Evaluating the Effects of Latent Hearing in Tropical Cyclone Sinlaku's Extratropical Transition using ARW and Energetics Analysis

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ABSTRACT

Of all the Tropical Cyclones (TC) that occur worldwide, 42% (27%) of the North Atlantic (western North Pacific) storms undergo Extratropical Transition (ET) into Extratropical Cyclones (EC). EC are asymmetric cold core systems as opposed to their warm core predecessors, and their radii of gale force winds ($17ms^{-1}$) may increase by a factor of two to three times their original radii. This expansion of the gale force winds can cause a significant amount of damage. In addition, these ET can trigger and amplify upper atmospheric waves, indirectly leading to the generation of other powerful storms across the world, which makes it imperative to study the dynamics and energetics involved with the ET. The ET of TC Sinlaku (2008), with the aid of a 500mb shortwave, was well observed through an international field campaign, THORPEX Pacific-Asian Regional Campaign (T-PARC). To understand the effects of latent heating when Sinlaku transitioned, this study has followed similar techniques to Kuo et al. (1990). Two different sets of simulations using the Weather Research and Forecasting (WRF) model with the Advance Research WRF core were conducted, involving a full set of physics and fake dry physics (neglecting latent heating). This study looked at the evolution of Horizontal Kinetic Energy and its components to examine the impact of latent heating on the energetics of of the ET processes. Results drawn from both simulations suggest that latent heating is crucial for the maintenance of the TC and the 500 mb trough, and for the ET process. This is clearly reflected by the significant differences in the kinetic energy of the two ARW simulations with and without latent heating.

1. Introduction

As Tropical Cyclones (TC) move to higher latitudes, they encounter colder sea surface temperature (SST) and stronger shear. Rather than decaying, the TC may begin to lose its symmetry and warm core structure and may undergo extratropical transition (ET) into an asymmetric cold core system (i.e. an Extratropical Cyclone, EC) (Hart, 2003). When a TC transitions into an EC, the radius of gale force winds ($17ms^{-1}$) may increase by a factor of two to three times its radius as a TC. This expansion of the gale force winds can cause a significant amount of damage. For instance, in 1996 TC Hortense brought high winds, power outages, and flooding that caused $3 million in damages to Cape Breton Island, N.S. (CBC, 2007). Another known storm was TC Noel in 2007, which caused downed trees and power lines in the northeastern United States and eastern Canada and left over 200,000 people without power. Coastal flooding washed out sections of coastal roads in Nova Scotia, littering the area with boulders (Brown, 2007). In addition, these ET can trigger and amplify upper atmospheric waves, indirectly leading to the generation of other powerful storms across the world (Parsons, 2007). Danielson et al. (2004) proposed that about half of these cyclones stem from downstream wave development. Thus, ET events can have broader impacts around the globe than what is normally perceived. Out of all the TCs that occur worldwide, 42% (27%) of the North Atlantic (western North Pacific) storms undergo ET. Over a 37-year period, 50% of landfalling TCs over the United States, Canada, or Europe, underwent ET (Hart and Evans 2001). Due to the high number of ET events and the devastation they leave in their wake, it is imperative to study the physics behind these transitions.

This project will focus on the very well-observed ET event from the T-PARC (THORPEX Pacific-Asian Regional Campaign) field experiment: TC Sinlaku (2008). Major goals of T-PARC included improving understanding and forecasts of the complete TC lifecycle through intensive observations, data assimilation and model simulations. The NRL P-3, C-130, DLR Falcon, and DOTSTAR planes collected targeted data for a variety of tropical systems in the Western North Pacific for August and September 2008. From this data set, we are given a wealth of information about this particular storm. This wealth of information allows for an effective analysis of this storm and improves the understanding of ET.

Current techniques to understand, identify, and predict these transitions are present in Klein et al. (2000), Hart (2003) and Evans and Hart (2001). Klein et al. used satellite images to create a conceptual model of transitioning systems. Hart (2003) developed a Cyclone Phase Space (CPS) diagram, which shows the evolution of a transitioning system, from a warm symmetric core to an asymmetric cold core. Evans and Hart (2001) demonstrated the application of the CPS to this class of TC and identified appropriate threshold values for the onset and completion of ET. However, even with all of this recent progress, we are far from understanding and accurately predicting these transitions and their post transition intensities, let alone the energetics that come to play.

Viega et al. (2008) studied the tropical transition of TC Caterina (2004) using energetics defined by the Lorenz technique (calculating eddy kinetic & potential energy, zonal kinetic & potential energy, time derivative of these four energies, etc.). It was argued that at the transition from and EC to a TC the Available Potential Energy of the environment was converted into

Kinetic Energy. This study implemented a similar calculation of kinetic energy along with its zonal and meridional counterparts:

$$KE = \frac{1}{2}\frac{p}{RT}\|\vec{V}\|^2 \tag{1}$$

$$ZKE = \frac{1}{2}\frac{p}{RT}\|u\|^2 \tag{2}$$

$$MKE = \frac{1}{2}\frac{p}{RT}\|v\|^2 \tag{3}$$

where p is pressure, T is temperature, $\|\vec{V}\|$ is the norm of the wind vector, and R is the gas constant for dry air (287 J kg^{-1} K^{-1}). Also, in Kuo et al. (1990) the use of the quasi geostrophic omega (ω) equation was used to analyze two different types of EC simulations: Fake dry and Full Physics. From the analysis of the ω, Kuo et al. stated that during the rapid intensification period of the EC, the storm mostly depended on diabatic processes and was the predominant term of the forcing mechanisms in the ω equation. Methods employed in that study are implemented in this project, however an analysis of the ω wasn't implemented directly but instead indirectly. The model used in this study outputs the vertical component of wind (w)

$$\rho w g \approx -\omega .$$

where ρ is density, and g is gravity (9.81 m s^{-2}). Thus, the focus of this project was to analyze the energetics that come into play under both Fake dry and Full Physics simulations of TC Sinlaku.

