7th European Conference on Severe Storms (ECSS2013) , 3 - 7 June 2013, Helsinki, Finland

The influence of mesoscale mid-level vortices on deep convection and implications for tropical cyclogenesis

M. E. Nicholls

University of Colorado, Co-operative Institute for Research in Environmental Sciences, Boulder. CO, USA

I. INTRODUCTION

The formation of a strong mid-level vortex in a mesoscale precipitating system influences the subsequent development of convection in a number of ways. It results in warming aloft, cooling at low levels, and large vertical wind shear at the radius of maximum winds. Moreover as the mid-level circulation intensifies the conversion of latent heat energy released in convective towers to kinetic energy of the balanced rotational flow becomes more efficient (Schubert and Hack 1980; Hack and Schubert 1986). In this paper these effects are discussed in the context of a developing tropical disturbance that transforms into a tropical cyclone.

Recent idealized cloud-resolving simulations of tropical cyclogenesis from a weak incipient mid-level vortex over a warm tropical ocean have produced apparently conflicting results (Montgomery et al. 2006, hereafter M06; Nolan 2007, hereafter N07). The first of these studies showed a pathway that can be summarized as follows: It involves a steady increase of the surface winds to tropical cyclone strength as the radius of maximum winds (RMW) gradually decreases. A notable feature of this evolution is the creation of small-scale lower tropospheric cyclonic vorticity anomalies by deep convective towers and subsequent merger and convergence by the low-level secondary circulation. The importance of vertical hot towers (Hendricks et al. 2004) in this process was emphasized by M06. The second pathway discussed by N07 was distinctly different: Genesis did not occur until the inner core had achieved deep near-saturation and the mid-level vortex had contracted, and intensified. Cyclogenesis occurs when a small-scale surface concentrated vortex (SSCV) forms abruptly near the centre of the larger-scale circulation. This smaller vortex becomes the core of an intensifying tropical cyclone. Moreover, N07 showed that prior to genesis that the strengthening of the mid-level vortex resulted in a significant increase in the efficiency of the conversion of latent heat energy to the kinetic energy of the cyclonic wind field, which would favour intensification of the SSCV. M06 used the Regional Atmospheric Modeling System (RAMS) for their study, whereas N07 used the Weather Research and Forecasting (WRF) model. Why were the results so different for two widely used models that were set up with similar initial conditions?

Light was shed on the perplexing difference between these two studies when results were obtained for new simulations with a different version of RAMS that showed evolution along both pathways occurring depending on the initial conditions (Nicholls and Montgomery 2013) A suite of experiments was conducted to examine the sensitivity to size, and strength of the initial vortex, moistening of the central core, inclusion of radiation, inclusion of ice, and sea surface temperature (SST). Results suggest that the sensitivity to the initial condition shown in these experiments bear a resemblance to being near a bifurcation point, so that relatively small changes of the initial conditions can lead to a change in the pathway taken to tropical cyclogenesis. In particular, as the sea surface temperature (SST) was increased it became more likely that the system would develop along the second pathway, referred to as pathway Two, that involved a substantial spin-up of the mid-level circulation prior to genesis. It was shown that the production of ice was of fundamental importance for development along pathway Two in these simulations, and that more ice was produced for higher SST's. This apparently was related to higher SST's favouring more intense and deeper convective cells that resulted in a more extensive stratiform anvil composed of ice aloft. At the base of the ice layer a mid-level inflow developed. The Coriolis force acting on this inflow air and convergence of the pre-existing circulation are likely to be mainly responsible for the spin-up of the mid-level circulation. The physical explanation for how an extensive stratifom ice layer aloft produces a more significant mid-level inflow still needs to be investigated. One important factor may be the relatively slow fall speed of many ice hydrometeors compared to liquid hydrometeors and its affect on the diabatic heating responsible for driving the mid-level inflow.

Moreover, the use of an alternative radiation scheme, changed the likelihood of evolution along a particular pathway demonstrating a sensitivity to model physics. Therefore the different physical parameterizations used by RAMS and WRF in the studies by M06 and N07 are likely to have had had an influence on the pathway that occurred. It is interesting that all the cases simulated by M06 showed development along pathway One, whereas all the cases simulated by N07 showed development along pathway Two.

