USERS' GUIDE FOR THE BSC CYCLONES TRACKER

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Tracking, Tropical Cyclone, Hurricane, GCM

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Summary

Due to ever increasing resolution, global climate models can now explicitly simulate the formation and the propagation of tropical cyclones. Because tropical cyclones are not a direct model output but instead require detection, an algorithm must be used to detect and track these storms.

This manuscript describes the tools provided at the BSC to detects the formation and propagation of tropical cyclones in climate simulations. The core tracking algorithm is derived from the GFDL Vortex Tracker V3.5b, which was modified to serve BSC purposes and architecture, and complemented with some post-processing tools. The tracker provides an estimate of the cyclone center position along with metrics for intensity and structure, using mean sea level pressure, wind velocity, vorticity, geopotential height and temperature.

It has been adapted to run with Autosubmit on BSC facilities and on the Jasmin server. Instructions to use the tool outside of this context are given as well.

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1 Introduction

This tool detects the formation and propagation of tropical cyclones in climate simulations produced by EC-Earth (or any other climate model). The core tracking algorithm is derived from the GFDL Vortex Tracker V3.5b, which was modified to serve BSC purposes, and complemented with some post-processing tools (statistics and plots at the global, basin and individual storm level). The tracker provides an estimate of the cyclone center position (latitude and longitude) along with metrics for intensity and structure at each time step. Maximum or minimum values of different atmospheric fields are used to track the position of the hurricane center:

- mean sea level pressure
- vorticity or wind velocity at 850 and 700 hPa,
- geopotential height at 850 and 700 hPa,
- wind speed at 10m.

Wind velocities in the mid-troposphere are also mandatory to estimate the subsequent position of the storm and to construct the track. Winds at 850 or 700 hPa can be used, but winds at 500 hPa have the most significant impact on storm tracks. Ideally, the three levels can be used to give better results. The algorithm also provides the variables required to construct cyclone phase diagrams for each detected cyclone. In this case, the input required are:

- the mean temperature field between 500 and 300 hPa (to detect a warm core), and
- the geopotential height at every 50 hPa, from 900 to 300 hPa (for the Hart's cyclone phase parameters).

The tracking can run without these fields however. More information about the original GFDL Vortex tracker can be found on the DTC (Development Testbed Center) Users' guide.

2 New Features

New features have been added to the original GFDL tracking algorithm. The tracker now consists of three parts: i) some pre-processing steps, ii) the tracking itself and iii) a post-processing step analyzing and visualizing the results.

Pre-processing features

- The formatting of CMORised files or raw GCM GRIB output in the format expected by the tracker.
- An executable that automatically makes the file fort.15 (contains info on time steps, see item 6.5. “Execution”) from an netcdf data files.
- The core GFDL tracker can only be launched over one datafile for one processor. This limitation has been addressed by using a loop calling the core tracker on different data files and by parallelizing this loop with some specific tools for multi-processor environment (autosubmit at BSC and bsub on the Jasmin server).

Modification of the tracking algorithm

- The tracker can now read NetCDF files as well as Grib files, although there is a limit of around 2GB on the size of the latter.
- Because data are often divided by individual months and the core tracker can only read one datafile at a time, there is a need to match the track at the end of a given month with the track at the beginning of the subsequent one. In order to continue the tracking without missing information or break tracks from one file to another, both data files should have one date in common. Thus, the tracker has been modified such that at its penultimate time step, a record of the storms still being tracked is output. This is used afterward as input by the following launch to join the tracks.
- Some minor bugs have also been found, corrected and reported to the GFDL's developers.

Post-processing features

- Removal from the output file of depressions that are either too weak, too short or don't have warm core characteristics.
- Evaluation of four new intensity parameters: IKE, PDI, ACE, TIKE.
- Summary of statistics for each storms detected.
- Statistics and graphs of total cyclone activity per basin and per year.
- Graphs showing the evolution of the strongest cyclones detected.
- Maps of tracks and other histograms

Finally, all, pre-processing, tracking and post-processing, can be launched through one unique tool.

3 Data

3.1 Variables needed

The BSC tracker requires the same atmospheric fields as input as the GFDL vortex tracker:

- The Mean Sea Level Pressure (MSLP) is mandatory: it allows the software to look for new lows, which is the goal of the BSC Cyclones tracker.
- Both components of the wind at either 850 hPa, 700 hPa or 500 hPa are mandatory. They are used to compute the path of each storms. All three levels are used if provided, with more weight given to the 500hPa level.
- Both components of the wind at 10m, 850 hPa and 700 hPa as well as the geopotential at 850 and 700 hPa are used to correct the center of the low. If not provided, the center of the low is fixed to the minimum of pressure.
- If 850 and 700hPa winds are not available but the absolute vorticity at the same levels is, the software can used it instead.
- Mean temperature between 500 hPa and 300 hPa allows the detection of a warm core. If not provided, the post-processing won't be able to discriminate between tropical cyclone (warm-cored) and extra-tropical cyclones (generally cold-cored).
- The geopotential height between 900 hPa and 300 hPa (50 hPa intervals) are the basis to compute the cyclone phase diagrams.

3.2 Format of the data

3.2.1 Used by the core tracker

The core tracker can read both GRIB and NetCDF data. For both formats, the grid must be regular (eg. grids points are parallel) and equally spaced between each latitude. In case of Gaussian grids, like in EC-Earth, it must be re-interpolated (see item 3.2.2.) "formatting tools"). The time variable must be set in hours, relative to a time reference. The value can't exceed 1666 hours (69 days) from the time reference due to the limitation of the fort.15 file (see item 6.5. "Execution"). To avoid losing information between two consecutive files, two consecutive datasets should have one date in common. Indeed, speed, direction and phase diagram parameters need the data of the next or of the previous time step to be computed.

The pressure levels should be in unit of Pa. The pressure levels required for the u and v wind components are 85000, 70000, 50000. The pressure levels (in Pa) for the geopotential are 90000, 85000, 80000, 75000, 70000, 65000, 60000, 55000, 50000, 45000, 40000, 35000 and 30000. If the level 90000 is not provided or filled with missing values, the analysis of the phase diagram will continue. But, if any other level is not provided, the analysis will end for that particular time step due to the lack of data.

The mean temperature variable could either be a 3-D variable (latitude, longitude, time) or a 4-D variable (latitude, longitude, time, pressure level). If pressure level is one of the dimension, the software will only read the level 40100 Pa to prevent reading a field which is not the mean. Finally, u and v surface winds could either be 3-D or 4-D variable, and in this last case, the level should be set at 10, in meter above surface.