2. Tropical Cyclone Sinlaku

TC Sinlaku's lifecycle consisted of a typical genesis (where it was known as wave 15W), two periods of Rapid Intensification, an Eye Wall Replacement Cycle, and an Extratropical Transition (ET). Figure 1 (below) is the best track map produced by the Joint Typhoon Warning Center:
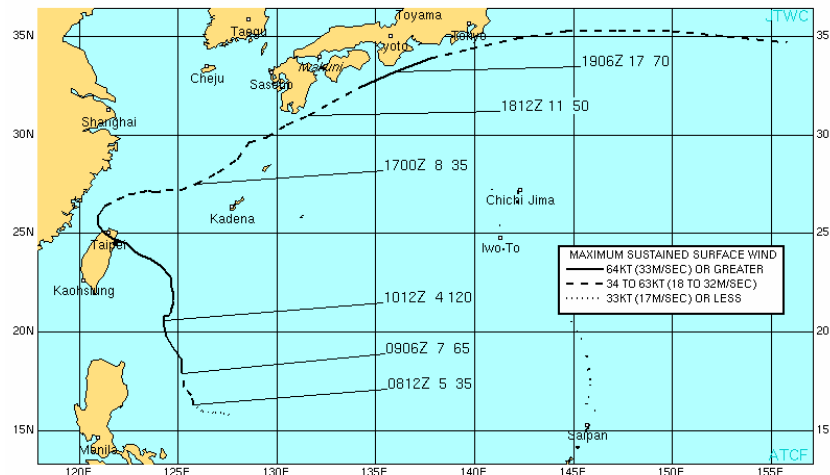

Fig. 1: TC Sinlaku's track over the Western North Pacific (Cooper et al. 2009). TC Sinlaku's peak winds were 100kts with a minimum central pressure of 935mb.

Wave 15W, pre-TC Sinlaku, had spent a significant portion of its lifecycle in the genesis phase according to the Daily Weather Report Summary (DWRP). Under the influence of shear 15W tried to get organized and by 7 September 2008 it began to develop an organized cloud mass towards the center and also showed signs of a rotating moisture field (DWRS, 7 September 2008), which indicated vorticity. JTWC stated that due to the low vertical shear and high ocean heat content the storm began its first Rapid Intensification period on the 8 September 2008 from a 35kt storm to a 120kt storm in less than 48hrs (Cooper et al. 2009). On 9 September 2008 12Z, 15W became known as TC Sinlaku with sustained winds of 55-60kts and a low pressure center of 986mb (DWRS, 9 September 2008). By the 10 September 2008, TC Sinlaku had developed an eye wall (DWRS, 10 September 2008) and by 18Z that same day TC Sinlaku had reached its peak strength of 125kts (sees Figure 2). The next day TC Sinlaku began undergoing its Eyewall Replacement Cycle (DWRS, 11 September 2008). Shortly after it reached its peak strength the TC made landfall over Taiwan, near Taipei (13 September 2008), where it began to weaken to 35kts.

Fig. 2: TC Sinlaku image from the NASA terra satellite on 10 September 2009, at its peak intensity of 100kts winds, with a central pressure of 935mb.

On 16 September 2008, the storm underwent phase one (transformation) of ET as defined by Klein et al. (2000). The TC began to impinge on a baroclinic zone, 500mb shortwave. This interaction started a flow of dry cold air towards the core of the TC that eroded most of the deep convection located to the western half of the system (see Figure 3a) (DWRS, 16-17 September 2008). At the same time there was warm air from the tropics being advected poleward and this poleward advection maintained the deep convection on the east side of the storm. The following day (17 September 2008) the wind shear from the Polar Jet began to interact with the storm's outflow to create its cirrus shield (see Figure 3b) (DWRS, 18 September 2008). TC Sinlaku