The processes leading to the formation of an SSCV for cases developing along pathway Two in their simulations were also examined by Nicholls and Montgomery (2013). These are summarized as follows: (1) A significant central cold pool develops at the surface at the same time a prominent mid-level vortex forms. This appears to be mainly caused by cold pools from earlier convection spiralling into the centre and merging. (2) There is also low-level cooling between z=2-5 km in the systems core probably caused by melting and evaporation of hydrometeors falling from the stratiform layer aloft. (3) Around the edge of the central cold pool there is a significant amount of positive vertical vorticity. (4) Deep moistening in the core of the system due to vertical transport by deep convective towers has occurred by this stage as was found by N07. (5) Convective activity continually generates small-scale regions of enhanced positive vertical vorticty in the lower troposphere, which are also low pressure regions. At some point one of the more significant vorticity anomalies that typically forms 15-30 km from the centre survives while spiralling into the centre. When it reaches the centre there is an increase in convective activity and an SSCV forms. Fuel for the convection comes from a band of relatively moist and warm air that is spiralling into the centre and that has trailed the vortcity anomaly. The convection at the centre creates a warm column of air that penetrates through the low-level cool air associated with the prominent mid-level vortex. It is possible that the low-level cooling may favour convective development at the centre due to a reduction in low-level static stability. A surface pressure drop of 2-3 mb occurs as an intense small-scale vortex forms. The low level positive vertical vortcity around the edge of the cold pool is an important source of vortcity for the developing SSCV. In some cases the SSCV when it first forms can be considered an intense individual VHT, but it can also involve multicellular convection. (6) The SSCV, which has a RMW typically between 5-10 km when it forms, quickly intensifies and often undergoes a modest growth resulting in a very small tropical cyclone.

In this article preliminary results are presented of a recent simulation that uses a two-moment microphysics scheme for all the hydrometeor categories and that shows development along pathway Two. Particular attention is paid to how the mid-level vortex and its associated temperature anomalies influence the development of deep convective cells. Finally, the possible relevance of these results to Mediterranean hurricanes, or Medicanes is discussed.

II. RESULTS OF A SIMULATION EVOLVING ALONG PATHWAY TWO

The model is the same as used by Nicholls and Montgomery (2013), but with some modifications. In particular two-moment microphysics is used for all the categories. This means that both the number concentration and mean size of the hydrometeors can vary. Furthermore, a substantially improved grid resolution is used. For this experiment three grids are configured with horizontal grid increments of 12, 3 and 1 km, with (x,y,z) dimensions of 170x170x48, 202x202x48, 302x302x48, respectively. Each finer scale grid is centred within the next coarsest grid. The vertical grid increment is 60 m and gradually stretched with height to the top of the domain at z=23 km.

Similarly to M06, the temperature structure is the mean Atlantic hurricane season sounding of Jordan (1958). The details of the procedure used to initialize the initial vortex are discussed by M06. For this experiment the radius of maximum winds is 75 km. The vortex has a maximum wind speed of 8 m s^{-1} at a height of 4 km above the surface, and a maximum surface wind speed of 4 m s^{-1}. The SST was set to 28 °C. Radiation was not included.

During the first twenty-four hours the maximum winds shifted to near the surface with speeds reaching in excess of 10 m s^{-1} by 50 h. Approximately at this time substantial mid-level inflow developed beneath the stratiform ice layer which had been produced by numerous deep convective cells. By 60 h a second prominent second mid-level vortex had formed.

Figure 1 a-c shows vertical x/z sections of the y-component of velocity v at t=87, 90 and 97 h, respectively, for a 180 km wide portion of the fine grid. A strong mid-level vortex with wind speeds of 15 m s^{-1} can be seen at t=87 h, inside the near surface RMW. At t=90 h a SSCV can just about be discerned close to the centre. Its circulation extends up to nearly 8 km above the surface. By 97 h a very small tropical cyclone has formed.

