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Mathematical Models in Engineering

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Mathematics
└ Modeling and Simulation

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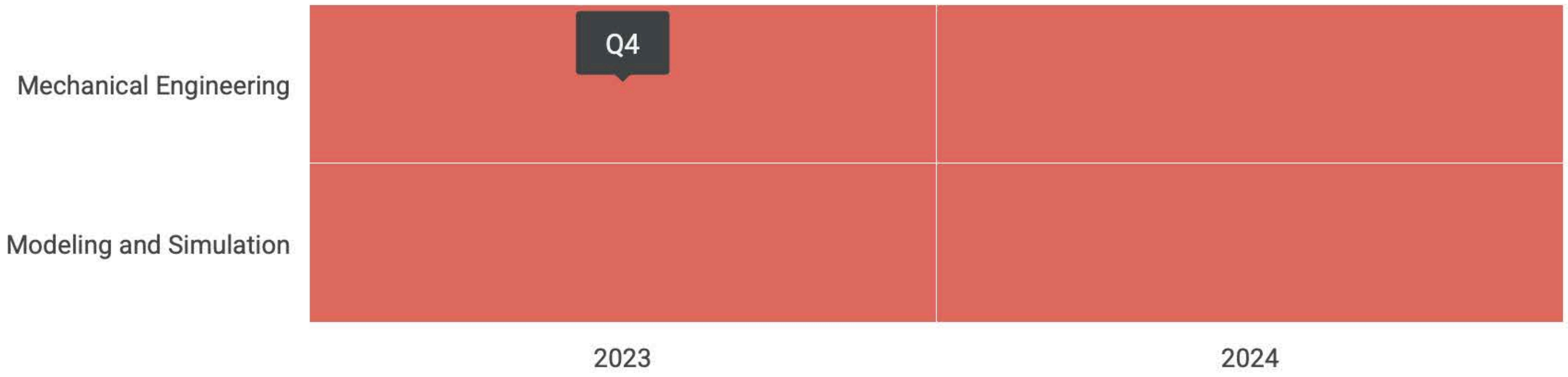

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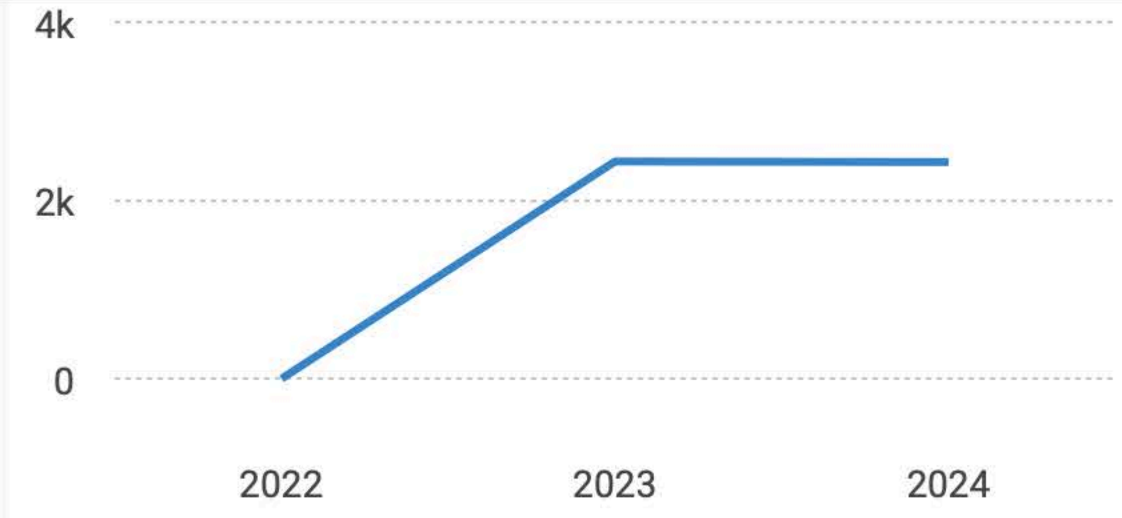

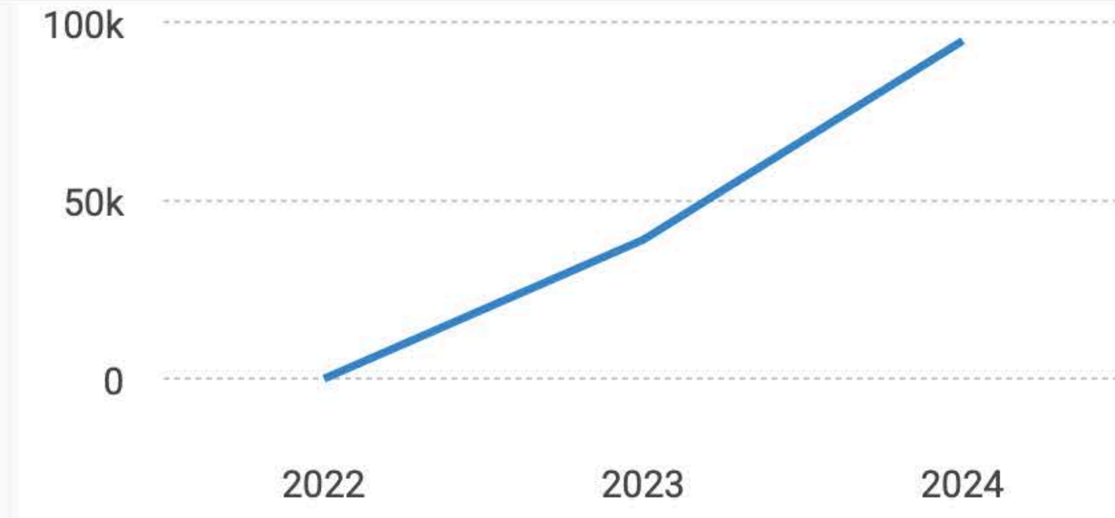

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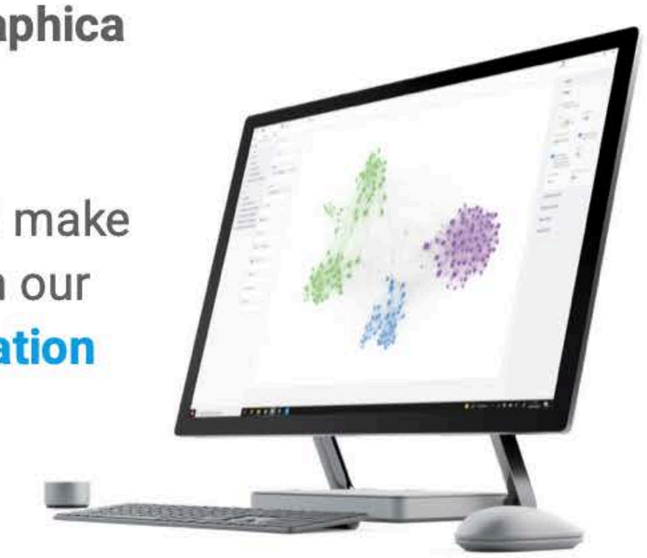

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COVERAGE

2022-2024

INFORMATION

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SCOPE

Mathematical Models in Engineering (MME) ISSN (Print) 2351-5279, ISSN (Online) 2424-4627 publishes mathematical results which have relevance to engineering science and technology. Formal descriptions of mathematical models related to engineering problems, as well as results related to engineering applications are equally encouraged.

MME 24041 - Published

Mathematical Models in Engineering, Vol. 10, Issue 3

Tensor analysis of tornadoes: a new analytical and numerical model

Mustamina Maulani; Valentinus Galih Vidia Putra;

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Highlights a new analytical and numerical model of tornado
Rigorous analysis
Compare the model with experiment
combine tensor analysis, computational modeling, as well as 2D and 3D simulations for simulating tornadoes

Attachments Graphical abstract

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Best Regards,

Submission accepted

Accept to Mathematical Models in Engineering

Revision Request

Reviewer reports are attached.
A minor revision is required before reconsideration.

The manuscript is really novel and interesting. It deserves to be published in the Journal after a minor revision.

The comparison between the computational results and the photo of a real tornado (Fig. 4) is unclear. The authors should elaborate to explain how the comparison could be made.

Another important issue. The recent movement against the paper mils requires to show that the authors are not newcomers to this field of research. In other words, please add at least one citation to your own work. In other words, at least one self-citation to your own work is needed.

Also, please note that it is essentially important to highlight the novelty of your study in order to attract the attention and citations from the International Engineering Community.

Please do not forget to add a separate amendments file with a careful description of all changes you had made according to reviewer'(s) comments.

Cover letter

MME 24041 - Revision required Mathematical Models in Engineering
Tensor analysis of tornadoes: a new analytical and numerical model
Valentinus galih Vidia Putra; Mustamina Maulani;

Dear Editor,
We thank the reviewer/(s) for their comprehensive comments which helped us a lot in the correction of the manuscript. The authors have thoroughly reviewed the comments, and the answers to each point are attached. Thank you for your kind.

Best regards,

Attachments

Manuscript | Manuscript PDF | Amendments

Manuscript submitted

Cover letter

Dear Editor

We are writing to submit our research paper entitled "Tensor analysis of tornadoes: a new analytical and numerical model" for consideration and possible publication in Mathematical Models in Engineering journal. This research introduces a groundbreaking mathematical formulation of tornadoes, utilizing the principles of tensor analysis and simulation within a non-inertial dynamics framework, spanning both two and three dimensions. The model captures the spherical upward movement of air in tornadoes, omitting vertical convection considerations. Key factors, such as geocentric latitude, the Coriolis effect, enhanced upper-atmosphere airspeed, and heightened air pressure, are integral to the tornado formation process. To ascertain the three-dimensional location of tornadoes, along with mathematical models depicting airflow motion and Earth's rotation in 3D space, we conducted numerical computations. Employing computer software for motion dynamics and numerical analysis, our study successfully illustrated tornado patterns, providing insights into their airflow characteristics. Our research represents an innovative approach to tornado simulation, merging tensor analysis and computational modeling alongside 2D and 3D simulations. The outcomes of this study offer valuable insights for practitioners and scientific experts, providing a comprehensive understanding of hurricanes through advanced models and simulations. We believe that this research aligns with the objectives and scope of Mathematical Models in Engineering, contributing novel insights to the field. I trust that the innovative methodology and findings presented in this paper will be of interest to the journal's readership. Thank you for considering our submission. I look forward to the opportunity to contribute to the advancement of research within Mathematical Models in Engineering.

Sincerely,

Author's statement

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The Authors agree with Ethics and Malpractice Statement (https://www.extrica.com/resources/publication-ethics).

The Authors agree that the manuscript will be published in print and electronic formats.

Contributions VALENTINUS GALIH VIDIA PUTRA and MUSTAMINA MAULANI conducted the simulations and the calculations. VALENTINUS GALIH VIDIA PUTRA and MUSTAMINA MAULANI wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

Acknowledgements The authors are grateful to the Republic of Indonesia's Ministry of Industry and Universitas Trisakti for providing adequate facilities. We also thank our colleagues who helped us with the research and analysis

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest The authors declare that they have no conflict of interest.

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Response to Reviewer comments

REVIEW-1

MME 24041 - Revision required Mathematical Models in Engineering
Tensor analysis of tornadoes: a new analytical and numerical model
Valentinus galih Vidia Putra; Mustamina Maulani;

Dear Editor,
We thank the reviewer/(s) for their comprehensive comments which helped us a lot in the correction of the manuscript. The authors have thoroughly reviewed the comments and the answers to each point are given below with relevant details.

A minor revision is required before reconsideration. The manuscript is novel and interesting. It deserves to be published in the Journal after a minor revision.

#1The comparison between the computational results and the photo of a real tornado (Fig. 4) is unclear. The authors should elaborate to explain how the comparison could be made.

Answer:

We appreciate your constructive feedback on our paper. In response to your comment, we have added: Based on **Fig.3** and **Fig.4**, we found a strong correlation between tornado height, air density and temperature, geocentric latitude, and initial speed, as shown in Eq. (49). As a result of our investigation and model results, we find that tornadoes have a low-pressure area with an increasing-pressure core. Research shows that this model can describe the spiraling upward motion of air within a tornado's path without including vertical convection In addition to high airspeeds in the upper atmosphere, geocentric latitude, and the Coriolis effect, higher atmospheric pressure also contributes to tornadoes. According to some researchers [2,4,10,11,14], tornadoes in the Northern Hemisphere move clockwise, which is consistent with our model at 45 degrees and 15 degrees. However, in the Southern Hemisphere, tornadoes normally move in the opposite direction or counterclockwise. As a result of the rotation of the Earth, the Coriolis effect deflects wind directions. Thus, the direction of a tornado's motion is determined by which hemisphere it occurs in.

#2 Another important issue. The recent movement against the paper mils requires to show that the authors are not newcomers to this field of research. In other words, please add at least one citation to your own work. In other words, at least one self-citation to your own work is needed.

Answer:

We appreciate your constructive feedback on our paper. In response to your comment, we have added in the introduction: The scientific application of this finding is that researchers at the Meteorology, Climatology, and Geophysics Agency will be able to analyze a tornado and geophysical phenomena more readily with simulations and models [5, 23].

#3 Also, please note that it is essentially important to highlight the novelty of your study to attract attention and citations from the International Engineering Community.

