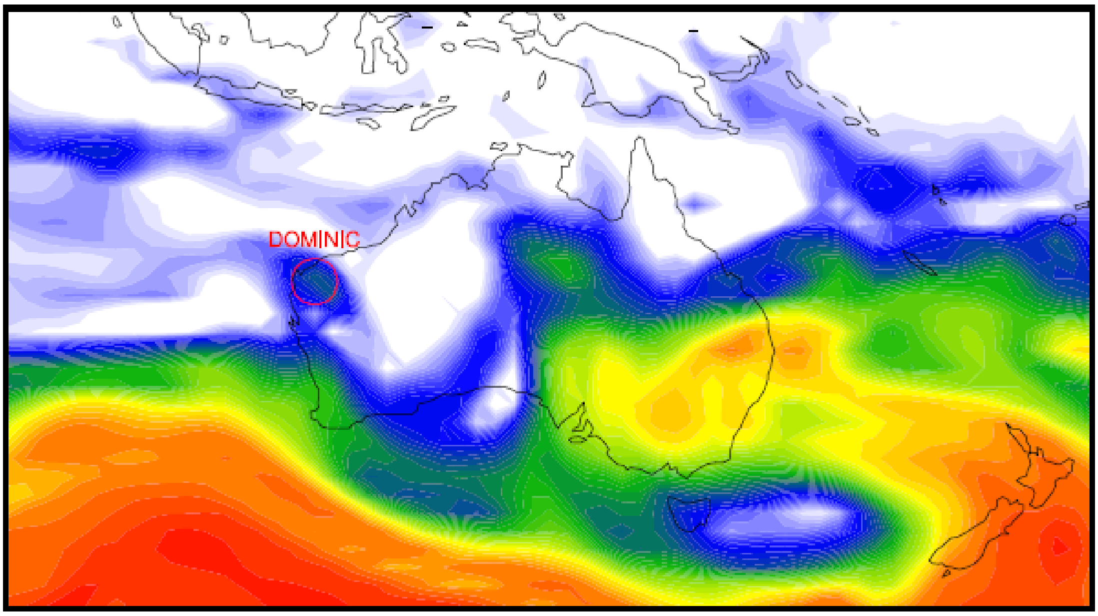
The link between tropical cyclones in Australia and Rossby wave breaking

Thibaut DAUHUT



Internship of research
PhyTEM – first year of Master degree
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Supervisors: Pr. Michael Reeder and Gareth Berry
Laboratory: Monash Weather And Climate

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1 Preamble

1.1 Contact and supervisors

At the beginning of this first year of masters, I attended the lesson 'Introduction to meteorology' by Francis Codron at the Pierre and Marie Curie University (UPMC, Paris 6). Thanks to him, I was able to contact Professor Christian Jakob, researcher in Monash Weather And Climate laboratory (MWAC). After a short correspondence, he suggested for me to discuss an internship option with Professor Michael Reeder who accepted its supervision. The latter proposed me to work on the latest study of Gareth Berry, researcher in MWAC as well.

1.2 Host laboratory

The MWAC laboratory is on Clayton campus of Monash University, in a suburb of Melbourne. This university is the biggest in Australia with 55,000 students and the most international one with eight campuses including one in Malaysia and one in South-Africa, a teaching center in Prato, Italy, and a graduate research school in Mumbai, India. MWAC undertakes research projects in the field of meteorology and climatology. Here are some examples of current works: study of alternation of symmetric and asymmetric phases in cyclone Katrina maturation, study of precipitation in the Australian Snowy Mountains, analysis of the shear over the Southern Ocean, study of the dynamics of gravity wave emission from upper jets and extratropical cyclones, study of the link between heat waves and Rossby wave breakings. The research activities of MWAC have recently received the highest rating of an "outstanding performance well above world standard" in the Australian Research Council's ERA report (Excellence in Research for Australia), making it the leading university-based research group in Atmospheric Science in Australia.

2 Methodology

2.1 Topic of study

In this study we focus on tropical storms and tropical cyclones which hit northern Australia during summer (December, January, February). Our analysis is on the synoptic scale: we envisage influence between phenomena from one side to the other side of the continent. It is a quite modern approach because we consider first the physical quantity *Ertel potential vorticity* whose importance in meteorology does not stop increasing since it has been highlighted by Hoskins and al. in 1985 [2].

2.1.1 Theory about Ertel potential vorticity and observation

Ertel potential vorticity is defined by:

$$P = \frac{\vec{\zeta_a} \cdot \vec{\nabla}\theta}{\rho}$$

where θ is the potential temperature, ρ is the density and $\vec{\zeta_a}$ is the absolute vorticity. Under Ertel's theorem, assuming that the fluid is inviscid and the motion is adiabatic, this quantity is conserved by an air particle, whatever its trajectory:

$$\frac{D}{Dt}P = 0$$

Such a particle conserves too its potential temperature θ during its adiabatic motion. If this particle is in convective balance with its environment then its potential temperature determines its height in the atmosphere. Furthermore, during its motion it will stay on a surface of same potential temperature – we speak about *isentropic* surface[1]. Thus, we choose to represent the Ertel potential vorticity on isentropic surfaces since a particle which is on it, will stay on it [2]. Comment: we will use either *potential vorticity* or even *pv* to speak in an easier way about absolute value of Ertel potential vorticity (this one being almost always negative above Australia, mostly because of the planetary vorticity).

Given that the surface temperature increases from pole to equator, the layer corresponding to a specific potential temperature θ does not have the same height along meridians (closer to the ground in tropics than in mid-latitudes). The layers corresponding to 315 K, 330 K and 350 K potential temperature – on which our analyses will be – cross the tropopause in mid-latitudes, see Figure 1. The stratospheric part (on pole side) is characterised by high values of potential vorticity[2].

