WMO/CAS/WWW

SEVENTH INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES

1.2: Inner-core Impacts

Rapporteur: Elizabeth A. Ritchie
University of Arizona
PO Box 210081
Tucson, AZ 85721-0081

Email: ritchie@atmo.arizona.edu
Phone: +1+520+626 7843

Working group: Mai Nguyen, Peter Otto, Greg Tripoli, Jonathan Vigh

1.2.1. Introduction

This report attempts to summarize the papers published during the last 4 years (from 2006 to 2010) on the subject of inner-core processes and the associated structure and intensity change in Tropical Cyclones (TCs). There are many papers that have been published addressing specifically topics associated with inner core changes of tropical cyclones. In addition, a substantial number of papers have small pieces addressing this topic, and the task of compiling all this information has been monumental. Here, we have attempted to summarize the more substantial papers addressing the topic of inner core impacts on intensity and structure. A more complete bibliography can be made available on request. The summary will be organized as follows:

1. Inner-core impacts on Intensification (normal),
2. Inner-core impacts on Rapid Intensification,
3. Inner-core impacts on Super Intensity,
4. Inner-core impacts on Weakening, and
5. Inner-core structure

1.2.2. Summary of new results in the last four years

1.2.2.1 Inner-core Impacts on Intensification

a) The primary circulation

Recent research has suggested that convergence of absolute angular momentum above the boundary layer (BL) spins up the outer circulation, which increases the vortex size but does little to the intensity of the core. Instead, the inner core intensifies by radial convergence within the boundary layer, where the flow becomes supergradient rather than being in gradient-wind balance (Smith et al. 2009).

.Pendergrass and Willoughby (2009) consider the effects of spatial variations in static stability, sloped eyewall heating of various shapes, and an independently varied continuous tangential wind profile. The vortex heating efficiency is found to be most sensitive to the intensity itself, with wind tendency suddenly increasing for an intensity of between 35 to 40 m s^{-1}. The tilt of the heat source, the shape of the vortex, and the exponential decay outside the eye are found to be less important than intensity and size by factors of 4-5.

Vigh and Schubert (2009) examined the role of diabatic heating in intensifying the storm using Eliassen's classic balanced vortex model. The location of the diabatic heating was varied to be within and without the region of high inertial stability. Results show that diabatic heating in the low inertial stability region outside the radius of maximum wind was inefficient at generating a warm core, no matter how large the current storm intensity. In contrast, diabatic heating in the high inertial stability region inside the radius of maximum wind was efficient at generating a localized temperature tendency, and this efficiency increased dramatically with storm intensity.

b) Barotropic Instability

Once the eyewall has formed, further intensification via the production of potential vorticity in the eyewall may cause the storm to take on the structure of a hollow potential vorticity tower. The radial and vertical motions associated with the diabatically-driven secondary circulation lead to intense horizontal gradients of momentum, temperature, and moisture in the vicinity of the eyewall. Eventually, these gradients can become so strong that the potential vorticity ring becomes barotropically unstable and breaks down into discrete mesovortices. The resulting advective mixing can cause a dramatic rearrangement of the inner core kinematic and thermal structure. Barotropic instability is the most significant such instability. Recent studies include both model and observsational studies of this mechanism (Modeling: Hausman et al. 2006; Hendricks and Schubert 2009; Hendricks et al. 2009; Jansson et al. 2006; Jansson et al. 2007; Rozoff et al. 2009; Rutherford et al. 2010a,b; Wada 2009; and Observational: Aberson et al. 2006a; Hendricks and Montgomery 2006; Aberson et al. 2006; Aberson and Halverson 2006; Molinari and Vollaro 2008; Marks et al. 2008; Barnes 2008)

c) Role of Intense Convection

Simulations of idealized hurricane-like vortices using MM5 by Nguyen et al. (2008) suggested that convectively-generated vortical hot towers were important in the intensification of simulated tropical cyclones. During the integrations, deep convective towers growing in the rotation-rich environment of the incipient core amplify the local vertical rotation and were the basic coherent structures of the tropical cyclone intensification process. This study found that the inner-core evolution was intrinsically unpredictable due to the random nature of convection.

d) Helicity and intensification

Extreme helicity found in the boundary layer of Hurricane Bonnie (1998) seemed to be associated with strongly rotating convective towers in the downshear left quadrant that were similar to supercell-like convective structures (Molinari and Vollaro 2008). They hypothesize that these cells were enhanced in strength because of their reduced entrainment and quasi-balanced dynamics, and enabled the storm to resist the negative impact of strong vertical wind shear. More generally, Molinari and Vollaro (2008; 2010a) showed that highly sheared storms produced 30% larger area-averaged CAPE and double the area-averaged

