11A.2

PREDICTION AND DIAGNOSIS OF THE MOTION AND RAPID INTENSIFICATION OF TYPHOON SINLAKU DURING TCS08 (TROPICAL CYCLONE STRUCTURE EXPERIMENT, 2008)

MARIE-DOMINIQUE LEROUX *
Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Australia.
Laboratoire de l'Atmosphère et des Cyclones, unité mixte CNRS – Meteo-France – Université de La Réunion, Sainte Clotilde, Reunion

1. INTRODUCTION

Numerical prediction of tropical cyclone (TC) tracks has significantly improved over the past few decades; however accurate prediction of their intensity has lagged behind.

TC intensification has been the subject of both observational and theoretical studies which have shown that it involves a combination of different factors: (a) ocean interaction (Emanuel 1986; Shay et al. 2000; Lin et al. 2005), (b) environmental forcing (Molinari and Vollaro 1989; Hanley et al. 2001; Davidson et al. 2008), (c) vortex structure (large and small RMW and size), about which little is known and is one aspect of the current study, and (d) internal processes that modify the vortex structure (Willoughby 1990; Montgomery and Kallenbach 1997; Schubert et al. 1999; Montgomery et al. 2006; Nguyen et al. 2006; Hendricks et al. 2009).

The present work is partially motivated by the fact that accurate prediction of the short-term track and intensity of TCs in the Australian operational numerical weather prediction system currently relies on vortex specification to define the TC inner-core at the observed location. The study thus consists of investigating item (c), the sensitivity of prediction of track and intensity to specification of initial vortex structure, while examining item (d), the pathway to intensification taken by vortices with different initial structures within a given environment (item b) which is formerly analysed in detail.

Experiments are conducted on the motion and rapid intensification (RI) of Typhoon Sinlaku which was observed during the 2008 Tropical Cyclone Structure experiment, TCS08 (Elsberry et al. 2008), over the Northwest Pacific.

We illustrate that the use of an initial vortex with a large radius of maximum wind (RMW) greatly improves the track prediction. We suggest that this is related to the increased influence of the β-effect associated with strong winds at the large RMW, under weak environmental steering.

Most of the 15-km forecasts produce the observed intensification but results at 5-km suggest that the pathway to RI, for the same environmental forcing, is dependent on initial storm structure. With an initially large RMW, the 5-km forecast is able to capture the observed double eyewall structure and the evolution of structure and intensity more skilfully. We illustrate the process and discuss some possible dynamical interpretations.

2. SUPERTYPHOON SINLAKU

From 9 to 12 September 2008, Typhoon Sinlaku underwent a period of Rapid Intensification (RI) defined by a minimum increase of 30 kt[1] over 24 hours (Kaplan and DeMaria 2003). Central pressure dropped to 935hPa by the end of that period during which Sinlaku underwent large motion and internal structure changes, including the development of multiple eyewalls and possibly multiple wind maxima at radii varying between 200 and 20 km. Fig. 1 illustrates an outer band of deep convection wrapping around the inner eyewall.

The main environmental low- and upper- level factors involved in the genesis and intensification of Sinlaku are sketched on Fig. 2. Sinlaku formed as large scale cloud features propagating from the east, west and south collided to the east of the Philippines. These features were associated respectively with an easterly wave (the precursor to Sinlaku), the northwest Pacific Monsoon (enhanced by the passage of a Madden-Julian Oscillation event), and possibly a

---

* *Corresponding author address:* Marie-Dominique Leroux, Meteo-France DIRRE, Cellule Recherche Cyclones, BP4, 97491 Ste Clotilde, La Réunion.
E-mail: mariedominique.leroux@gmail.com

