Exploring the TROPHY Tropical Cyclone Tracking Framework

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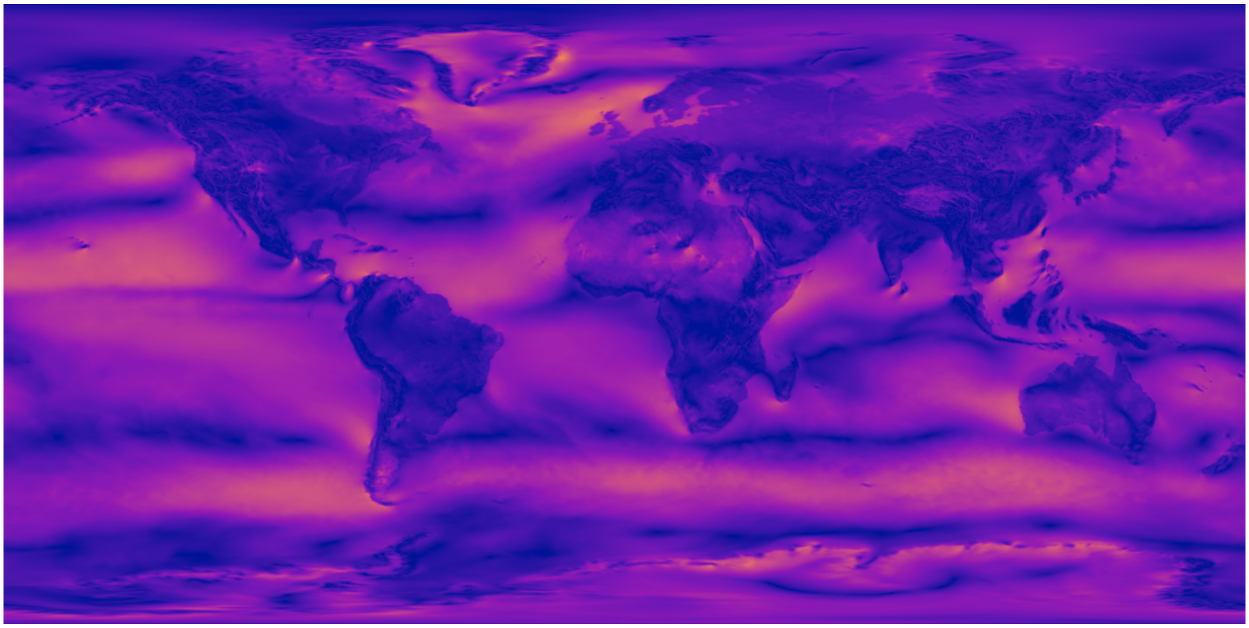

Fig. 1: Global Winds: 10-100m u/v-components of wind, 2020-23 (monthly averaged reanalysis).

Abstract—Tropical cyclones are among the most devastating natural disasters, capable of causing extensive damage and loss of life. Early detection before landfall is crucial for saving thousands to millions of lives annually. In this report, we implemented the technique described in the article *TROPHY: A Topologically Robust Physics-Informed Tracking Framework for Tropical Cyclones* by Lin Yan et al., using historical wind data provided by NOAA. We converted this meteorological data into a format more suitable for computer science visualization. However, our limited experience with the GRIB file format posed significant challenges, as this format was not intended for our specific application. These challenges severely restricted our ability to perform additional computations on the data. Despite these obstacles, we visualized and identified critical points, effectively filtering out noise to detect the cyclone's eye. Although we aimed for a comprehensive conclusion, time constraints required us to narrow the project's scope in order to produce definite results.