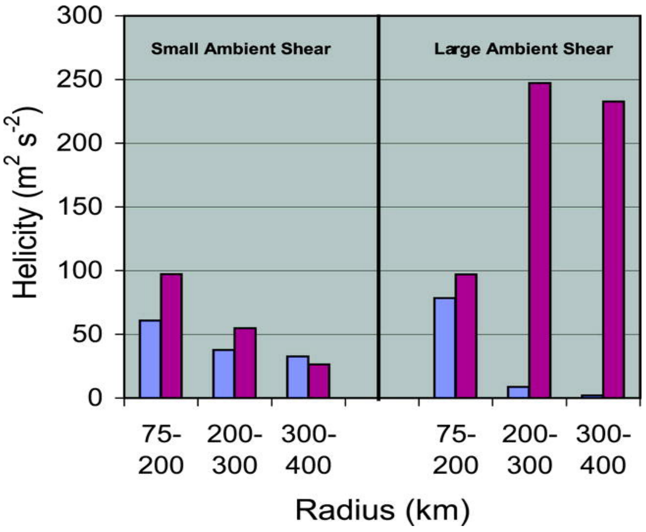

Fig. 1: Radial variation of 0–3-km helicity ($m^2\ s^{-2}$) averaged over 75–200, 200–300, and 300–400 km for 8 TCs during the NASA CAMEX experiments. The TCs on the left experienced small ambient shear and those on the right experienced large ambient shear. Upshear means are in blue and downshear in red.

[Adapted from Figure 4 of Molinari and Vollaro (2010) J. Atmos. Sci.]

helicity versus relatively unsheared storms (Fig. 1). The vortex-scale increase in these quantities apparently lessened the negative impact of large vertical wind shear on intensity.

e) Re-intensification After Landfall

Emanuel et al. (2008) simulated the reintensification of tropical cyclones over land in Northern Australia (which they dub '*agukabams*'), in which the warm core structure was retained after landfall. Large heat fluxes from hot, sandy soil that had been wetted by the storm's rainfall supported the redevelopment of eye and eyewall features.

1.2.2.2 Rapid Intensification

a) Eye-Eyewall Mixing

There are a number of recent modeling and observational studies that support the concept of a mixing of eye and eyewall air through strong convective hot towers and their associated eyewall mesovortices (e.g., Fig. 2). These include: Braun et al. (2006) who simulated Hurricane Bonnie (1998); Braun and Wu (2007) who simulated Hurricane Erin (2001); Reasor et al. (2009), who used airborne Doppler radar to examine the asymmetric rapid intensification of Hurricane Guillermo (1997); and Marks et al. (2008) who analyzed aircraft data from Hurricane Hugo (1988) and provided additional evidence for strong mixing by eyewall vorticity maxima.

Cram et al. (2007) further analyzed the simulation of Hurricane Bonnie (1998) of Braun et al. (2006) to investigate the transport and mixing characteristics in this vertically sheared storm. They found that there was transport and mixing of relatively high θ_e-air from the low-level eye to the eyewall, which enhanced the efficiency of the hurricane heat engine. A portion of the low-level inflow of the hurricane bypassed the eyewall to enter the eye, and this air both

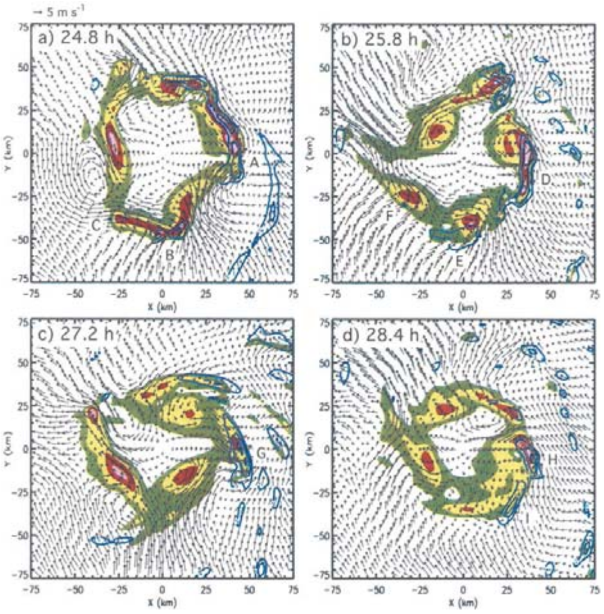

Fig. 2: (a)–(d) Absolute vorticity (colors), vertical velocity (contours, updrafts only), and storm-relative asymmetric wind vectors averaged over the 1–4-km layer for a simulation of Hurricane Bonnie (1998) during a simulated eyewall breakdown event. For details, see the referenced paper.

[Adapted from Figure 16 of Braun et al. (2006) J. Atmos. Sci.]

replaced the mass of the low-level eye and lingered for a sufficient time (order 1 h) to acquire enhanced entropy characteristics through interaction with the ocean beneath the eye.