[1] $1kt = 0.5144\, m.s^{-1}$

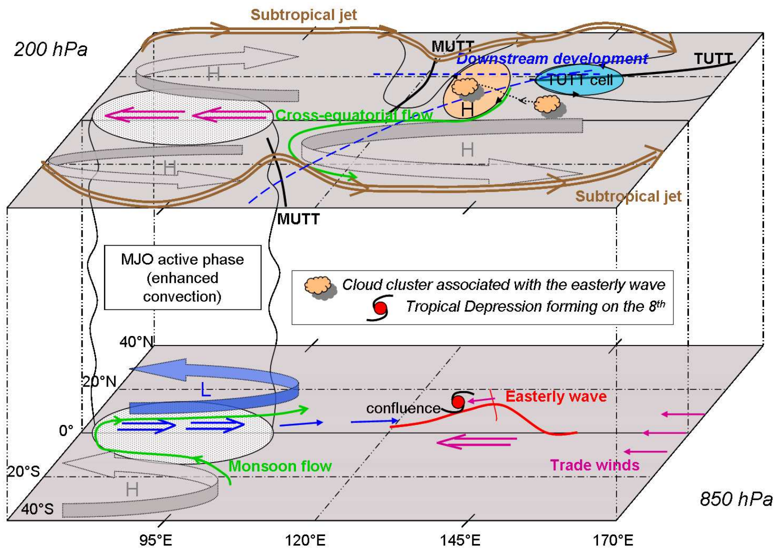

FIG. 2. Schematic synopsis of typhoon Sinlaku environmental flow during formation and intensification, at low (850 hPa) and high (200 hPa) levels.

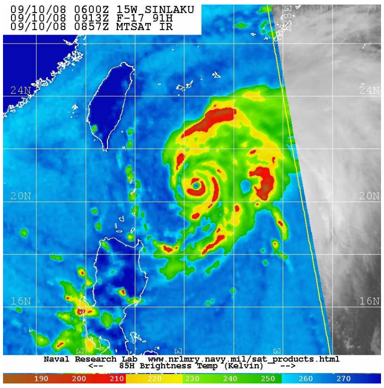

FIG. 1. Typhoon Sinlaku brightness temperature horizontal distribution from SSMIS 91 GHz channel at 09 UTC 10 September 2008. Source: http://www.nrlmry.navy.mil/tc_pages/tc_home.html

Planetary Rossby Wave from the Southern Hemisphere.

The environmental upper flow during formation and intensification was driven by three large scale features: (1) an amplifying upper trough off the coast of NW Australia and subsequent development of an upper ridge to its NE spawning accelerating easterlies near the equator, (2) an amplifying TUTT[2] to the NE of the developing storm, and (3) an amplifying MUTT[3] to the NW of the formation region.

Such large scale flow changes can potentially provide a favourable environment for formation and rapid intensification via (a) reduced vertical wind shear, (b) multiple extended outflow channels into the equatorial easterlies and ahead of the TUTT and MUTT, and (c) a modulation of the storm's vertical motion field via the interaction with the TUTT and MUTT, and possibly the passage of Planetary Rossby Waves (not demonstrated here).

From 9 to 12 September, hodographs for Sinlaku (not illustrated here) show that its environment evolved towards one of weak steering and weak vertical wind shear.

3. MODEL DESCRIPTION AND VORTEX INITIALIZATION

A hierarchy of 72 hours forecasts were performed at 15- and 5-km resolution with 29 vertical levels using the full-physics version of the operational Australian Bureau of Meteorology's Tropical Cyclone Limited Area Prediction System, TC-LAPS. The system includes sophisticated vortex specification, data assimilation, advanced numerics, a bulk explicit microphysics scheme and a mass flux convection parameterization. The synthetic vortex produced during the vortex specification is in gradient balance and does not include a representation of the storm's secondary circulation. Therefore, a diabatic nudging initialization uses the full model to balance the mass and wind fields, and build the secondary circulation and convective asymmetries to be consistent with available satellite cloud imagery, while pre-

---

[2] TUTT: Tropical Upper Tropospheric Trough

[3] MUTT: Midlatitude Upper Tropospheric Trough

serving the analysed vorticity and surface pressure. So at the base time of the forecast, the data assimilation, vortex specification and nudging initialization have created a quality representation of the storm's environment, inner-core circulation and cloud asymmetries.