Index Terms—Cyclone tracking, vector fields, topology

1 Introduction

Tropical Cyclones (TCs) are one of the most dangerous and devastating weather disasters in the world. According to NOAA, between 1980 and 2023, of the 363 billion dollar weather disasters, tropical cyclones have caused the most damage, with over $1.3 trillion dollars in damages [6]. Dollars aren't the only things that are affected by these massive natural disasters. People and their homes are lost. Family pets go missing. Priceless family heirlooms are lost or destroyed. Communities are devastated. Being able to detect these early would help alleviate some of this massive destruction. In order to spot them early, we must first be able to spot them. That is just what the TROPHY framework does.

A Topologically Robust Physics-Informed Tracking Framework (TROPHY), is just what it sounds like. Built by Lin Yan and colleagues, TROPHY was designed to realistically and efficiently detect and track TCs [8]. This helps locate and detect the movement of a TC before the human eye could spot on, saving precious time.

In this exploration, we attempt to incorporate the TROPHY framework into our own dataset. This proved to be more difficult than first thought, and without limited knowledge of meteorological studies, we were not able to complete this goal.

In this report, we discuss some of the previous work done on this topic, background information on the TROPHY framework, the results and evaluation of the work done, as well as the division of tasks.

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2 Previous Work

We look at related / previous work for both the TC tracking algorithms and the visualization process.

2.1 Reference Paper

This report was based on TROPHY: A Topologically Robust Physics-Informed Tracking Framework for Tropical Cyclones [8], a detailed article on the development and specifics behind the TROPHY framework. This article is where we gained most of our information for this project, such as...

- Global wind database

- TROPHY framework details
- Cyclone tracking algorithms
- Methods for evaluation

One thing to note with respect to this paper is that there is a heavy amount of meteorological information that can be hard to decipher without someone who specializes in the field. Because of this, we were not able to implement the entire TROPHY framework within this report. This will be discussed more later in this report.

2.2 File Format Workaround

To obtain workable data from the GRIB file format, we utilized a Python library called pygrib. Developed by Jeff Whitaker, pygrib "provides a high-level interface to the ECWMF ECCODES C library for reading GRIB files" [7]. This library enabled us to more efficiently manipulate the complex meteorological data into a format that was more suitable for our needs.

Initially, we encountered a steep learning curve due to the intricate nature of the GRIB format and our lack of prior experience. However, pygrib proved to be an invaluable tool, simplifying the process of data extraction and conversion. It allowed us to access and handle various meteorological parameters, such as wind speed and direction, pressure, and temperature, although it took some time to find a way to access all of these variables.

3 Background

We will review some of the background knowledge needed for parts of this report.

3.1 TROPHY Overview

As the overall TROPHY framework is well outside of the scope for this project, we will tone down the technical aspects of the framework. We still believe that is important to understand the basic idea behind the system.

To start, the feature tracking kit (FTK) is computed for the whole dataset and the classic robustness for the critical points. Then, the FTK tracks and the robustness of the critical points are used in the physics-informed feature selection. Following this, selected critical points are put through an adaptive-level strategy and are then integrated into the minimum multilevel robustness with the FTK to enhance the original FTK results. Finally, it is put through a stability filter function which highlights the cyclones.

3.2 Critical Point Importance

When locating a tropical cyclone via a 2D vector field, critical points play a key role in telling you where the eye of the cyclone is, thus telling you the location of the storm. For our case, we are looking at critical points $x \in \mathbb{X}$ in f where the vector vanishes. That being, $|f(x)| = 0$. As stated in the article by Yan et al. [8] "[a] critical point x can be classified w.r.t. its *degree* $\deg(x)$, defined as the number of field rotations while traveling along a closed curve counterclockwise surrounding x." For our application of this as well as that by Yan et al. we will be looking for a critical point with degree +1, that being a source/sink/center. This signifies the eye of the tropical cyclone, which pinpoints the middle of the storm, thus telling us right where it is.

3.3 Dataset

For this paper, we used the same data source as our reference: the ERA5 hourly single levels dataset from the Climate Data Store (CDS) [1]. The dataset, provided by the EU's Copernicus program and ECMWF, includes 10m u- and v-component winds for January 1–6, 2021, covering all times and the entire region. This dataset was used for all images in this report.

