisture is significant, the ⬚agrangian boundaries of the developing gyre serve to protect this region from lateral intrusions of dry air. Thus, the same convection that aids the development and concentration of cyclonic vorticity also provides moisture to the column, maintaining the preference for convective over stratiform precipitation – a preference, we have argued above, that favors low-level development. Our second hypothesis (H2) is confirmed, in part, by the ⬚u⬚taposition of analy⬚ed moisture (⬚⬚A-40) and observed deep convective precipitation (T⬚⬚ ⬚) within the gyre. The morphology of deep convective and stratiform cloud, and inferred profile of diabatic heating in the gyre, also support H2.

In freely evolving 2-⬚ turbulence or in nonlinear waves on a shear ⬚ow, closed recirculation regions occur as a result of hori⬚ontal advection induced by the PV itself. Such features are relatively long-lived and robust in their inner core ("coherent structures") while contributing to deformation (or instability) on their ⬚anks and in the neighboring ⬚ow. In some sense, coherent structures can be said "to contribute to the forward enstrophy cascade while remaining immune from its immediate effects." In the ideal nonlinear ⬚ossby-wave critical layer it is remarkable that the PV responsible for the ⬚elvin cat⬚s eye is located in the outer, not inner, region⬚associated, that is, with the large-scale wave and not with the evolving spiral of PV in the cat⬚s eye. This property arises from the morphology of the displacement field near the critical latitude⬚its local amplification owing to small intrinsic frequency. The same consideration forming the basis of our third hypothesis (H3) is also responsible for the predetermined "wire-frame" structure of streamlines in and around the ⬚elvin cat⬚s eye. In the conte⬚t of TC genesis we infer, then, that the details of potential vorticity and PV concentration in the proto-vorte⬚ are of secondary importance to the critical layer itself. This organi⬚ing principle has a finite lifespan and is eventually superceded in the TC intensification phase when the storm⬚s own PV begins to control the outer environment, leading to the demise of the parent wave and possible e⬚citation of new waves. Our analysis of pre-genesis environments has demonstrated (i) the robustness of the tropical wave critical layer as well as (ii) its contribution to vorticity/moisture entrainment/containment and (iii) protection of the proto-vorte⬚ from the e⬚terior ⬚ow. These properties suggest a role for the forward enstrophy cascade in TC genesis e⬚tending beyond the formation of a tropical wave critical layer in the first place. In the real world, however, simple analogies with waves and 2-⬚ turbulence are inadequate, owing to moist diabatic processes associated with deep convection, an essential ingredient in proto-vorte⬚development. Hori⬚ontal advection by synoptic and meso-α motions alone cannot account for TC formation, even though they are e⬚pected to create variance at meso-β

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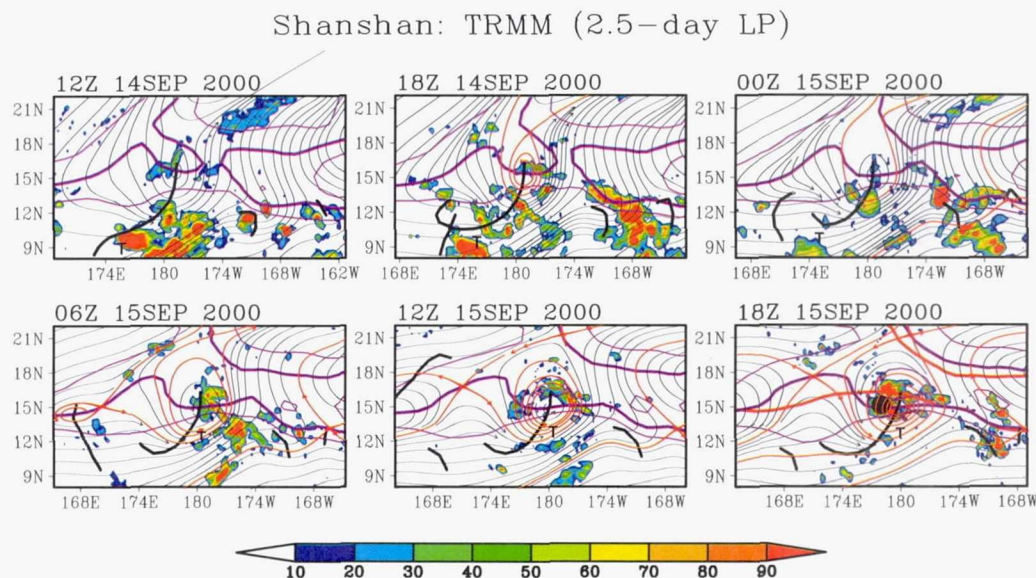
54