progressed on to phase two due to this added convection on the Eastern half of the system, which allowed for the storm to reintensify.
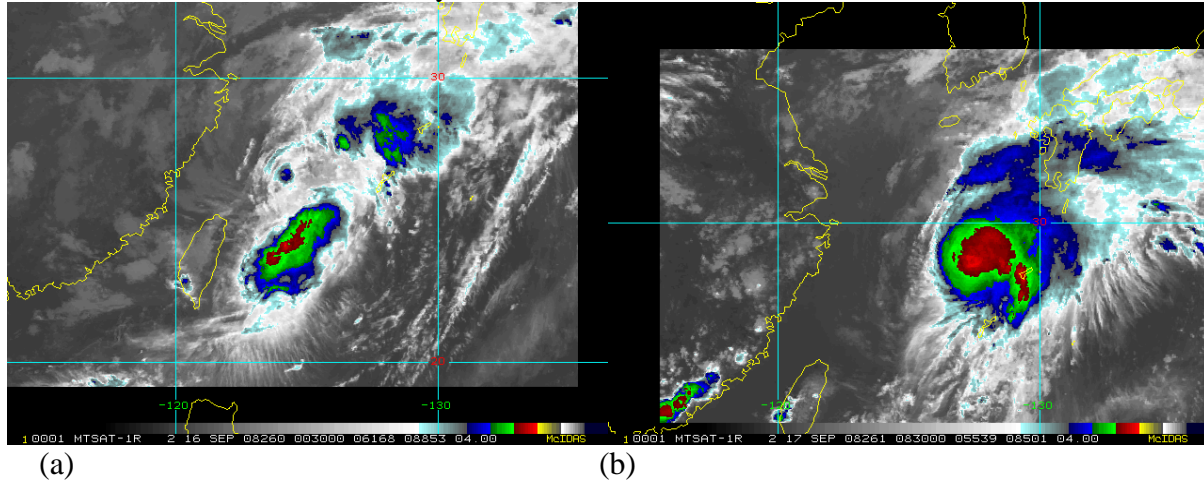

(a)　　　　　　　　　　　　　　　　　(b)

Fig. 3: Enhanced Infrared imagery for TC Sinlaku (a) on 16 September 2008 0030Z and (b) on 17 September 2008 0830Z as it underwent Transition from phase one to phase two.

As Sinlaku progressed to phase two (reintensification) of ET, TC Sinlaku underwent its second Rapid Intensification period on 17 -19 September 2008 from 35knts to 70knts (Cooper et al. 2009). In addition, on 17 September 2008, TC Sinlaku's eye was covered by a Cloud Dense Overcast (CDO) and persisted until 19 September 2008, where the CDO was sheared to the east and the low level cyclonic circulation was exposed (compare Fig. 3b to Fig. 4) (DWRS, 18-19, 21 September 2008). This shearing of the CDO was due to the polar jet advecting the upper warm core of TC Sinlaku downstream, converting the TC into a cold core system.
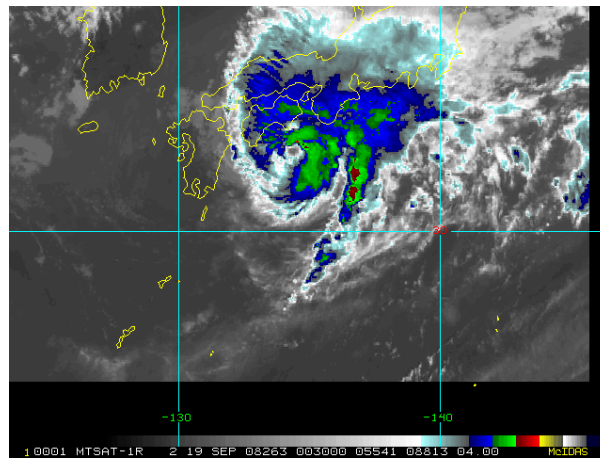

Fig. 4: The above image illustrates the erosion of the CDO at the core of TC Sinlaku through Enhanced Infrared imagery on 19 September 2008 0030Z.

The storm had barely missed making landfall on Japan as ET was occurring. This allowed for further interaction with the 500mb trough. The weak, warm core of the late TC remained over the surface center, while continual dry adiabatic descent eroded the eyewall. The cirrus shield further developed, suggesting warm frontogenesis was occurring. However, the warm frontogenesis was much stronger than the cold frotogenesis. At this stage the TC looked like an

EC. On 21 September 2008, TC Sinlaku became known as EC Sinlaku until it finally dissipated on the 23 September 2008 (DWRS, 21, 23 September 2008).
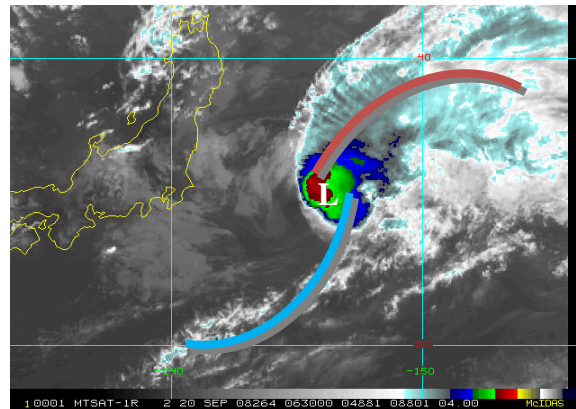

Fig. 5: Enhanced Infrared imagery for EC Sinlaku on 21 September 2008 0630Z, note the frontal features in blue (cold) and red (warm).

3. Methodology

This study followed similar processes as established by Kuo et al. (2001). But in this particular study, the Weather Research and Forecasting (WRF) model with the Advance Research WRF (ARW) dynamic core was utilized. The WSM 5-class Microphysics, Kain-Fritsch Cumulus, MM5 Similarity Theory for surface layer physics, 5-layer thermal diffusion Land-Surface, Yonsei University PBL, Rapid Radiative Transfer Model (RRTM) Longwave, and Goddard Shortwave Radiation schemes were used in the ARW simulations. The domain chosen for this study is defined by 741 X 371 points at 9km resolution centered at 35°N, 140°E on a Lambert conformal map projection. This domain was large enough to allow for the proper study of the 500mb shortwave that transitioned TC Sinlaku, according to preliminary analysis of the GFS Reanalysis data (not shown).