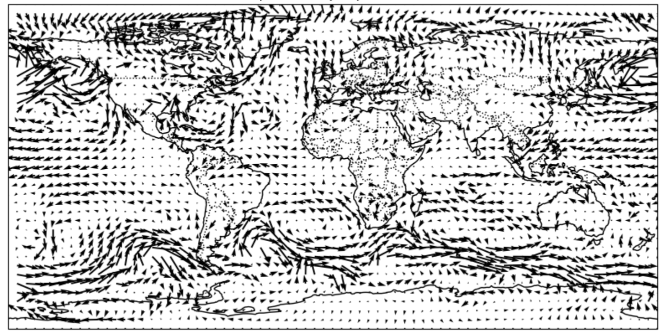


Fig. 2: A Global Map of Wind Vectors

3.4 The .grib File Format

Like in the article, this report is based on, we used historical wind data provided publicly by NOAA (The National Oceanic and Atmospheric Administration). According to NOAA, the GRIB file format is used by operational meteorological centers for stage and the exchange of gridded fields [5]. This file format works best for its main use – reporting specific meteorologic data regarding specific fields – not for our intended use – visualizing vector fields. For us, this has caused some issues; that mainly being time sink. Most of our time has been spent attempting to get this file format into something that we know how to work with, such as for this class, the .ply file format. Because of this, much of the TROPHY framework has become out of scope for us.

4 Results

After narrowing our focus, we concentrated on developing a global map of wind vectors using a specific dataset, shown in Fig. 2. The dataset—level 850 | time step 3 | January 1st, 2021, at 2:00 AM—provides a snapshot of wind direction and intensity at that moment. Using the Python script developed for this project, this type of visualization can be generated from any applicable dataset.

Once we achieved a functioning global map of wind vectors, our efforts shifted to enhancing its readability. Two primary issues with the initial maps became apparent:

- **Clarity for Specific Regions:** Visualizing the entire world made it difficult to discern details in specific areas.
- **Overcrowded Visuals:** On particularly windy days, large vector arrows sometimes overlap, causing the map to appear overwhelmingly dark.

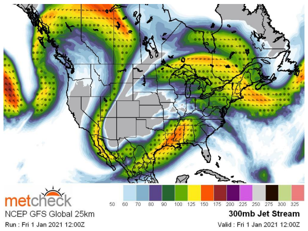
These challenges were mitigated in Fig. 2, where we deliberately selected a dataset that produced a more legible visualization.

To further enhance usability, we implemented an animation feature to show how wind vectors change over time. This dynamic visualization allows viewers to better understand both the direction and intensity of the winds and how these patterns evolve. Compared to static screenshots, animated maps provide greater insight into temporal changes, enabling more detailed inferences from the data.

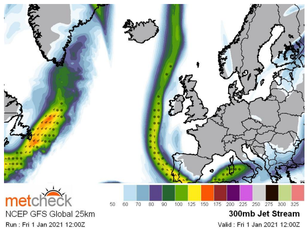
For example, animations make it easier to identify tropical cyclones. A static map might show a wind pattern resembling a cyclone, but without temporal context, viewers cannot confirm its behavior. With animation, the progression of the wind pattern over time can validate such observations.

5 Evaluation

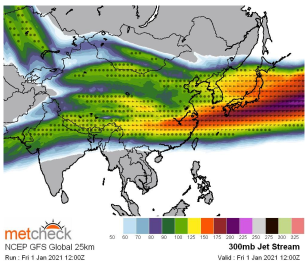
In order to evaluate the accuracy of our map, we decided to look at historical jet stream data and compare specific areas. Looking at Fig. 3, we see three different jet stream maps, each covering a different continent – those being North America, Europe, and Asia.