Answer:

We appreciate your constructive feedback on our paper. In response to your comment, we have added in the abstract: The novelty of this study is that this model can be used to explain tornado patterns. In our research, we combine tensor analysis, computational modeling, as well as 2D and 3D simulations for simulating tornadoes for the first time

Tensor analysis of tornadoes: a new analytical and numerical model

Mustamina Maulani[1]**, Valentinus Galih Vidia Putra** [2]
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[2] Basic and Applied Science Research Group in Theoretical and Plasma Physics, Department of Textile Engineering, Politeknik STTT Bandung, Bandung, Indonesia

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Abstract. This research proposes a new mathematical formulation of tornadoes based on the theory of tensor analysis and simulation in a non-inertial dynamics framework, both in two and three dimensions. This model may show the spherical upward movement of air in a tornado without taking into account vertical convection. A tornado requires several elements, including geocentric latitude, the Coriolis effect, increased airspeed in the upper atmosphere, and increased air pressure. Computing the three-dimensional location of the tornado or hurricane, as well as the mathematical models of airflow motion and the Earth's rotation in three-dimensional (3D) space, can determine a tornado's airflow characteristics. To show tornado patterns, we employed computer software that computed motion dynamics and did numerical computations. The study revealed that this model can be used to explain tornado patterns. In our research, we combine tensor analysis, computational modeling, as well as 2D and 3D simulations for simulating tornadoes. The practitioners and scientific experts may apply the study's findings to better understand hurricanes using models and simulations.

Comment [N1]: We added: The results of 2-D modeling and simulation indicated that the greater the initial tornado angular speed, the larger the tornado area. Three-dimensional modeling and simulation also show that tornadoes are more powerful at higher geocentric latitude angles.

Comment [N2]: Also, please note that it is essentially important to highlight the novelty of your study in order to attract the attention and citations from the International Engineering Community:

Thanks for the comments. explanations for the review have been added:

The novelty of this study is that this model can be used to explain tornado patterns. In our research, we combine tensor analysis, computational modeling, as well as 2D and 3D simulations for simulating tornadoes for the first time

Comment [N3]: The scientific application of this finding is that researchers at the Meteorology, Climatology, and Geophysics Agency will be able to analyze a tornado and geophysical phenomena more readily with simulations and models

Keywords: Tornado, Coriolis effect, numerical model, computational dynamics

1. Introduction

The Indonesian government is currently focusing on phenomena such as heat waves that have received attention, as well as tornadoes that have devastated various regions of Indonesia. A tornado hit Lebak Banten, Indonesia, on May 10, 2022. This incident caused damage to about 80 houses and schools. Tornadoes wreaked devastation in several districts of Lebak, Banten, resulting in losses of thousands of millions of rupiah. A tornado had also ripped across the Subang area the day before. The Regional Disaster Management Agency (BPBD) of Subang Regency claimed 21 locations were affected by the hurricane, with Cibogo and Subang Kota Districts suffering the most damage [1]. Tornado parameters must be studied due to their catastrophic impact. In recent years, physicists have employed computational physics and fluid mechanics to examine and model different natural processes, as well as material science [2]-[8]. Tornado investigation is an intriguing topic in Earth's atmosphere and geophysical sciences. Tornadoes are hazardous natural disasters that strike on a small scale and last only a few minutes. Actual tornado observations are difficult to collect [9]. Despite improvements in severe storm mathematical approaches, replicating and predicting small-scale tornadoes will remain difficult [2]. As a result, a computerized model has arisen as a way of studying and modeling tornadoes. Several researchers have been performed to simulate the tornado mechanism [2]-[4]. Scientists first used computational modeling to simulate tornadoes [10, 11]. Computation physics modeling, including artificial intelligence and numerical modeling, has various advantages over other forms of research approaches, including lower risk [5]-[7], lower cost [12, 13], and the need for fewer experimental data [14]-[18]. Computational dynamics enables researchers to further accurately compute various tornado patterns, wind direction and speed, latitude, the impacts of Earth's rotation as well as Coriolis forces, and wind pressure to completely comprehend and model tornado formation. Tornadoes & wind patterns are examples of the Coriolis effect. A tornado is distinguished by a low-pressure region with rising pressure at its center. Tornadoes, which divert airflow from all directions, need the Coriolis force to circulate. As a result, hurricanes hardly form in tropical areas and never cross the Equator [19]-[21]. This study gives a simple 2D and 3D model for generating a tornado-like vortex utilizing an advanced model and computation using tensor analysis reported by various researchers [20, 22]. The scientific application of this research is that researchers and practitioners will be able to more easily study hurricanes using simulation and models.

Comment [N4]:
please add at least one citation to your own work. In other words, at least one self-citation to your own work is needed.

Thanks for the comments. explanations for the review have been added:

The scientific application of this finding is that researchers at the Meteorology, Climatology, and Geophysics Agency will be able to analyze a tornado and geophysical phenomena more readily with simulations and models [5, 23]

2. Research methods

2.1. Tornado mathematical model

The foundation of our work is the theoretical framework of variables used to describe motion. Eq. expresses the acceleration in a fixed system in terms of location, speed, and acceleration in the rotating system in Eq. (1)

$$a = \ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' \quad (1)$$

Where ω is the angular velocity, $\dot{\omega}$ is the time derivative of ω. In the case where the primed system undergoes both translation and rotation, we obtain general equations for transforming from a fixed to a moving and rotating system, as shown in Eq.(2). This comprises the generic equations for transforming a stationary system into a moving and rotating one.

$$a = \ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A \quad (2)$$

After we have the motion equation in moving coordinates, we can write it as shown in Eqs. (3) to (6)

$$F = ma = m(\ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A) \quad (3)$$

$$F - m(\dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A) = m\ddot{r}' \quad (4)$$

$$F - (m\dot{\omega} \times r' + 2m\omega \times \dot{r}' + m\omega \times (\omega \times r') + mA) = m\ddot{r}' \quad (5)$$

$$F - (F_{Eul} + F_{cor} + F_{cent} + F_t) = m\ddot{r}' \quad (6)$$

Where F is the physical force, $F_{eul} = m\dot{\omega} \times r'$ is the Euler force, ω is the angular velocity, $F_{cor} = 2m\omega \times \dot{r}'$ is the Coriolis force, $F_{cent} = m\omega \times (\omega \times r')$ denotes the centrifugal force, and $F_t = mA$ denotes the force due to the translation of the coordinate system. The equation of motion in a moving system can be written as Eq. (7)

$$\sum F_{all} = m\ddot{r}' = \rho V \ddot{\boldsymbol{r}}' \quad (7.\ a)$$

$$\sum f = \rho \ddot{\boldsymbol{r}}' \quad (7.\ b)$$

Where f is the total force per unit volume, ρ is the density of the particle with a certain mass, and $\ddot{\boldsymbol{r}}'$ is the acceleration of the particle with a certain mass. We can extend the model by using Cauchy's equation in Eq.(8) and the generalized equation of motion in 3D movement proposed by [22] as in Eqs. (9) and (10).

$$\boldsymbol{\nabla} \cdot \boldsymbol{\sigma} + \boldsymbol{f_{tot}} = \rho \ddot{\boldsymbol{r}}' \quad (8)$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{\sigma} + \boldsymbol{f_g} - (f_{Eul} + f_{cor} + f_{cent} + f_t) = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}') \quad (9)$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{\sigma} + \boldsymbol{f_g} - f_{Eul} - f_{cor} - f_{cent} - f_t = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}') \quad (10)$$

where f_{tot} is the total force per unit volume, f_g is the gravitational attraction force, ρ is the density of the particle with a certain mass, and σ is the stress tensor. Consider the Euler force $f_{Eul} = 0$, the force due to the translation of the coordinate system $f_t = 0$, and since the centrifugal force is so small compared to the other terms, we can neglect it. The equation of motion then becomes

$$\left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} + \frac{\partial \sigma_{zx}}{\partial z}\right)\boldsymbol{i}' + \left(\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{zy}}{\partial z}\right)\boldsymbol{j}' + \left(\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}\right)\boldsymbol{k}' - \rho g \boldsymbol{k}' - 2\rho\left(\omega_x \boldsymbol{i}' + \omega_y \boldsymbol{j}' + \omega_z \boldsymbol{k}'\right) \times (\dot{x}'\boldsymbol{i}' + \dot{y}'\boldsymbol{j}' + \dot{z}'\boldsymbol{k}') = \rho\left(\ddot{x}' + \ddot{y}' + \ddot{z}''\right) \quad (11)$$

$$f_{px}\boldsymbol{i}' + f_{py}\boldsymbol{j}' + f_{pz}\boldsymbol{k}' - \rho g \boldsymbol{k}' - 2\rho\left(\omega_x \boldsymbol{i}' + \omega_y \boldsymbol{j}' + \omega_z \boldsymbol{k}'\right) \times (\dot{x}'\boldsymbol{i}' + \dot{y}'\boldsymbol{j}' + \dot{z}'\boldsymbol{k}') = \rho\left(\ddot{x}' + \ddot{y}' + \ddot{z}''\right) \quad (12)$$

To simplify the calculation of the model, it can be assumed that $\left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} + \frac{\partial \sigma_{zx}}{\partial z}\right)\boldsymbol{i}' + \left(\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{zy}}{\partial z}\right)\boldsymbol{j}' + \left(\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}\right)\boldsymbol{k}' = f_{px}\boldsymbol{i}' + f_{py}\boldsymbol{j}' + f_{pz}\boldsymbol{k}'$ and $\omega_x \boldsymbol{i}' + \omega_y \boldsymbol{j}' + \omega_z \boldsymbol{k}' = (0\boldsymbol{i}' + \omega\ cos\lambda \boldsymbol{j}' + \omega\ sin\lambda \boldsymbol{k}')$, yield

$$f_{px}\boldsymbol{i}' + f_{py}\boldsymbol{j}' + f_{pz}\boldsymbol{k}' - \rho g \boldsymbol{k}' = \rho(\ddot{\boldsymbol{r}}') + 2\rho\left(\omega_x \boldsymbol{i}' + \omega_y \boldsymbol{j}' + \omega_z \boldsymbol{k}'\right) \times (\dot{x}'\boldsymbol{i} + \dot{y}'\boldsymbol{j} + \dot{z}'\boldsymbol{k}) \quad (13)$$

$$f_{px}\boldsymbol{i}' + f_{py}\boldsymbol{j}' + f_{pz}\boldsymbol{k}' - \rho g \boldsymbol{k}' = \rho(\ddot{\boldsymbol{r}}' + 2(0\boldsymbol{i}' + \omega\ cos\lambda \boldsymbol{j}' + \omega\ sin\lambda \boldsymbol{k}') \times (\dot{x}'\boldsymbol{i} + \dot{y}'\boldsymbol{j} + \dot{z}'\boldsymbol{k})) \quad (14)$$

We can write $g = g_0 - \omega^2 Rcos\lambda$ because of the effect of Earth's rotation. Where g_0 denotes the actual gravitation acceleration, and $\omega^2 Rcos\lambda$ denotes the centripetal acceleration for the Earth's radius, R, and geocentric latitude, λ.

Comment [N5]: We have added it:

Eq. (1) expresses the acceleration in a fixed system in terms of location, speed, and acceleration in the rotating system

Comment [N6]: We have added it:

and r', $\dot{r}'$ and $\ddot{r}'$ are the position in the unit (m), velocity in the unit (m/s), and acceleration in the unit (m/s^2), respectively.

In this study, we choose the coordinate axis $O'x'y'z'$ such that the z' is vertical, the x' axis to the east, and the y' axis points north. The coordinate axes for analyzing tornado motion can be shown in **Fig. 1**.

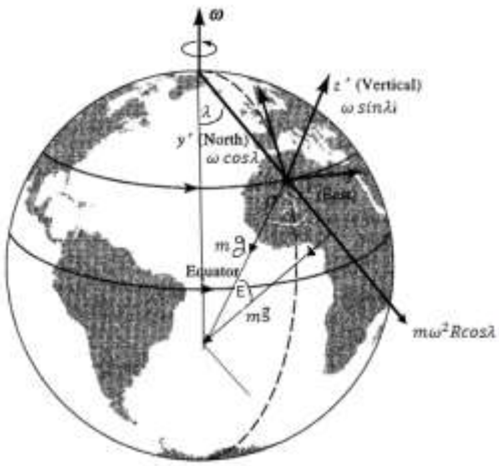

Fig. 1. Coordinate axes for analyzing tornado motion.

