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# Tropical Cyclone Tracking with varying parameter thresholds

## Semester Thesis

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# Abstract

An existing algorithm for tracking tropical cyclones in ICON output was sped up. The increased speed was used in order to evaluate assumptions on characterizing parameters for TCs. These parameters were varied and the results compared.

# Chapter 1

## Introduction

1. DONE Tcs are relevant for society due to their changing intensity and more people living on the coast
2. They exhibit interesting physics (tiefdrucksysteme mit Warmcore)
3. They are studied analytically, with field experiments and with simulations
4. Here their climatology is analyzed by analyzing simulation data

Tropical cyclones also known as Hurricanes or Typhoons are storms of extreme nature in many regards. Not only are they the most deadly and expensive natural catastrophes in the United States but also their physics is quite challenging with many open questions remaining.[1] Finally they are very likely to play a crucial role in the global heat balance and moisture circulation.[2][3]

### 1.1 Impact on society

While tropical cyclones form and intensify above the ocean, they have the largest impact on society during landfall. The damage happens due to a combination of strong winds and catastrophic storm surges. On average hurricanes inflict normalized damages of about \$10-billion/year in the United States.[4] A single strong storm can cause thousands of deaths. Hurricane Katrina e.g. in 2005 took the lives of over 1200 people.[5] Due to these enormous implications for society and opportunities to save lives and money, active research is happening on tropical cyclone impact reduction. With an unsure impact of climate change on tropical cyclone frequency and intensity and a trend of urbanization on the American east-coast, improving the understanding of tropical cyclones is of great importance.

### 1.2 Underlying Physics

Tropical Cyclones can be classified using the Saffir-Simpson wind scale. It is defined by the maximum wind observed in the cyclone. Due to their characteristic structure this wind usually occurs at the eyewall. This choice is motivated by the strong correlation between wind speeds and the inflicted damages.[6] The exact categorization can be seen in table 1.1.

Their occurrence frequency is displayed in Fig. 1.1

Tropical Cyclones are rotating low pressure systems that exhibit a warm core. They rotate around a pressure minimum with low wind speeds which is enclosed by the eyewall which in turn is the radius of maximum wind. The rotation around the center happens in different bands of updraft that are alternated with rain bands. Finally the the warm updraft in the center cools down on its way to the top. Resulting in a cold outflow at the top of the storm. This structure is depicted in Fig. 1.2. In order for a storm to develop a number of TC genesis criteria have to be met. Not all of

Tropical Cyclones		Other tropical low pressure systems	
category	wind speed [m/s]	name	wind speed [m/s]
1	33–42	tropical depression	$\leq 17$
2	43–49	tropical storm	18–32
3	50–58		
4	58–70		
5	$\geq 70$		

Table 1.1: Simpson scale defined by 1-minute maximum sustained winds[6]

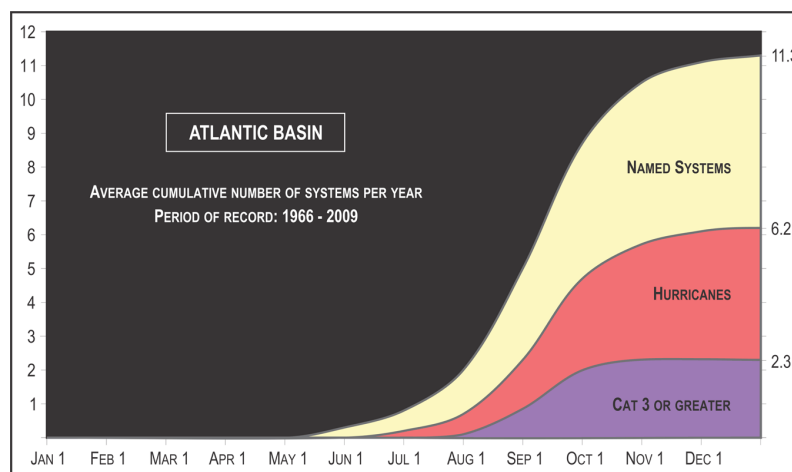


Figure 1.1: Average cumulative number of storms in the Atlantic. Named systems are mostly tropical storms but can also be tropical depressions.[7]

them have to be satisfied but they do offer a good indicator for the probability of storm formation. The criteria are as follows:

- sea surface temperature above  $26.5^{\circ}\text{C}$  to at least a depth of 50m
- sufficiently moist mid-troposphere for deep convection
- Appreciable moisture flux at the ocean-air interface to sustain a conditionally unstable thermodynamic environment (Montgomery & Smith, 2017)
- A distance of at least 5 from the equator, so that the Coriolis effect is strong enough to initiate the cyclone's rotation (Palmén, 1948).
- A pre-existing weather disturbance with sufficient vorticity and convergence, e.g. a tropical easterly wave.
- Low vertical wind shear between the surface and the upper troposphere

1. DONE Classification between tc, tornado, tropical depression...
2. DONE Mention climatology and categorisation
3. DONE Storm characteristics
4. Genesis criteria