Table 1: The name of the variables recognized by the tracker
The atmospheric fields can be 3-D variables (lat, lon, time) with level being included in the variable name, or 4-D (lat, ton, time, level) with level in m above surface for uas and vas, and in pressure (Pa) for the others.

	4-D variables	3-D Variables (where XXX is the level, ex: ua500)
Vorticity	VO / vor	vorXXX
U-Wind	U / ua	uaXXX
V-Wind	V / va	vaXXX
Geopotential Height	GH / zg	zgXXX
Geopotential	G / z	zXXX
Sea Level Pressure	***	MSL / psl
U-Wind surface	uas	U10M / u10 / uas
V-Wind surface	vas	V10M / v10 / vas
Temperature	T / ta	T / ta / ta401

For a grib dataset, the format needed is the same as the one described in the GFDL's Users guide. All the data must be merged into a single file, and the variable referenced with the code from a common table (Ncep, ECMWF...). Then, an index must be created from the data file using the tool provided with the GFDL's tracker, grbindex.exe. However, it should be noted that this tool does not work for large files (more than 2 GB). Although running the tracker with Netcdf data is more time consuming, it does not have this limitation on the size of the input.

All the fields must be included in one file to be read by the tracker, the variables being recognized with their name (Table 1). In order to use the pre-processing tools, all the data must be separated by month, with their name including the member name and finishing by YYYYMM.nc, where YYYY correspond to the year, MM to the month of the data in the file, (example: fc0_200510.nc).

3.2.2 Formatting tools

In case of specific format (CMOR architecture, special output of the model in grib), two distinct scripts are available to format either CMORized (netcdf) or grib data to the specific format expected by the tracker. Those scripts are part of the automatic pre-processing script. If the input are not in either of these formats, this step has to be done manually.

“CMOR.sh” has four arguments: the path of the data, the year, the month and the member identification. It expects the datapath to point to the folder “atmos” of CMORised data (example: …/BSC/EC-EARTH/a09i/S19900101/6hr/atmos). Then it looks for the variables, respectively psl, ua, va uas, vas, ta and zg. The data for each members must be in separate folders with the folder's name being the member's name. Then the data are expected to be split in monthly files with the name finishing by YYYYMM.nc, YYYY corresponding to the year, MM to the month of the data in the file (ex: psl_6hrPlev_EC-EARTH_a09i_S19900101_r1i1p1_199010-*199010.nc*).

“rawgrib.sh” has three arguments: the path of the data, the year and the month. The data path must point directly to the data files. The name of the files is expected to finish by YYYYMM.nc, YYYY corresponding to the year, MM to the month of the data in the file, and also contains the strings “GG” and “SH” (example: SMHI_GG_200510_200511.nc). “GG” files should includes pressure and surface wind on a Gaussian grid, and “SH” files all the others but in spherical coordinate. Both files are then merge and interpolated to a readable regular grid for the core tracker

Both scripts also compute the mean upper level temperature, make the interpolation for the levels of geopotential height that were not provided and include the first time step of the following month if they can find it. All of the operations are made using CDO.

4 How to use the tracker with Autosubmit

Various scripts have been developed to be used in conjunction with autosubmit. This should provide a few advantages, such as simplification in the execution, launch of parallel jobs, etc.

4.1 Installation

The first step in the installation process is to create a new autosubmit experiment by typing:

```
> module load autosubmit
> autosubmit expid -y a0ae -H moore -d “Short Description of the experiment”
```

This will create an ID for the experiment. The configuration files of the experiment test, “a0ae”, are automatically used as template for the new one. However, the user name should be changed in platforms_ID.conf, assuming the user can directly connect to the fat node moore. Then, the experiment can be created:

```
> autosubmit create ID
> autosubmit check ID
```

Before running the experiment, all the R libraries required for the post-processing are installed. This quick tool can be executed:

```
> /esnas/autosubmit/ ID /proj/BSC-Cyclone-Tracker-tools/R/library_install.R
```

Then type:

```
> autosubmit run ID
```

This launches a test experiment using data from ERA-Interim for the year 2005, located in /esnas/autosubmit/a0ae/data. If everything goes well, after a few minutes (~20 min) the result of the tracking should be available in:

/esnas/scratch/Earth/ user_name /Tracker/Test/fc0/.

See Appendix B for the description of the output.

4.2 Execution

After the first execution, all the scripts will be located in:

/esnas/autosubmit/ ID /proj/

From that point on, to use the tracker, the user only needs to change the namelist in the file "proj_ID.conf" under "esnas/autosubmit/ ID /conf/" to configure any other run of the tracker. The namelist includes all the parameters for the pre- and the post-processing, as well as the ones for the core algorithm, as presented in the Appendix A.

Finally, in "/esnas/autosubmit/ID/conf/expdef_ID.conf", the user can configure the start date of the experiment *(DATELIST)*, the name of the member *(MEMBER)*, the number of parallel jobs *(NUMCHUNKS)* and the length of one job in month (*CHUNKSIZE*). The multiplication of *NUMCHUNKS* by *CHUNKSIZE* gives the length in months of the full experiment. *CHUNKSIZE* also helps the user adjust the running time of a job, defined in jobs_ID.conf in the same folder, by the variable *WALLCLOCK* under [TRACKER].

Information about the duration required to analyze one month of data can be found in the section 7: "Sensibility study of the parameters".

All the results will be available in "/esnas/scratch/Earth/ user_name /Tracker/ *NAME_EXP* /" if *WORKING_PATH* has been set to default. If WORKING_PATH is not set to default, they will be in: *WORKING_PATH / NAME_EXP*. The directory contains one folder for each member name given by *MEMBER*.

5 How to use on Jasmin server

5.1 Installation

The BSC Cyclone Tracker is stored under svn/ in the repository:
http://proj.badc.rl.ac.uk/svn/primavera-private/WP2/storm_tracking/BSC-Cyclone-Tracker

It can be viewed on a web browser at:
http://proj.badc.rl.ac.uk/primavera-private/browser/WP2/storm_tracking/BSC-Cyclone-Tracker

Supversion ("svn"), a versionning and revision control system, provides different tools such as:

> svn co http://proj.badc.rl.ac.uk/svn/primavera-private/WP2/storm_tracking/BSC-Cyclone-Tracker

to download the whole tracker in a working directory, or:

> svn update

typed from the folder *BSC-Cyclone-Tracker/*, to update the program in the case of a new version released.