The present results were obtained using a vortex specification scheme described by Ma et al. (2009) and hereafter named VSSK. It is an enhanced version of the original profile of Fujita (1952). Key parameters of intensity are central pressure and maximum wind, and of structure are the Radius of Maximum Wind (RMW) and storm size, as indicated by for example, the Radius of 34 knot winds (R34) or the Radius of Outer Closed Isobar (ROCI). It is unclear how these structural characteristics influence the prediction of intensification. We will illustrate an important sensitivity to vortex structure as defined by RMW and R34, and discuss the different pathways to intensification taken by vortices with distinctly different initial structures.

4. IMPACT OF STORM STRUCTURE ON FORECASTS

A more reasonable representation of Sinlaku's observed intensification is first obtained by adjusting the vortex size parameter ROCI (which can be difficult to estimate in real time) from its original estimate of 185 km to the value of 400 km hindcast on UM analyses (not illustrated here).

Secondly, the sensitivity of the forecast to R34 is found to be very weak, possibly because the large-scale analysis is dominating at such large radii.

On the contrary, prediction of track and intensity appears highly sensitive to RMW (and thus vortex structure at inner radii). Fig. 3 illustrates the main results for a vortex initialized either with a large RMW value of 220 km, that can be associated with the developing outer band hindcast on the 85 GHz satellite imagery at the beginning of RI, or with a 55 km value that corresponds to the estimated radius of the inner eyewall. A larger initial RMW produces a superior forecast with a 72-hr track error reduced by 40% due to a better representation of the motion change from east to north beyond 36 hours. For this event, observational and analysis data provide evidence of the importance of the β-effect in defining the track changes. We suggest that from 10 September, the actual storm gradually became slow-moving and isolated from environmental influences, so that the β-effect increasingly influenced the propagation of the storm. Chan and Williams (1987) demonstrated that, in a zero mean flow, the northwestward propagation which results from non-linear effects (horizontal advection of vortex vorticity) increases with the radius of maximum wind in a constant-shape vortex. That is, the β-effect plays a more important role as the winds at large radii strengthen. This effect produces a westward and poleward component to the motion, that is not large (of order 2 m s^{-1}) but can be important when environmental influences are small and when the storm is large enough: two criteria that seem to be present for Sinlaku. Our simulations provide further evidence to support this contention as the β-effect acts more efficiently when we specify a larger RMW.

These experiments demonstrate that the prediction of storm motion and intensity can be highly related to the specification of the vortex structure. Although it is difficult to draw firm conclusions from a single case, the RMW appears to play a crucial role in forecasting the β-propagation of a slow-moving storm evolving in a weak environmental steering flow, such as experienced by Sinlaku. It underscores the need to optimize the initial parameters of each TC to best fit the observed storm structure and extent of low-level winds. To do so, a greater understanding of storm structure evolution during RI is needed.

5. STORM STRUCTURE CHANGES DURING RI

To improve our understanding of Sinlaku's RI with regard to vortex structure and inner-core processes, high resolution experiments are carried out. Both simulations with RMW $= 55$ km and 220 km are illustrated here, following the quantitative information retrieved from cloud signatures. The 5-km forecasts are nested in the medium resolution predictions, initialized from the 15-km analyses (with vortex specification included) and run using the same Bulk Explicit Microphysics and convective parameterization as previously.

Results show that the quality of the forecast is improved at high resolution for the large initial RMW (both track and intensity are very encouraging) whereas the small storm continues to over-intensify (below 900 hPa) suggesting that different inner-core processes might be involved. Fig. 4 illustrates for both storms the radial profile of tangential wind within the boundary layer, and its evolution every 6 hours during model integration.