Sitkowski and Barnes (2009) also analyzed Hurricane Guillermo as it rapidly deepened. They find that the deepening was correlated with an asymmetric spiraling inward of the eyewall which reduced the eyewall diameter by 10 km. They suggest that mixing between lower eye and eyewall air triggered this reduction and may have been a key first step in the intensification process.

b) Role of Convection in Rapid Intensification

Guimond et al. (2010) present a unique, ultra-high-resolution, multiscale observation dataset, of the development of convective hot towers and their coupling to the parent vortex. Convective bursts were observed during the mature stage and prior to a period of rapid intensification of Hurricane Dennis (2005). Significant downdrafts occurred on the flanks of the updrafts, with their accumulative effects hypothesized to result in the observed increases in the warm core. It was hypothesized by the authors that the subsidence was transported toward the eye by an inflow occurring over a deep layer from the convective core to the eye-eyewall interface. However, with the reported strength of the downdrafts (in the order of 10-12 m s^{-1}), it seems likely that these downdrafts were driven by evaporative cooling and their contribution the development of the warm core is questionable.

A more traditional view of the role of deep convection in intensification of tropical cyclones is provided by a 1.67 km simulation of Hurricane Dennis (2005) (Rogers 2010). In this study, rapid intensification was associated with a significant increase in the low level updraft mass flux, which was driven by heating from the convective bursts. The total updraft mass flux enhancement resulted in amplification of the secondary circulation and inertial stability, which lead to a rapid intensification phase.

Using GPS dropsonde observations, Barnes and Fuentes (2010) examined the potential role of the high θ_e reservoir in the rapid intensification of Hurricane Lili (2002), but find that the small volume of eye excess energy was not sufficient to sustain rapid intensification; rather, it may have provided a boost to episodic convection that may have in turned initiated the rapid intensification.

c) Observations of Eyewall Contraction

Lee and Bell (2007) used WSR-88D radar observations to measure axisymmetric wind fields, vertical vorticity, perturbation pressure, and reflectivity during the rapid intensification and eyewall contraction phase of Hurricane Charley's (2004). Their analyses showed that as the storm rapidly intensified, the vorticity ring evolved into a monopole—the first time this process has been observed by ground-based radar. Central pressure deficits showed a 33 hPa drop from over this 3-h period as the inner eyewall contracted from 13 km to 8 km. A secondary eyewall formed by the end of the 3-h period, though a secondary wind maximum was not immediately apparent in their axisymmetric wind analysis.

1.2.2.3 Superintensity

Bryan and Rotunno (2009) examine the magnitude of the super intensity mechanism in an axisymmetric hurricane model. By turning off the coefficient of heat exchange within the radius of maximum winds, they effectively eliminate the super intensity mechanism by preventing the buildup of a reservoir of high θ_e air in the eye. These simulations show that the area-integrated latent heat fluxes are the important driver of storm intensity, and that surface fluxes radially far from the eyewall have an important contribution to the storm's θ_e budget.

Several recent papers (Montgomery et al. 2006; Aberson et al. 2006; Bell and Montgomery 2008) presented observations from Hurricane Isabel showing that Isabel maintained an intensity significantly above the theoretically predicted maximum potential intensity on three separate days as it crossed the cold wake left behind by Hurricane Fabian a couple weeks previously. Isabel featured striking examples of mesovortices in the eye and eyewall during this period (Fig. 3), which must necessarily have mixed eye air into the eyewall.

1.2.2.4 Weakening

a) Asymmetric Warm Core Structure

Halverson et al. (2006) mapped out the three dimensional structure of the warm core in Hurricane Erin (2001) as it weakened due to lowering SSTs and southerly vertical shear. Erin displayed a classic wavenumber-1 vertical shear pattern, with the strongest convection initiating downshear and to the left of the shear vector similar to previous studies. A maximum warm core anomaly of +11°C was observed during the weakening phase. In addition, the warm core was asymmetric, with a significant thermal ridge at 850 hPa extending towards the weak echo quadrant. At 500 hPa, the warm core was biased toward the