A post-processer script was written to convert ARW NetCDF outputs into GRIB I format. This script also interpolated the ARW sigma levels into 41 distinct pressure levels at intervals of 25mb. After the GRIB I files were created, a graphical package called ARWgraphics.gs was implemented. This particular package was created out of a set of scripts, which were written in GrADS in order to provide graphical representation of meteorological parameters from the outputs of the ARW simulations for interpretation.

There were two simulations conducted in this study. The first of these simulations was conducted using the full set of physics stated previously. The full physics run is considered the control for this study. The second of these simulations considered mostly adiabatic processes. This second simulation contained all the physics aforementioned in the full physics run, but with two primary differences. The latent heating was turned off in the WSM 5-class Microphysics scheme. In addition, the second simulation didn't activate the Kain Fritch cumulus scheme.

Given the aforementioned domain, model, and physics, the ARW Model was initialized for the 17 September 2008 and simulated TC Sinlaku out to 120 hours. GFS soil moisture and soil temperature, along with the three-dimensional atmospheric data from ECMWF analysis at 2°

X 2° resolution (which can be found at http://tigge-portal.ecmwf.int/), were used as initial conditions for the simulation. The ECMWF analysis data that was ingested into the model consisted of surface and pressure level data of wind, temperature, dewpoint, mean sea level pressure, relative humidity, and geopotential height for 20 pressure levels (1000, 950, 925, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10). From these simulations, we can see startling differences between the full physics and fake dry runs.

4. Results and Discussion

One of the major differences between the two models simulations can easily be shown through the track and intensity errors (see Table 1 and 2 below).

HR	12	24	36	48	60	72	84	96	108	120
Dist. (km)	75	124	345	349	662	744	1141	1462	1085	990
Pmin (mb)	11	11	11	12	11	10	8	0	0	2

Table 1: The above table illustrates TC Sinlaku's error metrics according to the JTWC best track versus full physics model simulation.

HR	12	24	36	48	60	72	84	96	108	120
Dist. (km)	211	458	728	698	912	1110	N/A	N/A	N/A	N/A
Pmin (mb)	23	27	27	32	31	26	N/A	N/A	N/A	N/A

Table 2: The above table illustrates TC Sinlaku's error metrics according to the JTWC best track versus fake dry physics model simulation.

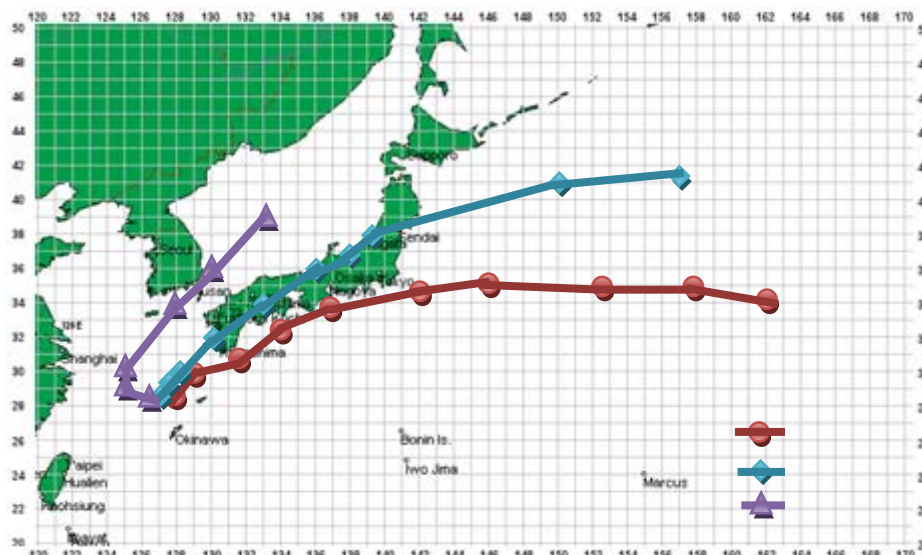For a graphical representation of the distance error metric, see Fig. 6 below.

Fig. 6: The image above shows the tracks for TC Sinlaku's best track (red circles), full physics simulation (blue diamonds), and fake dry run (purple triangles).

Further analysis of the error metrics alone suggests that the storm intensity remained closer to the truth in the full physics simulation as opposed to the fake dry run. The growth in

the error metric midway through the 120hr full physics forecast can also be explained. The simulated storm went over land, which weakened the Low much more significantly than what was observed by the actual storm. Once the simulated TC Sinlaku went over water, it began to slightly weaken, while the actual storm weakened much more significantly, making the error near 0mb (in other words, the observations caught up with the forecast). The TC in this simulation underwent ET.

In contrast, the fake dry run predicted that TC Sinlaku would never go over land and would die off within 72 hours. The radius of this storm expanded as forecast lead time grew. Also, not shown (except in Fig. 7b), is a strengthening of the subtropical High in the fake dry simulation (8mb more than the full physics run), which had extended over Japan, keeping TC Sinlaku from taking a more northeastward path. Since the storm was weakening, it became a shallower system. Once it had become a shallow system, it succumbed to the lower level steering flow, which guided the storm NNE in the simulation.