It appears that a secondary wind maximum develops in the inner core of the large storm (right panel), consistent with the study of Nguyen et al. (2006). It can be linked to a change in the radial distribution of the relative vorticity (RV). In the first hours,

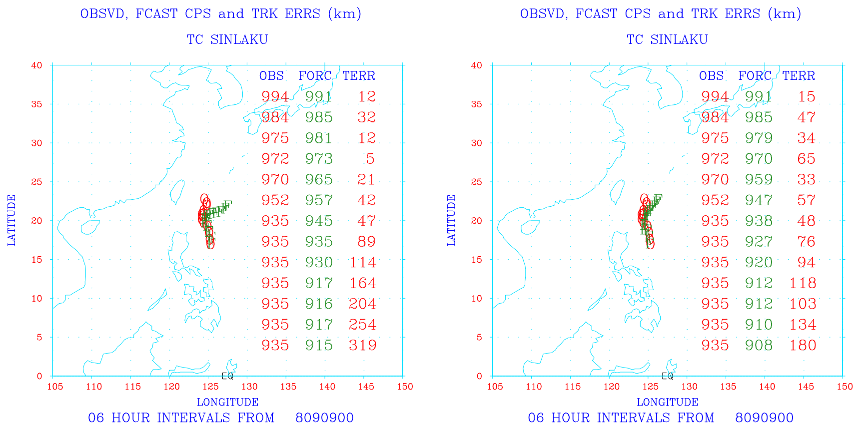

FIG. 3. Typhoon Sinlaku observed and predicted track and intensity from base time 00 UTC 9 September 2008. 72-hr forecast resolution is 0.15°. Left panel is from a small initial vortex ($RMW = 55\ km$, value estimated in real time). Right panel is for a large storm ($RMW = 220\ km$).

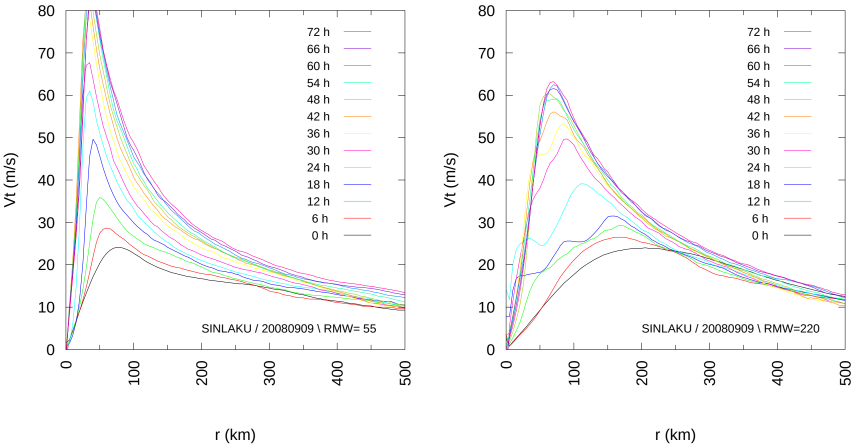

FIG. 4. Radial distribution of tangential wind speed at 0.975 σ-level every 6-h of model integration from base time 00 UTC 9 September 2008, at 0.05°-resolution. Left panel is from a small initial vortex ($RMW = 55\ km$). Right panel is for a large storm ($RMW = 220\ km$).

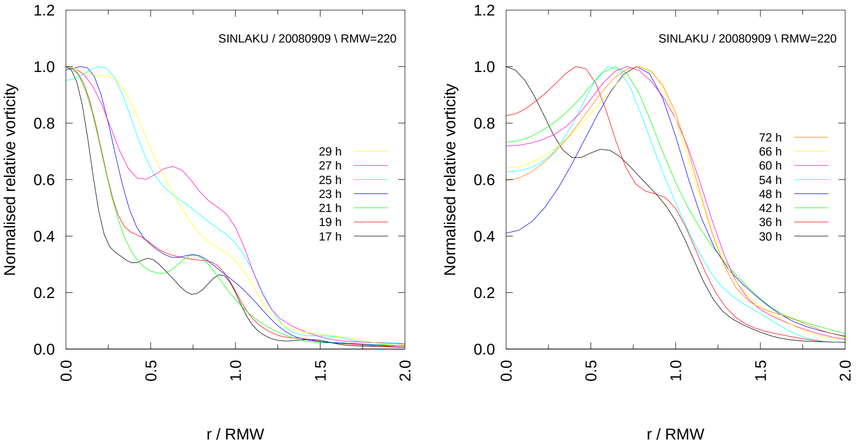

FIG. 5. Radial distribution of the normalized relative vorticity at 0.975 σ-level for the large storm ($RMW = 220\ km$) at specific times during model integration, from base time 00 UTC 9 September 2008.