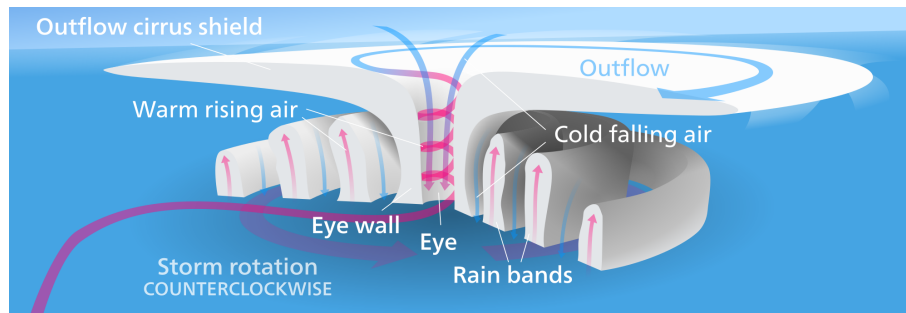


Figure 1.2: Structure of a Tropical Cyclone in the Northern hemisphere [8]

5. Carnot Cycle
6. Shortly mentioning WISHE Paradigm
7. Mention 1 or 2 of Heini Wernlis Publications
8. use emanuel review paper and cloud dynamics course material

### 1.3 Previous work on TC Tracking

1. Mention work of Christoph Raible/Raibler from Bern regarding TC Tracking
2. See what Heini Wernli has done

# Chapter 2

## Data and Methods

The purpose of this project was to evaluate the parameter thresholds for tracking TCs in ICON simulation data. In the following section the settings used for generating the simulation data and the algorithm itself will be explained.

### 2.1 Simulation Data

#### ICON Model

The Icosahedral Nonhydrostatic Model (ICON) is developed by the German Weather Service (DWD), the Max Planck Institute for Meteorology and several partner institutes. As the name implies the grid is in a first step generated by mapping the earth's surface to an Icosahedron (platic solid with 20 equilateral triangles as faces). The faces are then split up into smaller triangles in order to achieve the desired resolution. The model then delivers all typical meteorological quantities on this grid. The model uses the fully compressible and non-hydrostatic version of the Euler equations for the fundamental transport processes. Physical processes which cannot be resolved with the grid size are then parametrised by using complex functions that take into account the grid box mean values of the model variables. Physical processes which need to be treated in this way include solar and thermal radiation, cloud microphysics and turbulent transfer above the earth's surface.[9]

#### Analysed simulation output

The North Atlantic basin with its surrounding area ( `TODO` `xx1 - xx2 lon` and `yy1 - yy2 lat`) was simulated from the beginning of May until the beginning of December. The output data is saved for every six hours. Two different kinds of time lagged ensembles were used. Both used ERA5 reanalysis data for the initial weather state and the monthly boundary conditions. The first however, labeled "ref", used the first day of each month at 6:00 a.m. (`TODO` !confirm with Bernhard ) as the monthly boundary conditions. The second ensemble, labeled "rm", used monthly rolling mean boundary conditions based on the same reanalysis data. The members within each of these two ensembles were created by varying the initial weather state of the simulation. Namely each of the first 10 days of May were used as initial conditions for a separate simulation run. The output data from each run is mapped from the icosahedral to a Latitude-Longitude grid in order to facilitate distance calculations. Finally this results in 20 separate simulation runs that can be searched for TCs.

### 2.2 Algorithm

An existing algorithm developed by Bernhard Enz and inspired by [10] was improved in regards to runtime, robustness and readability. The gained speed was used in order to run the algorithm on

the same simulation data but with different threshold values that decide whether a TC was found or not. By comparing the different results reasonable thresholds and the importance of the different criteria were determined.

The algorithm consists of two steps. In the first step the TC candidates are found for each time step without taking into account if a storm already existed in the previous time-step. Afterwards all entries are analysed and connected to TC tracks if they lie close to each other temporally and spatially. Both steps will be explained in the following sections.

### 2.2.1 TC candidate search

TC candidates are found by searching the simulated domain using several criteria. They are summarised in Tab. 2.1 and will be explained in detail in the following sections.

criterion	parameters
sea level pressure minimum	slpdis
minimal vorticity threshold	vormin
warm core criterion	temdif, temdis

Table 2.1: Each criterion can be adjusted by changing its characterising parameter

#### Sea Level Pressure Minimum

As outlined in Sec. 1.2 TCs are low pressure systems. In fact some of the lowest pressures on earth were measured inside the eyes of TCs. Therefore the first step to finding TC candidates for a specific time-step is locating the sea level pressure minima. Here enormous speed up was achieved by replacing the previous manual minimum finding algorithm with a vectorised version from the image processing library scikit-image [11]. This function finds the local minima and requires them to be a certain distance apart. The stronger minimum is kept if two candidates are within the specified distance **slpdis**. The resulting minima are then further analysed.