Klein et al. showed that stronger storms have a better chance of surviving the high shear of the higher latitudes. Hart and Evans stated that the stronger the TC at the beginning of the transition (as in the full physics run compared to the fake dry run), the more likely was to transition into an EC. Our results are consistent with the conclusions of Klein et al. (2000) and Hart and Evans (2001).

Other notable differences between these simulations can be further seen in the intensity and spread of precipitation (see Fig. 7 below). Note that there is more intense precipitation occurring (Fig. 7a) in the full physics simulation; however the spread of precipitation is confined to a small area as opposed to the fake dry run (Fig. 7b). What is shown below is the fact that without latent heating, there is no concentrated forced ascent. Precipitation becomes much more wide spread in the fake dry run compared to that of the full physics run.
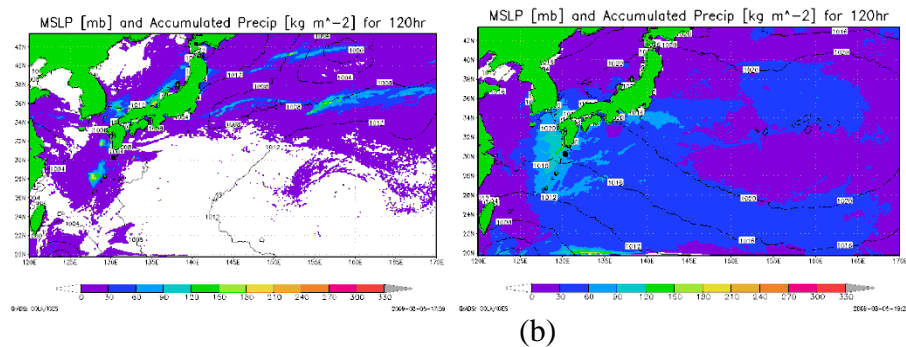
(a)   (b)

Fig. 7: The images above show the surface pressure after 120 hours of (a) full physics and (b) fake dry run as contours and the shaded values are the accumulated precipitation from model initiation out to 120 hours.

a. Full Physics Simulation

In this subsection, this study will further analyze the Full Physics simulation with respect to the observed Enhanced Infrared Satellite Imagery and Horizontal Kinetic Energy. Even though, the storm is a symmetric TC early on in the simulation, as the storm transitioned it

became asymmetric, thus it is justified to analyze the components that made up the Horizontal Kinetic Energy.

1.) COMPARISON OF SIMULATION TO ENHANCED INFRARED IMAGERY
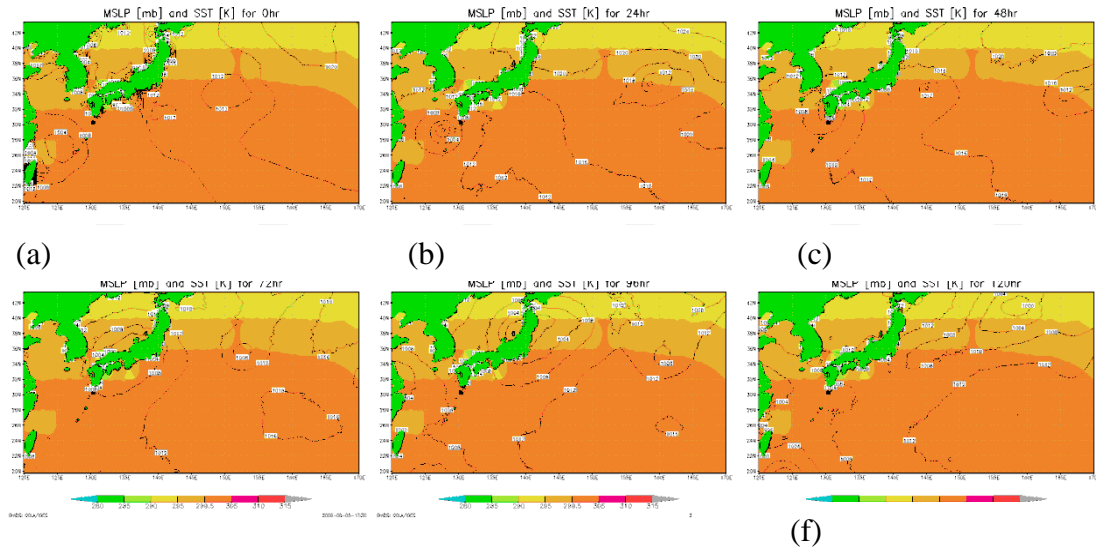

(a)   (b)   (c)

(f)