this distribution is an elevated ring structure (similar to Fig. 5 right panel) with a region of barotropic instability. As suggested by Schubert et al. (1999), this instability (plus convective instability) can create meso-vortices, also called Vortical Hot Towers (VHTs) by Montgomery et al. (2006). Via a mixing process, the VHTs relax the ring of RV into a stable monopolar distribution with a maximum in the center (see Fig. 5 left panel). These VHTs could explain, via stretching arguments, the sudden increase in maximum RV observed (not illustrated here) during that "monopole phase" occurring from hour 17 to around 30. The RV is then axisymmetrized and returns to a ring structure (see Fig. 5 right panel). It is suggested that the propagation of Vortex Rossby Waves (VRWs) is responsible for redistributing the vorticity produced by the VHTs, from the inner core to the region of maximum winds.

This process can elucidate the strengthening of the mean flow in the eyewall as observed in Fig. 4. The unstable ring structure persists later in the integration without transforming back to a monopole like during the RI period; even though a region of negative gradient exists, barotropic instability is apparently not triggered in that time scale. The ring structure is associated with an azimuthal wavenumber-three vertical velocity asymmetry, suggestive of a polygonal eyewall in which three vorticity centres can be seen subsequently rotating around each other (see Fig. 6).

During the initialization stage, we suggest that the inner eyewall was re-created in the simulated TC from the observed regions of deep convection localized on the GMS (with adiabatic ascent). Then what ensues is a quite new phenomenon. The inner RMW intensifies more rapidly than the outer one (maybe partly due to its small radius and to the period of relaxation) but instead of contracting inwards as usually observed, it extends outwards and finally merges with the contracting outer eyewall, leading to the accurate intensification of the storm. In that aspect, the model does not really forecast an eyewall replacement cycle but rather an "Interior Eyewall Formation" (IEF) and a "merging eyewall process", with seemingly a feedback between the two regions of maximum winds to produce the intensification. On the contrary, the small-RMW simulation initialized with a unique ring of convection is not able to simulate the observed outer bands forming, nor the possible interaction of the two eyewalls to produce a correct intensification. Of course, further experiments need to be carried out on other TCs that underwent an eyewall replacement cycle to extend the hypothesis and understand the operative IEF and "merging eyewall process". Preliminary experiments with Typhoon Jangmi indicate similar skill in forecasting track, structure and intensity, and some similar processes to that described here.

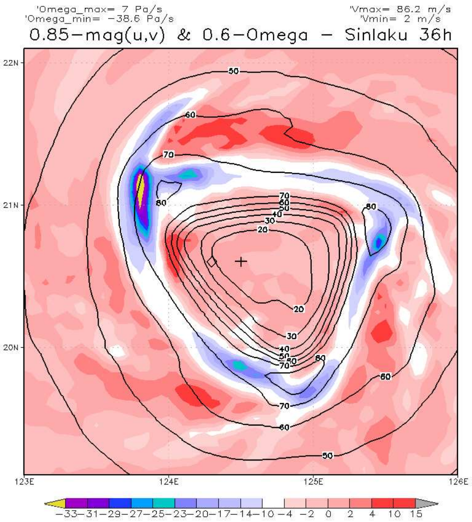

FIG. 6. 0.85 σ-level wind magnitude (contours in m s^{-1}) on top of the 0.6 σ-level omega field (shaded values in Pa s^{-1}) for the large storm ($RMW = 220\ km$) after 36h of model integration from base time 00 UTC 9 September 2008.

