

Diagnosis of Sensitivity of Energy Efficiency in Typhoon Sinlaku(2008) during TCS-08/T-PARC

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1 Introduction

Eliassen's balanced vortex model potentially offers a simple, fast and elegant way to explain tropical cyclone intensity change through diabatic heating and momentum source/sink. In this study, we derive the formula for the dynamic energy efficiency of heat and of momentum in balanced vortex. The derivation is an extension of the dynamic efficiency of heat (Hack and Schubert 1986). We first derive the available potential energy (APE) and kinetic energy (KE) equations of the gradient wind balanced system. The energy conversion term between the APE and KE then is written as the product of the heat and momentum source/sink and the dynamic energy efficiency factors of heat and momentum. The dynamic energy efficiency of heat and of momentum is determined by solving the Eliassen transverse circulation equation with the right hand side of the equation the radial temperature gradient. With the known vortex structure of inertial stability, static stability, and baroclinicity, and also the region of convective heating, the system dynamic energy factors of heat and of momentum can be computed. We will demonstrate the usefulness of the formula with observations from the TCS08 aircraft observations as well as numerical model simulations. This will show selected highlights of a study on sensitivity of energy efficiency, approaching the real case typhoon Sinlaku.

2 Overview of Typhoon Sinlaku and data

The Joint Typhoon Warning Center (JTWC) termed that the typhoon has named as Sinlaku at 0000 UTC 9 September 2008. On 1800 UTC 10 September, its intensity scale has gone up to maximum with wind speed up to 125kt ($\approx 64.3\text{m/s}$) and minimum central sea level pressure of 929hPa. Then it slowly weakened and its maximum wind speed decreased down to 35kt ($\approx 18\text{m/s}$) at 0000 UTC on 17 September. After the weakening stage, it began its second phase of intensification, when the maximum wind increased up to 70kt ($\approx 36\text{m/s}$) and minimum pressure decreased to 970hPa on 0600 UTC 19 September. During the reintensification stage of Typhoon Sinlaku, four aircraft missions took place including both the NRL P-3 and the Air Force Reserve WC130. In the second mission, the NRL P-3 flew near the eyewall of Typhoon Sinlaku at 0200 UTC 18 September at 3100 m altitude. This was optimal for the utilization of the onboard Electra Doppler Radar (ELDORA). The first approach was the eyewall from the eastern side of Sinlaku, and circled counterclockwise to the northern and western sectors on 18 September. During the first NRL P-3 observation, the variation of maximum wind speed was 60kt ($\approx 30.8\text{m/s}$) and minimum sea level pressure was 980hPa and the principal rain band was about 200km east of the TC center. Figure 1 shows the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra visible satellite picture overlapped with the NRL P-3 flight track. The impact of targeted dropsonde observations on the track forecast was also investigated using ensemble Kalman filter (EnKF). The vertical profile of temperature and dew point temperature from dropsondes are chosen to study the different atmospheric structures between the convective regions associated with the TC center and the principal rainband and the region between them.

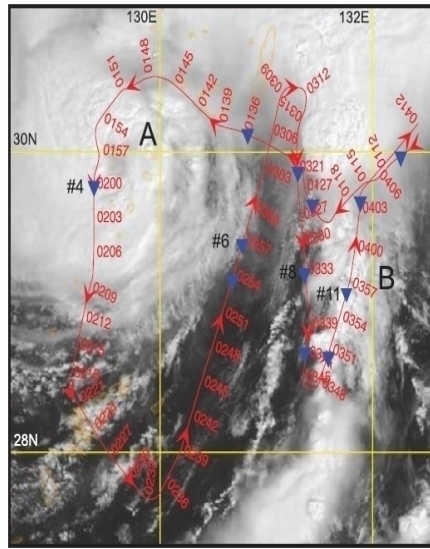


Figure 1. The NRL P-3 flight track showing on 0141 UTC 18 Sep 2008 MODIS Terra satellite visible image. The red line is the aircraft flight track with hour and minute marked (UTC). The red arrow heads indicates the aircraft's direction and the blue triangles shows the dropsonde locations. The number 4, 6, 8, and 11 dropsonde data are analyzed in this paper. Letters A and B shows the regions for dual-Doppler analysis during the periods (Kuo et al, 2012)