Shanshan: TRMM (2.5−day LP)

Fig. ⬜14. Streamlines of hori⬜ontal ⬜ow at 600 hPa for the genesis sequence of Super Typhoon Shanshan as in Fig. 34, with high values of T⬜⬜⬜ 3-h accumulated precipitation indicated by shading. ⬜nits⬜mm/day. The sequence of frames translates westward at the ⬜onal propagation speed of the parent wave at 600 hPa ($-5.7\pm2.8\,\mathrm{ms}^{-1}$) and streamlines are calculated and displayed in the co-moving frame.

via the forward enstrophy cascade. In discussing vorticity evolution and the topology of streamlines it is essential to distinguish the tropical cyclone from the sub-synoptic gyre in which it forms⬜

1. In tropical cyclones, isolated vortices are significantly amplified by diabatic processes associated with deep moist convection. It is impossible to obtain the values of vorticity observed in these systems by advective rearrangement alone⬜cloud system processes enhance vorticity by tilting and stretching of vorte⬜tubes (on the order of 100 times ambient values⬜⬜06). This chain of events is itemi⬜ed in our response to Interactive Comment 4. It is thought by nearly everyone (by top-down and bottom-up schools, in diabatic ⬜kman turbulence and VHT pathways) that vortices created on the cloud-system scale undergo hori⬜ontal upscale aggregation subsequently to form the tropical cyclone⬜this aggregation further organi⬜es deep convection and vorte⬜-scale convergence due to the radial overturning circulation.

2. In the marsupial paradigm, the creation of an isolated vortical air mass by advection in the hori⬜ontal plane pertains not to the tropical cyclone itself, but to the gyre in which TC formation may subsequently occur. (The role of upscale aggregation in the critical layer will be discussed in our modeling study.) We believe that whereas upscale aggregation of vorticity and its amplification by deep convection are essential to TC formation, they are not entirely responsible for the formation of a

closed tropical depression in the first place. This formation is at least partly due to the dynamics of moist waves and involves a direct enstrophy cascade from larger synoptic-scale disturbances to mesoscale vorticity anomalies. This argument rests on the coherent relationship observed between the critical layers of tropical waves and tropical cyclogenesis events occurring in such regions. Storm formation at or near the center of the translating gyre in many cases seems almost uncanny and suggests to our minds an invisible "guiding hand" from synoptic and meso-α scales.

It should be noted that a *predominant* role of the ⬜elvin cat⬜s eye is assigned to the time period leading up to and immediately following genesis. An intensifying storm is distinguished by its increasingly intense concentration of potential vorticity substance, and increasing autonomy as a result. It is a remarkable property of the point-vorte⬜train in parallel shear ⬜ow (Po⬜rikidis, 1997) that a similar cat⬜s eye pattern is produced without any outer disturbance at all. This similarity suggests an almost seamless transition from tropical wave critical layer to (one or more) tropical depressions. We con⬜ecture that the emergence of a developing storm and demise of the parent wave may be identified with such a transition, and quantified by its vorticity concentration relative to that of the original critical layer (as measured, say, by rms values within). This area of research merits further study.

Firmly established in our observations of gyres in the co-moving frame is that the advective rearrangement of vorticity draws air with cyclonic vorticity into the cat⬜s eye from an in⬜ection point north of the critical latitude (in