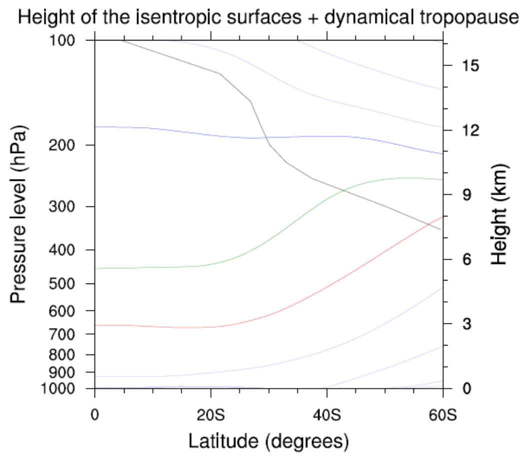

Figure 1: Average height and pressure level for the isentropic surfaces corresponding to 315 K, 330 K and 350 K in red, green and blue respectively. The 275 K, 285 K and 300 K surfaces are visible in grey below and the 370 K and 395 K surfaces are in grey above. The dynamical tropopause (surface of iso-potential vorticity P=1.5 PVU) is represented in black. The method of detection of the dynamical tropopause is described in Appendix, see caption of Figure 11. We notice here that the tropopause cut across our isentropic surfaces in mid-latitudes. The time range used to get the average is January 2000, to give an example of the situation in austral summer.

When we represent the potential vorticity field on an isentropic surface, we observe two parts: the tropospheric part with low potential vorticity values in the low latitudes and the stratospheric part with higher values on the pole side[3]. The pole could be regarded as a reservoir of potential vorticity. But the two parts are not totally uniform and we can see areas of higher potential vorticity in the tropospheric part – we speak about *cyclonic pv anomalies*[4] – and vice versa.

[1]Indeed the definition of θ comes from entropy conservation in adiabatic motion.

[2]The stratosphere is indeed characterised by an high stratification, then a high gradient of potential temperature and finally high values of potential vorticity. The range of those values is between 1.5 and 5 PVU (potential vorticity units) in stratosphere compared to several tenths of PVU in troposphere. 1 PVU = $10^6\ K\ m^2\ s^{-1}\ kg^{-1}$

[3]That can also be explained by the fact that planetary vorticity f is way higher on the pole side and becomes even dominant in the term of absolute vorticity ζ_a.

[4]When we say here 'vorticity value' it is rather 'absolute value' then, whatever the hemisphere, a high vorticity corresponds to a cyclonic one.

Furthermore, the interface between the two parts is not fixed: it is submitted to a phenomenon of undulation known as the *Rossby wave*[5]. Especially in summer, this undulation can be magnified until the breaking of the interface [5]. The reversal of the North-South pv gradient we observe then is what we call the *Rossby wave breaking* [7]. There is an illustration on the front page and on Figure 13 in Appendix.

2.1.2 Standard tropical cyclogenesis and distinction

Usually, when we consider tropical cyclogenesis, we begin by listing the necessary conditions known as Gray's genesis perameters[6] [3]. They are not sufficient for tropical cyclone formation but necessary and can be summarised as the ability to support deep convection in the presence of a low-level relative vorticity maximum and dynamical criteria of daily likelihood of genesis [4].

The main sources of cyclone formation, not described here, are African Easterly Waves, previous Subtropical Storm and especially around Australia: Equatorial Rossby Waves, Mixed Rossby and Gravity Waves and ITCZ[7] Breakdown [1].

In this study we focus on another possibility of precursor for the tropical cyclone formation: anomaly of potential vorticity coming from the stratosphere of the mid-latitudes. Anomaly of vorticity is already within the Gray's genesis parameters but it is *relative* vorticity in the *lower troposphere*. This one can be created by high convection in the tropics for instance. Althought we consider here rather *potential* vorticity, the Figure 12 in Appendix and its caption explain how diabatic convection of humid air can create cyclonic anomaly of *potential* vorticity in *lower* troposphere. As mentioned above, this is not the origin of the anomalies we are interested in. We investigate here the pv anomalies coming from the mid-latitudes, traveling adiabatically on an isentropic surface towards tropics (see Figure 1), where, meeting other factors in favour of cyclogenesis, they potentially lead to formation of cyclones.

2.1.3 Intuition and problems

The first observations of pv field showed that Rossby wave breaking leads to the 'spray' of cyclonic potential vorticity anomalies towards lower latitudes. As the potential vorticity is conserved during the motion of air particles[8], we can follow those anomalies moving along atmospheric streams. As explained above, our hypothesis is that they may lead to cyclogenesis once in tropics. The fact that the season of Rossby wave breaking corresponds to the season of tropical storms in Australia (summer) plays in favour of this hypothesis. Several questions are then raised: to what extent are cyclones actually associated with pv anomaly? Is this anomaly really prior to the cyclogenesis? In other words: what is exactly the relation of cause and effect between anomalies and cyclones? And if we assume that anomalies lead actually to cyclone formation, how many cyclones within all have anomaly coming from Rossby wave breaking as a precursor? Finally, the physical mechanism of influence between a high pv air particle and its environment needs to be established: how, physically, a pv anomaly could lead or help to form such powerful phenomena as tropical cyclones?

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[5] To be correct, a Rossby wave is a wavy solution of the potential vorticity equation. By misuse of language, the undulation of the interface is called after it because it is deeply linked with the potential vorticity equation.

[6] **1:** sufficient ocean thermal energy (SST>26° C to a depth of 60m **2:** enhanced mid-troposphere (700 hPa) relative humidity **3:** conditional instability **4:** enhanced lower troposphere relative vorticity **5:** weak vertical shear of the horizontal winds at the genesis site **6:** displacement by at least 5° latitude away from the equator.

[7] InterTropical Convergence Zone.

[8] Reminder: this motion stays on isentropic surface.

2.1.4 Preliminary study

First we checked that tropical cyclones and storms are indeed associated with pv anomalies. Two ways have been used:

- by representing the pv field for each time step during a season and adding the cyclones tracks (red circles like on the front page)
- by looking for the pv anomalies which match (same position at the same moment) with a cyclone or a storm and by representing their respective trajectories[9].

Those two studies lead to the following conclusion: every cyclone or storm is associated with at least one anomaly on one level. This can be easily understood: even if anomalies are not cyclones precursors, cyclones themselves generate vorticity which appear as an anomaly in the field.

This is particularly practical since we are able to find every storm on a pv map thanks to the anomaly that they generate. We can then focus on the moments prior to the cyclones and determine whether the considered anomaly is already present, and in this case, where it comes from.