3 Energy efficiency formula

The theoretical argument is based on the balanced vortex model especially on the Eliassen transverse circulation equation. For idealized vortex structures and idealized vertical structures of Q, the vertical coordinate we use is $z = \left(\frac{C_p \theta_0}{g}\right) \left[1 - \left(\frac{p}{p_0}\right)^k\right]$, where $p_0 = 1000hPa$ and $\theta_0 = 300K$ (appropriate mean potential temperature) are constant reference values of pressure and potential temperature.

The governing equations for the balanced vortex model are;

$$\text{Gradient balance equation, } \frac{du}{dt} = \left(f + \frac{v}{r}\right)v - \frac{\partial \phi}{\partial r} \quad (1)$$

$$\text{Tangential velocity equation, } \frac{dv}{dt} = -\left(fu + \frac{v}{r}\right)u - \frac{\partial \phi}{r \partial \phi} + F \quad (2)$$

$$\text{Hydrostatic equation, } \frac{\partial \phi}{\partial z} = \frac{\theta}{\theta_0} g \quad (3)$$

$$\text{Continuity equation, } \frac{\partial \sigma}{\partial z} + \frac{\partial \sigma u}{r \partial r} + \frac{\partial \sigma w}{\partial z} = 0 \quad (4)$$

$$\text{Thermodynamic equation } \frac{d\theta}{dt} = \frac{Q}{c_p \Pi} \quad (5)$$

By using Eliassen transverse circulation equation,

$$\frac{\partial}{\partial r} \left(A \frac{\partial(r\psi)}{r \partial r} + B \frac{\partial \psi}{\partial z} \right) + \frac{\partial}{\partial z} \left(B \frac{\partial(r\psi)}{r \partial r} + C \frac{\partial \psi}{\partial z} \right) = \frac{g}{c_p T_0} \frac{\partial Q}{\partial r} - \frac{\partial}{\partial r} \left(\left(f + \frac{2v}{r}\right) F \right) \quad (6)$$

The static stability A, the baroclinity B, and the inertial stability C can be given by

$$\sigma A := \frac{g}{\theta_0} \frac{\partial \theta}{\partial z} \quad (7)$$

$$\sigma B := -\frac{g}{\theta_0} \frac{\partial \theta}{\partial r} = -\frac{1}{r^3} \frac{\partial m^2}{\partial r} \quad (8)$$

$$\sigma C := \frac{1}{r^3} \frac{\partial m^2}{\partial r} \quad (9)$$

B can be written in terms of θ , and $m = rv + \frac{1}{2}fr^2$ is the absolute angular momentum (Schubert and McNoldy, 2010). Then to calculate efficiency, total kinetic energy, total potential energy, kinetic energy conversion rate, momentum forcing and total heating can be derived.

$$K = \iint \rho \frac{v^2}{2} r dr dz \quad (10)$$

$$A = \iint \rho C_p T r dr dz \quad (11)$$

$$\tilde{C} = \iint \rho \frac{T}{T_0} g w r dr dz \quad (12)$$

$$\tilde{D} = \iint \rho v F r dr dz \quad (13)$$

$$\tilde{H} = \iint \rho Q r dr dz \quad (14)$$

With Kinetic energy conversion rate equation,

$$\tilde{C} = \iint \rho \frac{T}{T_0} g w r dr dz = \iint \rho \eta_H Q dr dz - \iint \rho \eta_D v F dr dz = \bar{\eta}_H \tilde{H} - \bar{\eta}_D \tilde{D} \quad (15)$$

Efficiency can be derived,

$$\eta_H = e^{z/H} \frac{g}{T_0} \frac{\partial(r\chi)}{\partial r} \quad (16)$$

$$\eta_D = e^{z/H} \frac{C_p}{v} \left(f + \frac{2v}{r} \right) \frac{\partial(r\chi)}{\partial z} \quad (17)$$

The energy efficiency sensitivity from the ELDORA observation involves a procedure of calculating the “Heating efficiency” and the “Dynamic efficiency”.