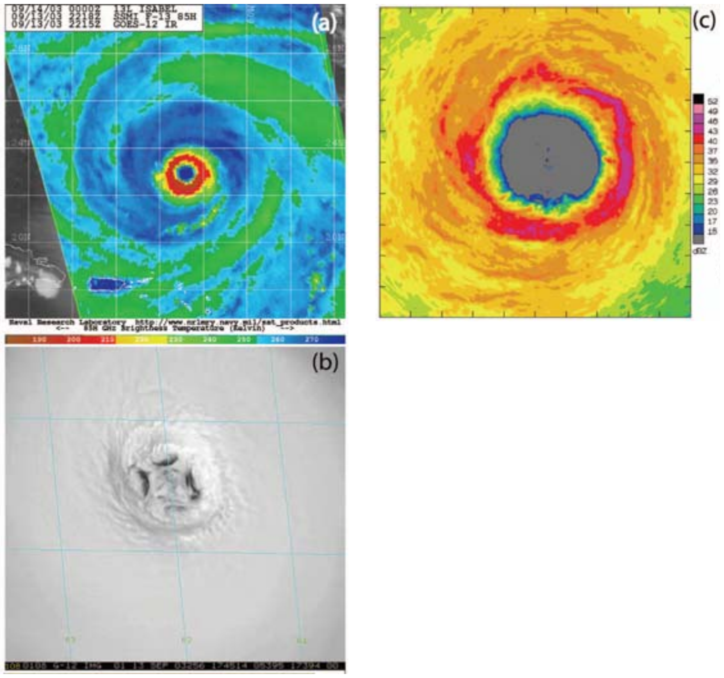

Fig. 3. Satellite and airborne radar imagery of Hurricane Isabel on 13 September. (a) Special Sensor Microwave Imager (SSM/I) 85-GHz brightness temperature at 2218 UTC (courtesy of NRL/Monterey); (b) visible image at 1745 UTC from GOES super-rapidscan operations; and (c) radar reflectivity (dBZ) from lower-fuselage (5 cm) radar onboard NOAA aircraft while flying inside the eye at ~2 km altitude. The mesovortices within the eye in (b) and the pentagonal shape of the high reflectivity in the eyewall in (c) are particularly striking features.

[Adapted from Montgomery et al. (2006), Bull. Amer. Meteor. Soc.]

maximum convection and latent heating. Dry, warm air was located southeast of the storm with an inversion, which likely impacted the convection in the eyewall.

b) barotropic instability

Peng et al. (2009) investigate the role of barotropic instablity at the outer wind profile using a combination of linear and nonlinear barotropic models, and a three-dimensional version of WRF model. In their simulations, asymmetries at outer radii (near 600 km radius) induce asymmetries at inner radii (near 300 km). In the case of the unstable mean vorticity profile, both of these asymmetries grow due to a positive feedback process. In addition, these results are not sensitive to the location of the initial asymmetries, but dependent on the basic-state vorticity profile. The authors conclude that the existence of barotropic instablity at outer radii can cause a significant weakening of the basic-state vortex.

c) Role of convection in weakening

Cecil et al. (2010) studied the intense convection that occurred in the eyewall of Hurricane Emily (2005) *after* the storm had reached peak intensity. The severe convection caused surprising turbulence for the ER-2 aircraft at 20 km height 8-10 hours after peak intensity had been reached and substantial filling had taken place. A peak updraft of 24 m s^{-1} was measured, with a nearby downdraft of 20 m s^{-1}. Very high electrical activity was measured. The authors surmise that the asymmetric convection (associated with moderate vertical wind shear) may have contributed to Emily's weakening.

1.2.2.5. Inner-core Structure

a) Eye Formation

An idealized modeling study by Zhang and Kieu (2006) found that the secondary circulation forced by latent heating in the eyewall can oppose the shear-forced vertical tilt lessening the detrimental effects of the environmental vertical shear by up to 40%. The authors also suggested that the subsidence warming that leads to eye formation results from detrainment of ascending air in the eyewall.

Nolan (2007) conducted an idealized modeling simulation in which a strong convective cell was observed to move very near the broad vortex of a tropical cyclone undergoing genesis. After just a couple of hours of intense vortex stretching and diabatic heating, this cell resulted in the rapid spin-up of a smaller scale vortex which then dominated the larger storm circulation and sometimes went on to form an eye. Such a process might be one particular mode by which convective hot towers may promote the rapid intensification of a storm.

Wirth and Dunkerton (2009) have investigated the dynamics of eye formation in diabatically-forced vortices by using a simple model which includes a thermal relaxation towards an equilibrium temperature and surface friction. They found that eye formation was a robust feature of strongly diabatic vortices, was governed by the ratio of the thermal forcing to frictional forcing, and occurred suddenly across a narrow range of the parameter space.

Heymsfield et al. (2006) found that the presence of strong environmental vertical wind shear, which forced asymmetric low-level convergence, lead to the formation of intense mesoscale convective systems away from the vortex center. By possibly forcing multiple regions of inner core subsidence, these mesoscale convective systems apparently disrupted the eye formation process. However, Shelton and Molinari (2009) found a case where, shear-induced subsidence near the core appeared to support a short-lived, hurricane-strength vortex.

b) Secondary eyewall formation – moat regions

Although the occurrence and behaviour of eyewall replacement cycles is well documented, the formation mechanisms are still debated with widely diverse explanations available. A comprehensive review on the different mechanisms for the secondary eyewall formation was recently given by Terwey and Montgomery (2008). They found that the secondary eyewall formed when there was an enhanced region of outer vorticity called a beta skirt around the tropical cyclone.

Rozoff et al. (2006) suggested that the formation of moat regions, which are present between the inner and the outer eyewall, may be associated with the rapid filamentation zones where the flow was dominated by strain. In these regions, the development of deep moist convection could be significantly distorted and even suppressed. However, Rozoff et al. (2008) later showed that the subsidence and warming temperature in the moats were governed by enhanced inertial stability associated with a strengthening outer eyewall.