#### Minimal Vorticity Threshold

If the vorticity at a pressure minimum is below the minimum threshold **vormin** it is discarded as a potential TC candidate.

#### Warm Core Criterion

The last qualifying characteristic is the warm core structure. The temperature at the height of 300 hPa in the pressure minimum is compared to the average temperature of the surrounding area at the same height. The form and strength of this warm core requirement can be adjusted by using the parameters **temdif** and **temdis**. The former corresponds to the required temperature difference between the center of the storm and its environment. Only storms that have a warm core that is at least **temdif** degrees warmer than the environment, are kept as valid TC candidates. The latter specifies the side-length of the square with the storm in the middle which is defined as environment.

#### Saving of TC information

At the end of each time-step the remaining candidates are saved with their corresponding date, time, position, maximum windspeed and sea level pressure in the center.

### 2.2.2 Creating TC tracks from previously found TC candidates

The TC tracks are created by checking the candidates for each time-step and comparing them to currently active TCs. At the beginning of each new time-step previously active TCs that were



interrupted are archived if they lived for at least 18 hours and deleted otherwise. Then for each entry it is checked which previous TC is within its maximum travel distance. This distance is set to 72 kilometres since a TC with a top speed of 20 m/s can travel this far within 6 hours. If several entries could have been reached by the same active TC, the entry with the lower sea level pressure is added to the track and the other entries are discarded. If no active TC within range of the entry is found a new active TC is created. Each TC is finally assigned a unique integer for identification.

### 2.2.3 Varying parameter thresholds

Naturally the results of the algorithm depend on the choice of the five parameters from Tab. 2.1. In order to answer the research question of this project the algorithm was run for different combinations of these parameters. For instance all combinations of the values in Tab. 2.2 were used.

parameter	unit	values
slpdis	m	25000, 50000, 100000
vormin	1/s	1e-6, 1e-5, 1e-4
temdif	K	0.5, 0.75, 1, 1.25
temdis	m	100000, 200000, 400000

Table 2.2: An exemplary list of parameters which results in 108 ( $=3*3*4*3$ ) combinations

In summary, the algorithm is run with every parameter set on all of the 20 simulation runs.

## 2.3 Tracking Data Analysis

### 2.3.1 Algorithm output data format

1. Quickly explaining what the algorithm outputs

### 2.3.2 Filtering out noise

After the tracking and stitching steps are completed, the algorithm results can still be improved by filtering the results. The largest improvement was achieved by requiring a certain sea surface temperature at TC genesis.

#### Sea Surface Temperature Criterion

As outlined in Sec. 1.2 the TCs need warm ocean water as an energy source, especially when they form. It has been shown that the large majority has a SST over 25.5°C [12]. Therefore it is expected that no reasonable TCs are filtered out when requiring a genesis SST of at least 24°C. However as can be seen in Fig. ?? a large part of the unwanted tracks in the north of the domain are removed.

### 2.3.3 Analysis of variation of parameters

Here I will discuss the analyses performed for different parameter combinations. would be grateful for some advice on how to evaluate validity of a parameter value and what analyses are interesting.

information	columns	description
timestamp	date	time and date of the TC entry
position	lon_idx, lat_idx, lon, lat	position of the found TC in longitude/latitude grid indices and coordinates
intensity	maxwind, curr_cat, cat	maximum wind within a 100km distance, snapshot category at the current time, maximum category of the corresponding TC
parameter combination	param_id	id of the parameter combination used for tracking
unique TC identifier	tc_id	unique TC identifier across all parameter combinations and simulation runs
simulation run	mem, exp	variables specifying the member and boundary conditions of the analysed simulation run
genesis sea level temperature	genesis_sst	genesis sea level temperature of the particular TC, identical across all time entries of a TC.

Table 2.3: description of the columns of the output pandas dataframe

**slpdis****vormin****temdif****temdis****winddis****maxhgt**

1. DONE Explain Criteria
2. mention long running time
1. Vectorization of Operations especially slp minimum finding
2. Parallelization of Experiments and Members
3. variation of parameters

## Chapter 3

# Results

### 3.1 Importance of different criteria

1. which criteria have a large impact on the found tcs
2. what are interesting thresholds
3. Include fascinating plots

### 3.2 Recommended parameter combination

1. propose combination of parameters for robust search



## Chapter 4

# Conclusion

1. repeat most important findings
2. mention further algorithm ideas
3. suggest more elaborate parallelization with eg dask for improved simulation data reading



## Appendix A

# Additional Plots

Blah, blah ...





# Nomenclature

## Symbols

EHC	Conditional equation	$[-]$
$e$	Willans coefficient	$[-]$
$F, G$	Parts of the system equation	$[K/s]$

## Indicies

a	Ambient
air	Air

## Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
TC	Tropical Cyclone
DWD	German Weather Service
MPIM	Max Planck Institute for Meteorology
ICON	Icosahedral Nonhydrostatic Model developed by the DWD and the MPIM

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