The R libraries need then to be installed, still from the folder BSC-Cyclone-Tracker/:

> chmod 755 R/library_install.R
> ./R/library_install.R

From the newly created folder BSC-Cyclone-Tracker/, Jasmin_ini.sh can be launched using a session on Lotus, to run a test experiment. Be aware that a ssh connection to lotus resets the current directory to default:

> ssh lotus.jc.rl.ac.uk
> cd your_working_directory/BSC-Cyclone-Tracker
> chmod 755 Jasmin_ini.sh
> ./Jasmin_ini.sh

At the end of the last script, 13 jobs should be submitted in the Lotus' queue. Their evolution can be checked by typing:

> bjobs -a

"PEND" means the job is waiting to run,"EXIT" that the run ended with an error status, "DONE" that the job ended properly. In the case of the example, only memb1_8, and pp_memb1 will need time for their processing, since the other jobs won't find any data.

If all went well, after a few minutes all the post-processed files can be found under your_working_directory /Test/memb1/

The example is run on a small sample from Era-Interim at 0.5° of the resolution enclosing the first days of August 2005. It's possible to follow the typhoon-2 Matsa around Taiwan.

5.2 Execution

The main parameters of the experiment can be changed in the file tracker.conf. Jasmin_ini.sh contains also some parameters involved in the launching of the parallel jobs: the name of the members (*member*), the start date (*sdate*), the number of month to consider by jobs (*chunksize*), and the number of jobs (*chunknum*),

All experiment should be launched with the same sequence:

```
> ssh lotus.jc.rl.ac.uk
> cd  your_working_directory/BSC-Cyclone-Tracker
> chmod 755 Jasmin_ini.sh
> ./Jasmin_ini.sh
```

The script launched through Jasmin_ini.sh should be located in your_working_directory /$exp/exec, where $*exp* is the name of the experiment. In the same folder, the files .out and .err resulting from the launch of each script should also be found. The outputs of the tracking itself are under $exp/memb.sdate where *memb* is the name of the member and *sdate* is the start date of the job. If the post-processing went well, those folders are suppressed. The output of the post-processing are located in exp/memb.

In case of a failure of one of the script, it may be relaunched manually in the queue:

```
> module load lsfmodules/9.1
> module load netcdf/gnu/4.4.7/4.3.2
> module load netcdff/gnu/4.4.7/4.2
> bsub < theJobs.sh
```

6 Further explanations in case of other use

6.1 Tools needed

Different tools are required by the software. However, not all of them are mandatory and some are used for some special features during the pre-processing or the post-processing. Here is a summary:

- A fortran 90 Compiler. This is mandatory, since the core algorithm is in Fortran. Different ones can be used, as explained later.
- The netCDF-Fortran library, needed to read NetCDF file. It should be installed with all the other NetCDF libraries. The version 4.2 of NetCDF works well.
- A Bash environment. All the pre-processing scripts are written in Bash.
- R 3.1 at least (or R studio). All the post-processing scripts are written in R.
- CDO (Climate Data Operator) 1.6.9 is used to format the files during the pre-processing step
- GEOS 3.5.0 for R packages.
- GDAL 1.9.2 for R packages.
- PROJ 4.8.0 for R packages.

6.2 Downloading

The tracker is available through the Git-lab repository: https://earth.bsc.es/gitlab/cp/BSC-Cyclone-Tracker-tools.git. However, it has an internal status access and can be only downloaded by members of the climate prediction group. For people with an account on Jasmin for the PRIMAVERA project, it is possible to download the repository from the svn server:

> svn co http://proj.badc.rl.ac.uk/svn/primavera-private/WP2/storm_tracking/BSC-Cyclone-Tracker

In any other case, please contact the developers.

6.3 Description of the files

4 folders and 11 files should be present in the downloaded repository.

The main folder, called “gfdl-vortextracker/”, contains all the source codes for the enhanced version of the core Tracker originating from the GFDL Vortex Tracker 3.5b. It has the same directory structure as that provided by GFDL where the original source code is located. The only difference is the presence of the file “configure-gnu.trk” for compiling the tracker with a gnu compiler (see next point 6.4 “Compilation”).

A second folder “tracker_util” includes the library that allows the core tracker to read grib files. This also comes from the GFDL source code and hasn't been touched, except for “configure-gnu.tracker_util” to include a gnu compiler.

The folder “formatting” contains the scripts that format different types of dataset format to a readable file for the tracker. It includes “CMOR.sh”, which deals with the data in a CMORized format (netcdf), and “rawgrib.sh” to read the grib files (direct output of EC-Earth). See the section 3.2.2 “Formating tools” for more information.

The last folder, named “R”, includes the post-processing R scripts. It contains:

- “resultProcessing.R”: the main file that makes the different post-processed output (See 6.6 “Post-processing”).
- “base_fun.R”: includes all the function used by the main file.
- “library_install.R”: a simple tool to install all the libraries needed.

The file “ini_tracker.sh” is used for the initialization of the tracker, namely the compilation, and is used with autosubmit. See the Compilation section (6.4.) for instructions on how to do it manually.

“launch.sh” is the core script that calls the different formatting procedures and allows multiple launches of the tracker over different data files. More precisely, it makes it possible to continue the tracking of any cyclones detected at a previous launch and merge the results of the different data files. At the end of the loop over the monthly data files required, it runs the tracker in tracking only mode over the next file if available, so that no data will be lost in case of parallel jobs launched.

“pplaunch.sh” merges all the result files of the different jobs and launches the R post-processing script. This is mainly used by autosubmit.

“writefort15.f” is a small tool that writes all the time steps in the file fort.15 in a readable format for the core tracker. It takes the information from the file namelist.15 created by launch.sh from the value in the general namelist “tracker.conf” (see Appendix A).

The file “tracker.conf” is a template with all the values set to launch a test experiment. However, the parameter *DATAPATH* should be changed to the local directory and *WORKING_PATH* to any directory it's possible to write in. With autosubmit, this file is copied to “proj_ID.conf” which is the one to be modified.

The file “namelist” is also a template for the namelist of the core tracker. However, it is not meant to be changed, except in very specific cases. It is filled by the script launch.sh with the value provided by the general namelist just before the launch of a run of the core tracker. (See Appendix A)

“memb1_200508.nc” includes the data from ERA-Interim for the first days of August 2005. It is a small sample test that can be used to follow the typhoon-2 Matsa around Taiwan.

“Jasmin_ini.sh” is used as an integrated tool to launch experiments on the Jasmin server. It could also be used as template for other platforms.

Finally, the three last files are the documentation: this user guide, the Users' Guide for the GFDL Vortex Tracker version 3.5b, and a README file containing a part of the information of the guide.

6.4 Compilation

Some tools are provided by GFDL for manual compilation of the tracker (see GFDL documentation). They can be found in gfdl-vortextracker/ and tracker_util/ for the core tracker and its library, respectively.