We also use $\omega_x = 0$, $\omega_y = \omega\ cos\lambda$, and $\omega_z = \omega\ sin\lambda$. Eq. (14) can be solved computationally, and we get Eqs. (15) and (16)

$$f_{px}\boldsymbol{i}' + f_{py}\boldsymbol{j}' + f_{pz}\boldsymbol{k}' - \rho g\boldsymbol{k}' = \rho\ddot{\boldsymbol{r}}' + 2\rho(\dot{z}'\omega\ cos\lambda - \dot{y}'\omega\ sin\lambda)\boldsymbol{i}' + \mathbf{2}\rho(\dot{x}'\omega\ sin\lambda)\boldsymbol{j}' - \mathbf{2}\rho(\dot{x}'\omega\ cos\lambda)\boldsymbol{k}' \quad (15)$$

$$\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right)\boldsymbol{i}' + \left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right)\boldsymbol{j}' + \left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right)\boldsymbol{k}' - \rho g\boldsymbol{k}' = \rho\ddot{\boldsymbol{r}}' + 2\rho(\dot{z}'\omega\ cos\lambda - \dot{y}'\omega\ sin\lambda)\boldsymbol{i}' + \mathbf{2}\rho(\dot{x}'\omega\ sin\lambda)\boldsymbol{j}' - \mathbf{2}\rho(\dot{x}'\omega\ cos\lambda)\boldsymbol{k}' \quad (16)$$

We can solve Eq. (16); hence we find Eqs. (17) to (19)

$$\ddot{\boldsymbol{x}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right) - 2\omega(\dot{z}'\ cos\lambda - \dot{y}'\ sin\lambda) \quad (17)$$

$$\ddot{\boldsymbol{y}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right) - 2\dot{x}'\omega\ sin\lambda \quad (18)$$

$$\ddot{\boldsymbol{z}}' = \left(\frac{1}{\rho}\left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right) - g\right) + \mathbf{2}\dot{x}'\omega\ cos\lambda \quad (19)$$

Assuming that $\frac{\partial\sigma_{zz}}{\partial z} = \frac{R\rho T}{T}\frac{\partial(T)}{\partial z} + \frac{R\rho T}{\rho}\frac{\partial(\rho)}{\partial z} = \sigma_o,\ and\ \sigma_{xx} = \sigma_{xy} = \sigma_{xz} = \sigma_{yy} = \sigma_{yz} = 0$, hence we get $e_{zz} = \frac{\sigma_{zz}}{E}, e_{yy} = -v\frac{\sigma_{zz}}{E}, and\ e_{xx} = -v\frac{\sigma_{zz}}{E}, e_{xy} = e_{xz} = e_{yz} = 0$, and we find Eqs. (20) to (22)

$$\ddot{\boldsymbol{x}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right) - 2\omega(\dot{z}'\ cos\lambda - \dot{y}'\ sin\lambda) = -2\omega(\dot{z}'\ cos\lambda - \dot{y}'\ sin\lambda) \quad (20)$$

$$\ddot{\boldsymbol{y}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right) - 2\dot{x}'\omega\ sin\lambda = -2\dot{x}'\omega\ sin\lambda \quad (21)$$

$$\ddot{\boldsymbol{z}}' = \left(\frac{1}{\rho}\left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right) - g\right) + \mathbf{2}\dot{x}'\omega\ cos\lambda = \frac{\sigma_o}{\rho} - \boldsymbol{g} + \mathbf{2}\dot{x}'\omega\ cos\lambda \quad (22)$$

We can integrate once concerning *t* to get the component of velocity, and we find, as shown in Eqs (23) to (25)

$$\dot{\boldsymbol{x}}' = \dot{x_o}' - 2\omega(z'\ cos\lambda - y'\ sin\lambda) \quad (23)$$

$$\dot{\boldsymbol{y}}' = \dot{y_o}' - 2x'\omega\ sin\lambda \quad (24)$$

$$\dot{\boldsymbol{z}}' = \dot{z_o}' + \left(\frac{\sigma_o}{\rho} - \boldsymbol{g}\right)\boldsymbol{t} + \boldsymbol{2}x'\omega\, cos\lambda \tag{25}$$

Then substitute $\dot{\boldsymbol{z}}'$ and $\dot{\boldsymbol{y}}'$ into Eq. (20), we find Eqs. (26) and (27)

$$\ddot{\boldsymbol{x}}' = -2\omega(\dot{z}'\, cos\lambda - \dot{y}'\, sin\lambda)$$
$$= -2\omega\left(\left[\dot{z_o}' + \left(\frac{\sigma_o}{\rho} - g\right)\boldsymbol{t} + \boldsymbol{2}x'\omega\, cos\lambda\right] cos\lambda - [\dot{y_o}' - 2x'\omega\, sin\lambda]\, sin\lambda\right) \tag{26}$$

$$\ddot{\boldsymbol{x}}' = -2\omega\left(\left[\dot{z_o}' + \left(\frac{\sigma_o}{\rho} - g\right) + \boldsymbol{2}x'\omega\, cos\lambda\right] cos\lambda - [\dot{y_o}' - 2x'\omega\, sin\lambda]\, sin\lambda\right)$$
$$\cong -2\omega\dot{z_o}'cos\lambda - 2\omega\left(\frac{\sigma_o}{\rho} - g\right)tcos\lambda + 2\omega\dot{y_o}'sin\lambda =$$
$$= 2\omega\left(g - \frac{\sigma_o}{\rho}\right)tcos\lambda - 2\omega(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda) \tag{27}$$

We integrate Eq.(27) again to get $\dot{x}'$**,** as shown in Eq. (28) and Eq.(29)

$$\int d\dot{x}' = \int \left[2\omega\left(g - \frac{\sigma_o}{\rho}\right)tcos\lambda - 2\omega(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda)\right]dt \tag{28}$$

$$\dot{x}' = \omega\left(g - \frac{\sigma_o}{\rho}\right)t^2cos\lambda - 2\omega t(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda) + \dot{x_o}' \tag{29}$$

and finally, we find x' by integrating Eq. (29)

$$x' = \frac{\omega\left(g - \frac{\sigma_o}{\rho}\right)t^3}{3}cos\lambda - \omega t^2(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda) + \dot{x_o}'t + x_o' \tag{30}$$

Then substitute Eq.(30) into Eqs. (24) and (25), we find Eqs. (31) and (32)

$$\dot{\boldsymbol{y}}' = \dot{y_o}' - 2x'\omega\, sin\lambda = \dot{y_o}' - 2\left(\frac{\omega g t^3}{3}cos\lambda - \omega t^2(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda) + \dot{x_o}'t + x_o'\right)\omega\, sin\lambda$$
$$\cong \dot{y_o}' - 2(\dot{x_o}'t\omega\, sin\lambda + x_o'\omega\, sin\lambda) \tag{31}$$

$$\dot{\boldsymbol{z}}' = \dot{z_o}' + \left(\frac{\sigma_o}{\rho} - \boldsymbol{g}\right)\boldsymbol{t} + \boldsymbol{2}x'\omega\, cos\lambda$$
$$= \dot{z_o}' + \left(\frac{\sigma_o}{\rho} - \boldsymbol{g}\right)\boldsymbol{t}$$
$$+ \boldsymbol{2}\left(\frac{\omega\left(g - \frac{\sigma_o}{\rho}\right)t^3}{3}cos\lambda - \omega t^2(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda) + \dot{x_o}'t\right)\omega\, cos\lambda \tag{32}$$

As a result of integrating Eqs (31) and (32), the positions, y' and z', are given by

$$y' = \dot{y_o}'t - 2\left(\frac{\dot{x_o}'t^2}{2}\omega\, sin\lambda + x_o't\omega\, sin\lambda\right) + y_o' = y_o' + \dot{y_o}'t - \dot{x_o}'t^2\omega\, sin\lambda - 2x_o't\omega\, sin\lambda$$
$$\approx y_o' + \dot{y_o}'t - 2x_o't\omega\, sin\lambda \tag{33}$$

$$z' = \dot{z_o}'t + z_o + \omega\, cos\lambda\dot{x_o}'t^2 + \frac{1}{2}\left(\frac{\sigma_o}{\rho} - g\right)t^2 = \dot{z_o}'t + \left(\omega^2 r_o'cos\lambda + \frac{1}{2}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2 + z_o \tag{34}$$

According to some scientists [19, 20], a tornado is a dangerous natural event that occurs on an insignificant scale and persists for only a few minutes. Assuming that $y_o' + \dot{y_o}'t = r_o'$, $x_o' = \dot{x}_o t = r_o'\omega t$, and $\dot{x}_o = \dot{y}_o = \dot{z}_o = r_o'\omega$, $\dot{r}_o$ is so small at a very short time yield

Comment [N7]: We changed it by: , we get Eqs. (35) and (36)

$$x' = \frac{\omega g t^3}{3}cos\lambda - \omega t^2(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda) + \dot{x_o}'t = \frac{\omega g t^3}{3}cos\lambda - \omega t^2(\dot{z_o}'cos\lambda - \dot{y_o}'sin\lambda) + r_o'\omega t$$
$$\approx r_o'\omega t \tag{35}$$

$$y' = r_o' - 2r_o'\omega^2t^2\, sin\lambda = r_o'(1 - 2sin\lambda\omega^2t^2) = r\left(1 - \frac{(\omega t)^2}{2}\right) = r_o'\cos(\omega t) \tag{36}$$

Which requires that $2sin\lambda = \frac{1}{2}$ or $sin\lambda = \frac{1}{4}$ or $\lambda \approx 15^o$ (that is near the Equator), yield

Comment [N8]: We changed it by: , we find

$$x' = r_o'\,\omega t = r_o'\sin(\omega t) \tag{37}$$

(38)

$$y' = r_o' \cos(\omega t)$$

$$z' = \dot{z_o}'t + \left(\omega^2 + \frac{1}{2cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\, cos\lambda + z_o = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\, cos\lambda \quad (39)$$

Hence we get Eqs. (40) to (42)

Comment [N9]: We added: From Eqs. (37) to (39),

$$x' = r_o' \sin(\omega t) = r_o' \cos(90^o - \omega t) \quad (40)$$

$$y' = r_o' \cos(\omega t) = r_o' \sin(90^o - \omega t) \quad (41)$$

$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\, cos\lambda \quad (42)$$

Assuming that $r_o' = \dot{r_o}'t$, and ignoring the effects of gravitational force and humidity, and using the equation of state, we obtain Eqs. (43) to (45)

$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2cos\lambda}\left(\frac{\sigma_o}{\rho}\right)\right)t^2\, cos\lambda \quad (43)$$

$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2cos\lambda}\left(\frac{1}{\rho}\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2\, cos\lambda \quad (44)$$

$$z' = \dot{r_o}'t^2 + \left(\omega^2 + \frac{1}{2\rho cos\lambda}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2\, cos\lambda \quad (45)$$

According to [21], in the condition of a static atmosphere, we can write $\frac{\partial\sigma_{zz}}{\partial z} = \frac{\partial(R\rho T)}{\partial z}$. The density ρ and pressure of the air σ_{zz} in Eq (44) vary with height z. These changes can be calculated from the equation of state; we obtain

$$\frac{d(\sigma_{zz})}{dz} = R\rho\frac{\partial(T)}{\partial z} + RT\frac{\partial(\rho)}{\partial z} \quad (46)$$

$$\frac{d(\sigma_{zz})}{dz} = \frac{R\rho T}{T}\frac{\partial(T)}{\partial z} + R\rho T\frac{1}{\rho}\frac{\partial(\rho)}{\partial z} \quad (47)$$

$$\frac{1}{\sigma_{zz}}\frac{d(\sigma_{zz})}{dz} = \frac{1}{T}\frac{\partial(T)}{\partial z} + \frac{1}{\rho}\frac{\partial(\rho)}{\partial z} \quad (48)$$

where T is an absolute temperature, and R is the specific gas constant of dry air. In Eq. (48), the density ρ and T vary with altitude, and assuming that $\frac{1}{\sigma_{zz}}\frac{d(\sigma_{zz})}{dz} = \frac{1}{2\rho}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)$, then we obtain the position z ', which indicates the height of tornadoes as shown in Eq.(49)

$$z' = \dot{z_o}'t + \left(\omega^2 cos\lambda + \frac{1}{2\rho}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2 = r_o{}'\omega t + \left(\omega^2 cos\lambda + \left(\frac{1}{T}\frac{\partial(T)}{\partial z} + \frac{1}{\rho}\frac{\partial(\rho)}{\partial z}\right)\right)t^2 \quad (49)$$

Where $2\rho = \sigma_{zz}$ is related to tornado pressure.

2.2. Tornado simulation using numerical modeling

In the present research, we generated a model utilizing computational modeling that numerous researchers have performed on tornado characteristics [20, 21, 10, 11]. In this research, Eqs (40), (41), and (49) address the difficulty of mathematically expressing positions in three dimensions when simulating tornado formation. Eqs. (29), (31), and (32) provide solutions to the difficulty of mathematically describing the velocity of the wind in growing tornadoes. In our research, MATLAB code was created to model tornado motion in two-dimensional and three-dimensional positions to explain tornado formation utilizing Eqs. (40), (41), and (49).

3. Results and Discussions

Fig. 2 shows a two-dimensional model of a tornado with the velocity of the wind varying to the west and north throughout the same period. Modeling results show that the greater the wind velocity to the north and west, the larger the region of the tornado movement. The simulation findings reveal that the tornado's area of rotation is affected by the velocity of the wind, tornado time, and earth rotational speed. The tornado may rotate and require Coriolis force to move.

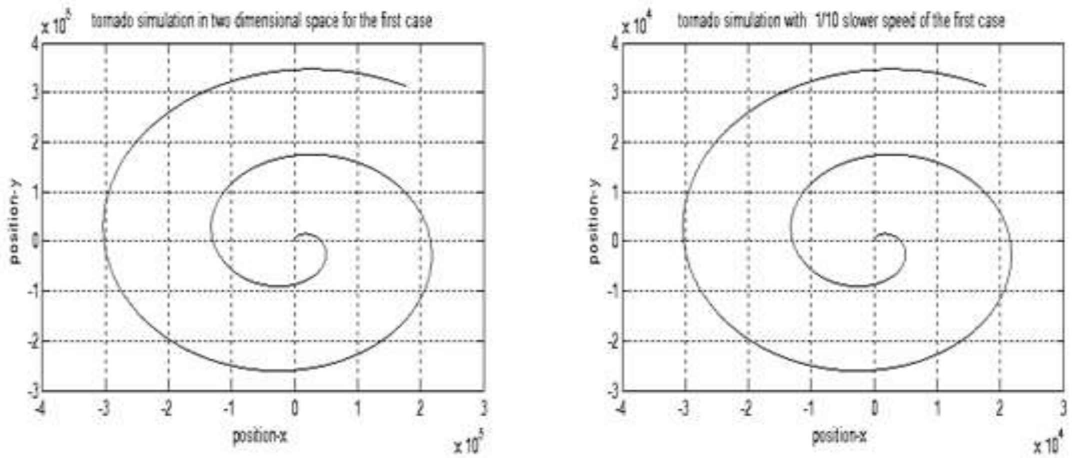

Fig. 2. Two-dimensional simulation of a tornado with wind speed variations.