2.1.5 Method of work

In chapter 3 a series of hypotheses will be checked by statistical analysis. We will have a general point of view, spatially (our observational window covers Australia) and temporally (we take into account all data of the past twenty years). For each hypothesis, a conclusion is drawn thanks to the work and a criticism concerning the method is formulated.

2.2 Informatical environment

2.2.1 NC Language

Our numerical study is led with the programming language *NCL* (NCAR[10] Command Language). This language is particularly efficient to generate maps on which one can plot physical fields and trajectories. This is why it is broadly used in geography, oceanography and meteorology. The Input and Output files to store the data have the extension `.nc` for NetCDF (Network Common Data Form): storage form of data in multidimensional matrices which all elements share the same type (integer, float, string etc.).

2.2.2 Datasets

The dataset *ERAI : ERA-Interim* (ECMWF [11] ReAnalysis) provides the physical data in the atmosphere since 1989. It is the fruit of a observational data re-analysis in order to make them suitable to the numerical studies. We use especially wind velocity and pv fields (available on 15 potential temperature levels) and the temperature field at the sea level. The temporal resolution is 6h and the spatial resolution is 1.5° (arcdegrees).

[9] This needs a tracking method for the pv anomalies, this method is described below.

[10] National Center for Atmospheric Research is a research and development center in United-States devoted to service, research and education in the atmospheric and related sciences. One of NCAR's missions is to support, enhance and extend the capabilities of the university community and the broader scientific community in understanding the behavior of the atmosphere.

[11] European Centre for Medium-Range Weather Forecasts is an intergovernmental organistation gathering 34 states. It provides meteorological forecasts and datasets for the scientific research.

The dataset *IBTrACS* (International Best Track Archive for Climate Stewardship) gathers all the observations about cyclones and tropical storms (position, category, maximal wind velocity, central pressure etc.).

2.2.3 Track method

The aim is to track the pv anomalies on selected isentropic surfaces. To do it we use two-dimensional fields, at the corresponding potential temperature, provided by ERAI. The data are smoothed n times. We consider a grid point as an *anomaly* only if its pv value is maximum within its neighbours'. Its value must though be higher than a threshold value s. This threshold has been added to avoid detection of minor maxima in the very low latitude margin, where the planetary vorticity is negligible. For the tracking, we consider that one anomaly has moved if the next time step (i.e. 6h later) we detect a maximum *nearby*. The most developed tracking method takes into account the advection due to the wind velocity. The *nearness* of two maxima leading to their association as former position / next position is determined thanks to the control parameter d, 'maximal distance'. The number of smooth passes n, the threshold value for a maximum s and the maximal distance for an association d are the three main control parameters. They got fixed to $n = 1$, $s = 0.01$ PVU and $d = \{5°, 7.5°, 7.5°\}$ for the levels {315 K,330 K,350 K} after several case studies (we observed our results by superposing the pv field, detected maxima and their tracks). Finally we speak about *backtracks* when we track the anomalies back in time (next time step is 6h earlier). This technique makes sense when we look for pv anomaly origin.

The corresponding programs are:

- the code `track_tc_pv_back.ncl` with a position and a date of the first detection of a cyclone as input and backtrack information (position and intensity over time) of the matching anomalies on each of the 3 considered levels as output, stored in `backtrack.nc`,
- the code `basin_all_backtracks_newyear.ncl` with *timor* or *coral* storage matrix (see 3.1) containing storm detections as input and the same thing as the previous code as output, but stored in a bigger matrix containing the backtrack triplets of *every* storm. This is a loop version of the previous code which finds its input (initial positions) in `austorms.nc` file[12].

The anomaly detection as only maximum point within its neighbours has some limitations. It takes into account neither the shape nor the size of the pv anomaly. However it is quite simple to compute. Furthermore, by checking a series of results with the superposition described above we were able to consider our method as relevant: the non-detection of anomalies and the detection of artefacts are negligible compared to *good* detections (we call *good detection* a detection we could have made naked eye given the pv map). We can imagine more developed methods, like for example by tracking the maxima of the Laplacian of the pv field or – more interesting – by determining the contour of the high pv areas (where the gradient is strong for instance) to allow more exotic anomaly shapes but then the tracking becomes terribly more complex.

[12]See overview of the programs at the end of the Appendix for more details and Section 3.1 about this file in particular.

2.2.4 Overview of the programs

The set of codes and input files is summarised by three tables at the end of the Appendix. Way more codes have been written, some were just different versions of previous ones with tiny changes in order to lead specific studies or to get specific plots. Only the main ones are presented here. The last table has been built in order to let the reader know where the Figures proposed in this report are from. The scripts are not given here because their volume is unfortunately too consequent.

3 Achieved work

The studied period, mentioned here by *those past twenty years*, has been arbitrarily chosen from 19 June 1989 to 19 June 2009. The geographic frame, which we call most often *over Australia*, is bigger than the continent surface and corresponds to the area between the equator and the 50° South parallel and between the 100° and the 170° East meridians. The first two sections give some important details about the use of the datasets, Sections 3.1 and 3.2. The first two studies (Sections 3.3 to 3.4) use only the ability to detect anomalies within the pv field. The next three use also the ability to track them over time (Sections 3.5 to 3.7). The last one, Section 3.8, focuses on specific pv anomalies.