4 Results

4.1 Balanced Vortex Model

Eliassen's Balanced Vortex Model potentially offers a simple, fast and elegant way to explain tropical cyclone intensity change through diabatic heating and momentum source or sink.

Figure 2 shows the result of typical development of a tropical cyclone of single eyewall in the (r,z) plane profile given by Schubert and Hack (1982) to calculate the efficiency. In the Figure 2a, contour which indicates tangential wind speed is maximum (20m/s) at 200km radius where the Q (heat energy) is concentrated. Figure 2b shows the concentrated θ (K) between 0 to 200 km radius. Figure 2c, what isolines of $r\chi$ shows is, in according to the formula $L\chi$ through $\frac{d\theta}{dr}$ we can see that χ needs the horizontal gradient of temperature. Since the temperature gradient in our experiment is generated near the center, result is that χ has value near the center, too. From Figures 2d and 2e, it is indicating that the heating forces upward motion inside 200km, with weak subsidence in the broad outlying region. Lastly, Figure 2f shows the Q and efficiency below 200km. And our efficiency is χ 's horizontal gradient, thus there will be efficiency near the center.

Figure 3a shows the TC development stages according to Schubert and Hack (1982). Stage D-E correspond to deepening stage. The red shading and segments correspond to 1st, 2nd and 3rd quartile of average η . And Figure 3b shows kinetic energy dynamic efficiency diagram according to Figure 3a. Each stage was categorized according to Schubert and Hack (1982) and as the tangential wind speed goes high, the efficiency is high. The red shading is indicating the probable deviation. Notice that in our idealized experiment, temperature is related to heating

