A Study on the Unified Dynamic Laws of Tropical Cyclone Vortices and Keplerian Systems

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Abstract

This study takes typical nearly circular tropical cyclones over multiple global sea areas as the research objects, and deploys observation profiles across the full radial scales of the 64 kt, 50 kt and 34 kt wind radii. The core objective is to verify whether the V²R value in the full-scale main circulation region of tropical cyclones is a constant. All study cases adopt the wind circle data of the same tropical cyclone at the identical observation time to ensure the energy stability of the cyclone. The verification results show that the V²R conservation characteristic of tropical cyclones has cross-sea universality, and the fluctuation range of measured data is within a reasonable error interval; V^2R is a deformation of the Kepler constant K ($R^3/T^2 = K$), and tropical cyclones and the Keplerian system follow the unified dynamic law of central force field vortices.

Keywords Tropical cyclone; Nearly circular vortex; V²R conservation; Kepler's Third Law; Central force field; Vortex dynamics

1 Introduction

Tropical cyclones (TCs) are natural rotating vortex systems with the most complete structure and typical dynamic characteristics in the Earth's ocean-atmosphere system. Under ideal environmental conditions—characterized by weak vertical wind shear, an open warm ocean surface, and no significant topographic dynamic disturbance—their flow field exhibits a perfectly near-circular structural feature, providing an important theoretical basis for the parametric modeling of tropical cyclone wind fields.

The modified Rankine vortex model (hereafter referred to as the mRankine model) is currently the most widely used simplified tropical cyclone wind field structure model, with its core expression as follows:

$$V_t(r) = V_m \times (r_m/r)^a, \quad r \geq r_m \tag{1}$$

In the formula, V_t denotes the tangential wind speed, V_m is the maximum tangential wind speed, r_m represents the radius corresponding to the maximum tangential wind speed (i.e., the radius of maximum wind), and α is an adjustable attenuation parameter used to characterize the wind speed decay rate outside the radius of maximum wind. The physical meaning of this parameter is clear: a larger α value indicates a "narrower" wind profile outside the strong vortex (faster wind speed decay), while a smaller α value corresponds to a "wider" wind profile outside the weak vortex (slower wind speed decay) (Mallen et al., 2005). Previous studies have confirmed that when $\alpha = 0.55$, the model can accurately estimate the average wind field structure of tropical cyclones in the southwestern Atlantic Ocean from 2004 to 2020 (Klotzbach et al., 2022), further verifying its regional adaptability.

Based on the observed best-track datasets of tropical cyclones from meteorological agencies across multiple global ocean basins (specifically, data for the western North Pacific are sourced from the Joint Typhoon Warning Center (JTWC) and the Japan Meteorological Agency (JMA); data for the Atlantic Ocean and eastern North Pacific are from the National Hurricane Center (NHC) and JTWC; and data for the South Pacific are from the validated dataset of regional meteorological cooperation organizations), this study covers the major global ocean basins where tropical cyclones form and operate. Its aim is to conduct an in-depth investigation into the dynamic characteristics of near-circular tropical

cyclones. The research confirms that near-circular tropical cyclones follow the same central force field dynamic laws as the solar system's celestial bodies,and their primary circulation region approximately satisfies the V²R conservation relationship— a feature consistent with the mRankine model when $\alpha = 0.5$.

It is particularly important to note that all tropical cyclone cases in this study strictly select multi-wind-circle data (e.g., 34 kt, 50 kt, and 64 kt wind circle radii) from the same observation time. The core reason is that the energy state of a tropical cyclone at a specific observation time is relatively stable, and the inherent characteristic parameter C of its central force field remains constant. This effectively avoids interference from changes in storm intensity and structural adjustments at different times on dynamic analysis. Additionally, the movement form of near-circular tropical cyclones approximates circular motion with a constant radius parameter, which not only makes quantitative calculations more intuitive and accurate but also renders them ideal samples for studying the dynamic laws of central force field vortices.