3.1 Storm classification over Australia

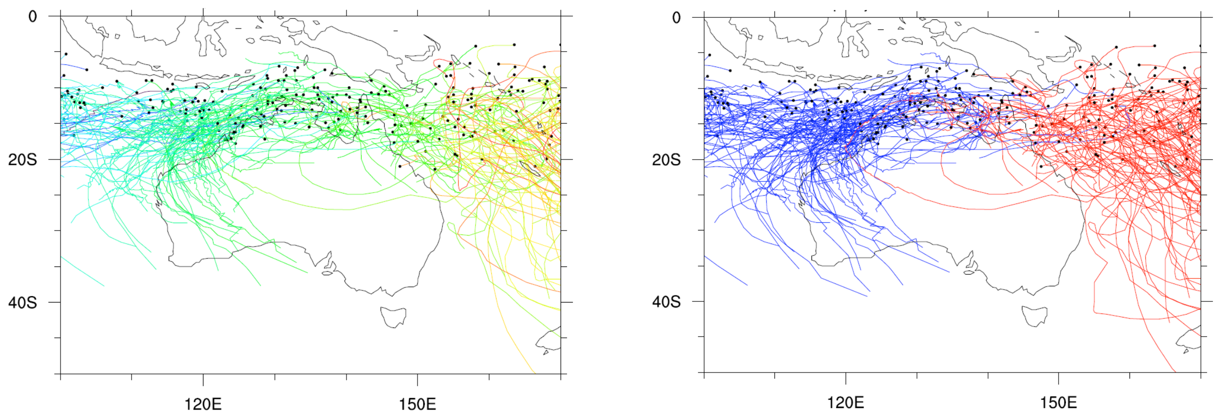

Figure 2: On Left: Trajectories of cyclones and main storms which hit Australia those past twenty years. Black dots represent first detections. On Right: after classification in *Timor* and *Coral* ; easy sorting in function of the longitude of last detection.

First we consider the storms recorded by IBTrACS. When we observe all the trajectories of the storms which have hit Australia, see Figure 2 on Left, we are able to set apart two kinds of trajectories:

- the ones of cyclones coming from tropics in the North part, hitting the Queensland coasts and going towards South-South-East,
- the ones of cyclones coming from North as well but hitting the coasts of Northern Territory and/or Western Australia; their trajectories are often curved towards South-West, traveled anti-clockwise and give the impression to follow the general motion of a Rossby wave breaking – breaking characterized as *anticyclonic* on this side of the Earth.

As storing the data of storms and cyclones over Australia, we kept this distinction in order to confirm this hypothesis: is the link with Rossby wave breaking of certain storms noticeable in their trajectory? The sorting process is quite simple: the storms have been stored in the *coral* matrix if the longitude of their last detected position is greater than 139° East, else in the *timor* matrix. Practically, the two matrices have been saved in the NetCDF file `austorms.nc`. The result of this sorting is shown on the Right of Figure 2, and despite some mistakes, it has been considered as enough satisfactory. This distinction led mostly to double the amount of code to write thereafter but enabled us in certain cases to check hypotheses or results.

Quantitatively, within the 207 storms recorded by IBTrACS which hit Australia those past twenty years, we count 82 of the first kind, called *coral* because their trajectories follow roughly the shape of the Great Barrier Reef, and 125 storms of the second kind, named *timor* after one of the basins in the North of Australia.

This distinction has turned out to be almost non relevant regarding the geographical origin of the pv anomalies associated with the storms (used to determine whether the storms are linked to Rossby wave breaking), as described in the section 3.7.

3.2 On which level should we track pv anomalies?

In this study we consider the pv field on the isentropic surfaces corresponding to the 315 K, 330 K and 350 K potential temperatures. Please refer to Figure 1 to know the corresponding height and pressure level during a month of summer. Those three levels have been chosen because they cut across the tropopause in the mid-latitudes; we can thus observe the Rossby wave breaking over Australia. As seen in the preliminary study the storms are systematically associated with cyclonic anomalies at least on one of the three levels. Although on the 350 K level this is less obvious because as the convection is particularly strong in cyclones and so the latent heat release is, an anticyclonic anomaly is generated at its top [6] (see explanation given in the caption of the Figure 12). It happens though after a certain lead time of maturation of the cyclone. The association storms – cyclonic anomalies has some limitations on this level but stays relevant in almost all cases.

We can reasonably wonder whether one of the levels is the most relevant to associate storms to pv anomalies. No specific study has been undertaken but all following analyses tally to assert that the 330 K level is still the best to track anomalies as cyclone *precursors*[13].

3.3 Seasonal fluctuations of pv anomaly number

Our initial hypothesis is founded on the correlation between cyclone favourable period (austral summer) and Rossby wave breaking season (roughly from October to May, what we call here *summery period* even if it lasts more than half a year) [7]. On the contrary, during austral winter (June, July, August) the tropopause interface on isentropic surfaces is also submitted to undulation but way less often to proper wave breaking. This fundamental distinction within the pv field can be observed on the Figure 3. To analyse how relevant the cause and effect link between Rossby wave breakings and pv anomaly spray towards the tropics is, a statistical study of the number of pv anomalies *over Australia* over time has been undertaken. The results are shown on the Figure 4.

[13] The precursor nature still needs to be established so much physically, which stays as a qualitative hypothesis here, as temporally, which will be studied later.

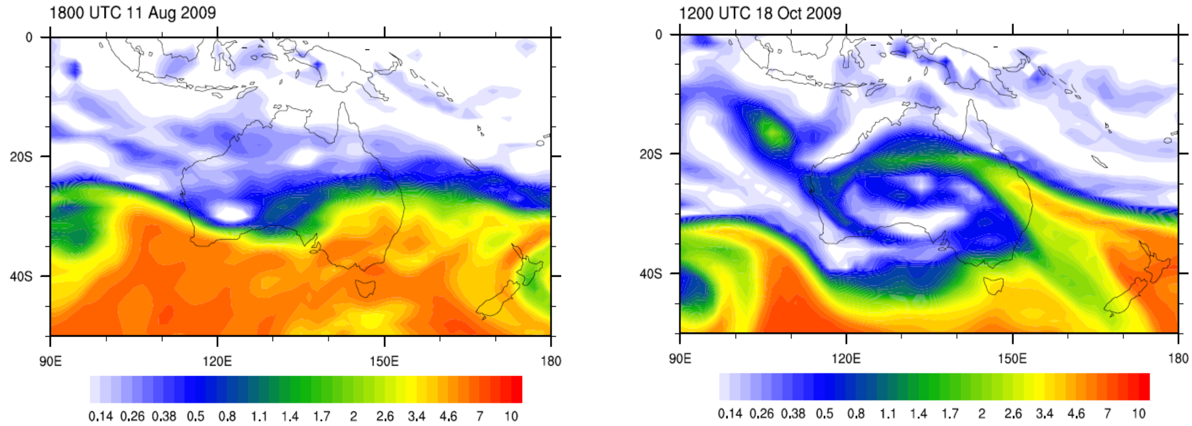

Figure 3: Examples of pv fields on 330 K isentrope in winter and in summery period, on Left and Right respectively. Those are the pv field at 6pm UTC on 11 august 2009 and at 12pm UTC on 18 october 2009. Other pv fields in summery period are proposed in Appendix, see Figure 13.