Fig. 8: The images above are the result from the ET of TC Sinlaku depicted by the full physics simulation, where values of Mean Sea Level Pressure (contoured) are overlaid with Sea Surface Temperatures (shaded contours).
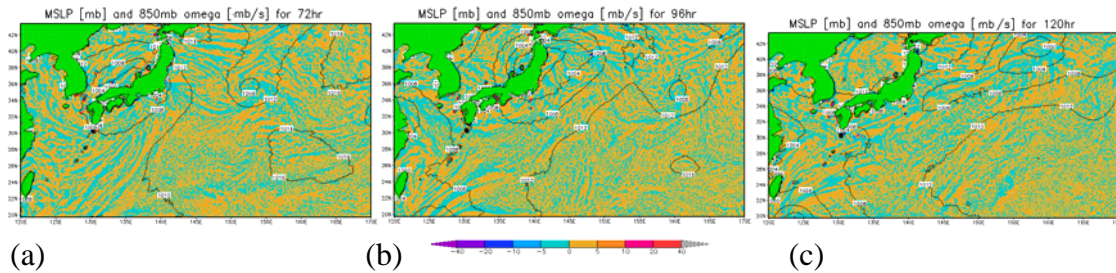

(a)   (b)   (c)

Fig. 9: The images above are the result from the ET of TC Sinlaku depicted by the full physics simulation from the start of the asymmetry, where values of Mean Sea Level Pressure (contoured) are overlaid with value of omega (shaded contours).

As it can easily be seen in Fig. 8 a-f, TC Sinlaku in this simulation did transition into an EC. However it should be noted that there is a time lag in the ET of the simulation (Fig. 8) compared to that of the observed storm (Fig. 10). In the simulation, TC Sinlaku began to become asymmetric after 20 September 2008, whereas in the satellite imagery it began on the 18 September 2008. The first signal of frontogenesis occurred on 18 September 2008; yet the model simulated its first signs on the 21st. One possible explanation to this three day delay in transition could be the fact that the real TC Sinlaku never interacted directly with Japan whereas the simulated version did.

Using omega, we can see where the vertical motion occurred, which is an estimate for convection regions. We can see a spiral pattern of positive and negative values of ω centered on the surface pressure. There is a slight increase (in width) in the SE quadrant of positive values of ω, indicating downward motion and probably a formation of a dry slot. However the areal extent of these positive values doesn't allow for definitive identification of a dry slot. So this raises the question of whether or not the full physics simulation is able to create a dry slot. Without a definitive answer to this question, it is hard to tell whether the physics options selected for the full-physics experiment are the ideal set of physics for an ET case, even though the storm underwent ET and had frontogenesis, asymmetry, and a slight reintensification 96 hours into the simulation.
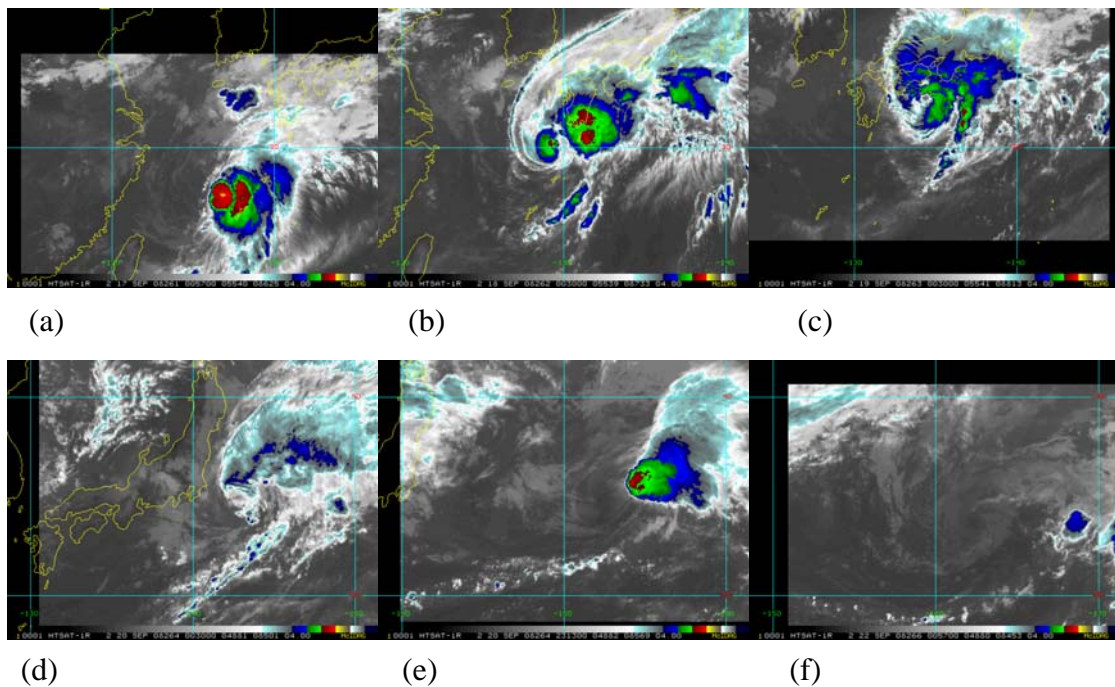