For general compilers, the user should run the following commands, first in tracker_util/, then in gfdl-vortextracker/:

> ./clean -a

> ./configure

At this step, the user will have to choose the right compiler when prompt on the terminal, and then:

> ./compile

However, the GFDL tools do not create the right configuration file in the case of gnu compilers. "configure-gnu.trk" and "configure-gnu.tracker_util" should be used instead.

In tracker_util/:

> ./clean -a

> cp configure-gnu.tracker_util configure.tracker_util

> ./compile

Then, in gfdl-vortextracker/:

> ./clean -a

> cp configure-gnu.trk configure.trk

> ./compile

For any other compiler not included, the configuration files need to be changed by the user.

Finally, the tracker executable can be found at:
"gfdl-vortextracker/trk_exec/tracker.exe"

6.5 Execution

The files required by the core tracker are exactly the same as those listed in the GFDL documentation. Most of them are automatically created by the script launch.sh. Here is a quick summary:

- fort.11: contains all the data. It can either be a grib or a NetCDF file. (See section 3.2.1 *"Format of the data used by the core tracker"* for more information)
- fort.31: contains the index of the data files. Only used in case of grib files (see GFDL documentation)
- fort.15: includes all the time steps with the following format: "NNNN MMMMM" where NNNN is the time step number and MMMMM, the number of minutes since the beginning of the simulation. The space counts as a character. Example: " 124 44640" or "   1   360". Thus, there

can't be more than 9999 timesteps, nor a step more than 99999 minutes (69 days) away from time reference.

- fort.14: contains the coordinates and some structure variables of the cyclone to be found at the first time step. Generally a copy of the fort.67 file produced by a previous run.
- namelist: all the parameters required by the GFDL tracker, as well as a few new ones.

Then, the tracker is launched by typing:

```
> ./tracker.exe < namelist
```

The tracker produces a handful of files, including:

- fort.66: Contains all the cyclone information (position, maximum wind speed, etc). It is the basis of the post-processing.
- fort.67: Summary of the cyclones being tracked at the penultimate time step. Can be used as input for the next run, with the name fort.14.

The script launch.sh might be used to launch the tracker over different data files, just by replacing the parameters otherwise filled by autosubmit.

6.6 Post-processing

The following R libraries are needed for the post-processing: stringr, abind, maps, maptools, rworldmap, raster, rgeos, geosphere, ggplot2, grid, gridExtra, gtable, parallel. They are to be installed before launching the process. Note that rgeos needs access to GEOS libraries to be installed.

The goal of the post-processing is first to clean the output file (fort.66) of all the uninteresting tracks detected: too short, not reaching a threshold intensity and not with a warm core. A storm, to be selected, must last at least *TIME_MIN*, with a warm core, and within *LAT_MAX* latitude North and South. It must also reach the threshold intensity *WIND_MIN*. However, if the warm core detection has failed (no temperature fields for example), all values are switched to true to continue the analysis. A summary in the form of tables and plots are then produced.

Storms are rename with the following syntax:

"YYYYMMDDHH_latD_longD_nameExp_member"

where YYYYMMDDHH is the date and the hour of first detection, latD and longD are the coordinate of first detection, and nameExp the name of the experience. Example: 1990010106_202S_0492E_Test_fc0.

The Integrated Kinetic Energy (IKE) is also computed for each time step and each storm, using:
http://storm.aoml.noaa.gov/hwind/assets/IKE_USE_Case_Oper_radii_2008_rev_2012.pdf

See Appendix A for the description of the different arguments, and Appendix B for the description of the outputs.

7 Sensitivity to various parameters

An analysis of the sensitivity to various tracking parameters has been performed, using a simulation of EC-Earth 3.2 at 30km of resolution, run over 3 members and four years for the months of May, June, July and August. The parameters tested correspond to the one described in Appendix A, and can be found in the file Tracker.conf

7.1 Cyclones detection and first point discovered

It is possible to limit the detection of cyclones by using geographical or storm structure parameters. However, it also impacts when and where the first point of a track is detected. All the variable discussed here can be changed in Tracker.conf.

7.1.1 Domain size

The domain over which the tracker searches for new lows might be limited to a box of boundaries given by *WESTBD*, *EASTBD*, *NORTHBD*, *SOUTHBD*. Every cyclone forming within this area or enter it are detected. However, if a storm moves outside of these boundaries, it continues to be tracked. Changing this area will impact the run time, since the latter is proportional to the area of the domain. Thus, if a worldwide dataset is provided, but the focus is on only one basin, the box's boundaries may be fixed to this basin in order to speed up the detection algorithm.

It should be noted that increasing the size of the search domain increases the chance of detecting non-tropical storms. The post-processing requires the storms to exhibit a warm core and high surface wind during a duration fixed by the user (*TIME_MIN*). It's not unusual for an extra-tropical storms to exhibit a weak warm core and strong surface winds during a few days and models might reproduce this feature. In the case of the simulation used, wintertime storms originating between 20º and 40º S in the Pacific were sometimes selected.

On the other hand, a small domain might miss some tropical storms, or at least the beginning of the track if it moves in the domain afterward. In this test case, all the tropical storms originated at a latitude lower than 20º (both North and South).

Finally, if the study is worldwide, for complete years, the domain might represent a spherical segment with latitudinal boundaries at 20º N and S. In the case of seasonally oriented study, the domain may be restricted in longitude and include all latitudes between 0º and 40º in case tropical lows form at higher latitude.

7.1.2 Maximum of Mean Sea Level Pressure

MSLPTHRESH is a new parameter added mainly to speed up the program in the testing phase. It corresponds to the maximum surface pressure for which the tracking algorithm will look for a possible storm. Set at 99000 Pa or 99500 Pa instead of 101000 Pa, it will speed up the software by 10 to a 100 times, especially for high-resolution input. While this speeds up the program, it also leads to some storms with higher surface pressure to be excluded or others to be detected later, hence leading to shorter tracks.

Set at 101500 Pa or above has a dramatic impact on execution time but doesn't have much impact on storms detection: the minimal pressure of the first detection of each storms was largely below 1015 hPa during the test with EC-Earth. In the case of specific basin studies, such as North Indian, this threshold might even be lowered to 101000 Pa or 100500 Pa since the pressure of the environment is much lower.

7.1.3 Detection of low

In order to be detected, the difference of pressure between the centre of the low and the environment must reach a threshold determined by the parameter *CONTINT*. This value corresponds to the difference of pressure between the low and a first closed isobar, and then between two successive closed isobars. Finally, the pressure of the last closed isobar is considered as the pressure of the environment.