hydrodynamically stable cases) supporting H1. Such a transport pathway, visible in the co-moving frame but oblivious to observers in the resting frame, does not immediately suggest moistening of the gyre by hori□ontal advection from a distant ITC□ to the south, nor drying from the equator. The topology of unstable cases differs, with one or more connections slightly south of centerline, suggesting that a developing gyre may entrain moisture from a nearby ITC□ to the south. When this pathway is available, entrained moisture accelerates the approach to column saturation. It was suggested in Sect. 2.2 that chaotic advection associated with mesoscale circulation anomalies may dilute or delay moistening of the cat□s eye by deep moist convection. We neglected to say at that point, by way of speculation, that the same anomalies may create *low-level vorticity boundaries* within the cat□s eye that stimulate deep convection via □k-man pumping, providing in situ moistening of the column, an essential ingredient in H2. This is one of a limited number of mesoscale mechanisms that may link chronologically the formation of a closed gyre at meso-α with TC genesis at meso-β. *Another mechanism relies on lateral confinement of small-scale waves e□cited by convection in the proto-vorte□* (□itchie et al., 2003). A third mechanism assists development by lateral confinement of out□ow boundaries (□ 06). All three mechanisms involve some degree of "imbalance" due to boundary-layer drag, inertia-gravity waves or density currents in the lower troposphere. The first mechanism (□k-man triggering) is likely to dominate in a rotating environment approaching column saturation, while the latter mechanisms (involving waves or density currents) typify convective clouds in a sub-saturated environment, with their downdrafts and cold-pool out□ow. Out□ow boundaries in SA□ imagery are distinctly absent in the inner core of developing storms but commonly seen in the outer bands (□atsaros et al., 2000□□lack et al., 2005□□unkerton et al., 2009b). From these precious observations we infer that successful development entails a transition from (i) a canonical □CS mi□ture of updrafts and downdrafts (with unbalanced motions in all a□imuthal directions having a negative net impact on boundary-layer moist entropy) to (ii) a smoother and more a□ially symmetric in-up-out meridional overturning circulation organi□ed and maintained by a combination of interior heating and □kman convergence. The radial in□ow and resulting tangential circulation assist further development by wind-induced surface evaporation.

A curious observation especially over the eastern Pacific is that the location of TC genesis often lies on or very near a boundary between moist and dry air in the environmental □ow. Without further study it is unclear what impact this moisture boundary has either on the dynamics of the incident wave (instability) or the development of coherent structures on the mesoscale. It seems possible that the ambient moisture and its hori□ontal transport in such situations have a greater role to play than implied in the preceding discussion. A closed gyre with ∼50□ overlap of an initially moist region inevitably will entrain the e□isting moisture in addition to any further moistening by deep convection triggered by the development of the gyre. Such entrainment, as already noted, shortens the time required to saturate the column. This argument does not account, however, for the overlap of gyre and moisture gradient in the first place. Perhaps the moisture gradient is helping to define the effective moist PV gradient (Sobel et al., 2001) seen by the incident wave (instability) and the resulting selection of phase speed, hence, critical latitude. □ore investigation of this observation is warranted.