Fig. 10: The enhanced infrared satellite images above result from the observed ET of TC Sinlaku for (a) 17 September 2008 0057Z,(b) 18 September 2008 0030Z,(c) 19 September 2008 0030Z, (d) 20 September 2008 0030Z, (e) 20 September 2008 2313Z and (f) 22 September 2008 0057Z.
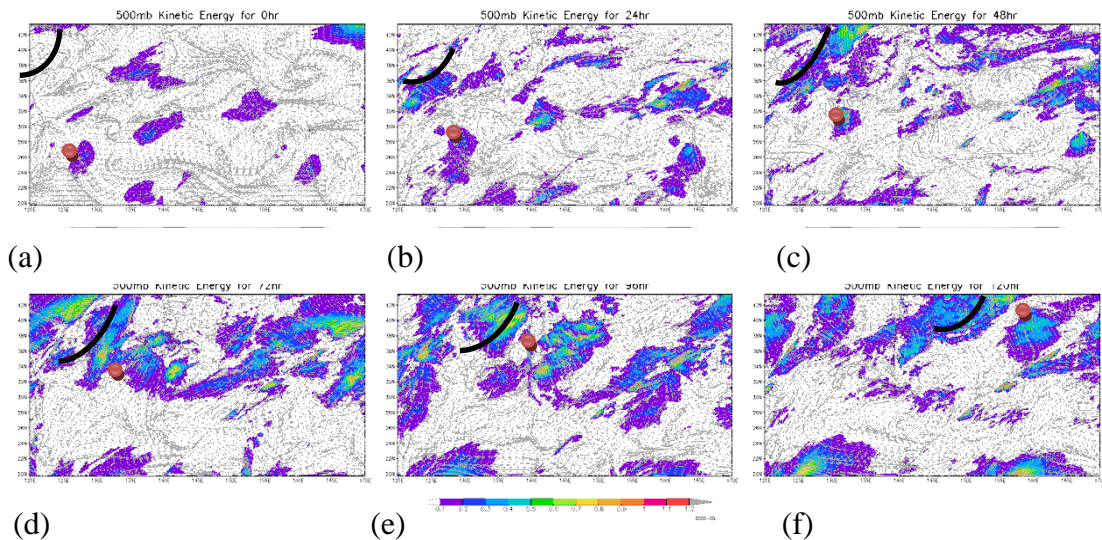
2.) KINETIC ENERGY

Fig. 11: The images above show the results from the ET of TC Sinlaku depicted by the full physics simulation, where steering at 500mb (stream lines) is overlaid with Horizontal kinetic energy (shaded contours).

Evaluating Fig. 11, as forecast lead time increases, so does overall environmental available Kinetic Energy. The Kinetic Energy associated with the TC up to the 120 forecast lead time is still separate and distinct from the environment and 500mb shortwave. The initialization (Fig 11a) shows no Kinetic Energy associated to the shortwave. However shortly after the initialization of the run, the shortwave begins to generate its own Kinetic Energy as it travels eastward. By 72 hours (Fig. 11d) the TC begins to impinge into baroclinic zone, and the Kinetic Energy of the entire system grows as one. This happens to be the case until the end of the simulation. However, at 120hrs of the simulation, the overall Kinetic Energy of the EC had increased and spread over a huge area. This spread over a bigger area could be contributed to the fact that the surface low pressure center has expanded.

3.) COMPONENTS OF THE HORIZONTAL KINETIC ENERGY
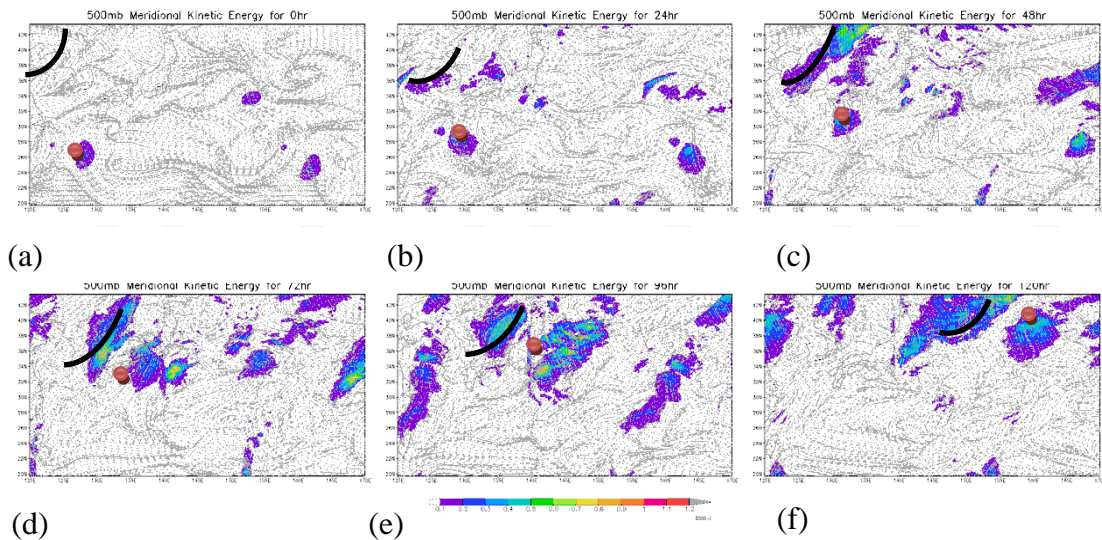

(a) (b) (c)

(d) (e) (f)

Fig. 12: The images above show the results from the ET of TC Sinlaku depicted by the full physics simulation, where steering at 500mb (stream lines) are overlaid with Meridional Kinetic Energy (shaded contours).