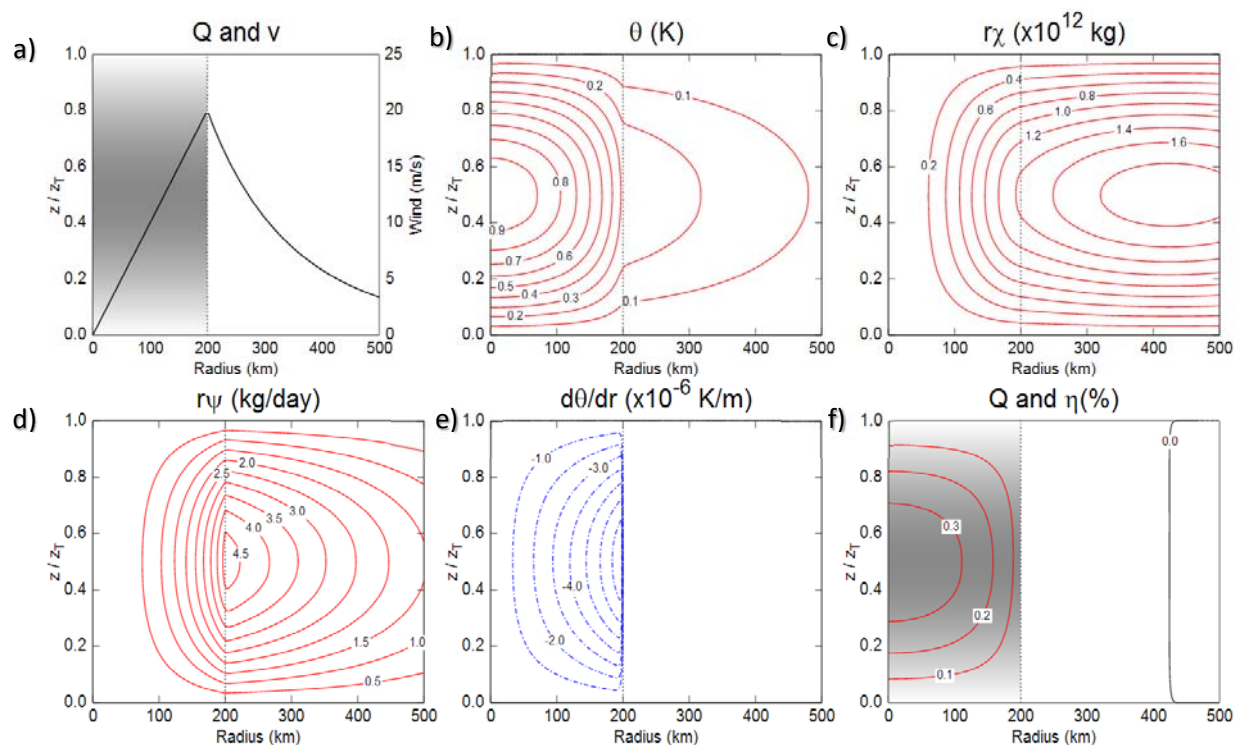


Figure 2. Single eyewall result and dynamic efficiency in the (r, z) plane, profile given by J.J. Hack (1982) to calculate the efficiency. (Tien-Yiao Hsu, NTU)

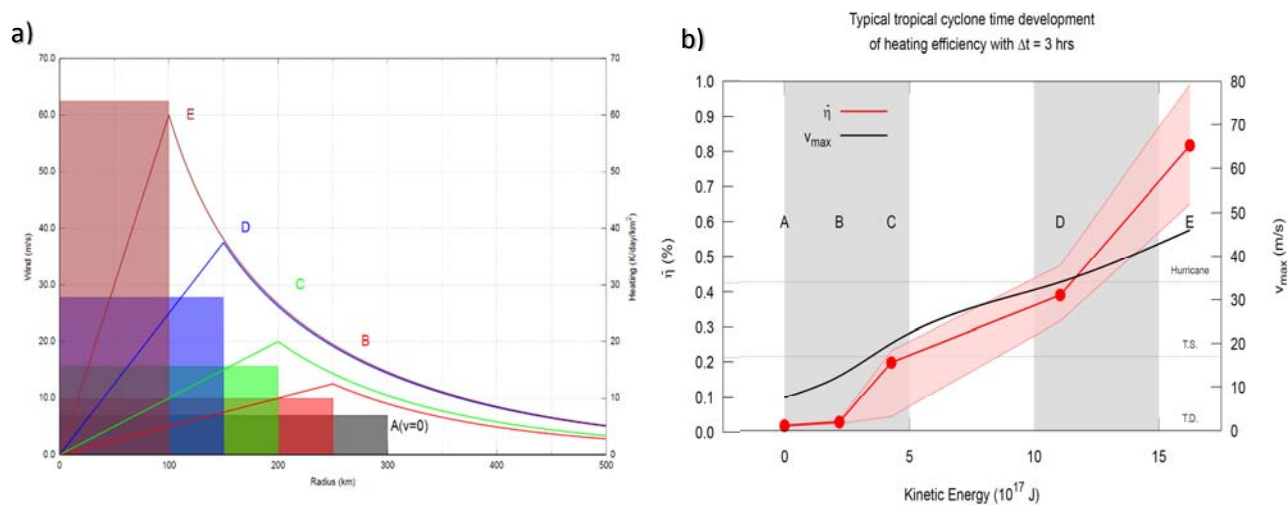


Figure 3. The TC development stages according to Hack and Schubert (1982) and kinetic energy dynamic efficiency diagram. (Tien-Yiao Hsu)

4.2 Typhoon Sinlaku

Figure 4a presents the storm-relative dual-Doppler wind (black bold vector) superimposed on the reflectivity at 2km above the mean sea level. The RFZs (Rapid Filamentation Zones) are hatched in blue color and the white bold contour indicates the convective area. This clearly indicates that deep convection covers only a limited area in the typhoon core region and most of the RFZ overlaps with the stratiform area inside the convective spiral bands. Figure 4b is Examination of region B (outer spiral band) at 2km altitude reveals that the RFZ is mostly collocated with the stratiform area and downward motion region in the inner side of the rainband (Kuo et al, 2012).