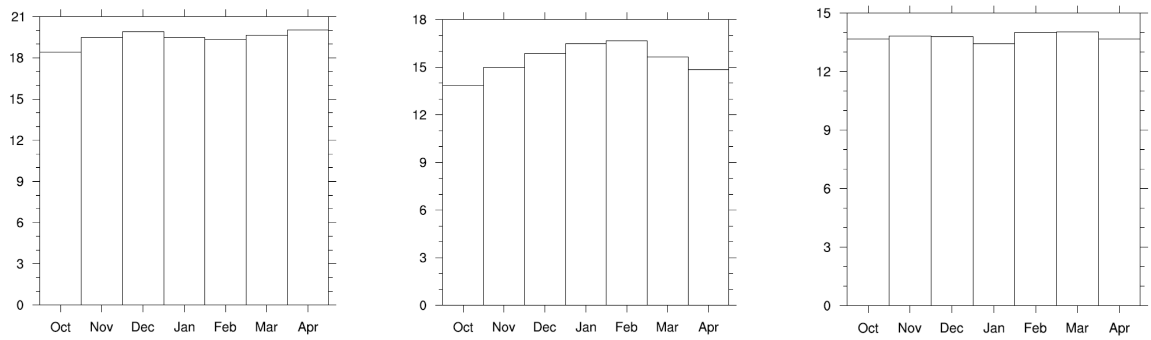

Figure 4: **Average number of pv anomalies *over Australia*.** The average is made over each month of the summery period and over the past twenty years. On Left the anomalies have been detected on the 315 K level, in the Middle on the 330 K level and on Right on the 350 K level. On the 350 K level, the fluctuations are too tiny to be able to draw any conclusion. So we can say that there is so no variability of pv anomaly number on the 350 K level, considering our method of detection. The curves showing anomaly average number evolution over one season for two different years are in Appendix, Figure 14. Another study has been led considering a smaller geographical window, to focus on the anomalies in the mid-latitudes; see Figure 10.

Only on the 330 K level we do observe an increase of pv anomaly number *over Australia* during spring until mid-summer and then a decrease in autumn. This seems to reflect the increase of Rossby wave breakings during summer and then confirm our field observations as on Figure 3. Note that this count of pv anomalies depends obviously and strongly on the detection method and that this latter is objectionable. Furthermore, the evolutions we got are particularly flat. That can be explained by the fact we chose a quite big window of observation. A more specific area has been delimited after the Section 3.7 and the following results are more satisfactory, see Section 3.8.

3.4 Correlation between storm number and pv anomaly number/intensity

As we think that pv anomalies could lead to storm genesis, we wonder whether during the profuse years for storms we also observe more pv anomalies than usually. Then we carry out a study of the correlation between storm number and the average number of pv anomalies during the corresponding summery period. We also consider the intensity of the pv anomalies. To count the number of storms per season we use the IBTrACS dataset. To count the pv anomalies over Australia and compute their mean intensity we use the detection method described in Section 2.2.3. The results are shown on Figure 5.

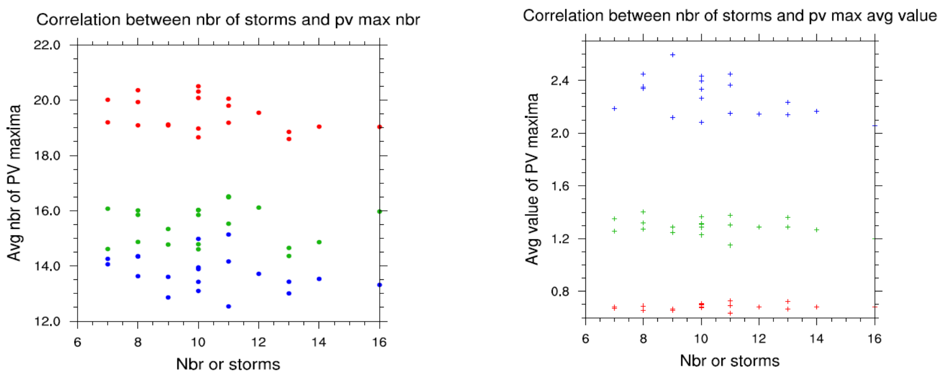

Figure 5: On Left: Average number of pv anomalies over Australia during a summery period over the number of storms the same season. Red, green and blue for 315 K, 330 K and 350 K levels. On Right: Mean intensity of the pv anomalies during a summery period over the number of storms the same season. No correlation has been found. Other attemps in Appendix, Figures 15 and 16.

There is neither correlation between storm number and pv anomaly number the same year nor between storm number and pv anomaly mean intensity. Again, we can object that the region considered to count the pv anomalies is too big. This study has been led again in Section 3.8 with a more specific area of interest but no more correlations have been found.

3.5 Behaviours of pv anomalies before storm formation

When we represent the trajectories of the anomalies we succeded to track, we observe several behaviours on the different studied levels. Two main behaviours are particularly interesting. In several cases, the pv anomalies follow a curved trajectory rolling up anticyclonicly like the Rossby wave breaking. This kind of behaviour is illustrated by Billy cyclone, see Figure 6 where Erica cyclone has been added for comparison. In other cases, we notice that anomalies from different levels and from different direction are meeting a bit before being associated with a cyclone or a storm. This kind of behaviour is illustrated by Tina and Frank cyclones, see Figure 7.

A manual study of all the backtracks has been led to determinate the proportion of the different kinds of trajectories we have highlighted. The results are summarised in Table 1. It reveals that the part of cases where anomalies from different levels meet before storm genesis is not negligible: about one quarter. On the other hand the curled trajectories are quite rare but interstingly, we found them only within *timor* storms i.e. storms having themselves a curled trajectory. This study is particularly subjective and is proposed here mostly to give an idea of which kind of backtracks we obtained eventually.