Looking at Fig. 12a-c, the Meridional Kinetic Energy associated with the TC is still separate and distinct from the environment and 500mb shortwave. In the initialization, and out to 24 hours (Fig 12a-b), there is hardly any Meridional Kinetic Energy associated with the shortwave. However, shortly after the first 24 hours, the shortwave begins to generate its own Kinetic Energy as it travels eastward. By 72 hours (Fig. 12d), the TC begins to impinge into baroclinic zone, and the Kinetic Energy of the entire system grows as one. This happens to be the case until the end of the simulation. As in Fig. 11e, Fig. 12e also has an increase and wide spread of the overall Meridional Kinetic Energy. Comparing the overall magnitudes between the two components of Horizontal Kinetic Energy, its easily seen that Meridional is greater than the Zonal Kinetic Energy (not shown). The 500mb shortwave Zonal Kinetic Energy is much weaker than that of the Merdional Kinetic Energy. TC Sinlaku isn't identifiable just by Zonal Kinetic Energy alone.

b. Adiabatic Simulation

In this subsection, this study will further analyze the fake dry run with respect to the Horizontal Kinetic Energy. Since this storm never did transition into an EC, the storm stayed mostly symmetric. Therefore breaking up the Horizontal Kinetic Energy into its components would not yield any more insight; hence it has been eliminated from this analysis.
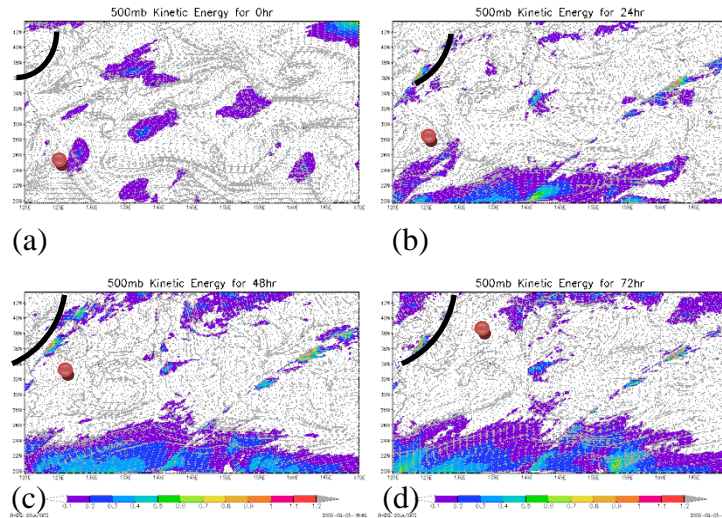
Fig. 13: The images above show the results from the ET of TC Sinlaku depicted by the adiabatic simulation, where steering at 500mb (stream lines) is overlaid with horizontal kinetic energy (shaded contours). The storm location is depicted by the red dot, while the 500mb trough axis is depicted by the black line.

As mentioned previously, TC Sinlaku dies within 72 hours of simulation time, hence the analysis of the Horizontal Kinetic Energy spans 72 hours. It should be noted that in Fig. 13a, the Kinetic Energy was high, but within 24 hours it was significantly weakened for the simulated TC. Since the TC is no longer being fed by latent heating, it loses the internal energy needed to sustain itself. Thus it stands to reason that the TC will become shallower and deeply affected by lower level steering. This is evident by the fact that the storm took a NNE track rather than a NE track, and by the fact that the storm died within 72 hours. Also the 500mb trough that supposedly transitioned TC Sinlaku seemed to be slightly less dependent on latent heating in order for it to intensify. The 500mb does intensify for the next 48 hours but moves much more slowly and is weaker than its full physics counterpart. This leads to the conclusion that latent heating plays an important role for these two distinct systems.

5. Conclusions

Even though the storm underwent ET in the full physics simulation the further analysis of ꙮ revealed no dry slot which was observed in the ET of the TC. Thus it is hard to tell whether the set of physics chosen for the full physics simulation is the ideal set of physics for ET cases. It was seen that within 72 hours of simulation time, TC Sinlaku dies (in the fake dry run) due to the lack of latent heating. The lack of latent heating also made this storm shallower, making it succumb to low level steering currents. Also the 500mb trough seemed to be affected by the lack of latent heat release as evident in the Horizontal Kinetic Energy analysis. Thus, latent heating is important and needed for both the 500mb trough and the TC, especially so for ET. In the full physics run, TC Sinlaku transitions into an EC. It showed similar structure to those observed via satellite. There also seems to be some interaction in Kinetic Energy as TC Sinlaku underwent ET. Further analysis in the future may reveal more about this interaction.

Although this study evaluated the Kinetic Energy of the ET transition of Typhoon Sinlaku, it is far from actually solving the problem of fully understanding and forecasting these transitions. Further work must be done to get a better understanding of this ET. Calculating other types of energy metrics may be one way to get a better understanding and get closer to producing more accurate forecast about these transitions. Since this study was done over one forecast period (17 September 2008), however, just doing this analysis on one forecast period doesn't provide statistically significant results. Therefore future work would also include a similar analysis over multiple forecast periods over different numbers of TCs that transition into ECs. Conducting multiple simulations with different WRF-ARW physics schemes may help get a closer to truth representation of the ET. Regardless of the statistical flaws in this study, it is still the first in-depth analysis of the ET of TC Sinlaku (2008) from an energetic perspective and, hopefully, not the last.

6. Acknowledgements

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