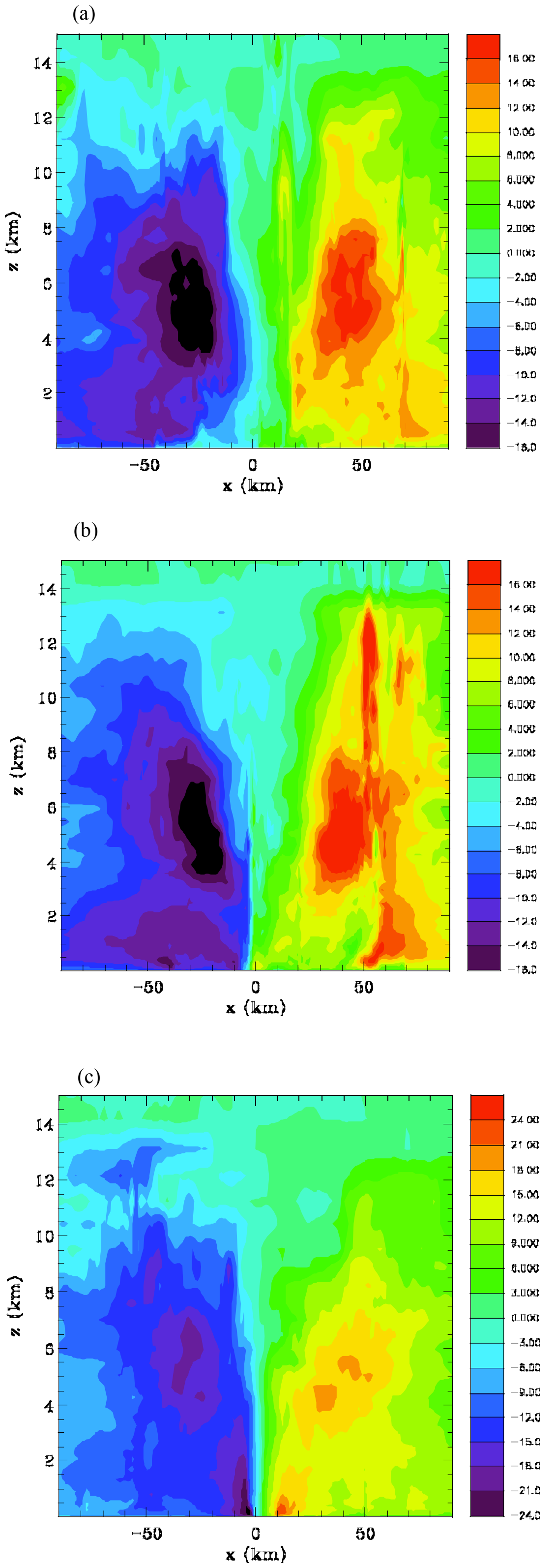
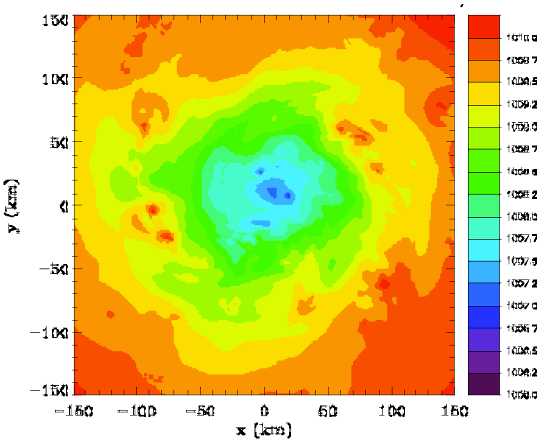


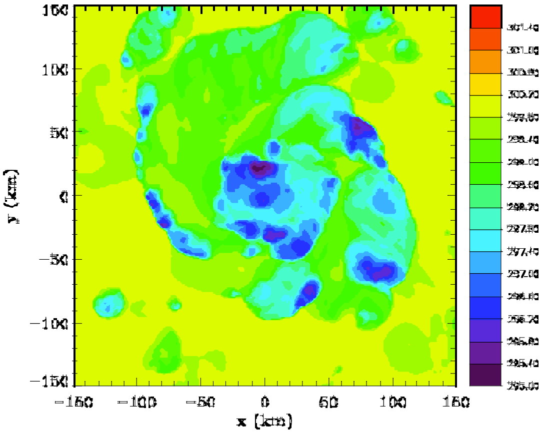
FIG 1: Vertical x/z section of the y-component of velocity v through the centre of the domain, at (a) t=87 h (b) t=90 h and (c) t=97 h.