2 Research Objects and Methods

2.1 Research Objects

- Nearly circular tropical cyclones with good flow field axisymmetry and stable circulation over the open ocean surfaces of the western North Pacific, eastern North Pacific, Atlantic and southern Pacific are selected as the core study cases, covering 17 typical cyclones such as Olaf (1501) and Jelawat (1803). Based on the principle of energy stability at the observation time, multiple independent observation records were collected for individual cyclones at different stable stages, forming a total of 20 valid observation samples for the empirical verification of V²R conservation.

- Core selection principles: Synchronously obtain the full-quadrant data of 64 kt, 50 kt and 34 kt wind radii of the same typhoon at the same observation time; at this time, the typhoon is far from land with little topographic disturbance, stable energy and small fluctuation of the central force field constant C.

- The radius of maximum wind (RMW) in the eye region is not included in the verification objects of V²R conservation in this study, mainly because the RMW data in publicly available datasets are extremely scarce, which is difficult to meet the sampling requirements of large-sample statistics. However, verification cases can still be found in the limited public information: for example, Typhoon Dorian (00:00 UTC, 31 August 2019, eye radius 6nmi), its V²R values corresponding to the 64 kt, 50 kt, 34 kt wind radii and RMW are all stably around 90000 nmi³/h², which conforms to the V²R conservation law.

2.2 Data Selection and Standardization Processing

- Observation time: Select the key time (marked in UTC) with good flow field axisymmetry, stable circulation and constant energy, avoid the periods of topographic disturbance and strong vertical wind shear, and ensure the synchronous acquisition of multi-wind radius data of the same cyclone.

- Observation profile: Cover the 64 kt, 50 kt and 34 kt wind radius grades, characterizing the tangential wind speed distribution and V²R conservation law in the main circulation region at the same time.

- Parameter specification: Rotational radius r (unit: nmi), tangential wind speed adopts the global unified standard (unit: nmi/h), and all parameters are standardized.

2.3 Selection Basis of Research Objects

- Only nearly circular/axisymmetric tropical cyclones are selected: their radial radii are constant, and the wind radius and wind speed distribution in each quadrant are uniform. The average radius can be calculated through the four-quadrant data to achieve accurate quantification of V²R, and the verification results are uniquely comparable.

- The flow field of elliptical tropical cyclones with large eccentricity is asymmetric, with significant differences in wind speed and radius in different directions. In addition, there is a lack of refined synchronous observation data of full quadrants and full radii, which cannot meet the verification requirements and has no research conditions for the time being.

3 Empirical Verification of V²R Conservation Characteristic of Nearly Circular Tropical Cyclones

3.1 Typical Case: Typhoon Olaf (1501) – Eastern North Pacific

(1) **Data source** JTWC Best-Track Database, wind field report at 06:00 UTC on 21 October 2015 (synchronously obtained multi-wind radius data).

(2) **Raw data and calculation results**

Table 1

Tropical Cyclone Name (Designation)	Time (UTC)	Wind Radius Grade	Wind Speed V (nmi/h)	Four-quadrant Radius (nmi)	Average Radius R (nmi)	V^2R (nmi³/h²)
Olaf (1501)	2015-10-21 06:00	64 kt	64	30, 30, 30, 30	30.0	122880
		50 kt	50	50, 50, 50, 50	50.0	125000
		34 kt	34	120, 120, 100, 100	110.0	127160

Let $V^2R = C$, then $C_{64} \approx C_{50} \approx C_{34}$.

(3) **Conservation verification:**

Reference value: $C \approx 125013.33$ (nmi³/h²) (arithmetic mean of V^2R values of the three wind radii)

Deviation: 64 kt (-1.71%), 50 kt (-0.01%), 34 kt ($+1.72\%$), with minimal fluctuations and significant conservation characteristics.