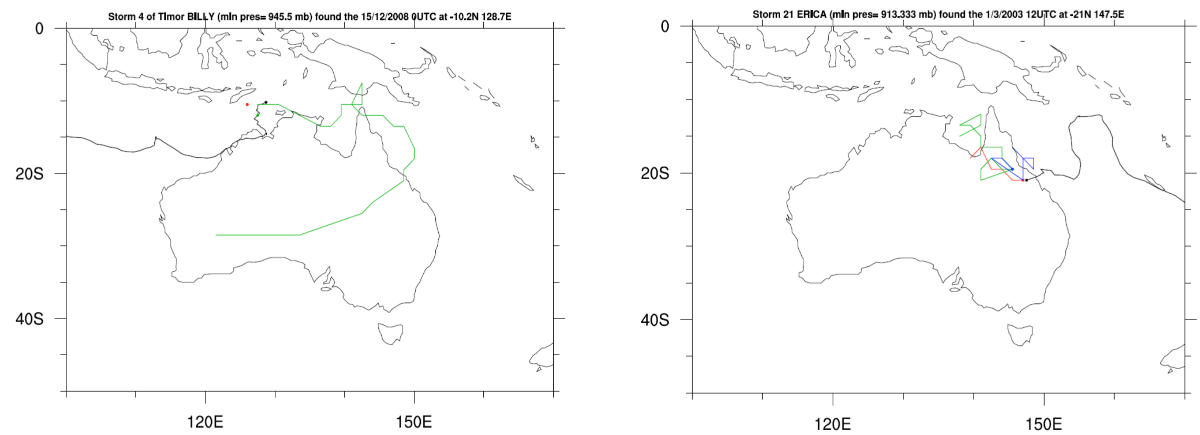

Figure 6: On Left: The track of the anomaly associated with Billy shows an 'anticyclonic' motion (roolling up anticlockwise), similar to Rossby wave breaking. On Rigth: For comparison, anomalies associated with Erica cyclones do not have such a trajectory. Red, Green, Blue for levels 315 K, 330 K, 350 K.

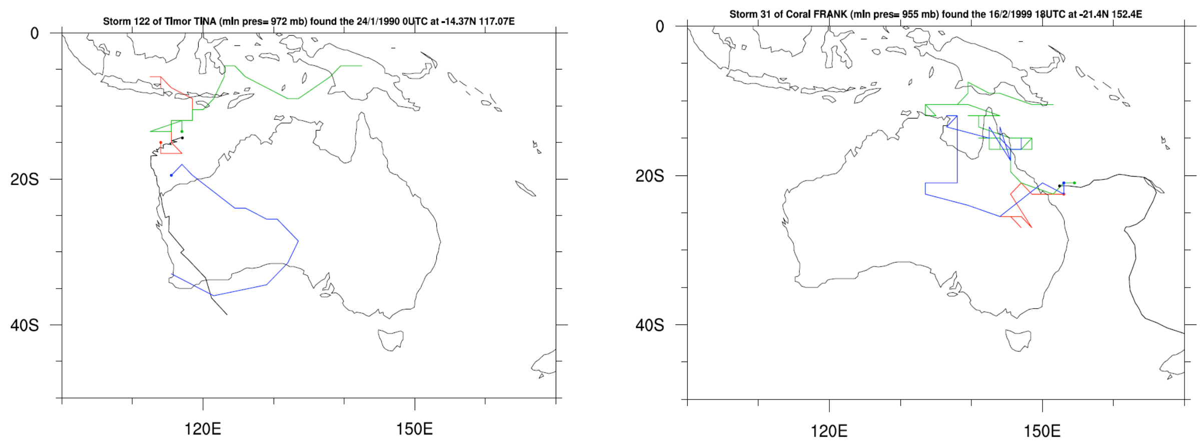

Figure 7: Two examples of cyclones whose anomalies from at least two different level come from different areas and meet a bit before cyclogenesis. Red, Green, Blue for levels 315 K, 330 K, 350 K.

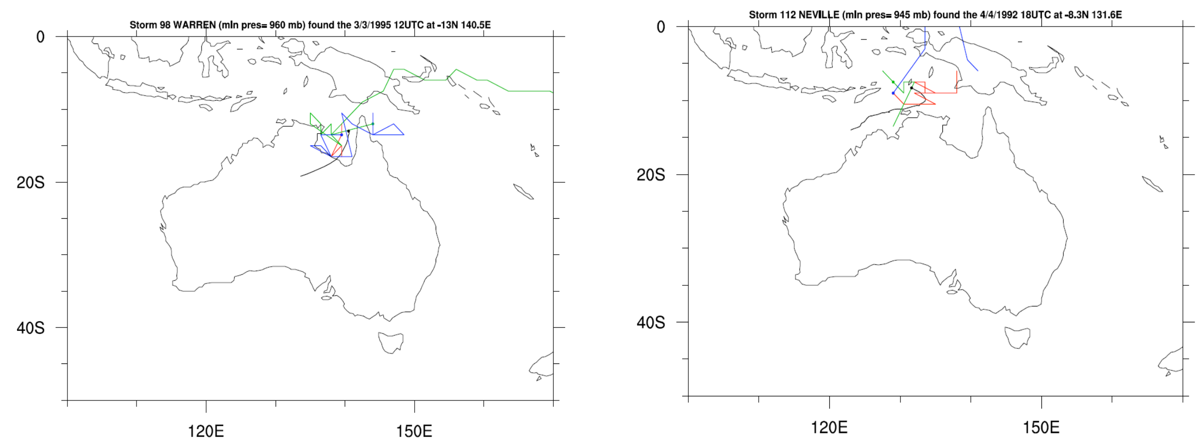

Figure 8: Two examples of cyclones whose anomalies have an erratic trajectory. Red, Green, Blue for levels 315 K, 330 K, 350 K.

Kind of trajectory	Timor	(percentage)	Coral	(percentage)	Total	(global percantage)
curled	6	4,8 %	0	0 %	6	2,9 %
merge	33	26,4 %	15	18,3 %	48	23,2 %
erratic	38	30,4 %	17	20,7 %	55	26,6 %
indeterminate	25	20 %	15	18,3 %	40	19,3 %

Table 1: Statistics on the kind of pv anomaly trajectories observed. The two first kinds are not incompatible.