Fig. 3 depicts a three-dimensional simulation of a tornado with variations in wind speed to the west and north over the same period and geocentric latitude variations of 45 degrees and 15 degrees. **Fig. 4** depicts a tornado at Mount Kencana, Banten, Indonesia, where a tornado appears when there is a change in temperature and high density, as well as a high wind rotation.

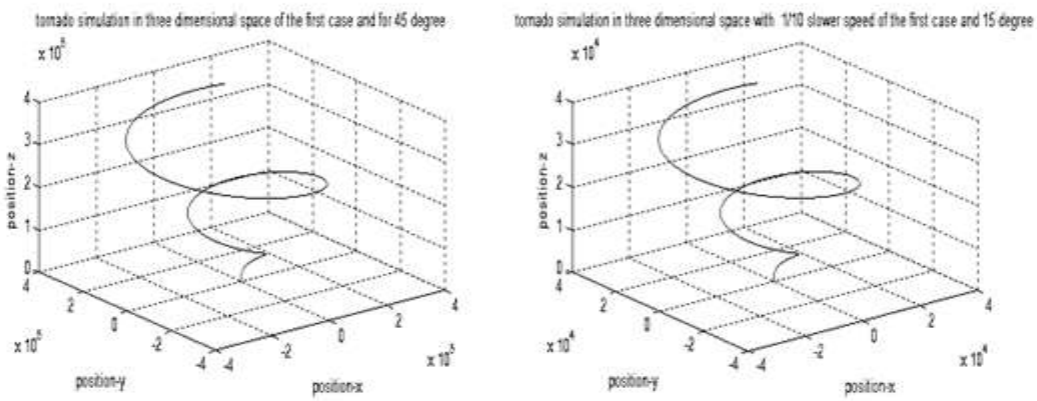

Fig. 3. Three-dimensional simulation of a tornado with wind speed and geocentric latitude variations.

Fig. 4.Tornado in Gunung kencana, Banten, Indonesia [1].

Comment [N10]: The comparison between the computational results and the photo of a real tornado (Fig. 4) is unclear. The authors should elaborate to explain how the comparison could be made.

Answer: Thanks for the comments. explanations for the review have been added

Based on **Fig.3** and **Fig.4**, we found a strong correlation between tornado height, air density and temperature, geocentric latitude, and initial speed, as shown in Eq. (49). As a result of our investigation and model results, we find that tornadoes have a low-pressure area with an increasing-pressure core. Research shows that this model can describe the spiraling upward motion of air within a tornado's path without including vertical convection In addition to high airspeeds in the upper atmosphere, geocentric latitude, and the Coriolis effect, higher atmospheric pressure also contributes to tornadoes. According to some researchers [2,4,10,11,14], tornadoes in the Northern Hemisphere move clockwise, which is consistent with our model at 45 degrees and 15 degrees. However, in the Southern Hemisphere, tornadoes normally move in the opposite direction or counterclockwise. As a result of the rotation of the Earth, the Coriolis effect deflects wind directions. Thus, the direction of a tornado's motion is determined by which hemisphere it occurs in.

In this research, Eqs. (40), (41), and (49) address the difficulty of mathematically expressing places in three-dimensional space when simulating tornado formation. Eqs. (29), (31), and (32) provide solutions to the difficulty of mathematically describing wind velocity in forming tornadoes. The modeling results demonstrate that the higher the geocentric latitude angle, the more likely a tornado will form. This research suggests that huge tornadoes can form in places with high geocentric latitudes. In this study, we discovered the equation for the motion of a tornado in three-dimensional coordinates, as shown in Eqs. (17) through (19). Our findings revealed a strong link involving tornado height and changes in air density and temperature, as well as geocentric latitude and beginning speed, as given in Eq. (49). Our investigation and model results validate various academics' claims that a low-pressure area with an increasing-pressure core characterizes tornadoes. Tornadoes require Coriolis force for movement. As a result, storms are uncommon in tropical regions and rarely cross the Equator, and this study confirms prior observations [14]-[18]. According to the research, this model could describe the spiraling upward motion of air in a tornado's path without incorporating vertical convection. This modeling revealed no differences with experts' opinions that certain variables can cause tornadoes. Tornadoes are created by various elements, including geocentric latitude, the Coriolis effect, higher airspeed in the upper atmosphere, and higher atmospheric pressure [14–18]. The airflow characteristics of a tornado can be calculated by calculating the 3-D and mathematical models of airflow motion and the Earth's rotation in three-dimensional (3D) space. This research provides a basic 2D and 3D model to generate a tornado-like vortex using simple modeling and calculation. This research's scientific applicability is that professionals and scientific experts can utilize the models to study tornadoes more easily.

Comment [N11]: The problem of mathematically expressing places in three-dimensional space when simulating tornado formation is addressed by Eqs (40), (41), and (49).

Conclusions

This research reported a theoretical formulation of tornadoes in a non-inertial mechanics framework, utilizing fluid mechanics and numerical simulation. This model depicted the spiraling upward motion of air in a tornado while ignoring vertical convection. Several conditions were required for a tornado to occur, including geocentric latitude, the Coriolis effect, increased airspeed in the upper atmosphere, and increased air pressure. We calculated the airflow characteristics of a tornado and solved the three-dimensional position of the tornado or hurricane in three-dimensional (3D) space, as well as the differential equations of airflow velocity and the Earth's rotation. To demonstrate tornado patterns, motion dynamics modeling, and numerical computations were performed using computer software. The study concluded that this model might explain tornado patterns. Using the modeling and simulation data from this work, practitioners and scientists can gain a better understanding of hurricanes. To obtain more precise models, we proposed that additional studies be performed utilizing various methodologies, such as quantum neural networks / QNNs and artificial neural networks in future research.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author upon reasonable request.

Author contributions

VALENTINUS GALIH VIDIA PUTRA and MUSTAMINA MAULANI conducted the simulations and the calculations. VALENTINUS GALIH VIDIA PUTRA and MUSTAMINA MAULANI wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

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Letter of Acceptance

This is to confirm that the manuscript titled

"Tensor analysis of tornadoes: a new analytical and numerical model"

authored by Valentinus galih Vidia Putra, Mustamina Maulani Maulani has undergone peer review process and is accepted to Mathematical Models in Engineering.

Best Regards,
Prof. Dr. Minvydas Ragulskis

Editor in Chief, Mathematical Models in Engineering

Full Professor at Department of Mathematical Modelling, Kaunas University of Technology
Member Elect, Lithuanian Academy of Sciences

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Tensor analysis of tornadoes: a new analytical and numerical model

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Abstract. This research proposes a new mathematical formulation of tornadoes based on the theory of tensor analysis and simulation in a non-inertial dynamics framework, both in two and three dimensions. This model may show the spherical upward movement of air in a tornado without taking into account vertical convection. A tornado requires several elements, including geocentric latitude, the Coriolis effect, increased airspeed in the upper atmosphere, and increased air pressure. Computing the three-dimensional location of the tornado or hurricane, as well as the mathematical models of airflow motion and the Earth's rotation in three-dimensional (3D) space, can determine a tornado's airflow characteristics. To show tornado patterns, we employed computer software that computed motion dynamics and did numerical computations. The results of 2-D modeling and simulation indicated that the greater the initial tornado angular speed, the larger the tornado area. Three-dimensional modeling and simulation also show that tornadoes are more powerful at higher geocentric latitude angles. The novelty of this study is that this model can be used to explain tornado patterns. In our research, we combine tensor analysis, computational modeling, as well as 2D and 3D simulations for simulating tornadoes for the first time. The scientific application of this finding is that researchers at the Meteorology, Climatology, and Geophysics Agency will be able to analyze a tornado and geophysical phenomena more readily with simulations and models.

Keywords: tornado, coriolis effect, numerical model, computational dynamics.

1. Introduction

The Indonesian government is currently focusing on phenomena such as heat waves that have received attention, as well as tornadoes that have devastated various regions of Indonesia. A tornado hit Lebak Banten, Indonesia, on May 10, 2022. This incident caused damage to about 80 houses and schools. Tornadoes wreaked devastation in several districts of Lebak, Banten, resulting in losses of thousands of millions of rupiah. A tornado had also ripped across the Subang area the day before. The Regional Disaster Management Agency (BPBD) of Subang Regency claimed 21 locations were affected by the hurricane, with Cibogo and Subang Kota Districts suffering the most damage [1]. Tornado parameters must be studied due to their catastrophic impact. In recent years, physicists have employed computational physics and fluid mechanics to examine and model different natural processes, as well as material science [2-8]. Tornado investigation is an intriguing topic in Earth's atmosphere and geophysical sciences. Tornadoes are hazardous natural disasters that strike on a small scale and last only a few minutes. Actual tornado observations are difficult to collect [9]. Despite improvements in severe storm mathematical approaches, replicating and predicting small-scale tornadoes will remain difficult [2]. As a result, a computerized model has arisen as a way of studying and modeling tornadoes. Several researchers have been performed to simulate the tornado mechanism [2-4]. Scientists first used computational modeling to simulate tornadoes [10, 11]. Computation physics modeling, including artificial intelligence and numerical modeling, has various advantages over other forms of research approaches, including lower risk

[5-7], lower cost [12, 13], and the need for fewer experimental data [14-18]. Computational dynamics enables researchers to further accurately compute various tornado patterns, wind direction and speed, latitude, the impacts of Earth's rotation as well as Coriolis forces, and wind pressure to completely comprehend and model tornado formation. Tornadoes & wind patterns are examples of the Coriolis effect. A tornado is distinguished by a low-pressure region with rising pressure at its center. Tornadoes, which divert airflow from all directions, need the Coriolis force to circulate. As a result, hurricanes hardly form in tropical areas and never cross the Equator [19-21]. This study gives a simple 2D and 3D model for generating a tornado-like vortex utilizing an advanced model and computation using tensor analysis reported by various researchers [20, 22]. The scientific application of this finding is that researchers at the Meteorology, Climatology, and Geophysics Agency will be able to analyze a tornado and geophysical phenomena more readily with simulations and models [5, 23].

2. Research methods

2.1. Tornado mathematical model

The foundation of our work is the theoretical framework of variables used to describe motion. Eq. (1) expresses the acceleration in a fixed system in terms of location, speed, and acceleration in the rotating system:

$$a = \ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r', \tag{1}$$

where ω is the angular velocity, $\dot{\omega}$ is the time derivative of ω and r', $\dot{r}'$ and $\ddot{r}'$ are the position in the unit (m), velocity in the unit (m/s), and acceleration in the unit (m/s^2), respectively. In the case where the primed system undergoes both translation and rotation, we obtain general equations for transforming from a fixed to a moving and rotating system, as shown in Eq. (2). This comprises the generic equations for transforming a stationary system into a moving and rotating one:

$$a = \ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A. \tag{2}$$

After we have the motion equation in moving coordinates, we can write it as shown in Eqs. (3) to (6):

$$F = ma = m(\ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A), \tag{3}$$
$$F - m(\dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A) = m\ddot{r}', \tag{4}$$
$$F - (m\dot{\omega} \times r' + 2m\omega \times \dot{r}' + m\omega \times (\omega \times r') + mA) = m\ddot{r}', \tag{5}$$
$$F - (F_{Eul} + F_{cor} + F_{cent} + F_t) = m\ddot{r}', \tag{6}$$

where F is the physical force, $F_{eul} = m\dot{\omega} \times r'$ is the Euler force, ω is the angular velocity, $F_{cor} = 2m\omega \times \dot{r}'$ is the Coriolis force, $F_{cent} = m\omega \times (\omega \times r')$ denotes the centrifugal force, and $F_t = mA$ denotes the force due to the translation of the coordinate system. The equation of motion in a moving system can be written as Eq. (7):

$$\sum F_{all} = m\ddot{r}' = \rho V \ddot{r}', \quad \sum f = \rho \ddot{r}', \tag{7}$$

where f is the total force per unit volume, ρ is the density of the particle with a certain mass, and $\ddot{r}'$ is the acceleration of the particle with a certain mass. We can extend the model by using Cauchy's equation in Eq. (8) and the generalized equation of motion in 3D movement proposed by [22] as in Eqs. (9) and (10):

$$\nabla \cdot \sigma + f_{tot} = \rho \ddot{r}', \tag{8}$$

$$\nabla \cdot \sigma + f_g - (f_{Eul} + f_{cor} + f_{cent} + f_t) = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}'), \quad (9)$$
$$\nabla \cdot \sigma + f_g - f_{Eul} - f_{cor} - f_{cent} - f_t = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}'), \quad (10)$$

where f_{tot} is the total force per unit volume, f_g is the gravitational attraction force, ρ is the density of the particle with a certain mass, and σ is the stress tensor. Consider the Euler force $f_{Eul} = 0$, the force due to the translation of the coordinate system $f_t = 0$, and since the centrifugal force is so small compared to the other terms, we can neglect it. The equation of motion then becomes:

$$\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right)\mathbf{i}' + \left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right)\mathbf{j}' + \left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right)\mathbf{k}' - \rho g\mathbf{k}' - 2\rho\left(\omega_x\mathbf{i}' + \omega_y\mathbf{j}' + \omega_z\mathbf{k}'\right) \times (\dot{x}'\mathbf{i}' + \dot{y}'\mathbf{j}' + \dot{z}'\mathbf{k}') = \rho\left(\ddot{x}' + \ddot{y}' + \ddot{z}''\right), \quad (11)$$

$$f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g\mathbf{k}' - 2\rho\left(\omega_x\mathbf{i}' + \omega_y\mathbf{j}' + \omega_z\mathbf{k}'\right) \times (\dot{x}'\mathbf{i}' + \dot{y}'\mathbf{j}' + \dot{z}'\mathbf{k}') = \rho\left(\ddot{x}' + \ddot{y}' + \ddot{z}''\right). \quad (12)$$