6. CONCLUSION

The results indicate that with an enhanced specification of vortex structure and increased resolution, TC-LAPS forecasts of typhoon track and intensity can be greatly improved. Further, high resolution experiments have provided insights on the evolution of TC inner structure during RI. There is no doubt that ongoing strategic research on understanding vortex behaviour will result in improving prediction of such high impact weather events. A main issue can be raised from the present work: how can we specify vortex structure which has two wind maxima, and how does the intensification then occur?

Acknowledgments.

The author would like to express her thanks to the Centre for Australian Weather and Climate Research for generously welcoming her and supplying computing facilities and access to data for the completion of this project. The author is also grateful to Yimin Ma for his expertise on the VSSK scheme and to Chi Mai NGuyen for her helpful discussion and comments on section 5.

REFERENCES

Chan, J. C.-L. and R. T. Williams, 1987: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci.*, **44**, 1257–1265.

Davidson, N. E., C. M. Nguyen, and M. Reeder, 2008: Downstream development during the rapid intensification of hurricanes Opal and Katrina: the distant trough interaction problem. *Extended abstracts, 28th Conference on Hurricanes and Tropical Meteorology*, Amer. Meteor. Soc., Orlando, Florida, 28 April – 2 May, CD–ROM.

Elsberry, R. L., P. A. Harr, R. Ferek, S. Chang, and D. Eleuterio, 2008: Tropical Cyclone Structure (TCS08) Field Experiment in the Western North Pacific during 2008. *Extended abstracts, 28th Conference on Hurricanes and Tropical Meteorology*, Amer. Meteor. Soc., Orlando, Florida, 28 April – 2 May, CD–ROM.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585–604.

Fujita, T., 1952: Pressure distribution within a typhoon. *Geophys. Mag.*, **23**, 437–451.

Hanley, D., J. Molinari, and D. Keyser, 2001: A compositive study of the interactions between tropical cyclones and upper-tropospheric troughs. *Mon. Wea. Rev.*, **129**, 2570–2584.

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.

Kaplan, J. and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the north Atlantic basin. *Wea. Forecast.*, **18**, 1093–1108.

Lin, I. I., C. C. Wu, K. A. Emanuel, I. H. Lee, C. R. Wu, and I. Pun, 2005: The Interaction of Supertyphoon Maemi (2003) with a Warm Ocean Eddy. *Mon. Wea. Rev.*, **133**, 2635–2649.

Ma, Y., M. Kafatos, and N. Davidson, 2009: Surface Pressure Profiles and Initialization for Hurricane Prediction. Part I: Analysis of Observed and Synthetic Structures. For submission to Mon. Wea. Rev.

Molinari, J. and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy momentum fluxes. *J. Atmos. Sci.*, **46**, 1093–1105.

Montgomery, M. T. and R. J. Kallenbach, 1997: A theory of vortex Rossby waves and its application to spiral bands and intensity changes in hurricanes. *Quart. J. Roy. Meteor. Soc.*, **123**, 435–465.

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

Nguyen, C. M., M. Reeder, N. E. Davidson, M. Montgomery, and R. Smith, 2006: High resolution ensemble simulations of hurricane Katrina: two distinct regimes of the vortex inner core structure. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology*, Amer. Meteor. Soc., Monterey, California, 24 – 28 April, CD–ROM.

Schubert, W. H., M. T. Montgomery, R. K. Taft, T. A. Guinn, S. R. Fulton, J. P. Kossin, and J. P. Edwards, 1999: Polygonal eyewalls, asymmetric eye contraction, and potential vorticity mixing in hurricanes. *J. Atmos. Sci.*, **56**, 1197–1223.

Shay, L. K., G. J. Goni, and P. G. Black, 2000: Effects of a warm oceanic feature on Hurricane Opal. *Mon. Wea. Rev.*, **128**, 1366–1383.

Willoughby, H. E., 1990: Temporal changes of the primary circulation in tropical cyclones. *J. Atmos. Sci.*, **47**, 242–264.