An over-arching conclusion emerging from this study regarding easterly waves – whether neutral waves, quasimodes, or hydrodynamic instabilities – is that the □u□taposition of wave critical latitude, in□ection point, and moisture gradient (if any) is centrally important to genesis. The first and most easily appreciated conclusion is that the critical latitude south (not north) of the easterly □et a□is is the locus of cyclonic vorticity and its subsequent amplification. The second and less obvious conclusion, which becomes obvious in the co-moving frame, is that a neutral or slowly-decaying quasi-mode having its dominant phase speed *outside* the range of mean □ow speeds within the region of reversed potential vorticity gradient is able to tap the mean cyclonic vorticity near the in□ection point of the □et. In stable cases (□orthern Hemisphere) streamlines in the co-moving frame connect northward (via the hyperbolic point) – not southward, as implied in the resting frame. Standard meteorological charts in the □arth-relative frame completely obscure the point. This situation contrasts with that of an unstable disturbance with critical latitude *inside* this range, closer to the □et a□is. In unstable cases, streamlines in the co-moving frame connect to the south, although the separatri□ orientation may be shallow (□S□ or WSW) once the disturbances reach finite amplitude, forming a "curved teardrop" shape poleward of the original location of the ITC□. A possibly significant role for hydrodynamically *stable* waves in this conte□t is counter-intuitive□one might be tempted to think that large-scale instability implies a more vigorous sequence of events that would lead to genesis more readily than what might be triggered by a neutral or slowly decaying wave. □ut we must be willing to entertain less intuitive ideas in order to understand the possible preference for neutral or slowly decaying modes in TC genesis. (i) These modes are maintained by diabatic heating (H3) in addition to their "dry" maintenance (compact spectral content). (ii) □enesis is an interactive multi-scale process and not simply a consequence of moist hydrodynamic instability. If the quasi-mode configuration as described above favors mesoscale development, then it may actually be more favorable for genesis than a more vigorous unstable wave. Oddly enough, the fact that the instability paradigm in reality applies only to a minority of cases seems to support such counter-intuitive thinking.
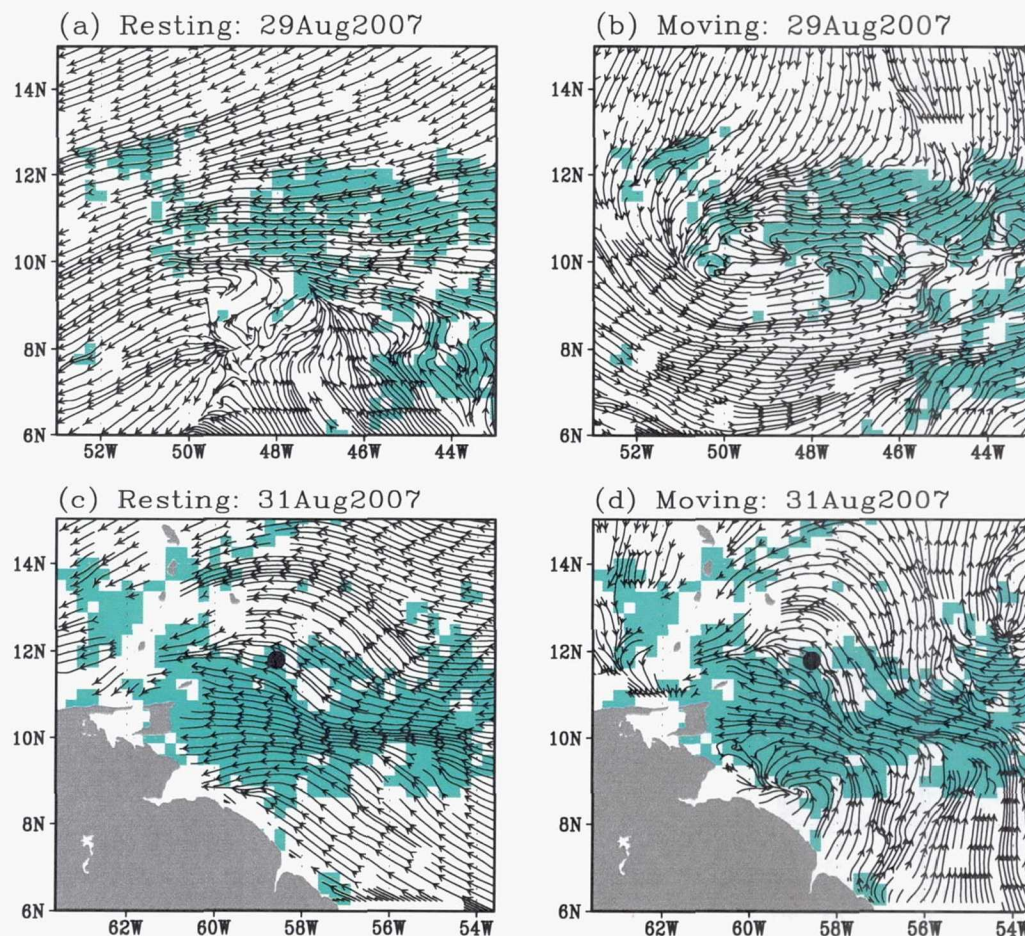
Fig. ⬚1. Streamlines of surface ⬚ow obtained from ⬚uikSCAT images of Hurricane Feli⬚(2007) in late August 2007. **(a, c)** ⬚esting frame⬚ **(⬚, d)** co-moving frame (C_p ⬚−6.7±0.5 ms^{-1}). ⬚egions of possible rain contamination are indicated by cyan shading.