Thus, this parameter does not only impact the detection and the first point discovered but also the precision of the variables “pressure of the environment” and “difference of pressure with environment” given in the post-processed output. In this case, lower value should give more precise result.

Since a closed isobar must be detected at each time step, it also impacts when the tracking ends. A very high value of the parameter might even lead to truncate and split tracks between each intense phases. Conversely, a lower value might allow the beginning of the tracking at first evidence while the low that never intensify afterward are removed during the cleaning step in the post-processing. However, it might also lead to connecting two different systems together. For example, with Era-Interim reanalysis, the strong remnant of Hurricane Katrina that re-intensified over the Labrador sea were connected to another low in the Northern Atlantic. The use of the other parameters (mainly *MSLPTHRESHGRAD* and *V850THRESH*, see 7.2 “End of the tracking”) that also impact the end of the tracking are necessary to addressed that problem.

In the case of the test with EC-Earth, this parameter has been lowered to 100 Pa with very good results for the detection. However, there was some problems with very high resolution (~13 km) to compute the pressure of the last closed isobar and its distance to the center. Both were dramatically underestimated. A higher value for this parameter might help solve that issue, but this was not tested.

7.2 End of the tracking

MSLPTHRESHGRAD and *V850THRESH* are two parameters designed to stop the tracking when the low becomes too weak. The first corresponds to the minimum pressure gradient and the second, to the minimum tangential wind. However, for the test with EC-Earth, the default values provided by the GFDL's trackers (respectively 0.0015 Pa and 1.5 m/s) have no impact on the end of tracking. In other words, the tracking ended for reasons unrelated to the magnitude of the surface winds and of the surface pressure. The main reason stopping the tracking is usually a failure to detect a new low (see previous paragraph 7.1.3).

Other factors might also cause the tracking to stop: the tracked storms can't exceed a speed of 60 knots (111 km/h) and the difference of distance between the minimum of sea level pressure and the maximum of vorticity at 850 hPa can't exceed 400 km. Those number can only be changed through a modification of the GFDL's code and a re-compilation, whereas the others are in Tracker.conf

7.3 Post-processing discrimination

The tracker will detect many weak systems that aren't considered tropical cyclones. A cleaning of the result thus takes place during the post-processing, using a series of different parameters. Their impacts are analyzed here.

7.3.1 Warm Core

WCORE_DEPTH is first needed by the core tracker though it eventually allows the discrimination during the post-processing. It works in a similar way to *CONTINT*: it is the minimum difference between the maximum temperature of the center of a storm and a closed isotherm around it. It has no impacts on the tracks themselves, but the selection of storms during the post-processing is very sensible to it. Lower values lead to more cyclone being selected at the cleaning step while higher values reduce the number of storms. Though the method discriminates well between hurricanes and most of the extra-tropical storms, the tests with EC-Earth show that the results are more ambiguous with weaker tropical storms. If a higher value is set, warm core won't be detected for many of the tropical storms. On the other hand, with lower values, some extra-tropical storms with warm core will be detected. With a full year test of EC-Earth, a handful of extra-tropical storms at low latitude during the wintertime remained even after the cleaning.

Finally this parameters should vary depending on the goal of the study. In the context of EC-Earth tests, a threshold of 2º C restricted the results to hurricane-strength storms while a threshold of 0.5º selected all strong warm-cored storms. Those values might change depending on the resolution and on the model.

A lower value of *WCORE_DEPTH* might be coupled with a more limited search domain, or slight changes in the mean of selection of the storms in the post-processing (see next point 7.3.2 “R parameters”) to improve the results depending on the needs.

7.3.2 R parameters

The three remaining parameters, still located in Tracker.conf are only used during the post-processing phase to make the selection of the most relevant storms:

TIME_MIN is the number of hours the storms must exhibit a warm core. It is set by default at 24 hours, since the tropical cyclones are named if they last at least one complete day with tropical characteristics. However, the effect of that parameter also depends on the parameter *WCORE_DEPTH* which controls the presence of warm core. Both can be adjusted so that long enough and warm enough lows can be selected.

LAT_MAX has been designed to restrict the last criterion in an equatorial band and limited the number of clearly extra-tropical cyclones selected. The default value is 40º, which is fine for Atlantic basin according to observations but could be lowered for other basins.

Finally, all the storms must reach a wind threshold, WIND_*MIN*, which therefore defines the genesis of the storm as tropical storm. It could also be set to higher value to define hurricane genesis for example, or to a lower one for detecting weaker storms, or to account for the resolution of the model. Another parameter, *scale*, already corrects the problem of time scale, in order to convert the raw mean wind provided into a 1-min sustained wind. The default value of *WIND_MIN* is then set to tropical storm threshold as defined by the Saffir-Simpson scale, after that correction.

7.4 Execution time

Execution time is an important parameter, especially using autosubmit, because in that case a time limit is required for each step of the program (pre-processing, core tracking and post-processing).

Pre-processing is mainly affected by the formatting processes using CDO which time duration is proportional to the final size of each files treated and thus to the resolution and the number of variable selected.

Most of the time consumed for the core tracking is spent looking for new lows in the area of interest. The total search time depends on the resolution, the size of the area of research and the parameter *MSLPTHRESH*, which is the maximum pressure that could have a new low (Table 2). Note that the effect of the latter parameter depends itself on the search area: North Indian basin has a lower mean pressure during the summer monsoon than any other basin, thus for an equivalent surface area and the same parameters, this basin will require more time. In case of a very low pressure limit or a very small area, it’s the reading of the files at each time step that will take the most time. This is only affected by the resolution and the number of variables selected and will prevent the program to work in less than a minute for each monthly file.

Table 2: Overview of the tracking processing duration for different cases
The length is given for the treatment of one monthly file with a 6-hourly time step, Moore is a cluster with individual processor slightly slower than the one of the local computer used but allowing a lot of parallel jobs. Some result are an extrapolation due to the failure of the program (time limit reached). Note that the time duration might be reduced by half from one file to another, depending on the characteristics of the MSLP field provided. Results with a lower MSLPTHRESH parameter (ex: 99500, 100000) are not shown but reduced dramatically the time duration, by up to a factor of 100, compared to higher value (ex: 102000)

Resolution	*MSLPTHRESH*	Longitude wide (in degree)	Latitude wide (in degree)	Machine	Time duration
T1279	102000	360	60	local	~ 120h
T1279	101000	360	50	Moore	~48-70h
T1279	101000	270	30	Moore	10-16h
T1279	100500	360	50	local	~55h
T255	101500	360	80	local	2-3h
T255	101500	360	20	local	20-30min
T255	101000	360	60	local	1-2h

T255	101000	270	30	Moore	3-7min

For the post-processing, the most consuming step is the selection of the storm, which is proportional to the number of storms detected, which itself depends on a series of parameters (number of month, resolution, size of the area of search, *MSLPTHRESH*, *MSLPTHRESHGRAD*, *V850THRESH*, *CONTINT*). One year could last from a few seconds up to one or two hours in cases of very high resolution and weak threshold parameters (more than 5GB of memory needed in that case). The plots and files are created in about 10 minutes.