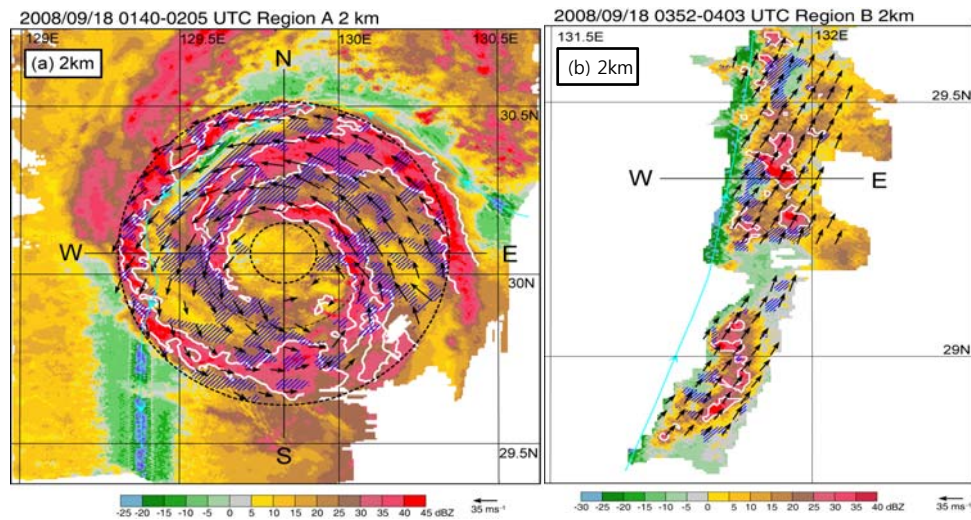


Figure 4. TCS08 aircraft observed filamentation of Sinlaku shows TCS08 Aircraft observed filamentation of Typhoon Sinlaku (2008) at 2km above sea level. 0140-0205 UTC 18 Sep 2008 NRL P-3 storm-relative dual-Doppler wind is shown as black bold vectors with scale indicated at the bottom-right corner, superimposed on the ELDORA radar reflectivity (dBZ) with the bold white contour indicating the convective area and RFZs (Rapid Filamentation Zones) are hatched in blue (Kuo et al.,2012).