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Translation of non-se⬚uential imagery

Our method for translation of analyses and imagery into a co-moving frame of reference following the parent wave is easily applied to non-sequential images (e.g., sparse or irregular temporal sampling from polar-orbiting satellites) if the wave⬚s propagation speed and direction are known from other data sources. For historical cases a retrospective estimate of C_p is straightforward (see te⬚ t) whereas in real-time applications a one-sided estimate should suffice. In either event, analyses from meteorological centers and global forecast models will provide the requisite information about waves. The e⬚istence of a closed gyre is insensitive to small ($\sim$1 ms^{-1}) errors in the estimate of C_p while its e⬚act location and orientation of ⬚ow separatri⬚are more sensitive to this choice. ⬚arger errors are fatal⬚as demonstrated in Sect. 3, ma⬚or differences generally e⬚ist between streamline and stream function patterns in a resting frame (C_p ⬚0)

and a frame of reference moving westward at a speed typical of Atlantic easterly waves ($C_p \sim$−5 to −10 ms^{-1}). We suggest a rule of thumb that a priori information of waves be good enough (sufficiently large and/or persistent waves, plus reliable analysis) to specify C_p to within 1–2 ms^{-1}. If this criterion is met, a simple correction to the resting view of non-sequential imagery can be made if the speed of incident waves is reasonably constant. We illustrate the effect of translation on the surface wind field obtained from a ⬚uikSCAT image of Hurricane Feli⬚(2007) in the western Atlantic/eastern Caribbean Sea (Fig. ⬚1). Feli⬚was born within an easterly wave with phase speed typical of central Atlantic waves ($C_p = $−6.7±0.5 ms^{-1}). ⬚y the time of best-track genesis on 31 August (panels c, d) there was considerable rain contamination of retrieved winds (cyan shading). Similar to what was observed in Chris 2000, a closed gyre is seen in the co-moving frame (b) 48 h prior to "genesis" whereas the resting frame (a) on 29 August gives the appearance of an open wave. Once again the resting frame is misleading and misses a key element in the genesis sequence⬚

the closure of near-surface circulation. Although our analysis of Feli□ is retrospective, no temporal filter was needed either in Fig. □1 or in the derivation of phase speed C_p on which the □onal translation is based. □ain contamination was not an issue at this time, e□cept in the □□ quadrant of the gyre. □uikSCAT imagery evidently can play an important role in identifying a closed surface circulation in the co-moving frame, particularly in the earliest stages of genesis when deep convective precipitation is less prevalent or intense than in later stages. It was noted previously by Sharp et al. (2002) that vorticity anomalies in □uikSCAT data can identify storms prior to their best-track genesis time. Vorticity is □alilean invariant but a noisy quantity□translating streamlines provide an alternative measure that is less sub□ect to retrieval errors, unresolved finestructure and rain contamination, provided that the speed of translation is known from other data sources.

□ppendi□ □

□mplications of climate change

The role of off-equatorial circulations as a link between *hurricanes* and *climate change* is recogni□ed in the papers cited. These topics, along with *air quality*, are the most important in contemporary atmospheric science and their relationship deserves scrutiny at a dynamical, not merely statistical, level of understanding. The effect of climate change on hurricanes is not simply to increase the potential intensity (PI) of a hurricane and thereby *increase hurricane intensity ipso facto*. □eaving aside frontier matters concerning the formulation and accuracy of current PI theory (□manuel, 2005□ □ontgomery et al., 2006a□Smith et al., 2008) actual hurricane intensities form a continuous probability distribution function (P□F) bounded above by a limiting intensity. SST is but one of several factors e□plaining the P□F and its variation (□e□aria et al., 2005) so it is not merely a question of how PI varies with SST. □or can we ignore the number of storms reaching tropical depression status and how this might change in the future□the percentage of developers versus wave-troughs is small in the present climate – nowhere near saturation. Though little attention has been given to the issue, perhaps for lack of evidence, the *number of storms generated* is an integral part of the climate-change question. We consider it unlikely that nature will somehow produce more storms of high intensity without producing more storms at all levels of intensity. A counterpoint was advanced by Held (2007) based on results obtained with a simple □C□ □Held and collaborators suggested that while the ma□imum intensity would *increase*, the number of intense storms would *decrease*, as if to suggest a bound on cumulative storm energy, perhaps owing to available moisture (see also □enggston et al., 2007□□nutson, 2007□□nutson et al., 2007, 2008). However, at a recent workshop □ender (2008) presented new re-