To simplify the calculation of the model, it can be assumed that:

$$\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right)\mathbf{i}' + \left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right)\mathbf{j}' + \left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right)\mathbf{k}' = f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}',$$
$$\omega_x\mathbf{i}' + \omega_y\mathbf{j}' + \omega_z\mathbf{k}' = (0\mathbf{i}' + \omega\cos\lambda\mathbf{j}' + \omega\sin\lambda\mathbf{k}'),$$

yield:

$$f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g\mathbf{k}' = \rho(\ddot{\mathbf{r}}') + 2\rho\left(\omega_x\mathbf{i}' + \omega_y\mathbf{j}' + \omega_z\mathbf{k}'\right) \times (\dot{x}'\mathbf{i} + \dot{y}'\mathbf{j} + \dot{z}'\mathbf{k}), \quad (13)$$
$$f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g\mathbf{k}' = \rho\left(\ddot{\mathbf{r}}' + 2(0\mathbf{i}' + \omega\cos\lambda\mathbf{j}' + \omega\sin\lambda\mathbf{k}') \times (\dot{x}'\mathbf{i} + \dot{y}'\mathbf{j} + \dot{z}'\mathbf{k})\right). \quad (14)$$

We can write $g = g - \omega^2 R\cos\lambda$ because of the effect of Earth's rotation. Where g denotes the actual gravitation acceleration, and $\omega^2 R\cos\lambda$ denotes the centripetal acceleration for the Earth's radius, R, and geocentric latitude, λ. In this study, we choose the coordinate axis $O'x'y'z'$ such that the z' is vertical, the x' axis to the east, and the y' axis points north. The coordinate axes for analyzing tornado motion can be shown in Fig. 1.

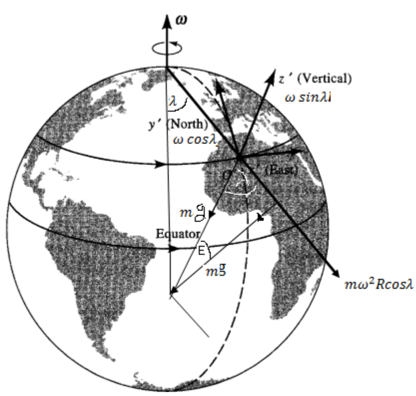

Fig. 1. Coordinate axes for analyzing tornado motion.

We also use $\omega_x = 0$, $\omega_y = \omega\cos\lambda$, and $\omega_z = \omega\sin\lambda$. Eq. (14) can be solved computationally, and we get Eqs. (15) and (16):

$$f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g\mathbf{k}' = \rho\ddot{\mathbf{r}}' + 2\rho(\dot{z}'\omega\cos\lambda - \dot{y}'\omega\sin\lambda)\mathbf{i}' + 2\rho(\dot{x}'\omega\sin\lambda)\mathbf{j}' - 2\rho(\dot{x}'\omega\cos\lambda)\mathbf{k}', \tag{15}$$

$$\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right)\mathbf{i}' + \left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right)\mathbf{j}' + \left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right)\mathbf{k}' - \rho g\mathbf{k}' = \rho\ddot{\mathbf{r}}' + 2\rho(\dot{z}'\omega\cos\lambda - \dot{y}'\omega\sin\lambda)\mathbf{i}' + 2\rho(\dot{x}'\omega\sin\lambda)\mathbf{j}' - 2\rho(\dot{x}'\omega\cos\lambda)\mathbf{k}'. \tag{16}$$

We can solve Eq. (16); hence we find Eqs. (17) to (19):

$$\ddot{\mathbf{x}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right) - 2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda), \tag{17}$$

$$\ddot{\mathbf{y}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right) - 2\dot{x}'\omega\sin\lambda, \tag{18}$$

$$\ddot{\mathbf{z}}' = \left(\frac{1}{\rho}\left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right) - g\right) + 2\dot{x}'\omega\cos\lambda. \tag{19}$$

Assuming that $\frac{\partial\sigma_{zz}}{\partial z} = \frac{R\rho T}{T}\frac{\partial(T)}{\partial z} + \frac{R\rho T}{\rho}\frac{\partial(\rho)}{\partial z} = \sigma_o$, and $\sigma_{xx} = \sigma_{xy} = \sigma_{xz} = \sigma_{yy} = \sigma_{yz} = 0$, hence we get $e_{zz} = \frac{\sigma_{zz}}{E}$, $e_{yy} = -v\frac{\sigma_{zz}}{E}$, and $e_{xx} = -v\frac{\sigma_{zz}}{E}$, $e_{xy} = e_{xz} = e_{yz} = 0$, and we find Eqs. (20) to (22):

$$\ddot{\mathbf{x}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right) - 2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda) = -2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda), \tag{20}$$

$$\ddot{\mathbf{y}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right) - 2\dot{x}'\omega\sin\lambda = -2\dot{x}'\omega\sin\lambda, \tag{21}$$

$$\ddot{\mathbf{z}}' = \left(\frac{1}{\rho}\left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right) - g\right) + 2\dot{x}'\omega\cos\lambda = \frac{\sigma_o}{\rho} - g + 2\dot{x}'\omega\cos\lambda. \tag{22}$$

We can integrate once concerning t to get the component of velocity, and we find, as shown in Eqs. (23) to (25):

$$\dot{\mathbf{x}}' = \dot{x_o}' - 2\omega(z'\cos\lambda - y'\sin\lambda), \tag{23}$$

$$\dot{\mathbf{y}}' = \dot{y_o}' - 2x'\omega\sin\lambda, \tag{24}$$

$$\dot{\mathbf{z}}' = \dot{z_o}' + \left(\frac{\sigma_o}{\rho} - g\right)t + 2x'\omega\cos\lambda. \tag{25}$$

Then substitute $\dot{\mathbf{z}}'$ and $\dot{\mathbf{y}}'$ into Eq. (20), we find Eqs. (26) and (27):

$$\ddot{\mathbf{x}}' = -2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda) = -2\omega\left(\left[\dot{z_o}' + \left(\frac{\sigma_o}{\rho} - g\right)t + 2x'\omega\cos\lambda\right]\cos\lambda - [\dot{y_o}' - 2x'\omega\sin\lambda]\sin\lambda\right), \tag{26}$$

$$\begin{aligned}\ddot{\mathbf{x}}' &= -2\omega\left(\left[\dot{z_o}' + \left(\frac{\sigma_o}{\rho} - g\right) + 2x'\omega\cos\lambda\right]\cos\lambda - [\dot{y_o}' - 2x'\omega\sin\lambda]\sin\lambda\right) \\ &\cong -2\omega\dot{z_o}'\cos\lambda - 2\omega\left(\frac{\sigma_o}{\rho} - g\right)t\cos\lambda + 2\omega\dot{y_o}'\sin\lambda \\ &= 2\omega\left(g - \frac{\sigma_o}{\rho}\right)t\cos\lambda - 2\omega(\dot{z_o}'\cos\lambda - \dot{y_o}'\sin\lambda).\end{aligned} \tag{27}$$

We integrate Eq. (27) again to get $\dot{x}'$, as shown in Eq. (28) and Eq. (29):

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$$\int d\dot{x}' = \int \left[2\omega\left(g - \frac{\sigma_o}{\rho}\right) t\cos\lambda - 2\omega(\dot{z_o}'\cos\lambda - \dot{y_o}'\sin\lambda)\right] dt, \tag{28}$$

$$\dot{x}' = \omega\left(g - \frac{\sigma_o}{\rho}\right) t^2\cos\lambda - 2\omega t(\dot{z_o}'cos\lambda - \dot{y_o}'\sin\lambda) + \dot{x_o}', \tag{29}$$

and finally, we find x' by integrating Eq. (29):

$$x' = \frac{\omega\left(g - \frac{\sigma_o}{\rho}\right) t^3}{3}\cos\lambda - \omega t^2(\dot{z_o}'\cos\lambda - \dot{y_o}'\sin\lambda) + \dot{x_o}'t + x_o'. \tag{30}$$

Then substitute Eq.(30) into Eqs. (24) and (25), we find Eqs. (31) and (32):

$$\begin{aligned}\dot{\mathbf{y}}' &= \dot{y_o}' - 2x'\omega\sin\lambda \\ &= \dot{y_o}' - 2\left(\frac{\omega g t^3}{3}\cos\lambda - \omega t^2(\dot{z_o}'\cos\lambda - \dot{y_o}'\sin\lambda) + \dot{x_o}'t + x_o'\right)\omega\sin\lambda \\ &\cong \dot{y_o}' - 2(\dot{x_o}'t\omega\sin\lambda + x_o'\omega\sin\lambda)\end{aligned} \tag{31}$$

$$\begin{aligned}\dot{z}' &= \dot{z_o}' + \left(\frac{\sigma_o}{\rho} - g\right)t + 2x'\omega\cos\lambda = \dot{z_o}' + \left(\frac{\sigma_o}{\rho} - g\right)t \\ &+2\left(\frac{\omega\left(g - \frac{\sigma_o}{\rho}\right)t^3}{3}\cos\lambda - \omega t^2(\dot{z_o}'\cos\lambda - \dot{y_o}'\sin\lambda) + \dot{x_o}'t\right)\omega\cos\lambda.\end{aligned} \tag{32}$$

As a result of integrating Eqs. (31) and (32), the positions, y' and z', are given by:

$$\begin{aligned}y' &= \dot{y_o}'t - 2\left(\frac{\dot{x_o}'t^2}{2}\omega\sin\lambda + x_o't\omega\sin\lambda\right) + y_o' = y_o' + \dot{y_o}'t - \dot{x_o}'t^2\omega\sin\lambda - 2x_o't\omega\sin\lambda \\ &\approx y_o' + \dot{y_o}'t - 2x_o't\omega\sin\lambda,\end{aligned} \tag{33}$$

$$\begin{aligned}z' &= \dot{z_o}'t + z_o + \omega\cos\lambda\dot{x_o}'t^2 + \frac{1}{2}\left(\frac{\sigma_o}{\rho} - g\right)t^2 \\ &= \dot{z_o}'t + \left(\omega^2 r_o'\cos\lambda + \frac{1}{2}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2 + z_o.\end{aligned} \tag{34}$$

According to some scientists [19, 20], a tornado is a dangerous natural event that occurs on an insignificant scale and persists for only a few minutes. Assuming that $y_o' + \dot{y_o}'t = r_o'$, $x_o' = \dot{x_o}t = r_o'\omega t$, and $\dot{x_o} = \dot{y_o} = \dot{z_o} = r_o'\omega$, $\dot{r_o}$ is so small at a very short time, we get Eqs. (35) and (36):

$$\begin{aligned}x' &= \frac{\omega g t^3}{3}\cos\lambda - \omega t^2(\dot{z_o}'\cos\lambda - \dot{y_o}'\sin\lambda) + \dot{x_o}'t \\ &= \frac{\omega g t^3}{3}\cos\lambda - \omega t^2(\dot{z_o}'\cos\lambda - \dot{y_o}'\sin\lambda) + r_o'\omega t \approx r_o'\omega t,\end{aligned} \tag{35}$$

$$y' = r_o' - 2r_o'\omega^2t^2\sin\lambda = r_o'(1 - 2\sin\lambda\omega^2t^2) = r\left(1 - \frac{(\omega t)^2}{2}\right) = r_o'\cos(\omega t). \tag{36}$$

Which requires that $2\sin\lambda = \frac{1}{2}$ or $\sin\lambda = \frac{1}{4}$ or $\lambda \approx 15°$ (that is near the Equator), we find:

$$x' = r_o'\,\omega t = r_o'\sin(\omega t), \tag{37}$$

$$y' = r_o'\cos(\omega t), \tag{38}$$

$$z' = \dot{z_o}'t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\cos\lambda + z_o$$
$$= r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\cos\lambda. \quad (39)$$

From Eqs. (37) to (39), we get Eqs. (40) to (42):

$$x' = r_o'\sin(\omega t) = r_o'\cos(90^o - \omega t), \quad (40)$$
$$y' = r_o'\cos(\omega t) = r_o'\sin(90^o - \omega t), \quad (41)$$
$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\cos\lambda. \quad (42)$$

Assuming that $r_o' = \dot{r_o}'t$, and ignoring the effects of gravitational force and humidity, and using the equation of state, we obtain Eqs. (43) to (45):

$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho}\right)\right)t^2\cos\lambda, \quad (43)$$
$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{1}{\rho}\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2\cos\lambda, \quad (44)$$
$$z' = \dot{r_o}'t^2 + \left(\omega^2 + \frac{1}{2\rho\cos\lambda}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2\cos\lambda. \quad (45)$$

According to [21], in the condition of a static atmosphere, we can write $\frac{\partial\sigma_{zz}}{\partial z} = \frac{\partial(R\rho T)}{\partial z}$. The density ρ and pressure of the air σ_{zz} in Eq (44) vary with height z. These changes can be calculated from the equation of state; we obtain:

$$\frac{d(\sigma_{zz})}{dz} = R\rho\frac{\partial(T)}{\partial z} + RT\frac{\partial(\rho)}{\partial z}, \quad (46)$$
$$\frac{d(\sigma_{zz})}{dz} = \frac{R\rho T}{T}\frac{\partial(T)}{\partial z} + R\rho T\frac{1}{\rho}\frac{\partial(\rho)}{\partial z}, \quad (47)$$
$$\frac{1}{\sigma_{zz}}\frac{d(\sigma_{zz})}{dz} = \frac{1}{T}\frac{\partial(T)}{\partial z} + \frac{1}{\rho}\frac{\partial(\rho)}{\partial z}, \quad (48)$$

where T is an absolute temperature, and R is the specific gas constant of dry air. In Eq. (48), the density ρ and T vary with altitude, and assuming that $\frac{1}{\sigma_{zz}}\frac{d(\sigma_{zz})}{dz} = \frac{1}{2\rho}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)$, then we obtain the position z', which indicates the height of tornadoes as shown in Eq. (49):

$$z' = \dot{z_o}'t + \left(\omega^2\cos\lambda + \frac{1}{2\rho}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2 = r_o'\omega t + \left(\omega^2\cos\lambda + \left(\frac{1}{T}\frac{\partial(T)}{\partial z} + \frac{1}{\rho}\frac{\partial(\rho)}{\partial z}\right)\right)t^2. \quad (49)$$

where $2\rho = \sigma_{zz}$ is related to tornado pressure.