(a) Jet stream map over North America on the first of January, 2021 [2]



(b) Jet stream map over Europe on the first of January, 2021 [3]



(c) Jet stream map over Asia on the first of January, 2021 [4]

Fig. 3: Jet stream maps of North America, Europe and Asia on January 1st, 2021 [2–4]

5.1 North America

In North America, our map (Fig. 2) shows high wind speeds flowing north along California's coast, curving east into Canada, and eastward winds over the Great Lakes continuing up the eastern seaboard, aligning with Fig. 3a. However, differences emerge in the Gulf Coast, where the evaluation set shows strong northeast winds, while ours shows northward winds, and in the western states (Idaho to Arizona), where a southward wind stream in the evaluation set is absent in ours.

5.2 Europe

In Europe (Fig. 3b), the evaluation set captures northward winds originating from the eastern United States and Canada, transitioning into a southward flow from the east side of Iceland. This wind travels southward over Spain and Portugal and through the Strait of Gibraltar. Europe represents the most accurate region in our analysis, with only minor differences between the maps, none of which warrant specific mention.

5.3 Asia

The Asia evaluation (Fig. 3c) reveals the most discrepancies between the datasets. Both maps share a prominent pattern of eastward winds over China, Korea, and Japan. However, a key difference arises in the region between the Philippines and Vietnam, where our map shows a pronounced southwestward wind. This wind pattern is entirely absent from the evaluation set.

5.4 Discrepancies

Notable discrepancies between the datasets can be observed in all regions. While these differences do not necessarily indicate flaws in our data or visualization methods, it is important to consider potential reasons for their occurrence. One likely explanation is the use of different datasets. Our data was sourced from a publicly available NOAA dataset, whereas the provenance of the Metcheck data [2–4] remains uncertain. Variations in data collection methods could also significantly contribute to the observed differences.

5.5 Evaluation Recap

Overall, our visualization effectively captured the wind vector patterns present in our dataset. While discrepancies were observed, many key similarities reinforce the accuracy and reliability of our approach. The differences highlight the need for careful consideration of data sources and collection methodologies in comparative analyses.

6 Division of Tasks

We discuss the division of tasks within this assignment.

6.1 Seiji Koenigsberg's Tasks

- Research and learn how to visualize .grib file data
- Visualize the data from the .grib files
- Find ways to improve the visibility and readability of created maps

Comments: I spent considerable time researching the .grib file format and exploring various methods to parse the dataset. I came across pygrib, a Python library specifically designed for parsing .grib files, and used it to create a Python script. This script allows users to explore the different variables within a .grib file, extract wind vectors at various heights, times, and locations, and visualize these wind vectors. The visualization can be displayed either as a static snapshot for a specific time or as an animation showing changes in wind vectors over time. Additionally, I incorporated functionality to adjust the density of wind vectors on the visualization, ensuring the screen always displays a sufficient amount of detail.

6.2 Joshua Tumlinson's Tasks

- Organize and write report
- Perform evaluation of results
- Do background research on project topic

Comments: My main goal when it came to the coding aspect of this assignment was to get a basic version of the TROPHY framework up and running as well as getting a feature tracking kit working. Since most of our time was taken up with trying to find out how to work around the .grib file format, I changed my focus towards developing this document.

7 Conclusion

While we couldn't fully implement the TROPHY framework, we achieved a significant accomplishment: converting and visualizing GRIB data in a way that could potentially track tropical cyclones. Throughout the project, we faced challenges like file formatting issues and a steep learning curve with new coding libraries. Despite these obstacles and limitations, we created a detailed global wind flow visualization.

By leveraging the pygrib library, we overcame the inherent difficulties associated with the GRIB file format, enabling us to access and manipulate raw meteorological data more efficiently. This allowed us to generate a visualization that serves as a promising starting point for future projects. Although we did not achieve all our objectives, the experience provided us with valuable insights and foundational knowledge that will be beneficial for tackling future challenges.

Overall, despite the constraints imposed by time and technical difficulties, our work demonstrated the potential for advanced visualization techniques in cyclone tracking.

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