Level	mean length	standard deviation
315 K	3.5	3.13
330 K	5.75	4.18
350 K	2.5	2.93

Table 2: Statistics on backtrack lengths of pv anomalies associated with the considered storms. The data are here **in days**.

3.6 Precursor nature of pv anomalies

Having the backtracking program described in 2.2.3, we can wonder how long we are able to track pv anomalies associated with storms back in time. This lead to statistical results shown on diagrams of Figure 19 in Appendix. The means and standard deviations of the backtrack lengths are given by the Table 2.

With our tracking method, though simple, we are able to track pv anomalies associated with storms about 3 days before storm genesis (even if they are only at a stage of tropical low). On 330 K the result is even more satisfactory since we are able to notice an anomaly 5.8 days before the first detection of the associated storm in average. So long before the storm genesis, we can assert that the anomaly is no more a consequence of the storm but rather considering the anomaly as precursor. The cyclonic anomaly origin remains to be identified: does it come form a strong convection area in the tropics or rather from an air particle coming from the mid-latitudes and carrying a high potential vorticity, as we suspect?

3.7 Geographical origin of pv anomalies

Now we would like to check whether the pv anomalies associated with cyclones come indeed from Rossby wave breaking. As wave breakings happen in the mid-latitudes, whatever the considered level[14], an easy way to check it is to find the origins of the pv anomalies and to determine their latitude. All the backtracks of pv anomalies associated with storms over the past twenty years and on the three considered levels are stored in `all_backtracks.nc` file. We consider the last position of those backtracks i.e. the most prior detection before the storm. In chronological order, it is the first detection of an anomaly which eventually leads to a storm. Then we carry out a statistical study on the latitude of this first detection. For instance, the cyclones on Left of Figures 7 and 6 are associated with anomalies coming from the mid latitudes whereas those of the Figure 8 are not.

[14] Note: Rossby wave breakings happen in higher latitudes for lower levels, thus Rossby wave breakings on 350 K is way closer to tropics than on the 315 K and 330 K levels.

Level	Mean latitude of origin	Std deviation	Ratio from the mid-latitudes
315 K	12.7° S	4.42°	1.66 %
330 K	13.1° S	6.53°	**10.6 %**
350 K	11.8° S	6.61°	5.56 %

Table 3: Statistics on the latitude of the first detection of pv anomalies leading to a storm over Australia. We call mid-latitudes the area more southern than the 22° South parallel. The Table 4.3.4 shows the results taking into account the distinction between *timor* and *coral* storms.

The results of this statistical study is summarised in the Table 3. We notice that a non negligible part of the storms are associated with pv anomalies coming from the mid-latitudes (latitudes higher than 22° S): about 10% on the 330 K level and so more than 10% are associated with at least one anomaly (on any level) coming from mid-latitudes. One other result is that there is no significative differences between *timor* and *coral* storms. The *timor* storms do not seem to be more associated with anomalies coming from mid-latitudes i.e. from Rossby wave breaking. Thus, the initial distinction is not really relevant.

We can also plot all the trajectories of the pv anomalies associated with storms, on each level, see Figure 17 in Appendix. All the earliest detection of anomalies associated with storms are shown on the Figure 9. Here the mean position of the earliest detections is represented by a cross whose size is the corresponding standard deviation. The last map of Figure 9 shows the position of the storm genesis (black dots), the mean position and the standard deviation (black cross) and the past three crosses (red, green, blue) for the mean position of the earliest detection of the pv anomalies on the 315 K, 330 K and 350 K levels respectively. We observe then a light trend for the pv anomalies to come from the South-East.

The tracking method is quite limited (we often lose an anomaly during its backtrack) and so the expression 'origin of the anomalies' needs to be considered carefully. However this study attempted to operate at most this simple tracking method and eventually the results we obtained are already quite promising.

3.8 Focus on the mid-latitude pv anomalies

As we know now that a non negligible part of the tropical cyclones and tropical storms of Australia are associated with pv anomalies coming from the mid-latitudes, we are able to lead again some of our previous studies focussing on those specific storms. Especially, we have relaunched the detection of pv anomalies, no more over all Australia, but in a *box* delimited by the 22° and the 37° South parallels and the 110° and the 170° East meridians. The seasonal fluctuations is illustrated on Figure 10.

We observe now a clear increase of the number of pv anomalies on the 315 K and 330 K levels in this *box* during summer. This can be explained by the motion of the tropopause during the year: on a considered insentropic surface, the tropopause is indeed in higher latitudes during summer. The *box* contains then more troposphere in which we detect more pv anomalies than in stratosphere. In those high latitudes, pv anomalies are mostly provided by Rossby wave breaking and correspond to the potential vortex precursors leading to cyclogenesis. The evolution on the level 350 K is not so clear. We suppose that is due to the fact that the box correspond to a stratospheric part on the level 350 K during the most of the period October-April considered. We tried too to find any correlation between the number of anomalies in this