Using a three-dimensional full-physics tropical cyclone model, Wang (2008a) came to a similar conclusion as Rozoff et al. (2008) on the secondary role of the rapid filamentation zones in the formation of moats. This author suggested that the moat was mainly controlled by the subsidence associated with the overturning flow from eyewall convection and downdraft from the anvil stratiform outside of the eyewall. Instead, the rapid filamentation zones were proposed by Wang (2008a) as a favorable environment for the organized inner spiral bands, which have a typical time scale of several hours.

c) Tropical cyclone spiral bands

Modeling studies further investigate both the idealized nature of vortex Rossby waves and spiral bands (e.g., Schecter and Montgomery 2006; 2007) and real-case examples (Franklin et al. 2006; Braun et al. 2006).

Observational evidence of vortex Rossby waves was found in Hurricane Elena, 1985 using radar reflectivity (Corbosiero et al. 2006). Outside the eyewall, individual peaks in the wave-number 2 convective asymmetries were associated with repeated instances of cyclonically rotating, outward-propagating inner spiral bands at speeds consistent with vortex Rossby wave theory.

d) Hub Clouds

Schubert et al. (2007) examined the central hub cloud and surrounding clear-air moat that are sometimes observed in the lower eye of a tropical cyclone. An analytical solution of the Sawyer-Eliassen transverse circulation equation was derived and the dimensional dynamical eye size was found to be the crucial parameter in controlling the radial distribution of subsidence in the eye. When the eye size was small, the subsidence was nearly uniform, with less than 10% variation across the eye. When the eye size was large the subsidence rate at the edge of the eye was more than twice that at the center. Such a distribution of subsidence should result in a warm ring structure, rather than a warm core structure.

e) Slope of the Radius of Maximum Winds

Stern and Nolan (2009) analyzed Doppler-derived wind data from aircraft observations in multiple storms and found that the slope of the radius of maximum winds varies nearly linearly with radius so that a greater slope outward of the radius of maximum wind occurred for larger radii. In contrast to previous studies, they find very little relationship between slope and intensity. Another key finding was that there is almost no relationship between intensity and radius of maximum wind. While a relationship between intensity and radius of maximum wind often existed for an individual storm as its eyewall contracted, a strong relationship was not apparent when looking across data from multiple storms. Slope was less sensitive to higher sea-surface temperatures.

1.2.3. Summary.

In summary, inner-core processes in TCs are a topic that has received a lot of attention in the past four years. Although in this report there has been an attempt to separate out those studies that dealt only with structural changes from those that dealt with intensity of tropical cyclones, the delineation is somewhat artificial. However, the major fundings for each as are follows.

The role of convection in all aspects of tropical cyclone intensification and weakening has been amply studied using both observational datasets and mesoscale models. The organisation or lack thereof, of convection around the eye, appears to be extremely important for later intensification or weakening as was shown previously and reported on in the last IWTC report on environmental impacts on structure and intensity (Ritchie 2006). However, there are more recent studies since that report that have studied in greater detail the relationship between convective organisation and later intensity (or lack thereof). In addition, the role of, and physical characteristics of the boundary layer air both near the eyewall and in the nearby surroundings in spinning up strong convection has been examined. Less research now appears to be occurring regarding vortex Rossby wave processes as mechanisms for intensity or structure change.

Mechanisms for rapid intensification are obviously a very important topic. There are recent studies that suggest that the mixing of eye and eyewall air through strong convective hot towers and their associated eyewall mesovortices can be a precursor to rapid intensification and there is also a possibility of a tropical cyclone reaching a so-called “super intensity” – and intensity greater than the environmental conditions suggest can occur. However, we do note that other studies suggest the same processes as a precursor to “intensification” rather than “rapid intensification”, and so the mechanisms for one or the other need to be sorted out.

Another area of research that has received a fair amount of interest is that of secondary eyewall formation. Proposed mechanisms for secondary eyewall formation are partially environmental (and not covered here) and partially “inner-core”, and so the treatment of this area of research may be disjointed. However, there is substantial evidence to suggest that being able to understand (and finally predict) onset of secondary eyewall formation has potential payoff for prediction of future intensity of the tropical cyclone.

Research into inner core structure of the tropical cyclone (separate from intensity change), has been focused on four different areas: 1) the formation of the eye; 2) spiral bands and maintenance of the “moat” regions between convective bands; 3) the phenomenon of “hub clouds” in the eye; and 4) the slope of the radius of maximum winds in tropical cyclones. Of these, the second and fourth sub topics are incremental additions of previous IWTC reports. The topic of mechanisms of eye formation is very important in terms of better understanding the transition from a weak tropical cyclone to a strong tropical cyclone. The topic of hub clouds mechanisms is extremely interesting, although no linkage to potential useful operational information exists yet.