APPENDIX A: Description of the namelist and other parameters

1 Tracker.conf

This namelist includes all the parameters that can be modified from one run to the next without touching the code and recompiling. It is directly read by the script "Jasmin_ini.sh". It is copied by autosubmit into the file "proj_ID.conf" located with the other configuration files. That file is the one to be modified when using autosubmit.

If neither autosubmit nor "Jasmin_ini.sh" are used, the parameters could directly be changed in the parameter section of the script launch.sh (for general parameters and core tracker namelist) and pplaunch.sh (for R post-processing script)

General parameters:

DATAPATH	Where to find the data
WORKING_PATH	Where to put all the temporary files and the output
FORMAT	Architecture of the data: "*CMOR*", "*rawgrib*" or "*onefile*"
KEEP_FORMATTED_DATA	*T* or *F* to save or not the formatted file when "*FORMAT*" = "*CMOR*" or "*rawgrib*"
NAME_EXP	Name of the experiment. Name of the folder under *WORKING_PATH* where to find the output. Also included in the name of the storms
EDATE15, SDATE15	First / Last time step of the data to be analyzed. Use to create fort.15. Could be set at -1 to take the first / last time step of the data file misanalysed (fort.11).
TSTEP15	Time step between each new search for lows. Use to create fort.15. Must be a multiple of the time step of the data files Could be set at -1 to take the time step of the data file fort.11

For the core tracker namelist :

TYPE	Format of the data: "*grib*" or "*netcdf*"

WESTBD, EASTBD, NORTHBD, SOUTHBD	Latitude / Longitude of the domain where to find new lows
MSLPTHRESH	Maximum surface pressure that a new low could have
MSLPTHRESHGRAD	Threshold for the minimum MSLP gradient (in hPa/km) that must be reached in order to continue the tracking
V850THRESH	Threshold for the minimum azimuthally-average 850 hPa cyclonic tangential wind speed (m/s) that must be exceeded in order to keep tracking
CONTINT	Minimal pressure difference (in Pa) between two isobars and thus between a low and its environment.
WCORE_DEPTH	Contour interval (in K) used to determine if a storm has a warm core: minimum temperature difference between a low and its environment. Though it eventually allows the discrimination during the post-processing, it is first needed by the core tracker.
VERB	Give the level of details printed to terminal. Choose from 0 (no output) to 1 (error messages only), 2 (more messages) or 3 (all messages).

For the R post-processing script :

SCALE	Scaling of the surface wind computed to match 1-minute sustain wind. It could be *“1min”* (no change), *“10-min”*, *“1hour”*, *“3hours”*.
LAT_MAX	Latitude maximal of the warm-cored storms to compute their duration (see TIME_MIN) in the post-processing
TIME_MIN	Time minimum (in hours) that a storm should last with a warm core in order to be selected
WIND_MIN	Wind minimum (in knots before scaling) that a storm must reach in order to be considered. If set to *“NA”*, the threshold is set to tropical storm intensity after scaling. Also considered as the cyclogenesis point.
MAX_LANDFALL	Maximum number of landfall that can be computed for a given storm.

The R post-processing script “resultProcessing.R” also takes as argument *NAME_EXP*, and an autosubmit variable, *%NUMPROC%* or *no_cores*, which correspond to the number of processors allowed for the given job.

2 Namelist

This is the slightly modified namelist of the GFDL Vortex Tracker. It should not be modified when using autosubmit or the Jasmin tools.

Name	**Correspondence in Tracker.conf**	
Under datein:		
inp%bcc, inp%byy, inp%bmm, inp %bdd, inp%bhh		Two digits variables giving respectively the century, the year, the month, the day and the hour for the initial time forecast. It has no impact on the output of the post-processing.
inp%model		Model ID number that defines the table. It is only needed if the data format is in GRIB. See ID number in Table 3
inp%lt_units		Lead time units used by the PDS in the GRIB header in hour or minute. Not use in case of NetCDF
inp%file_seq		It specifies whether the tracker will process one big input file *“onebig”* or multiple files *“multi”*. Not use in case of NetCDF
inp%modtyp		Type of model: *“global”* or *“regional”*.
inp%nesttyp		Type of the nest grid: movable or fixed. A NetCDF files should always have a fixed grid.
inp%filetype	TYPE	This is a new parameter giving the format of the input data: *“grib”* or *“netcdf”*

Under atcfinfo:

atcfnum	Obsolete integer
atcfname	String of 4 characters referring to the model used. It only appears in the name of the storms in the raw outputs
atcfymdh	10-digit date (yyyymmddhh) used in the raw outputs. It should be set to the time origin of the data file analyzed in order to be used in the post-processing to compute all the absolute date (name of the storms, date of formation, date of landfall, etc). In *“launch.sh”*, it is given by autosubmit variables or by *“Jasmin_ini.sh”*
atcffreq	Frequency (in centahours) of output. Default value is *600* (six hourly). It must be a multiple of the time step of the input. In *“launch.sh”*, it set to the time step of the file analyzed

Under trackerinfo:

trkrinfo%westbd, trkrinfo%eastbd, trkrinfo%northbd, trkrinfo%southbd	WESTBD, EASTBD, NORTHBD, SOUTHBD	Boundary of the domain where to search for new lows. In case of a spherical segment with a global model, the eastern boundary must be set to the last point of the grid (not 0, nor 360, but 360-Δlon)
trkrinfo%type		Type of tracking to do. The BSC cyclones tracker is designed to be used in *tcgen* mode, meaning it looks for new low and begin the tracking of the newly found storms. *midlat* can also be used to track storms, but it only uses mslp to determine its center, which target mid-latitude storms according to the GFDL User’s Guide. The option *tracker* is also available, to track already provided low. It is sometimes used in *“launch.sh”* when simultaneous jobs are launched together. It allows the continuation of the tracking of a storm with the same name, although the period should be treated by an other job. However, this is only done for one month.