sults for the Atlantic basin, using higher resolution to obtain more accurate intensity estimates, indicating that both the intensity *and* number of intense storms would increase significantly in a "warmer world" scenario. Here, the wings of the intensity distribution are elevated by borrowing from the center of the distribution. (□umber conservation is constrained by the e□perimental design, not predicted.) Owing to the nonlinear relation between the cube of intensity and cumulative storm energy (□manuel, 2005) such a change cannot occur if available moisture is a limiting factor on intensity. Interestingly, the increase in intense storms was confined primarily to the main development region of the Atlantic basin. Although some theoreticians have e□pressed acceptance of the "moisture supply" theory, the newer results of □ender and collaborators are consistent with our reasoning. Two reasons underlying this "common sense" viewpoint are (i) it is likely for physical *and* statistical reasons that if more storms are generated, the number of intense storms will increase – "more eggs" once fertili□ed "imply more chicks, implying more chickens" given enough food – and (ii) regions of genesis and highest intensity are (for the most part) well separated spatially, thanks to the □onal motion of storms, restricting the ability of intense storms to inhibit new storms in their wake to distances of less than 1000 km (Schumacher et al., 2009). In this respect, storms of the real world differ from those of a hori□ontally periodic geometry, in which the inhibition can be significant.

□lossary

□ottom-up development□ A pathway to tropical cyclogenesis that assigns logical and chronological precedence to phenomena in the lower troposphere prior to the upward growth of a tropical depression-strength vorte□. These phenomena may occur at meso-α (e.g., critical layer formation in an easterly wave), meso-β (e.g., low-level convergence due to a convective heating profile, □kman convergence induced by boundary-layer drag) or meso-γ (convective heating profile associated with one or more vortical hot towers).

coherent structure□ In geophysical (quasi-2-□) turbulence, an unusually large or long-lived □ow feature (e.g., solitary wave, isolated hori□ontal eddy, or train of □elvin cat□s eyes in a nonlinear critical layer) that disrupts locally or episodically the turbulent aspects of the □ow□vi□, disorder, particle dispersion, and energy or enstrophy cascades. The □reat □ed Spot on □upiter is a well-known e□ample.

co-moving frame□A frame of reference translating hori□ontally at the velocity of the parent wave or proto-vorte□. Streamlines or stream function appear different in resting versus co-moving frames, unless the translation speed is □ero trivially. The proper choice of translation speed may vary with height owing to vertical shear and wave-vorte□interaction.

critical layer□The region surrounding a nonlinear wave□s critical latitude or level in shear □ow. In the enclosed □elvin

cat's eye, 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 cat's eye on either side are included in the definition.

critical points In 2-D flow, the points where both components of horizontal velocity vector vanish. The nature of a critical point is determined by the local velocity gradient tensor. Two examples are (i) a gyre center, to or from which particles may converge or diverge; (ii) a saddle, or hyperbolic point, where a closed gyre is connected to the outer flow, and particles simultaneously converge (along one axis) and diverge (along the orthogonal axis).

diabatic activation A term introduced in this paper to describe how a propagating Rossby-like wave (e.g., easterly wave) is maintained or amplified by a diabatic Rossby vortex within. Without diabatic activation, such a wave exists as a dynamical feature in the lower troposphere, whose signature may be seen in low cloud or deep-layer water vapor, but with deep moist convection that is either absent or poorly organized.

diabatic Rossby wave/vortex A hybrid structure consisting of a low-level vortex, excited and maintained by moist diabatic heating in the lower troposphere, co-existing with a quasi-balanced wave in this layer, such that the wave and vortex interact in a mutually beneficial way Their speeds of horizontal propagation, though not necessarily identical, are similar enough over the lifespan of the disturbance so that the vortex remains in approximately the same phase of the wave.

dividing streamline In steady 2-D flow, the streamline intersecting a nearby saddle point. Particles on opposite sides of the dividing streamline belong to different manifolds of the flow.

easterly wave A prominent synoptic-scale feature of the summer tropics, centered ten or more degrees off the equator just poleward of the ITCZ, originating and propagating westward across tropical Africa, the tropical Atlantic, and eastern or central tropical Pacific. They are usually accompanied by cloudiness near the trough, and have been documented in radiosonde data and satellite imagery since the early 1950s and 1970s, respectively.