1.2.4 Recommendations

Based on the state of research on inner-core mechanisms for tropical cyclone intensity and structure, recommendations coming out of this report include the following:

1. Research in understanding the mechanisms that result in overall intensification of the tropical cyclone primary circulation should continue. The primary mechanisms include: the role of convective organisation; the physical characteristics of the eye-eyewall boundary-layer in developing very intense (hot tower) eyewall convection; secondary eyewall formation; and formation of the eye.

2. Research in improving the understanding of mechanisms that either result in weakening of the tropical cyclone primary circulation, or appear to appear to offset anticipated weakening because of environmental conditions should continue. Some of the current work includes: the diagnosis of helicity in anticipating strong asymmetric convection that offsets environmental shear weakening; and the asymmetric organisation of convection around the eyewall that perhaps results in weakening.

3. Research in understanding mechanisms associated with rapid intensification of tropical cyclones, especially just prior to landfall should continue.

4. Research in understanding mechanisms of structure change associated with intensification or weakening of tropical cyclones should continue. Some of these mechanisms include: eye formation; organisation of convection; and the development of secondary eyewall.

Acknowledgements

Acknowledgments and thanks go to the working group members of this report who worked hard (and in one case in considerable pain and suffering) to provide the support material that went into this report. Institutions supporting these people include: Monash University Australia, the Australian Bureau of Meteorology, the University of Wisconsin, the National Centers for Atmospheric Research, and last, but not least, the University of Arizona.

References

Aberson, S. D. and J. B. Halverson, 2006: Kelvin-Helmholtz billows in the eyewall of Hurricane Erin. *Mon. Wea. Rev.*, 1036–1038.

Aberson, S. D., J. P. Dunion, and Marks, F. D., Jr., 2006a: A photograph of a wavenumber-2 asymmetry in the eye of Hurricane Erin. *J. Atmos. Sci.*, 387– 391.

Aberson, S. D., M. Montgomery, M. Bell, and M. Black, 2006b: Hurricane Isabel (2003). new insights into the physics of intense storms. Part II: Extreme localized wind. *Bull. Amer. Meteor. Soc.*, 1349–1354.

Barnes, G.M., 2008: Atypical thermodynamic profiles in hurricanes. *Mon. Wea. Rev.*, **136**, 631–643.

Barnes, G. M. and P. Fuentes, 2010: Eye excess energy and the rapid intensification of Hurricane Lili (2002). *Mon. Wea. Rev.*, **138**, 1446–1458.

Bell, M.M. andM. T.Montgomery, 2008: Observed structure, evolution and potential intensity of category five Hurricane Isabel (2003) from 12–14 September. *Mon. Wea. Rev.*, **136**, 2023–2046.

Braun, S., M. T. Montgomery, and Z. Pu, 2006: High-Resolution Simulation of Hurricane Bonnie (1998). Part I: The Organization of Eyewall Vertical Motion. J. Atmos. Sci., 63, 19-42.

Braun, S. A. and L. Wu, 2007: A numerical study of Hurricane Erin (2001). Part II: Shear and the organization of eyewall vertical motion. *Mon. Wea. Rev.*, **135**, 1179–1194.

Braun, S., M. Montgomery, K. Mallen, and P. Reasor, 2010: Simulation and Interpretation of the Genesis of Tropical Storm Gert (2005) as Part of the NASA Tropical Cloud System and Processes Experiment. J. Atmos. Sci., 67, 999-1025.

Bryan, G. H. and R. Rotunno, 2009: The maximum intensity of tropical cyclones in axisymmetric numerical model simulations. *Mon. Wea. Rev.*, **137**, 1770–1789.

Cecil, D. J., K. R. Quinlan, and D.M. Mach, 2010: Intense convection observed by NASA ER-2 in Hurricane Emily (2050). *Mon. Wea. Rev.*, **138**, 765–780.

Chen, Y., G. Brunet, and M. Yau, 2003: Spiral Bands in a Simulated Hurricane. Part II: Wave Activity Diagnostics. J. Atmos. Sci., 60, 1239-1256.

Chen, Y. and M. Yau, 2001: Spiral Bands in a Simulated Hurricane. Part I: Vortex Rossby Wave Veri_cation. J. Atmos. Sci., 58, 2128-2145.

Corbosiero, K., J. Molinari, A. Aiyyer, and M. Black, 2006: The Structure and Evolution of Hurricane Elena (1985). Part II: Convective Asymmetries and Evidence for Vortex Rossby Waves. Mon. Wea. Rev., 134, 3073-3091.

Cram, T., J. Persion, M. Montgomery, and S. Braun, 2007: A Lagrangian Trajectory View on Transport and Mixing Processes between the Eye, Eyewall and Environment Using a High-Resolution Simulation of Hurricane Bonnie (1998). J. Atmos. Sci., 64, 1835-1856.

Emanuel, K., J. Callaghan, and P. Otto, 2008: A hypothesis for the redevelopment of warm-core cyclones over northern Australia. *Mon. Wea. Rev.*, **136**, 3863–3872.