The situation preceding the formation of the SSCV was quite complex. At 83 h a small surface low pressure region had formed 10 km west of the centre. It moved cyclonically around the centre and its distance from the centre of the domain increased. Figure 2 a-c shows horizontal sections at the lowest grid level above the surface (z=29.5 km) of pressure, potential temperature and vertical relative vorticity. The anomaly is 20 km to the west of the centre on the edge of a central cold pool. It also has a significant amount of positive vertical vorticity. It can be seen that there is a strong correlation between the edges of regions that are cold and positive vertical vorticity by comparing Fig.1b and Fig. 1c. Figure 3 show the same fields one hour later at t=87 h. The small low pressure anomaly is now 25 km to the north and is considerably larger. It also has significantly enhanced vertical vorticity. Active convection was responsible for this development. The anomaly is still on the edge of the central cold region, which is quite non-uniform in this case. It is the product of numerous convective downdrafts.

(a) Pressure



(b) Potential temperature



(c) Vorticity

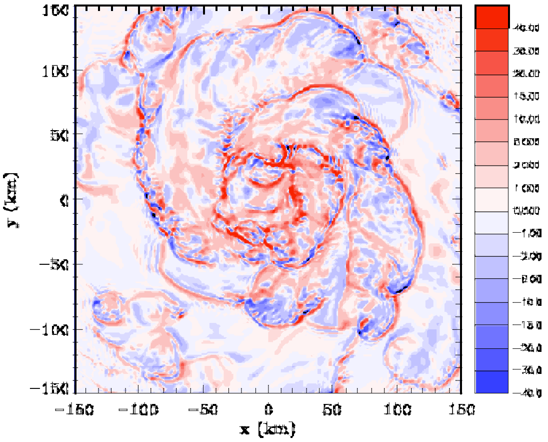


FIG. 2: Horizontal sections at t=86 h. (a) Pressure (mb) (b) potential temperature (K) and (c) vertical vorticity (x10^{-4} rad s^{-1}), at z=29.5 m.

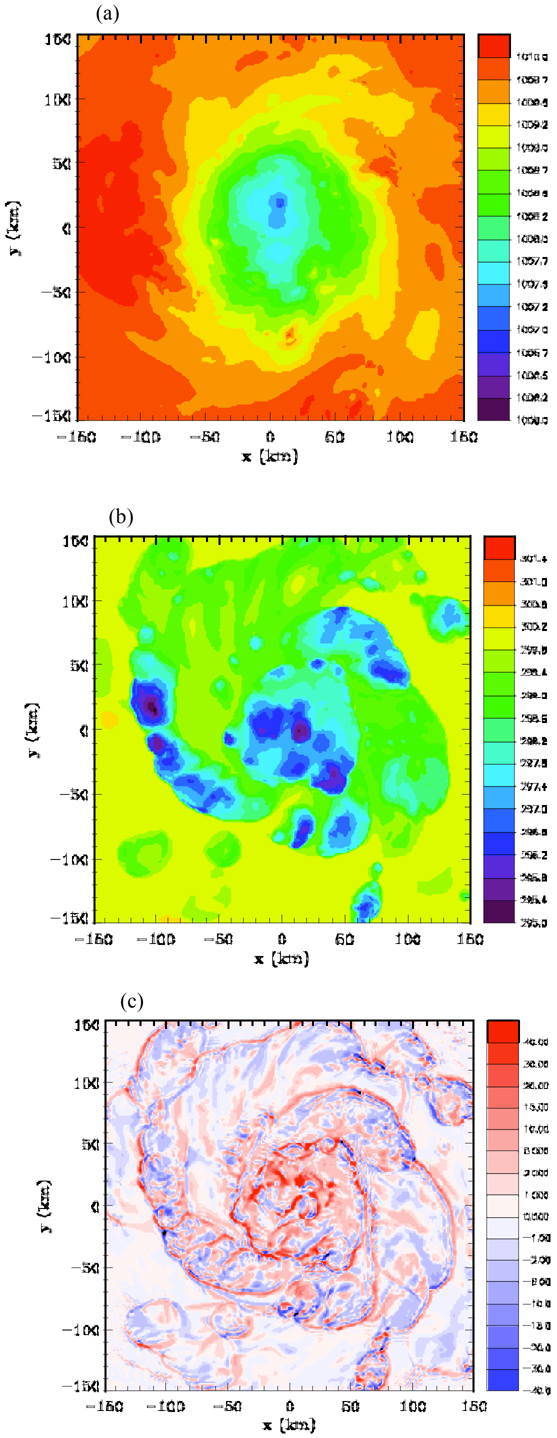
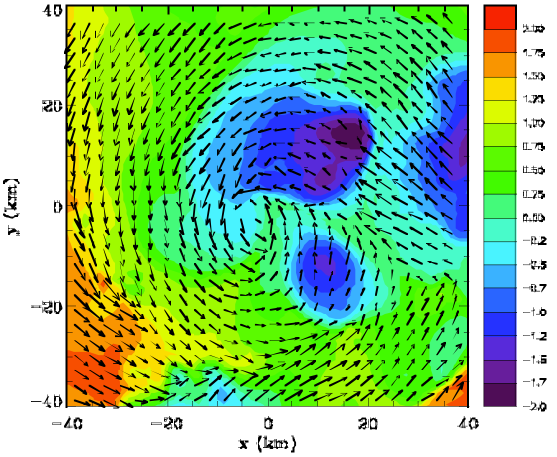