forward enstrophy cascade A process in quasi-2-D turbulence whereby strong vortical eddies irreversibly deform weaker eddies into filaments on progressively smaller scales.

gauge function As used here, a scalar function with zero horizontal Laplacian that can be added to stream function or velocity potential, without altering the vertical component of vorticity, or horizontal divergence. Gauge theories and transformations are widely used in classical and quantum electrodynamics, but have a more general mathematical meaning.

heating profile In this context, the vertical profile of moist diabatic heating. Heating profiles in the tropics are defined and labeled according to their association with typical precipitating cloud structures, such as deep convective, congestus, stratiform, anvil and shallow cumulus cloud.

hydrodynamic instability of ITCZ In theoretical literature the Intertropical Convergence Zone (ITCZ) is idealized as an east-west vortex strip which, once perturbed, may undergo subsequently a (dry or moist) form of barotropic instability, resulting in excitation of zonally propagating waves and coherent vortices of finite horizontal size embedded therein. According to the marsupial paradigm, a quasi-closed gyre generated by large-scale instability may become the "mother pouch" of an incipient tropical cyclone if environment and mesoscale processes allow.

inverse energy cascade A process in quasi-2-D turbulence whereby small vortical features merge to form progressively larger features, such as large eddies, Rossby waves and zonal jets. For such a cascade to be maintained, energy input at small scales is necessary.

marsupial paradigm A conceptual framework introduced in this paper to describe how a hybrid diabatic Rossby wave/vortex (existing in a wave critical layer or in isolation) may become a tropical depression and thereafter, a tropical cyclone. The marsupial paradigm embraces three new hypotheses regarding (H1) the vortical organization of the critical layer at meso-α, (H2) moisture supply to the proto-vortex and protection from dry or dusty air outside, and (H3) a mutually beneficial interaction of wave and vortex. The simpler term *pouch theory* has been introduced to encompass H2.

mesoscale convective vortex A byproduct of deep moist convection observed in the tropics and summer midlatitudes when an organized mesoscale convective system (MCS) excites horizontal vortical motion in the interior troposphere. The altitude where such motion maximizes depends on the vertical profile of moist diabatic heating. Convection always develops upward, but when accompanied by stratiform cloud at mid-levels (with evaporative cooling below) the resulting profile of moist diabatic heating becomes top-heavy, exciting vortical motion in the mid-troposphere. In tropical cyclogenesis, merger of adjacent MCVs is thought to create a starting point for top-down development.

multi-scale interaction A mathematical and theoretical concept describing how processes on different scales interact simultaneously, and in some cases, synergistically to support one another. An important result of multi-scale interaction is that turbulent cascades are interrupted or "short-circuited" by instantaneous communication across widely separated scales. Another is long-range interaction, whereby waves communicate information to large distances, faster than is possible in advective turbulence. The co-existence and possible synergy of waves and turbulence (or of waves and vortices) is arguably the most important form of multi-scale interaction in geophysical fluid dynamics.

Okubo-Weiss parameter A measure of the shape-preserving component of a vortical flow, in comparison to (i) the shape-destroying component associated with shearing deformation, and (ii) straining deformation. The sign convention is arbitrary; "positive" may be chosen to emphasize the former, in shape-preserving phenomena (e.g., TC

genesis) or the latter, in filamentary phenomena (e.g., stirring and mi□ing).

organi□ed deep moist convection□ Tropical convection, particularly over the oceans, is often organi□ed on sub-seasonal time scales by atmospheric dynamics rather than by fi□ed features such as coasts and topography. The form of organi□ation varies widely, and may be associated with mesoscale convective systems, density currents, gravity waves, equatorial waves, and e□tratropical intrusions. When convection is phase-locked to the underlying dynamic structure to such an e□tent that this structure cannot be understood without the effect(s) of the convection, we have a *convectively coupled* disturbance.

□rr mechanism□ In shear □ow, a wave tilted initially against the shear is rotated to an upright alignment, leading to wave growth, and further rotated into the shear, causing wave decay. The growth rate is determined by the shear, which in some cases may e□ceed the growth rate of the most unstable eigenmode.

proto-vorte□□ The initial vortical structure within a hybrid diabatic □ossby wave/vorte□, which may subsequently grow to a tropical depression-strength vorte□. The finestructure of a proto-vorte□ is seldom observed directly□even the best meteorological analyses visuali□e such a disturbance as if "under a pane of knobbly glass" in the famous words of □ichael □cIntyre.