Franklin, C., G. Holland, and P. May, 2006: Mechanisms for the generation of mesoscale vorticity features in tropical cyclone rainbands. Mon. Wea. Rev., 134, 2649-2669.

Guimond, S., G. Heymsfeld, and F. Turk, 2010: Multiscale Observations of Hurricane Dennis (2005): The E_ects of Hot Towers on Rapid Intensi_cation. J. Atmos. Sci., 67, 633-654.

Halverson, J. B., J. Simpson, G. Heymsfield, H. Pierce, T. Hock, and E. A. Ritchie, 2006: Warm core structure of Hurricane Erin diagnosed from high altitude dropsondes during CAMEX-4. *J. Atmos. Sci.*, **63**, 309–324.

Hausman, S. A., K. V. Ooyama, and W. H. Schubert, 2006: Potential vorticity structure of simulated hurricanes. *J. Atmos. Sci.*, **63**, 87–108.

Hendricks, E. A. and M. T. Montgomery, 2006: Rapid scan views of convectively generated mesovortices in sheared tropical cyclone Gustav (2002). *Wea. Forecasting*, **21**, 1041–1050.

Hendricks, E. A. and W. H. Schubert, 2009: Transport and mixing in idealized barotropic hurricane-like vorticies. *Quart. J. Roy. Meteor. Soc.*, **135**, 1456– 1470.

Hendricks, E. A., W. H. Schubert, R. K. Taft, H. Wang, and J. P. Kossin, 2009: Life cycles of hurricane-like vorticity rings. *J. Atmos. Sci.*, **66**, 705–722.

Heymsfield, G. M., J. B. Halverson, E. A. Ritchie, J. Simpson, J. Molinari, and L. Tian, 2006: Structure of highly sheared tropical storm Chantal during CAMEX-4. *J. Atmos. Sci.*, **63**, 268–287.

Hendricks, E., W. Schubert, R. Taft, H. Wang, and J. Kossin, 2009: Life Cycles of Hurricane-Like Vorticity Rings. J. Atmos. Sci., 66, 705-722.

Houze, R. A., W.-C. Lee, and M. Bell, 2009: Convective Contribution to the Genesis of Hurricane Ophelia (2005). Mon. Wea. Rev., 137, 2778-2800.

Jansson, T. R. N., M. P. Haspang, K. H. Jensen, P. Hersen, and T. Bohr, 2006: Polygons on a rotating fluid surface. *Phys. Rev. Lett.*, **96**, doi: 10.1103/PhysRevLett.96.174502.

Jansson, T. R. N., M. P. Haspang, K. H. Jensen, P. Hersen, and T. Bohr, 2007: Polygons on a rotating fluid surface. *Phys. Rev. Lett.*, **98**, doi: 10.1103/PhysRevLett.98.049901.

Kahn, B. H. and D.M. Sinton, 2008: A preferred scale for warm-core instability in a nonconvective moist basic state. *J. Atmos. Sci.*, **65**, 2907–2921.

Kossin, J. and M. Sitkowski, 2009: An Objective Model of Identifying Secondary Eyewall Formation in Hurricanes. Mon. Wea. Rev., 137, 876-892.

Lee, W.-C. and M. M. Bell, 2007: Rapid intensification, eyewall contraction, and breakdown of Hurricane Charley (2004) near landfall. *Geophys. Res. Lett.*, **34**, L02802, doi:10.1029/2006GL027889.

Marks, F. D., P. G. Black, M. T. Montgomery, and R. W. Burpee, 2008: Structure of the eye and eyewall of Hurricane Hugo (1989). *Mon. Wea. Rev.*, **136**, 1237–1259.

Molinari, J. and D. Vollaro, 2008: Extreme helicity and intense convective towers in Hurricane Bonnie. *Mon. Wea. Rev.*, **136**, 4355–4372.

Molinari, J. and D. Vollaro, 2010: Distribution of helicity, CAPE, and shear in tropical cyclones. *J. Atmos. Sci.*, **67**, 274–284.

Montgomery, M., M. Nicholls, T. Cram, and A. Saunders, 2006: A vortical hot tower route to tropical cyclogenesis. J. Atmos. Sci., 63, 355-386.

Montgomery, M. T., M. M. Bell, S. D. Aberson, and M. L. Black, 2006: Hurricane Isabel (2003). new insights into the physics of intense storms. Part I: Mean vortex structure and maximum intensity estimates. *Bull. Amer. Meteor. Soc.*, 1335–1347.

Nolan, D. S., 2007: What is the trigger for tropical cyclogenesis? *Aust. Meteorol. Mag.*, **56**, 241–266.

Nguyen, S., R. Smith, and M. Montgomery, 2008: Tropical-cyclone intensification and predictability in three dimensions. Quart. J. Roy. Meteor. Soc., 134, 563-582.

Pendergrass, A. G. and H. E.Willoughby, 2009: Diabatically induced secondary flows in tropical cyclones. Part I: Quasi-steady forcing. *Mon. Wea. Rev.*, **137**, 805–821.