FIG. 3: As in Fig. 2 at 87 h.

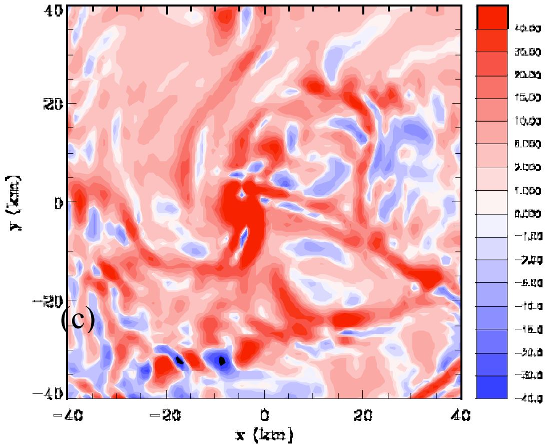
The anomaly spiralled towards the centre in the next two hours and convection intensified, which created a SSCV. Figure 4 shows zoomed fields at t=89 h illustrating its development. Fig. 4a shows that the SSCV is at the centre of the domain and on the edge of a small local surface cold pool. It is feeding mainly on a flow of relatively warm air coming from the north and spiralling into the centre. This air is also relatively moist (not shown). Fig. 4b shows that the low level vertical vortcity has high positive values in the anomaly, and also that there is significant positive vertical vorticity in the air streaming into it. Fig. 4c shows a vertical section in the y-plane of potential temperature and contoured y-component of velocity v. Convection has produced a warm column of air that extends through the low level cool air associated with the mid-level vortex. This figure also shows the cold pool is very shallow with a depth of only 0.5 km. Fig. 4d that is a horizontal section of vertical velocity at z=4.3 km shows convective updrafts on the north side of the low level vortcity centre. They are also on the edge of the surface cold pool. Cooled air caused by evaporation of rain that fell from the convection contributed to the cold pool. It is possible that low-level uplift caused by the spreading cold pool helped to force the convective activity.

The RMW at the surface grew initially reaching 17 km at 92 h. But then the RMW started to decrease. The azimuthally averaged tangential winds near the surface reached 12 m s^{-1} by 94 h. The RMW continued to decrease to only 7 km by 99 h and it remained at that size as the system rapidly intensified to hurricane strength.