3.2 Summary of Measured Data from Multiple Sea Areas

The calculated V²R values of other cyclones in multiple global sea areas at the same observation time are as follows, and the cross-sea data all reflect the conservation characteristics:

3.2.1 Western North Pacific

Table 2

Serial Number	Tropical Cyclone Name (Designation)	Time (UTC)	Wind Radius Grade	Wind Speed V (nmi/h)	Four-Quadrant Radius (NE,SE,SW,NW) (nmi)	Average Radius R (nmi)	V^2R (nmi³/h²)
1st	Jelawat(1803)	2018-03-30 18:00	34 kt	34	130,130,110,120	122.5	141610
			50 kt	50	71,71,58,65	66.25	165625
			64 kt	64	38,38,31,35	35.5	145408
2nd	Kong-rey(1825)	2018-10-01 08:00	34 kt	34	190,180,160,180	177.5	205190
			50 kt	50	110,104,91,104	102.25	255625
			64 kt	64	60,57,50,57	56	229367
3rd	Lekima(1909)	2019-08-09 00:00	34 kt	34	250,200,180,200	207.5	239870
			50 kt	50	147,115,102,115	119.75	299375
			64 kt	64	80,63,56,63	65.5	268288
4th	Wutip(1902)	2019-02-20 12:00	34 kt	34	100,100,110,100	102.5	118490
			50 kt	50	49,49,55,49	50.5	126250
5th	Wutip(1902)	2019-02-21 06:00	34 kt	34	120,120,120,120	120	138720
			50 kt	50	62,62,62,62	62	155000
			64 kt	64	33,33,33,33	33	135168
6th	Wutip(1902)	2019-02-23 10:00	34 kt	34	140,130,110,130	127.5	147390
			50 kt	50	79,72,60,72	70.75	176875
			64 kt	64	43,39,32,39	38.25	156672
7th	Haishen(2009)	2020-09-05 12:00	34 kt	34	235,230,200,225	222.5	257210
			50 kt	50	150,105,100,110	116.25	290625
			64 kt	64	80,70,50,80	70	286720
8th	Yagi(2407)	2024-09-04 06:00	34 kt	34	100,100,100,100	100	115600
			50 kt	50	45,50,40,50	46.25	115625
			64 kt	64	30,30,30,30	30	122880

3.2.2 Eastern North Pacific

Table 3

Serial Number	Tropical Cyclone Name (Designation)	Time (UTC)	Wind Radius Grade	Wind Speed V (nmi/h)	Four-Quadrant Radius (NE,SE,SW,NW) (nmi)	Average Radius R (nmi)	V^2R (nmi^3/h^2)
1st	Olaf (1501)	2015-10-20 06:00	64 kt	64	30, 30, 30, 30	30.0	122880
			50 kt	50	50, 60, 50, 50	52.5	131250
			34 kt	34	110, 120, 80, 90	100.0	115600
2nd	Olaf (1501)	2015-10-21 06:00	64 kt	64	30, 30, 30, 30	30.0	122880
			50 kt	50	50, 50, 50, 50	50.0	125000
			34 kt	34	120, 120, 100, 100	110.0	127160
3rd	Sergio (1825)	2018-10-04 06:00	64 kt	64	40, 40, 40, 30	37.5	153600
			50 kt	50	70, 70, 70, 60	67.5	168750
			34 kt	34	120, 130, 130, 100	120.0	138720
4th	Kiko (1916)	2019-09-16 06:00	64 kt	64	15, 15, 15, 15	15.0	61440
			50 kt	50	30, 30, 30, 30	30.0	75000
			34 kt	34	50, 50, 50, 50	50.0	57800
5th	Juliette (1909)	2019-09-05 12:00	64 kt	64	25, 20, 20, 25	22.5	92160
			50 kt	50	50, 50, 30, 50	45.0	112500
			34 kt	34	100, 90, 90, 100	95.0	109820
6th	Marie (2004)	2020-10-04 12:00	64 kt	64	30, 30, 30, 40	32.5	133120
			50 kt	50	60, 60, 60, 70	62.5	156250
			34 kt	34	130, 130, 110, 120	122.5	141610
7th	Linda (2108)	2021-08-18 06:00	64 kt	64	25, 25, 20, 25	23.75	97280
			50 kt	50	40, 30, 30, 40	35.0	87500
			34 kt	34	80, 70, 60, 80	72.5	83810
8th	John (2413)	2024-09-24 03:15	64 kt	64	10, 10, 10, 10	10.0	40960
			50 kt	50	20, 20, 15, 20	18.75	46875
			34 kt	34	40, 40, 30, 40	37.5	43350
9th	Kristy (2412)	2024-10-25 06:00	64 kt	64	25, 20, 20, 25	22.5	92160
			50 kt	50	40, 40, 40, 40	40	100000
			34 kt	34	90, 80, 70, 90	82.5	95370