Peng, J., T. Li, M. Peng, and X. Ge, 2009: Barotropic Instability in the Tropical Cyclone Outer Region. Quart. J. Roy. Meteor. Soc., 135, 851-864.

Reasor, P. D., M. D. Eastin, and J. F. Gamache, 2009: Rapidly intensifying Hurricane Guillermo (1997). Part I: Low-wavenumber structure and evolution. *Mon. Wea. Rev.*, **137**, 603–631.

Ritchie, E. A., 2006: Topic 1.1: Environmental effects. Topic Chairman and Rapporteur Reports of the Sixth WMO International Workshop on Tropical Cyclones IWTC-VI, WMO Tech. Doc. WMO/TD ####.

Rogers, R., 2010: Convective-scale structure and evolution during a highresolution simulation of tropical cyclone rapid intensification. *J. Atmos. Sci.*,

67, 44–70.

Rozoff, C. M., W. H. Schubert, D. Brian, and J. Kossin, 2006: Rapid Filamentation Zones in Intense Tropical Cyclones. J. Atmos. Sci., 63, 325-340.

Rozoff, C. M., W. H. Schubert, and J. Kossin, 2008: Some dynamical aspects of tropical cyclone concentric eyewalls. Quart. J. Roy. Meteor. Soc., 134, 583-593.

Rozoff, C. M., J. P. Kossin, W. H. Schubert, and P. J. Mulero, 2009: Internal Control of Hurricane Intensity Variability: The Dual Nature of Potential Vorticity Mixing. J. Atmos. Sci., 66, 133-147.

Rutherford, B., G. Dangelmayr, J. Persing, M. Kirby, and M. T. Montgomery, 2010a: Lagrangian mixing in an axisymmetric hurricane model. *Atmos. Chem. Phys.*, **10**, 6777–6791.

Rutherford, B., G. Dangelmayr, J. Persing, W. H. Schubert, and M. T. Montgomery, 2010b: Advective mixing in a nondivergent barotropic hurricane model. *Atmos. Chem. Phys.*, **10**, 475–497.

Schecter, D. and M. Montgomery, 2006: Conditions that Inhibits the Spontaneous Radiation of Spiral Inertia-GravityWaves from an Intense Mesoscale Cyclone. J. Atmos. Sci., 63, 435-456.

Schecter, D. and M. Montgomery, 2007: Waves in a Cloudy Vortex. J. Atmos. Sci., 64, 314-337.

Schubert, W. H., C. M. Rozoff, J. L. Vigh, B. D. McNoldy, and J. P. Kossin, 2007: On the distribution of subsidence in the hurricane eye. *Quart. J. Roy. Met. Soc.*, **133**, 595–605.

Shelton, K. L. and J. Molinari, 2009: Life of a six-hour hurricane. *Mon. Wea. Rev.*, 51–67, doi:10.1175/2008MWR2472.1.

Sippel, J., J. Nielsen-Gammon, and S. Allen, 2006: The Multiple-Vortex Nature of Tropical Cyclogenesis. Mon. Wea. Rev., 134, 1796-1814.

Sitkowski, M. and G. M. Barnes, 2009: Low-level thermodynamic, kinematic, and reflectivity fields of Hurricane Guillermo (1997) during rapid intensification. *Mon. Wea. Rev.*, **137**, 645–663.

Smith, R., M. Montgomery, and V. Nguyen, 2009: Tropical Cyclone Spin-up Revisited. Quart. J. Roy. Meteor. Soc., 135, 1321-1335.

Stern, D. P. and D. S. Nolan, 2009: Reexamining the vertical structure of tangential winds in tropical cyclones: Observations and theory. *J. Atmos. Sci.*, **137**, 3579–3600.

Terwey, W. and M. Montgomery, 2008: Secondary eyewall formation in two idealized, full-physics modeled hurricanes. Journal of Geophysical Research, 113, D12112.

Vigh, J. L. andW. H. Schubert, 2009: Rapid development of the tropical cyclone warm core. *J. Atmos. Sci.*, **66**, 3335–3350.

Wada, A., 2009: Idealized numerical experiments associated with the intensity and rapid intensification of stationary tropical-cyclone-like vortex and its relation to initial sea surface temperature and vortex-induced sea-surface cooling. *J. Geophys. Res.*, **114**, D18111, doi:10.1029/2009JD011993.

Wang, Y., 2008a: Rapid Filamentation Zone in a Numerically Simulated Tropical Cyclone. J. Atmos. Sci., 65, 1158-1181.

Wirth, V. and T. J. Dunkerton, 2009: The dynamics of eye formation and maintenance in axisymmetric diabatic vortices. *J. Atmos. Sci.*, **66**, 3601–3620.

Zhang, D.-L. and C. Q. Kieu, 2006: Potential vorticity diagnosis of a simulated hurricane. Part II: Quasi-balanced contributions to forced secondary circulations. *J. Atmos. Sci.*, **63**, 2898–2914.