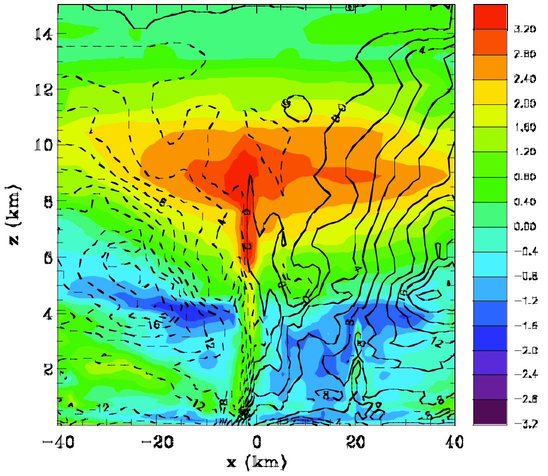
(a) Temperature perturbation X/Y



(b) Vertical vorticity X/Y



(c) Potential temperature, v X/Z



(d) Vertical velocity z=4.3 km X/Y

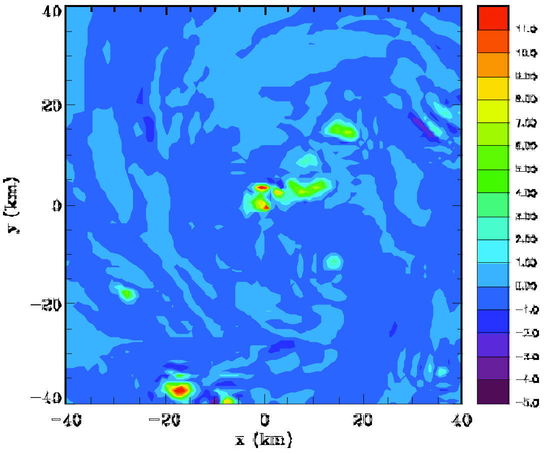


FIG. 4: Zoomed fields at t=89 h. Horizontal sections of (a) temperature perturbation (K) and wind vectors (max 16 m s^{-1}) and (b) vertical vorticty, at z= 29.5 m. (c) Vertical x/z section of potential temperature perturbation (K) and y-velocity v, contoured at 2 m s^{-1} intervals, at y=-0.5 km. (d) Horizontal section of vertical velocity at z=4.3 km.

III. CONCLUSIONS

The system underwent cyclogenesis along pathway Two, which involves the development of a prominent mid-level vortex. For this simulation the small scale low-level pressure and vortcity anomaly formed quite close to the centre where vertical wind shear was relatively weak. For some of the cases simulated by Nicholls and Montgomery (2013) the convective cell that generated the anomaly formed in appreciable vertical shear, which caused it to tilt. The cells rain shaft was downshear of the updraft and this led to small cold pool forming at the surface downstream. The cell was persistent and trailed the cold pool as it spiralled into the centre, and was itself trailed by the vorticity anomaly. One case developed in a unique way. A mesoscale convective system that was 50 km from the domain centre created a strong raised mesoscale vortex, which played a role in the development of a relatively large SSCV with a radius of maximum winds of 11 km when it reached the centre. Another interesting evolution occurred when a small-scale vorticity anomaly with active convection around it was impacted by the outflow from a squall line. This appeared to have a favourable influence on the subsequent formation of a SSCV. In one experiment an outflow from a convective cluster 70 km from the centre collided with a cold pool near the centre leading to the development of an intense cell in a region of low-level positive vertical vorticity, which then formed into an SSCV. Many anomalies that formed in these simulations did not survive, often being detrimentally influenced by an outflow from nearby convection. There is clearly a fortuitous aspect to the formation process of a SSCV.

Most of the cases that evolved along pathway Two remained very small and would fall into the category of midget tropical cyclone. However, one case that had a large initial mid-level vortex with a RMW of 125 km, grew in size from a RMW of 5 km when near surface average tangential winds were 12 m s^{-1} to a RMW of 23 km at tropical storm strength (17.4 m s^{-1}).

Many questions remain about the physical mechanisms involved during development along pathway Two. So far there has not been any direct observational evidence indicating development along this pathway. It has only been found to occur in idealized numerical model simulations with RAMS and WRF. If it does exist in nature it is unlikely to be the main mechanism large tropical cyclones form since it usually seems to result in small systems, but it might be an important genesis mechanism for small tropical cyclones.