		This variable is set by *“launch.sh”*
trkrinfo%mslpthresh	MSLPTHRESHGRAD	Threshold for the minimum MSLP gradient (in hPa/km) that must be met in order to continue the tracking
trkrinfo%choose_t2		This is a new parameter. It is a character set to *“y”* if the following parameter is to be used, *“n”* otherwise. It allows the users to use the default GFDL configuration (see hereafter)
trkrinfo %mslpthresh2	MSLPTHRESH	This is also a new parameter. It gives the highest pressure that a new low could have. If not used, the highest pressure is set to the mean pressure plus one standard deviation.
trkrinfo %v850thresh	V850THRESH	Threshold for the minimum azimuthally-average 850hPa cyclonic tangential wind speed (m/s) that must be exceeded in order to keep tracking.
trkrinfo%gridtype		Type of domain grid: *“global”* or *“regional”*. It should always be *“global*”, regional ones having not been tested.
trkrinfo%contint	CONTINT	Interval (in Pa) between the minimum pressure of a possible new low and the closed isobar to be detected. If this closed isobar is not detected, the low won't be considered. The difference between the minimum pressure of a low and its last closed isobar is also a multiple of this interval.
trkrinfo%out_vit		This parameters has been slightly changed from its original purpose in the GFDL tracker. It is still a character set to *“y”* in order to write out a record of the storms (TCVitals records, see GFDL user’s guide), but this one containing the information for the storms found at the penultimate time step. This was made in order to continue the tracking of the same storm over an other data files

Under phaseinfo:

phaseflag		Set whether *(“y”)* or not *(“n”)* to compute the cyclone thermodynamic phase

phasescheme		Set which scheme to use for checking the cyclone phase. Option *“cps”* is Hart's cyclone phase space, *“vtt”* is a simple 300-500 hPa warm core check based on Vitart, and *“both”* tells the program to use both schemes. Both output are used in the post-processing by default.
wcore_depth	WCORE_DEPTH	Contour interval (in K) used to determine if a closed contour exists in the 300-500 hPa temperature data. Used by the vtt scheme.

Under structinfo:

structflag		Determines whether *(“y”)* or not *(“n”)* to compute additional diagnostics of the cyclone wind structure. However, it isn't saved during the post-processing.
ikeflag		Determines whether *(“y”)* or not *(“n”)* to calculate the Integrated Kinetic Energy (IKE) and Storm Surge Damage Potential (SDP). However, it isn't saved during the post-processing, but the IKE is recomputed.

Under fnameinfo:

gmodname, rundescr, atcfdescr		Model name, description and other information of the input files. Only for Grib in case *file_seq = multi*

Under waitinfo:

use_waitfor		Determine whether the tracker must wait for input files *(“y”)* or not *(“n”)*. It has not been tested with the BSC cyclones tracker

Under verbose;

verb	VERB	give the level of detail printed to terminal. Choose from 0 (no output) to 1 (error messages only), 2 (more messages) or 3 (all messages).

Table 3: ID model in case of Grib files

1	GFS	13	SREF Ensemble
2	MRF	14	NCEP Ensemble
3	UKMET	15	CMC
4	ECMWF (including EC-Earth)	16	CMC Ensemble
5	NGM	17	HWRF
6	NAM	18	HWRF Ensemble
7	NOGAPS	19	HWRF-DAS (HDAS)
8	GDAS	20	Ensemble RELOCATION
10	NCEP Ensemble	21	UKMET hi-res (NHC)
11	ECMWF Ensemble		

Appendix B: Description of the outputs

1 Summary of the files produced

All the files presented here should be found under: *“WORKING_PATH/NAME_EXP/MEMBER.pp/file”*

Figure 1: Map of the Tropical cyclone basins used for the study

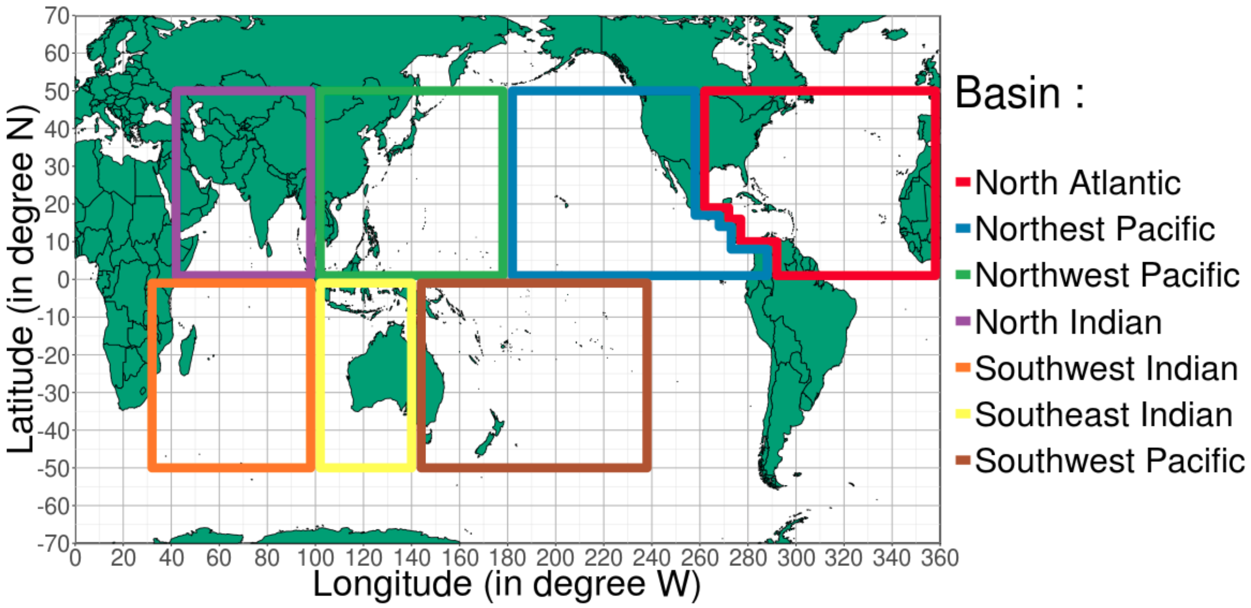

Table 4: The different basins and their respective tropical season

Long name	North Atlantic	North East Pacific	North West Pacific	North Indian	South West Indian	South East Indian	South West Pacific
Short name	NAT	NEP	NWP	NIN	SWI	SEI	SWP
Start of the season	01-06	15-05	01-01	01-04	15-11 year -1	01-11 year -1	01-11 year -1
End of the season	30-11	30-11	31-12	31-12	15-05	30-05	30-05

Table 5: Description of the columns of the file result_basin_basinName_nameExp.txt
(where basinName is the short name of the basin). It summarizes the cyclone activity for each year (one line per year) and for each basin (one file per basin). For the trans-basin cyclone, only the part of the track inside the basins is considered. The example is taken from the tracking of the cyclones of the year 2005 in the Atlantic using ERA-Interim data between June and October.