2.2. Tornado simulation using numerical modeling

In the present research, we generated a model utilizing computational modeling that numerous researchers have performed on tornado characteristics [20, 21, 10, 11]. In this research, Eqs. (40), (41), and (49) address the difficulty of mathematically expressing positions in three dimensions when simulating tornado formation. Eqs. (29), (31), and (32) provide solutions to the difficulty of mathematically describing the velocity of the wind in growing tornadoes. In our research, MATLAB code was created to model tornado motion in two-dimensional and three-dimensional positions to explain tornado formation utilizing Eqs. (40), (41), and (49).

3. Results and discussions

Fig. 2 shows a two-dimensional model of a tornado with the velocity of the wind varying to the west and north throughout the same period. Modeling results show that the greater the wind velocity to the north and west, the larger the region of the tornado movement. The simulation findings reveal that the tornado's area of rotation is affected by the velocity of the wind, tornado time, and earth rotational speed. The tornado may rotate and require Coriolis force to move.

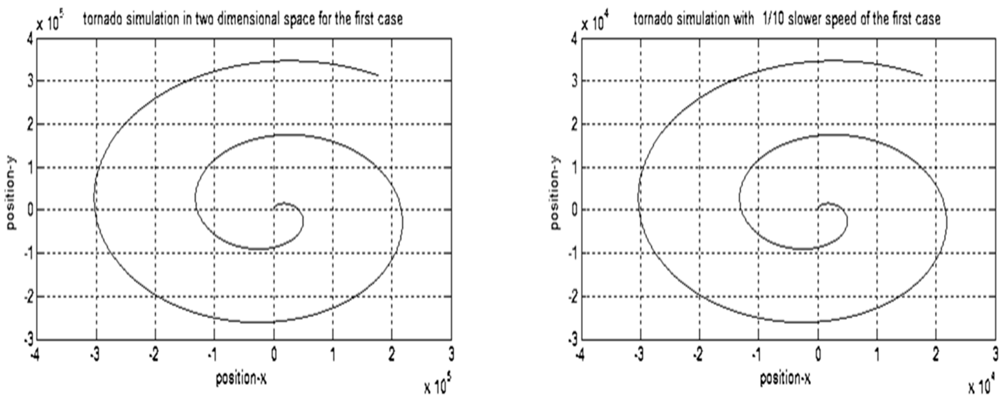

Fig. 2. Two-dimensional simulation of a tornado with wind speed variations

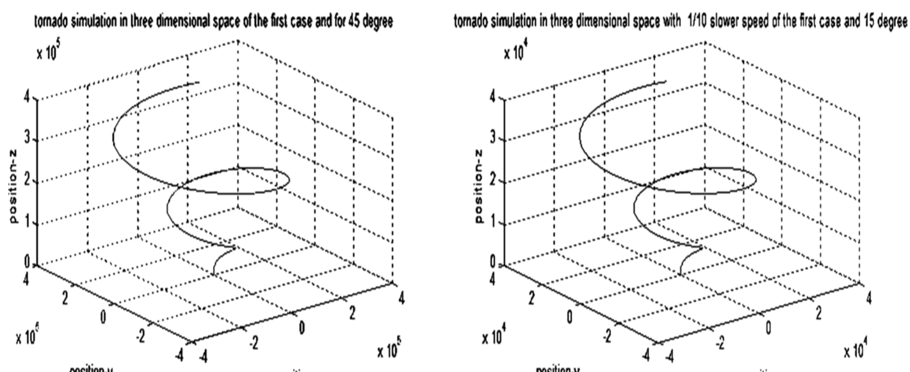

Fig. 3. Three-dimensional simulation of a tornado with wind speed and geocentric latitude variations

Fig. 3 shows a three-dimensional simulation of a tornado with variations in wind speed to the west and north over the same period and geocentric latitude variations of 45 degrees and 15 degrees. Fig. 4 shows a tornado at Mount Kencana, Banten, Indonesia, where a tornado appears when there is a change in temperature and high density, as well as a high wind rotation. Based on Fig. 3 and Fig. 4, we found a strong correlation between tornado height, air density and temperature, geocentric latitude, and initial speed, as shown in Eq. (49). As a result of our investigation and model results, we find that tornadoes have a low-pressure area with an increasing-pressure core. Research shows that this model can describe the spiraling upward motion of air within a tornado's path without including vertical convection. In addition to high airspeeds in the upper atmosphere, geocentric latitude, and the Coriolis effect, higher atmospheric pressure also contributes to tornadoes. According to some researchers [2, 4, 10, 11, 14], tornadoes in the Northern Hemisphere move clockwise, which is consistent with our model at 45 degrees and 15 degrees. However, in the Southern Hemisphere, tornadoes normally move in the opposite direction or counterclockwise. As a result of the rotation of the Earth, the Coriolis effect deflects wind directions. Thus, the direction of a tornado's motion is determined by which hemisphere it occurs in.

Fig. 4. Tornado in Gunung kencana, Banten, Indonesia [1]

The problem of mathematically expressing places in three-dimensional space when simulating tornado formation is addressed by Eqs (40), (41), and (49). Eqs. (29), (31), and (32) provide solutions to the difficulty of mathematically describing wind velocity in forming tornadoes. The modeling results demonstrate that the higher the geocentric latitude angle, the more likely a tornado will form. This research suggests that huge tornadoes can form in places with high geocentric latitudes. In this study, we discovered the equation for the motion of a tornado in three-dimensional coordinates, as shown in Eqs. (17) through (19).

Our findings revealed a strong relation involving tornado height and changes in air density and temperature, as well as geocentric latitude and beginning speed, as given in Eq. (49). Our investigation and model results validate various academics' claims that a low-pressure area with an increasing-pressure core characterizes tornadoes. Tornadoes require Coriolis force for movement. As a result, storms are uncommon in tropical regions and rarely cross the Equator, and this study confirms prior observations [14-18]. According to the research, this model could describe the spiraling upward motion of air in a tornado's path without incorporating vertical convection. This model revealed no differences with experts' opinions that certain variables can cause tornadoes. Tornadoes are created by various elements, including geocentric latitude, the Coriolis effect, higher airspeed in the upper atmosphere, and higher atmospheric pressure [14-18]. The airflow characteristics of a tornado can be calculated by calculating the 3-D and mathematical models of airflow motion and the Earth's rotation in three-dimensional (3D) space. This research provides a basic 2D and 3D model to generate a tornado-like vortex using simple modeling and calculation. This research's scientific applicability is that professionals and scientific experts can utilize the models to study tornadoes more easily. The results of 2-D modeling and simulation indicated that the greater the initial tornado angular speed, the larger the tornado area. Three-dimensional modeling and simulation also show that tornadoes are more powerful at higher geocentric latitude angles.

4. Conclusions

This research reported a theoretical formulation of tornadoes in a non-inertial mechanics framework, utilizing fluid mechanics and numerical simulation. This model depicted the spiraling upward motion of air in a tornado while ignoring vertical convection. Several conditions were required for a tornado to occur, including geocentric latitude, the Coriolis effect, increased airspeed in the upper atmosphere, and increased air pressure. We calculated the airflow characteristics of a tornado and solved the three-dimensional position of the tornado or hurricane in three-dimensional (3D) space, as well as the differential equations of airflow velocity and the Earth's rotation. To demonstrate tornado patterns, motion dynamics modeling, and numerical computations were performed using computer software. The study concluded that this model could explain tornado patterns. Using the modeling and simulation data from this work, practitioners and scientists can gain a better understanding of hurricanes. To obtain more precise models, we proposed that additional studies be performed utilizing various methodologies, such as quantum neural networks / QNNs and artificial neural networks in future research.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Valentinus Galih Vidia Putra and Mustamina Maulani conducted the simulations and the calculations. Valentinus Galih Vidia Putra and Mustamina Maulani wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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Tensor analysis of tornadoes: a new analytical and numerical model

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Tensor analysis of tornadoes: a new analytical and numerical model

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Abstract. This research proposes a new mathematical formulation of tornadoes based on the theory of tensor analysis and simulation in a non-inertial dynamics framework, both in two and three dimensions. This model may show the spherical upward movement of air in a tornado without taking into account vertical convection. A tornado requires several elements, including geocentric latitude, the Coriolis effect, increased airspeed in the upper atmosphere, and increased air pressure. Computing the three-dimensional location of the tornado or hurricane, as well as the mathematical models of airflow motion and the Earth's rotation in three-dimensional (3D) space, can determine a tornado's airflow characteristics. To show tornado patterns, we employed computer software that computed motion dynamics and did numerical computations. The results of 2-D modeling and simulation indicated that the greater the initial tornado angular speed, the larger the tornado area. Three-dimensional modeling and simulation also show that tornadoes are more powerful at higher geocentric latitude angles. The novelty of this study is that this model can be used to explain tornado patterns. In our research, we combine tensor analysis, computational modeling, as well as 2D and 3D simulations for simulating tornadoes for the first time. The scientific application of this finding is that researchers at the Meteorology, Climatology, and Geophysics Agency will be able to analyze a tornado and geophysical phenomena more readily with simulations and models.

Keywords: tornado, coriolis effect, numerical model, computational dynamics.

1. Introduction

The Indonesian government is currently focusing on phenomena such as heat waves that have received attention, as well as tornadoes that have devastated various regions of Indonesia. A tornado hit Lebak Banten, Indonesia, on May 10, 2022. This incident caused damage to about 80 houses and schools. Tornadoes wreaked devastation in several districts of Lebak, Banten, resulting in losses of thousands of millions of rupiah. A tornado had also ripped across the Subang area the day before. The Regional Disaster Management Agency (BPBD) of Subang Regency claimed 21 locations were affected by the hurricane, with Cibogo and Subang Kota Districts suffering the most damage [1]. Tornado parameters must be studied due to their catastrophic impact. In recent years, physicists have employed computational physics and fluid mechanics to examine and model different natural processes, as well as material science [2-8]. Tornado investigation is an intriguing topic in Earth's atmosphere and geophysical sciences. Tornadoes are hazardous natural disasters that strike on a small scale and last only a few minutes. Actual tornado observations are difficult to collect [9]. Despite improvements in severe storm mathematical approaches, replicating and predicting small-scale tornadoes will remain difficult [2]. As a result, a computerized model has arisen as a way of studying and modeling tornadoes. Several researchers have been performed to simulate the tornado mechanism [2-4]. Scientists first used computational modeling to simulate tornadoes [10, 11]. Computation physics modeling, including artificial intelligence and numerical modeling, has various advantages over other forms of research approaches, including lower risk

[5-7], lower cost [12, 13], and the need for fewer experimental data [14-18]. Computational dynamics enables researchers to further accurately compute various tornado patterns, wind direction and speed, latitude, the impacts of Earth's rotation as well as Coriolis forces, and wind pressure to completely comprehend and model tornado formation. Tornadoes & wind patterns are examples of the Coriolis effect. A tornado is distinguished by a low-pressure region with rising pressure at its center. Tornadoes, which divert airflow from all directions, need the Coriolis force to circulate. As a result, hurricanes hardly form in tropical areas and never cross the Equator [19-21]. This study gives a simple 2D and 3D model for generating a tornado-like vortex utilizing an advanced model and computation using tensor analysis reported by various researchers [20, 22]. The scientific application of this finding is that researchers at the Meteorology, Climatology, and Geophysics Agency will be able to analyze a tornado and geophysical phenomena more readily with simulations and models [5, 23].