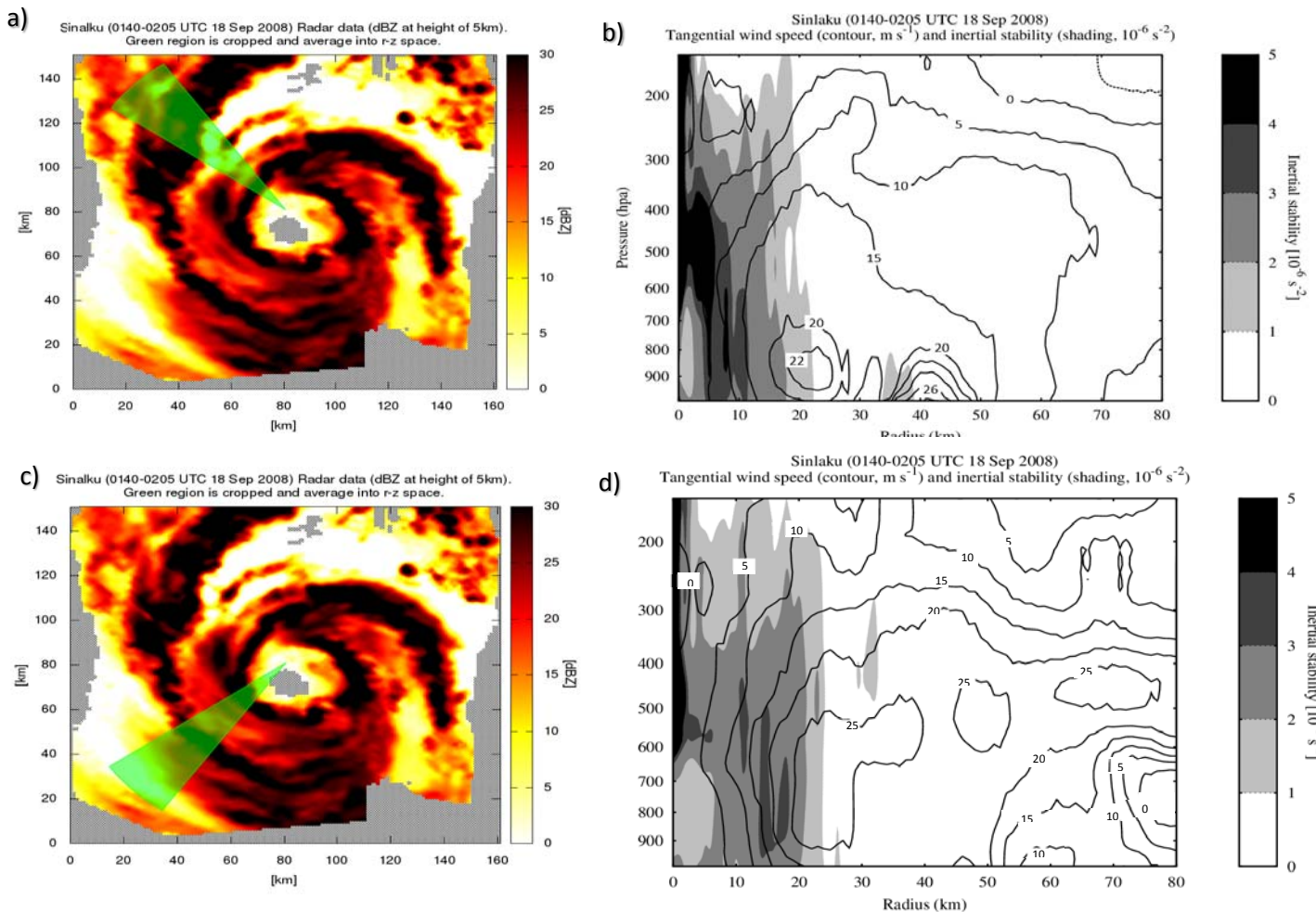


Figure 5. On the left hand side (a,c) is showing reflectivity (dBZ) at 5km altitude of Typhoon Sinlaku (2008) overlapped with green shading which shows cropped and average into r-z space. On the right hand side (b,d) shows the tangential wind speed (m/s) with contour and inertial stability with shading.

Figure 5a shows the reflectivity (dBZ) at 5km altitude of Typhoon Sinlaku from 0140 to 0205 UTC 18 Sept. 2008 and each figures (on the left side) shows different green region where it was cropped and averaged into r-z space. Figure 5b shows tangential wind speed and inertial stability for each sections that has been selected. It shows that as tangential wind speed is high, inertial instability is also high.

5 Summery

In this study dynamic energy efficiency in TC is derived and calculated with typhoon Sinlaku (2008) data and from the vortex model. It shows concentric eyewalls structure may enhance overall efficiency compare to the single eyewall structure. Also, considering about Hack and Schuberts (2010), efficiencies are related with deformation of Rossby height and Rossby radius when Ekman pumping may contribute greatly to energy efficiency in the late stage of the TC life.

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