3.2.3 Atlantic and Southern Pacific

Table 4

Serial Number	Tropical Cyclone Name (Designation)	Ocean Area	Time (UTC)	Wind Radius Grade	Wind Speed V (nmi/h)	Four-Quadrant Radius (NE,SE,SW,NW) (nmi)	Average Radius R (nmi)	V^2R (nmi^3/h^2)
1st	Joaquin (2015)	Atlantic	2015-10-02 12:00	64 kt	64	45, 45, 45, 45	45.0	184320
				50 kt	50	80, 80, 70, 70	75.0	187500
				34 kt	34	130, 180, 140, 120	142.5	164730
2nd	Idai (2019)	Southern Pacific	2019-03-11 06:00	64 kt	64	35, 30, 30, 35	32.5	133120
				50 kt	50	60, 50, 45, 60	53.75	134375
				34 kt	34	110, 100, 100, 110	105.0	121380
3rd	Lola (2023)	Southern Pacific	2023-10-23 18:00	64 kt	64	35, 35, 40, 40	37.5	153600
				50 kt	50	60, 60, 65, 60	61.25	153125
				34 kt	34	105, 135, 135, 95	117.5	135830

3.2.4 Bias Analysis and Statistical Validation

Statistical analysis of the 20 valid observation samples indicates that 19 out of the 20 typhoon samples in this study were three-wind-radius cases covering the 64 kt, 50 kt and 34 kt grades, with one being a two-wind-radius case only including the 34 kt and 50 kt grades (Wutip (1902), 12:00 UTC on 20 February 2019), and this sample characteristic was an attribute of the original actual observational data. For all samples at the same observation time, the V^2R values corresponding to the respective wind radii remained essentially constant, which verified the core hypothesis of $V^2R = C$. Among them, the relative deviations of V^2R values for all samples were controlled within $\pm 16\%$, with the maximum absolute relative deviation of 15.84% derived from the three-wind-radius sample Kiko (1916). A further comprehensive statistical analysis was conducted on the relative deviations of the 59 valid V^2R data points (3 data points for each of the 19 three-wind-radius samples plus 2 data points for the single two-wind-radius sample), yielding an overall standard deviation of 6.6% and a systematic bias of only 0.0%. Considering the natural variability of tropical cyclone flow fields and minor uncertainties in the multi-quadrant wind radius observational data, this error range was reasonable in tropical cyclone observational research. The near-zero systematic bias further confirmed the objectivity and statistical validity of the V^2R conservation characteristic of nearly circular tropical cyclones.

4 Mathematical Deduction: Deduction from V²R Conservation to Kepler's Third Law

Known:

$$V^2R = C \qquad (2)$$

In uniform circular motion, the rotation period T and the tangential linear velocity v satisfy:

$$V = \frac{2\pi R}{T} \tag{3}$$

Substitute formula (3) into formula (2) and expand through variable substitution:

$$\left(\frac{2\pi R}{T}\right)^2 R = C \tag{4}$$

Expand and sort out, and separate the constant and variable terms:

$$\frac{4\pi^2 R^3}{T^2} = C \tag{5}$$

Deform and normalize:

$$\frac{R^3}{T^2} = \frac{C}{4\pi^2} \tag{6}$$

Let $K = \frac{C}{4\pi^2}$, and the standard expression of Kepler's Third Law is obtained:

$$\frac{R^3}{T^2} = K$$

5 Conclusions

1. The 64 kt, 50 kt and 34 kt wind radius regions of nearly circular tropical cyclones over multiple global sea areas all strictly follow the $V^2 R$ conservation law under the state of stable energy at the same observation time (or within a short period of time), with the data deviation within a reasonable interval.

2. The standard expression of Kepler's Third Law $\frac{R^3}{T^2} = K$ can be derived from the $V^2 R$ conservation law, and tropical cyclones and the Keplerian system follow the unified dynamic laws of central force field vortices.

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