2. Research methods

2.1. Tornado mathematical model

The foundation of our work is the theoretical framework of variables used to describe motion. Eq. (1) expresses the acceleration in a fixed system in terms of location, speed, and acceleration in the rotating system:

$$a = \ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r', \tag{1}$$

where ω is the angular velocity, $\dot{\omega}$ is the time derivative of ω and r', $\dot{r}'$ and $\ddot{r}'$ are the position in the unit (m), velocity in the unit (m/s), and acceleration in the unit (m/s^2), respectively. In the case where the primed system undergoes both translation and rotation, we obtain general equations for transforming from a fixed to a moving and rotating system, as shown in Eq. (2). This comprises the generic equations for transforming a stationary system into a moving and rotating one:

$$a = \ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A. \tag{2}$$

After we have the motion equation in moving coordinates, we can write it as shown in Eqs. (3) to (6):

$$F = ma = m(\ddot{r}' + \dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A), \tag{3}$$
$$F - m(\dot{\omega} \times r' + 2\omega \times \dot{r}' + \omega \times \omega \times r' + A) = m\ddot{r}', \tag{4}$$
$$F - (m\dot{\omega} \times r' + 2m\omega \times \dot{r}' + m\omega \times (\omega \times r') + mA) = m\ddot{r}', \tag{5}$$
$$F - (F_{Eul} + F_{cor} + F_{cent} + F_t) = m\ddot{r}', \tag{6}$$

where F is the physical force, $F_{eul} = m\dot{\omega} \times r'$ is the Euler force, ω is the angular velocity, $F_{cor} = 2m\omega \times \dot{r}'$ is the Coriolis force, $F_{cent} = m\omega \times (\omega \times r')$ denotes the centrifugal force, and $F_t = mA$ denotes the force due to the translation of the coordinate system. The equation of motion in a moving system can be written as Eq. (7):

$$\sum F_{all} = m\ddot{r}' = \rho V \ddot{r}', \quad \sum f = \rho \ddot{r}', \tag{7}$$

where f is the total force per unit volume, ρ is the density of the particle with a certain mass, and $\ddot{r}'$ is the acceleration of the particle with a certain mass. We can extend the model by using Cauchy's equation in Eq. (8) and the generalized equation of motion in 3D movement proposed by [22] as in Eqs. (9) and (10):

$$\nabla \cdot \sigma + f_{tot} = \rho \ddot{r}', \tag{8}$$

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$$\nabla \cdot \sigma + f_g - (f_{Eul} + f_{cor} + f_{cent} + f_t) = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}'), \quad (9)$$

$$\nabla \cdot \sigma + f_g - f_{Eul} - f_{cor} - f_{cent} - f_t = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}'), \quad (10)$$

where f_{tot} is the total force per unit volume, f_g is the gravitational attraction force, ρ is the density of the particle with a certain mass, and σ is the stress tensor. Consider the Euler force $f_{Eul} = 0$, the force due to the translation of the coordinate system $f_t = 0$, and since the centrifugal force is so small compared to the other terms, we can neglect it. The equation of motion then becomes:

$$\begin{aligned}\left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} + \frac{\partial \sigma_{zx}}{\partial z}\right)\mathbf{i}' + \left(\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{zy}}{\partial z}\right)\mathbf{j}' + \left(\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}\right)\mathbf{k}' \\ - \rho g \mathbf{k}' - 2\rho(\omega_x \mathbf{i}' + \omega_y \mathbf{j}' + \omega_z \mathbf{k}') \times (\dot{x}'\mathbf{i}' + \dot{y}'\mathbf{j}' + \dot{z}'\mathbf{k}') = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}''),\end{aligned} \quad (11)$$

$$\begin{aligned}f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g \mathbf{k}' - 2\rho(\omega_x \mathbf{i}' + \omega_y \mathbf{j}' + \omega_z \mathbf{k}') \times (\dot{x}'\mathbf{i}' + \dot{y}'\mathbf{j}' + \dot{z}'\mathbf{k}') \\ = \rho(\ddot{x}' + \ddot{y}' + \ddot{z}'').\end{aligned} \quad (12)$$

To simplify the calculation of the model, it can be assumed that:

$$\begin{aligned}\left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} + \frac{\partial \sigma_{zx}}{\partial z}\right)\mathbf{i}' + \left(\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{zy}}{\partial z}\right)\mathbf{j}' + \left(\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}\right)\mathbf{k}' \\ = f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}',\end{aligned}$$

$$\omega_x \mathbf{i}' + \omega_y \mathbf{j}' + \omega_z \mathbf{k}' = (0\mathbf{i}' + \omega\cos\lambda \mathbf{j}' + \omega\sin\lambda \mathbf{k}'),$$

yield:

$$f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g \mathbf{k}' = \rho(\ddot{\mathbf{r}}') + 2\rho(\omega_x \mathbf{i}' + \omega_y \mathbf{j}' + \omega_z \mathbf{k}') \times (\dot{x}'\mathbf{i} + \dot{y}'\mathbf{j} + \dot{z}'\mathbf{k}), \quad (13)$$

$$f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g \mathbf{k}' = \rho(\ddot{\mathbf{r}}' + 2(0\mathbf{i}' + \omega\cos\lambda \mathbf{j}' + \omega\sin\lambda \mathbf{k}') \times (\dot{x}'\mathbf{i} + \dot{y}'\mathbf{j} + \dot{z}'\mathbf{k})). \quad (14)$$

We can write $g = \mathfrak{g} - \omega^2 R\cos\lambda$ because of the effect of Earth's rotation. Where $\mathfrak{g}$ denotes the actual gravitation acceleration, and $\omega^2 R\cos\lambda$ denotes the centripetal acceleration for the Earth's radius, R, and geocentric latitude, λ. In this study, we choose the coordinate axis $O'x'y'z'$ such that the z' is vertical, the x' axis to the east, and the y' axis points north. The coordinate axes for analyzing tornado motion can be shown in Fig. 1.

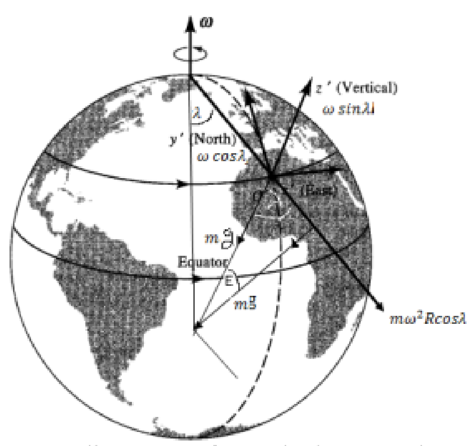

Fig. 1. Coordinate axes for analyzing tornado motion.

We also use $\omega_x = 0$, $\omega_y = \omega\cos\lambda$, and $\omega_z = \omega\sin\lambda$. Eq. (14) can be solved computationally, and we get Eqs. (15) and (16):

$$f_{px}\mathbf{i}' + f_{py}\mathbf{j}' + f_{pz}\mathbf{k}' - \rho g\mathbf{k}' = \rho\ddot{\mathbf{r}}' + 2\rho(\dot{z}'\omega\cos\lambda - \dot{y}'\omega\sin\lambda)\mathbf{i}' + 2\rho(\dot{x}'\omega\sin\lambda)\mathbf{j}' - 2\rho(\dot{x}'\omega\cos\lambda)\mathbf{k}', \tag{15}$$

$$\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right)\mathbf{i}' + \left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right)\mathbf{j}' + \left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right)\mathbf{k}' - \rho g\mathbf{k}' = \rho\ddot{\mathbf{r}}' + 2\rho(\dot{z}'\omega\cos\lambda - \dot{y}'\omega\sin\lambda)\mathbf{i}' + 2\rho(\dot{x}'\omega\sin\lambda)\mathbf{j}' - 2\rho(\dot{x}'\omega\cos\lambda)\mathbf{k}'. \tag{16}$$

We can solve Eq. (16); hence we find Eqs. (17) to (19):

$$\ddot{\mathbf{x}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right) - 2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda), \tag{17}$$

$$\ddot{\mathbf{y}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right) - 2\dot{x}'\omega\sin\lambda, \tag{18}$$

$$\ddot{\mathbf{z}}' = \left(\frac{1}{\rho}\left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right) - g\right) + 2\dot{x}'\omega\cos\lambda. \tag{19}$$

Assuming that $\frac{\partial\sigma_{zz}}{\partial z} = \frac{R\rho T}{T}\frac{\partial(T)}{\partial z} + \frac{R\rho T}{\rho}\frac{\partial(\rho)}{\partial z} = \sigma_o$, and $\sigma_{xx} = \sigma_{xy} = \sigma_{xz} = \sigma_{yy} = \sigma_{yz} = 0$, hence we get $e_{zz} = \frac{\sigma_{zz}}{E}$, $e_{yy} = -v\frac{\sigma_{zz}}{E}$, and $e_{xx} = -v\frac{\sigma_{zz}}{E}$, $e_{xy} = e_{xz} = e_{yz} = 0$, and we find Eqs. (20) to (22):

$$\ddot{\mathbf{x}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{yx}}{\partial y} + \frac{\partial\sigma_{zx}}{\partial z}\right) - 2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda) = -2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda), \tag{20}$$

$$\ddot{\mathbf{y}}' = \frac{1}{\rho}\left(\frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{zy}}{\partial z}\right) - 2\dot{x}'\omega\sin\lambda = -2\dot{x}'\omega\sin\lambda, \tag{21}$$

$$\ddot{\mathbf{z}}' = \left(\frac{1}{\rho}\left(\frac{\partial\sigma_{xz}}{\partial x} + \frac{\partial\sigma_{yz}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}\right) - g\right) + 2\dot{x}'\omega\cos\lambda = \frac{\sigma_o}{\rho} - g + 2\dot{x}'\omega\cos\lambda. \tag{22}$$

We can integrate once concerning t to get the component of velocity, and we find, as shown in Eqs. (23) to (25):

$$\dot{\mathbf{x}}' = \dot{x}_o' - 2\omega(z'\cos\lambda - y'\sin\lambda), \tag{23}$$

$$\dot{\mathbf{y}}' = \dot{y}_o' - 2x'\omega\sin\lambda, \tag{24}$$

$$\dot{\mathbf{z}}' = \dot{z}_o' + \left(\frac{\sigma_o}{\rho} - g\right)t + 2x'\omega\cos\lambda. \tag{25}$$

Then substitute $\dot{\mathbf{z}}'$ and $\dot{\mathbf{y}}'$ into Eq. (20), we find Eqs. (26) and (27):

$$\ddot{\mathbf{x}}' = -2\omega(\dot{z}'\cos\lambda - \dot{y}'\sin\lambda) = -2\omega\left(\left[\dot{z}_o' + \left(\frac{\sigma_o}{\rho} - g\right)t + 2x'\omega\cos\lambda\right]\cos\lambda - [\dot{y}_o' - 2x'\omega\sin\lambda]\sin\lambda\right), \tag{26}$$

$$\ddot{\mathbf{x}}' = -2\omega\left(\left[\dot{z}_o' + \left(\frac{\sigma_o}{\rho} - g\right) + 2x'\omega\cos\lambda\right]\cos\lambda - [\dot{y}_o' - 2x'\omega\sin\lambda]\sin\lambda\right) \cong -2\omega\dot{z}_o'\cos\lambda - 2\omega\left(\frac{\sigma_o}{\rho} - g\right)t\cos\lambda + 2\omega\dot{y}_o'\sin\lambda = 2\omega\left(g - \frac{\sigma_o}{\rho}\right)t\cos\lambda - 2\omega(\dot{z}_o'\cos\lambda - \dot{y}_o'\sin\lambda). \tag{27}$$

We integrate Eq. (27) again to get $\dot{x}'$, as shown in Eq. (28) and Eq. (29):

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$$\int d\dot{x}' = \int \left[2\omega\left(g - \frac{\sigma_o}{\rho}\right) t\cos\lambda - 2\omega(\dot{z}_o{}'\cos\lambda - \dot{y}_o{}'\sin\lambda)\right] dt, \tag{28}$$

$$\dot{x}' = \omega\left(g - \frac{\sigma_o}{\rho}\right) t^2\cos\lambda - 2\omega t(\dot{z}_o{}'\cos\lambda - \dot{y}_o{}'\sin\lambda) + \dot{x}_o{}', \tag{29}$$

and finally, we find x' by integrating Eq. (29):

$$x' = \frac{\omega\left(g - \frac{\sigma_o}{\rho}\right) t^3}{3}\cos\lambda - \omega t^2(\dot{z}_o{}'\cos\lambda - \dot{y}_o{}'\sin\lambda) + \dot{x}_o{}'t + x_o'. \tag{30}$$

Then substitute Eq.(30) into Eqs. (24) and (25), we find Eqs. (31) and (32):

$$\begin{aligned} \dot{\mathbf{y}}' &= \dot{y}_o{}' - 2x'\omega\sin\lambda \\ &= \dot{y}_o{}' - 2\left(\frac{\omega g t^3}{3}\cos\lambda - \omega t^2(\dot{z}_o{}'\cos\lambda - \dot{y}_o{}'\sin\lambda) + \dot{x}_o{}'t + x_o{}'\right)\omega\sin\lambda \\ &\cong \dot{y}_o{}' - 2(\dot{x}_o{}'t\omega\sin\lambda + x_o{}'\omega\sin\lambda) \end{aligned} \tag{31}$$

$$\begin{aligned} \dot{z}' &= \dot{z}_o{}' + \left(\frac{\sigma_o}{\rho} - g\right)t + 2x'\omega\cos\lambda = \dot{z}_o{}' + \left(\frac{\sigma_o}{\rho} - g\right)t \\ &+2\left(\frac{\omega\left(g - \frac{\sigma_o}{\rho}\right)t^3}{3}\cos\lambda - \omega t^2(\dot{z}_o{}'\cos\lambda - \dot{y}_o{}'\sin\lambda) + \dot{x}_o{}'t\right)\omega\cos\lambda. \end{aligned} \tag{32}$$