□uasi-mode□□ot an e□act eigenmode, but a long-lived superposition of modes having appro□imately the same phase speed□hence, appro□imately the same critical latitude or level.

saturation fraction□ A column-integrated measure of moisture relative to what the column can hold, given the observed temperature versus pressure in the column.

spontaneous aggregation□ In ideali□ed studies of tropical cyclogenesis or diabatic □kman turbulence in hori□ontally uniform environments without waves or sweet spots, a mechanism whereby ad□acent vortical elements merge adiabatically via the inverse energy cascade, or diabatically via nonadvective transport of PV substance, and grow subsequently to form a tropical cyclone.

strati□ed tur□ulence paradigm□□ased on the pioneering works of □im □iley, □oug □illy and □im □cWilliams (in the conte□t of geophysical turbulence) and as applied to tropical meteorology (invoking the scale analysis of □ule Charney and □im Holton), a concept that describes the seemingly random relationship of lower and upper tropospheric □ows when deep coupling is absent. For e□ample, when an e□tratropical disturbance intrudes the tropical upper troposphere, without altering a pre-e□isting disturbance in the tropical lower troposphere, a vertical shear may be generated that is either favorable or inimical to tropical cyclogenesis□the point being, the superposition is a result of separate processes having no immediate relationship to one another.

top-down development□A pathway to tropical cyclogenesis that assigns logical and chronological precedence to phenomena in the middle troposphere prior to their downward e□tension to the lower troposphere or boundary layer. As with bottom-up development, these phenomena may occur at meso-α (e.g., downward gyre development in an easterly wave, thermal capping in the cat□s eye) or meso-β (e.g., descending showerhead, downward burrowing of merged mid-level convective vortices). □pward and downward pathways are not mutually e□clusive, insofar as the meso-α development may occur in one direction, while the meso-β development occurs in another.

translating closed gyre□A structure that may be identified in meteorological analyses of stream function, streamlines or tra□ectories, by viewing a tropical wave critical layer in its co-moving frame, i.e., a frame of reference moving at the phase speed of the wave. For stream function, the translation can be achieved directly by adding the appropriate gauge function.

tropical depression□ Although no formal definition can be found, a tropical depression-strength vorte□ is thought to e□ist when circular hori□ontal winds approach 30 knots and deep, persistent convection is well-organi□ed by a putative closed circulation. It can be said that forecasters regard a proto-structure with features loosely resembling a mature hurricane as a good candidate for a "depression" – the more such features, the better. Their classification evidently guarantees (in all but a few instances) subsequent growth to a named tropical storm. It is not only the statistical narrowness of the tropical depression classification, but a physical threshold for instability leading to intensification, that is responsible for their success. In other words, "tropical depression" is a physically meaningful, albeit imprecisely defined, concept.

vortical hot towers□ □eep moist convective clouds that rotate as an entity and/or contain updrafts that rotate in helical fashion (as in rotating □ayleigh-□enard convection). Although early observations suggested that VHTs are neither necessary nor sufficient for tropical cyclogenesis, it is becoming increasingly clear from cloud-representing numerical simulations that moist vortical updrafts are the essential building blocks of the tropical storm within the rotating proto-vorte□. These hot vortical plume structures amplify pre-e□isting cyclonic vorticity and equivalently induce concentrations of vorticity substance much larger than that of the aggregate vorte□.

wave refraction□ When a wave propagates in a background state with spatio-temporal variation, its wavenumber and frequency change owing to refraction. In shear □ow, wave phase may be imagined to open or close like a Venetian blind□this process occurs in the two spatial dimensions orthogonal to the wave vector. Phases may be stretched or compressed, as a piece of taffy□this process occurs in the spatial dimension parallel to the wave vector. The Orr mechanism arises from the first effect, whereas "wave accumulation" or "wave capture" arise from the second. A local increase of wave amplitude at first order caused by linear wave

refraction may result in wave breaking, or transfer of energy to other waves, vortices and turbulence.

□dited by □P. Haynes

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