SST's over the Mediterranean are considerably cooler than those used for these idealized simulation that use SST's typical of the tropical oceans. Pathway Two is favoured by warm SST's which produce stronger deeper convective cells and more ice. Nevertheless, medicanes usually form when there is a cold and deep upper-level trough. This results in cold air over a relatively warm sea surface, and moreover the air is humid. Such an environment is favourable for hurricane-like development (Emanuel 2005). It is possible that this environment could produce considerable quantities of ice aloft. On the other hand, it has been known for some time that mid-level vortices in the trough region of tropical disturbances are typically pre-cursors to tropical cyclogenesis (e.g. Zehr 1992; Mapes and Houze 1995; Harr and Elsberry 1996; Harr et al. 1996; Bister and Emanuel 1997). Observations of medicanes have not yet indicated that this is also a typical feature of their formation. Moreover, the mid-level vortex that developed leading up to genesis in the simulation shown here, by N06 and by Nicholls and Montgomery (2013), are quite intense, considerably more so than those found in the stratiform region of a typical mesoscale convective system. Therefore the absence of evidence might be indicative of them not being a general feature of medicane formation. They are however rare events and there is a lack of observational data for these systems as noted by Tous and Romero (2012), so no definite conclusions can be drawn at present. Therefore, the possible existence of this pathway as a mechanism for medicane genesis should be taken into consideration by forecasters and researchers of these Mediterranean systems.

IV. ACKNOWLEDGMENTS

The author would like to thank Professor Michael Montgomery for helpful discussions, Saurabh Barve for providing computational assistance, Steve Saleeby for help with the microphysics scheme, and Donavan Wheeler for developing some of the visualization code. This research was supported by the National Science Foundation, under Grant NSF AGS 0965721.

V. REFERENCES

Bister, M., and Emanuel, K., 1997: The Genesis of Hurricane Guillemero: TEXMEX Analyses and a Modeling Study. *Mon. Wea. Rev.,* 125, 2662-2682.

Emanuel, K, 2005: Genesis and Maintenance of “Mediterranean Hurricanes”. *Adv. in Geos.*, 2, 217-220.

Hack, J. J., and Schubert, W. H., 1986: Nonlinear Response of Atmospheric Vortices to Heating by Organized Cumulus Convection. *J. Amos. Sci.,* 43, 1559-1573.

Harr, P. A., and Elsberry, R. L., 1996: Structure of a Mesoscale Convective System Embedded in Typhoon Robyn During TCM-93. *Mon. Wea. Rev.,* 124, 634-652.

Harr, P. A., Kalafsky, M. S., and Elsberry, R. L., 1996: Environmental Conditions Prior to Formation of a Midget Tropical Storm During TCM-93. *Mon. Wea. Rev.,* 124, 1693-1710.

Hendricks, E. A., Montgomery, M. T, and Davis, C. A. 2004: On the Role of “Vortical” Hot Towers on Tropical Cyclone Formation. *J. Atmos. Sci.,* 61, 1200-1232.

Mapes, B. E., and Houze, R. A., 1995: Diabatic Divergent Profiles in Western Pacific Mesoscale Convective Systems. *J. Atmos. Sci.,* 52, 1807-1828.

Montgomery, M. T., Nicholls, M. E., Cram, T. A., and Saunders, A. B., 2006: A Vortical Hot Tower Route to Tropical Cyclogenesis. *J. Atmos. Sci.,* 63, 355-386, 2006.

Nicholls, M. E., and Montgomery, M. T., 2013: An Examination of Two Pathways to Tropical Cyclogenesis Occurring in Idealized Simulations with a Cloud-Resolving Numerical Model. Submitted to *Atmos. Chem. Phys.*

Nolan, D., 2007: What is the Trigger for Tropical Cyclogenesis? *Aus. Met. Mag.*, 56, 241-266.

Schubert, W. H., Hack, J. J., Silva Dias, P. L., and Fulton, S. R., 1980: Geostrophic Adjustment in an Axisymmetric Vortex. *J. Atmos. Sci.,* 37, 1464-1484.

Tous, M., and Romero, R., 2012: Meteorological Environments Associated with Medicane Development. *Int. J. Climatol.,* 33, 1-14, doi: 10.1002/joc.3428.

Zehr, R. M., 1992: Tropical Cyclogenesis in the Western North Pacific. *NOAA Tech. Rep.* NESDIS, 61, 181 pp (Available from U.S. Department of Commerce, NOAA/NESDIS, 5200 Auth Rd, Washington, DC 20233).