As a result of integrating Eqs. (31) and (32), the positions, y' and z', are given by:

$$\begin{aligned} y' &= \dot{y}_o{}'t - 2\left(\frac{\dot{x}_o{}'t^2}{2}\omega\sin\lambda + x_o{}'t\omega\sin\lambda\right) + y_o' = y_o' + \dot{y}_o{}'t - \dot{x}_o{}'t^2\omega\sin\lambda - 2x_o't\omega\sin\lambda \\ &\approx y_o' + \dot{y}_o{}'t - 2x_o't\omega\sin\lambda, \end{aligned} \tag{33}$$

$$\begin{aligned} z' &= \dot{z}_o{}'t + z_o + \omega\cos\lambda\dot{x}_o{}'t^2 + \frac{1}{2}\left(\frac{\sigma_o}{\rho} - g\right)t^2 \\ &= \dot{z}_o{}'t + \left(\omega^2 r_o'\cos\lambda + \frac{1}{2}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2 + z_o. \end{aligned} \tag{34}$$

According to some scientists [19, 20], a tornado is a dangerous natural event that occurs on an insignificant scale and persists for only a few minutes. Assuming that $y_o' + \dot{y}_o{}'t = r_o'$, $x_o' = \dot{x}_o t = r_o'\omega t$, and $\dot{x}_o = \dot{y}_o = \dot{z}_o = r_o'\omega$, r_o is so small at a very short time, we get Eqs. (35) and (36):

$$\begin{aligned} x' &= \frac{\omega g t^3}{3}\cos\lambda - \omega t^2(\dot{z}_o{}'\cos\lambda - \dot{y}_o{}'\sin\lambda) + \dot{x}_o{}'t \\ &= \frac{\omega g t^3}{3}\cos\lambda - \omega t^2(\dot{z}_o{}'\cos\lambda - \dot{y}_o{}'\sin\lambda) + r_o'\omega t \approx r_o'\omega t, \end{aligned} \tag{35}$$

$$y' = r_o' - 2r_o'\omega^2 t^2 \sin\lambda = r_o'(1 - 2\sin\lambda\omega^2 t^2) = r\left(1 - \frac{(\omega t)^2}{2}\right) = r_o' \cos(\omega t). \tag{36}$$

Which requires that $2\sin\lambda = \frac{1}{2}$ or $\sin\lambda = \frac{1}{4}$ or $\lambda \approx 15°$ (that is near the Equator), we find:

$$x' = r_o'\,\omega t = r_o' \sin(\omega t), \tag{37}$$

$$y' = r_o' \cos(\omega t), \tag{38}$$

$$z' = \dot{z_o}'t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\cos\lambda + z_o$$
$$= r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\cos\lambda. \quad (39)$$

From Eqs. (37) to (39), we get Eqs. (40) to (42):

$$x' = r_o'\sin(\omega t) = r_o'\cos(90^o - \omega t), \quad (40)$$
$$y' = r_o'\cos(\omega t) = r_o'\sin(90^o - \omega t), \quad (41)$$
$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho} - g\right)\right)t^2\cos\lambda. \quad (42)$$

Assuming that $r_o' = \dot{r_o}'t$, and ignoring the effects of gravitational force and humidity, and using the equation of state, we obtain Eqs. (43) to (45):

$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{\sigma_o}{\rho}\right)\right)t^2\cos\lambda, \quad (43)$$
$$z' = r_o'\,\omega t + \left(\omega^2 + \frac{1}{2\cos\lambda}\left(\frac{1}{\rho}\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2\cos\lambda, \quad (44)$$
$$z' = \dot{r_o}'t^2 + \left(\omega^2 + \frac{1}{2\rho\cos\lambda}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2\cos\lambda. \quad (45)$$

According to [21], in the condition of a static atmosphere, we can write $\frac{\partial\sigma_{zz}}{\partial z} = \frac{\partial(R\rho T)}{\partial z}$. The density ρ and pressure of the air σ_{zz} in Eq (44) vary with height z. These changes can be calculated from the equation of state; we obtain:

$$\frac{d(\sigma_{zz})}{dz} = R\rho\frac{\partial(T)}{\partial z} + RT\frac{\partial(\rho)}{\partial z}, \quad (46)$$
$$\frac{d(\sigma_{zz})}{dz} = \frac{R\rho T}{T}\frac{\partial(T)}{\partial z} + R\rho T\frac{1}{\rho}\frac{\partial(\rho)}{\partial z}, \quad (47)$$
$$\frac{1}{\sigma_{zz}}\frac{d(\sigma_{zz})}{dz} = \frac{1}{T}\frac{\partial(T)}{\partial z} + \frac{1}{\rho}\frac{\partial(\rho)}{\partial z}, \quad (48)$$

where T is an absolute temperature, and R is the specific gas constant of dry air. In Eq. (48), the density ρ and T vary with altitude, and assuming that $\frac{1}{\sigma_{zz}}\frac{d(\sigma_{zz})}{dz} = \frac{1}{2\rho}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)$, then we obtain the position z', which indicates the height of tornadoes as shown in Eq. (49):

$$z' = \dot{z_o}'t + \left(\omega^2\cos\lambda + \frac{1}{2\rho}\left(\frac{\partial\sigma_{zz}}{\partial z}\right)\right)t^2 = r_o'\omega t + \left(\omega^2\cos\lambda + \left(\frac{1}{T}\frac{\partial(T)}{\partial z} + \frac{1}{\rho}\frac{\partial(\rho)}{\partial z}\right)\right)t^2. \quad (49)$$

where $2\rho = \sigma_{zz}$ is related to tornado pressure.

2.2. Tornado simulation using numerical modeling

In the present research, we generated a model utilizing computational modeling that numerous researchers have performed on tornado characteristics [20, 21, 10, 11]. In this research, Eqs. (40),

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(41), and (49) address the difficulty of mathematically expressing positions in three dimensions when simulating tornado formation. Eqs. (29), (31), and (32) provide solutions to the difficulty of mathematically describing the velocity of the wind in growing tornadoes. In our research, MATLAB code was created to model tornado motion in two-dimensional and three-dimensional positions to explain tornado formation utilizing Eqs. (40), (41), and (49).

3. Results and discussions

Fig. 2 shows a two-dimensional model of a tornado with the velocity of the wind varying to the west and north throughout the same period. Modeling results show that the greater the wind velocity to the north and west, the larger the region of the tornado movement. The simulation findings reveal that the tornado's area of rotation is affected by the velocity of the wind, tornado time, and earth rotational speed. The tornado may rotate and require Coriolis force to move.

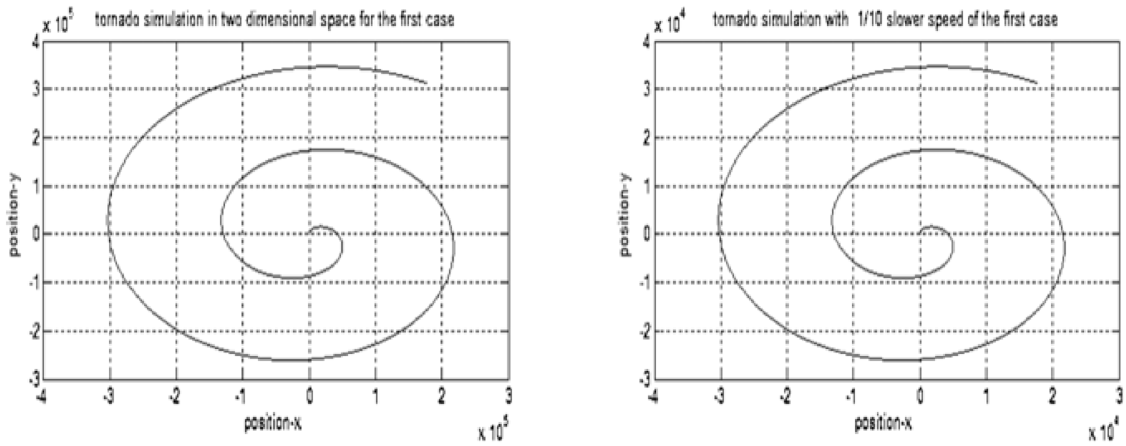

Fig. 2. Two-dimensional simulation of a tornado with wind speed variations

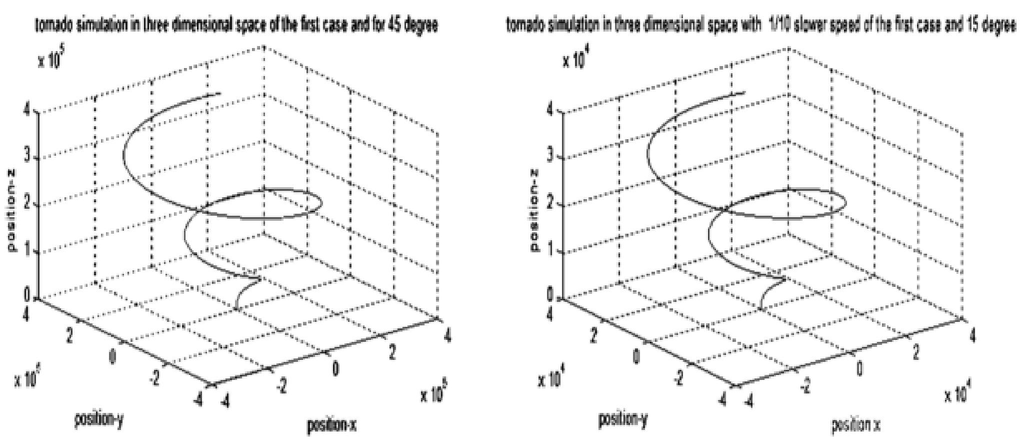

Fig. 3. Three-dimensional simulation of a tornado with wind speed and geocentric latitude variations

Fig. 3 shows a three-dimensional simulation of a tornado with variations in wind speed to the west and north over the same period and geocentric latitude variations of 45 degrees and 15 degrees. Fig. 4 shows a tornado at Mount Kencana, Banten, Indonesia, where a tornado appears when there is a change in temperature and high density, as well as a high wind rotation. Based on Fig. 3 and Fig. 4, we found a strong correlation between tornado height, air density and temperature, geocentric latitude, and initial speed, as shown in Eq. (49). As a result of our investigation and model results, we find that tornadoes have a low-pressure area with an increasing-pressure core. Research shows that this model can describe the spiraling upward motion of air within a tornado's path without including vertical convection. In addition to high airspeeds in the upper atmosphere, geocentric latitude, and the Coriolis effect, higher atmospheric pressure also contributes to tornadoes. According to some researchers [2, 4, 10, 11, 14], tornadoes in the Northern Hemisphere move clockwise, which is consistent with our model at 45 degrees and 15 degrees. However, in the Southern Hemisphere, tornadoes normally move in the opposite direction or counterclockwise. As a result of the rotation of the Earth, the Coriolis effect deflects wind directions. Thus, the direction of a tornado's motion is determined by which hemisphere it occurs in.

Fig. 4. Tornado in Gunung kencana, Banten, Indonesia [1]

The problem of mathematically expressing places in three-dimensional space when simulating tornado formation is addressed by Eqs (40), (41), and (49). Eqs. (29), (31), and (32) provide solutions to the difficulty of mathematically describing wind velocity in forming tornadoes. The modeling results demonstrate that the higher the geocentric latitude angle, the more likely a tornado will form. This research suggests that huge tornadoes can form in places with high geocentric latitudes. In this study, we discovered the equation for the motion of a tornado in three-dimensional coordinates, as shown in Eqs. (17) through (19).

Our findings revealed a strong relation involving tornado height and changes in air density and temperature, as well as geocentric latitude and beginning speed, as given in Eq. (49). Our investigation and model results validate various academics' claims that a low-pressure area with an increasing-pressure core characterizes tornadoes. Tornadoes require Coriolis force for movement. As a result, storms are uncommon in tropical regions and rarely cross the Equator, and this study confirms prior observations [14-18]. According to the research, this model could describe the spiraling upward motion of air in a tornado's path without incorporating vertical convection. This model revealed no differences with experts' opinions that certain variables can cause tornadoes. Tornadoes are created by various elements, including geocentric latitude, the Coriolis effect, higher airspeed in the upper atmosphere, and higher atmospheric pressure [14-18]. The airflow characteristics of a tornado can be calculated by calculating the 3-D and mathematical models of airflow motion and the Earth's rotation in three-dimensional (3D) space. This research provides a basic 2D and 3D model to generate a tornado-like vortex using simple modeling and calculation. This research's scientific applicability is that professionals and scientific experts can utilize the models to study tornadoes more easily. The results of 2-D modeling and simulation indicated that the greater the initial tornado angular speed, the larger the tornado area. Three-dimensional modeling and simulation also show that tornadoes are more powerful at higher geocentric latitude angles.

4. Conclusions

This research reported a theoretical formulation of tornadoes in a non-inertial mechanics framework, utilizing fluid mechanics and numerical simulation. This model depicted the spiraling

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upward motion of air in a tornado while ignoring vertical convection. Several conditions were required for a tornado to occur, including geocentric latitude, the Coriolis effect, increased airspeed in the upper atmosphere, and increased air pressure. We calculated the airflow characteristics of a tornado and solved the three-dimensional position of the tornado or hurricane in three-dimensional (3D) space, as well as the differential equations of airflow velocity and the Earth's rotation. To demonstrate tornado patterns, motion dynamics modeling, and numerical computations were performed using computer software. The study concluded that this model could explain tornado patterns. Using the modeling and simulation data from this work, practitioners and scientists can gain a better understanding of hurricanes. To obtain more precise models, we proposed that additional studies be performed utilizing various methodologies, such as quantum neural networks / QNNs and artificial neural networks in future research.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Valentinus Galih Vidia Putra and Mustamina Maulani conducted the simulations and the calculations. Valentinus Galih Vidia Putra and Mustamina Maulani wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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