Description	Year	Number of				
		Tropical Cyclone	Hurricane	Major Hurricane	landfall as Tropical Cyclone	landfall as Hurricane
Name in file	year	TC	HR	MHR	lfTC	lfHR
Example	2015	15	4	1	10	2

ACE (in 10^4 m/s)	PDI (in 10^6 m/s)	Track IKE (in TJ)	number storms in January, February, ...	Number of days		
				between the first and the occurrence of a tropical cyclone inside the active season	with an active tropical cyclone	with an active Hurricane
ACE	PDI	TIKE	m01, m02,...	Season_length	TC_days	HR_days
62	33	1605	…,2,2,3,8,3,...	139	62	12

Table 6: Description of the different columns in result_storms_nameExp_member.txt
It gives a summary for each storm, with one line per storms. The last part of the table is multiplied by the number maximum of landfall (variable MAX_LANDFALL). The example comes from the tracking of the Major Hurricane Rita in ERA-Interim.

**: indicates that the value is computed for the part of the track with a warm core*

Description	Name of the	Year of first	Month of	Basin of first	Vortex centre position at

	storm	detection	first detection	detection	genesis	
					Latitude	Longitude
Name in file	name	year	month	basin	gen_lat	gen_lon
Example	2005091906_222N_0736W_Test_fc0	2005	9	NAT	22.2	-73.6

Lifetime (in days)			Maximum Wind (in knots) *	Minimal pressure (in hPa) *	Maximum difference in pressure between the center and the environment (in hPa) *
Total detected	As Tropical cyclone	As Hurricane			
tot_lifetime	TC_lifetime	HR_lifetime	wind_max	pres_min	pres_diff_max
7.75	5.75	1	79	979	15

Maximal storm size *	Maximal storm core size *	Accumulated Cyclone Energy (in 10^4 m/s)	Potential Dissipation Index (in 10^6 m/s)	Maximum IKE (in TJ) *	Track IKE (in TJ) *	Number of landfall
size_max_wind	size_max_pres	ACE	PDI	IKE_max	TIKE	landfall
298	989	7	4	39	171	1

date of the landfall (hour precision, interpolated)	latitude of the landfall (in degree North)	longitude of the landfall (in degree East)	Maximum wind at landfall (interpolated, in knots)	Country hit	Presence of warm core just after or just before the landfall
lf_date.1	lf_lat.1	lf_lon.1	lf_maxWind.1	lf_country.1	lf_warmCore.1

2005-09-24 10:00:00	29.76	-93.75	54	United States of America	1

Table 7: Description of the different column of the file result2_nameExp_member.txt.
It includes all the results computed for each selected storm and at each time step. It is sorted by date. The example comes from the tracking of the Major Hurricane Rita in ERA-Interim.

Description	Name	Date and hour of the timestep	Vortex centre Position		Maximum surface wind (in knots)	Minimum pressure (in hPa)
			Latitude	Longitude		
Name in file	name	date	lat	lon	maxWind	minP
Example	2005091906_222N_0736W_Test_fco	2005-09-23 18:00:00	27.6	-92.2	79	979

Pressure of the environment (last closed isobar, in hPa)	Storm size (mean radius of the last closed isobar, in km)	Storm core size (mean radius of the maximum wind, in km)	Cyclone phase parameters (x10)		
			B (asymmetry)	Thermal wind 900-600 hPa	Thermal wind 600-300 hPa
envP	radiusMaxP	radiusMaxW	Beta	TwindBot	TwindTop
994	169	100	3.8	258	1

Presence of a warm core (a closed isotherm)	Storm moving direction (degrees)	Storm moving speed ($m.s^{-1}$)	Mean 850-hPa Vorticity (s^{-2})	Mean 700-hPa Vorticity (s^{-2})
WarmCore	dir	speed	vort850	vort700
TRUE	310	4.1	NA	NA

Wind radii (nm) for the threshold for each quadrant												Integrated Kinetic Energy (TJ)
Threshold 34 knots				Threshold 50 knots				Threshold 64 knots				
radius W34ne	radius W34se	radius W34sw	radius W34nw	radius W50ne	radius W50se	radius W50sw	radius W50nw	radius W64ne	radius W64se	radius W64sw	radius W64nw	IKE
170	165	0	132	73	0	0	68	0	0	0	0	31.23

2 Summary of the plot produced

All the plots presented here should be found under: *“WORKING_PATH/NAME_EXP/MEMBER.pp/fplot”*

2.1 Histograms

“nameExp_season.eps”: Summary of the seasonal activity, given the mean number of tropical cyclones by month and by basin. It’s a plot of the file *result_basin_basinName_nameExp.txt*

*“nameExp_Hist_**.eps”:* Repartition of some of the variable for all the tropical storm selected, with ** the variable:

- *DiffPres*: Difference of pressure maximum between the center of the low and the environment
- *MaxWind*: Wind maximum
- *MinPres*: Pressure minimum
- *SizePres*: Maximum distance between the center of the low and the last closed isobar
- *SizeWind*: Maximum distance between the center of the low and the maximum in surface wind.

Maximum and minimum values are computed using all the points of the track with tropical storm intensity and warm core

2.2 Maps

“nameExp_point_density.png”: Map of cyclogenesis density defined as the mean number of cyclogenesis per year, around a point of 400km. The cyclogenesis point is defined as the first point of a track where the maximum wind speed exceeds the threshold *WIND_MIN*, which refers to tropical storm by default.

“nameExp_storm_density.png”: Map of track density defined as the mean number per year of storms with a point at less than 400 km of a same point.

“nameExp_tracks-SCALE.png”: Plots of all the tracks selected after the post-processing. The points represent the beginnings of the tracks (first detection). The crosses represent landfalls. The color represent the equivalent intensity of the cyclone on the Saphir-Simpson scale, using the maximum wind corrected to match the 1-min sustained wind value of the scale. No discrimination is made on the map between tropical and extra-tropical part of a tracks.

2.3 Hurricane

A folder called hurricane, beside the previous plots, contained the charts detailing the lifetime of the most intense hurricane detected. They are called *“nameStorm.ps”* and composed by 4 graphs. The upper left one is a map of the track with the color representing the maximum wind at each time step. A represent the beginning of the track, Z the end. The lower left plot is a time series of the maximum wind (violet), the minimal pressure (orange) and the Integrated Kinetic Energy (IKE, in green). The red (blue) dots or lines below the series represent the presence (lack) of a warm core. The two right charts are the so-called phase diagrams, representing the structure of the storm.