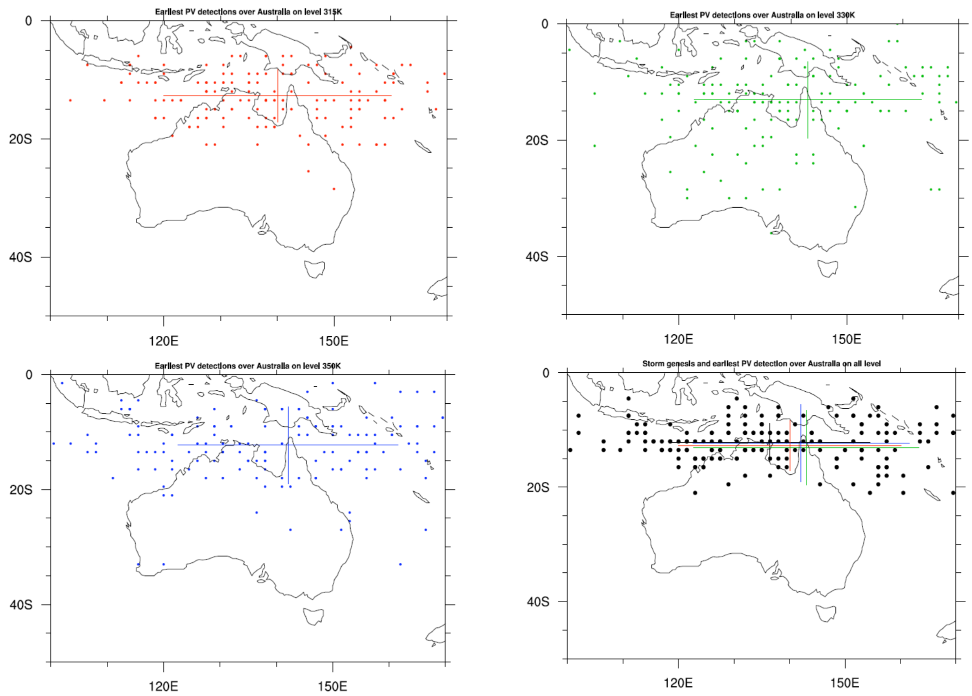

Figure 9: Top Left, Top Right and Bottom Left are the positions of the earliest detection of the pv anomalies leading to storms over Australia, respectively on the levels 315 K (red), 330 K (green) and 350 K (blue). The crosses show the average position in each case, their size corresponds to the standard deviation. The last map represent the position of the first detections of the storms, the black cross show the average position and standard deviation and the pv anomaly origin in average is reprented again by the colored crosses. Maps of the pv anomaly backtracks on each level can be found in Appendix, Figure 17

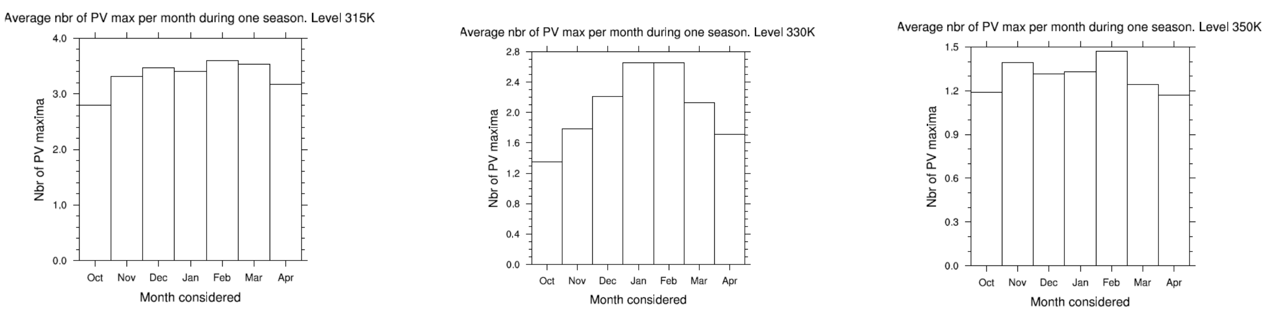

Figure 10: Average number of pv anomalies in the *box* (defined in section 3.8). The average is made over each month of the summery period and over the past twenty years. On Left the anomalies have been detected on the 315 K level, in the Middle on the 330 K level and on Right on the 350 K level. We get now the same evolution on the level 315 K as on the level 330 K. On the 350 K level, we are still not able to draw any conclusion because the fluctuations are now too erratic.

box or their intensity with the number of storms or tropical cyclones like in Section 3.4 but it has been fruitless; see Figure 20 in Appendix.

4 Conclusions

4.1 Outcome of the study

In this study, we highlighted the pre-existence of potential vorticity anomaly in the formation of cyclones or tropical storms. Those anomalies are noticeable in the atmosphere, especially on the 330 K level, about 5 days before the genesis of the storm. This, even with a simple tracking method as the one we used, described in the Section 2.2.3. It could be particularly worthy for meteorological forecasters. However, during profuse years for tropical storms we have not observed any increase of pv anomaly number or intensity. The exact origin of those anomalies has not been established but in 10% of all cases we have been able to track them further than 22° South, which let think that they have not been generated in the tropics. The phenomenon of Rossby wave breaking, which is observed over Australia roughly from October to May, is by our observations a suitable way to produce cyclonic pv anomalies in the mid-latitudes.

4.2 Possibilities of future research

Many possibilities are left for further investigations. First, the tracking method can obviously be improved. Gareth is implementing a method to track contours rather than only dots moving in the time. Second, all the physic analysis of the influence of a high potential vorticity air particle has to be carried out. This was planed in my project but had to be given up because of lack of time. Then a method of detection of the phenomenon of Rossby wave breaking could be developed. Finally, many times we were able to observe pv streamers, due to Rossby wave breaking, stretched and then destabilized, leading to several pv anomalies. This intermediate phenomenon could be an interesting topic of research.

4.3 Self improvement

4.3.1 Interest for the domain

This internship was first and foremost the opportunity for me to know if I enjoyed to work as researcher in a domain I have always been appealed to: meteorology. I have to thank sincerely Michael Reeder and Gareth Berry to have proposed to me this topic of internship and to have regularly helped me to carry on this project, I definitely enjoyed it. The more I learn in meteorology, the more I want to know and this is why I am still keeping as aim to become a researcher in this field. I thank Michael for letting me attend his lesson of 'Advanced Dynamical Meteorology' too. It helped me to understand better my topic of investigation, to learn a lot about Rossby waves and to get some advance and curiosity for my studies next year. Concerning the "*tools*" to lead our research, I have always enjoyed numerical physics but I was first a bit afraid to have to work all the time on computer. It has not been so terrible finally. It has been the opportunity to learn all about NC language and to see how efficient it is. However I am still thinking that our investigations could be supplemented by some fluid mechanics experiments (a bit like I did last year) and I hope to have the opportunity once to work at the interface of experimentation and numerical analysis.

4.3.2 Journal Club

The life in the laboratory has been quite pleasant in great part because I met very nice and interesting people there. There has been a really enjoyable team dynamic. Within all I have to note an initiative that I found extremely worthy for everyone and which was supervised by Maria Tsukernik as I was in MWAC: the Journal Club. The principle is simple: every two weeks, the people who want come with one article they found in a scientific Journal and summarise it in five minutes. The references are shared so that everyone can find the paper after the review. As nobody is able to have an exhaustive knowledge of all what is published in meteorology and climatology (excepted perhaps people of the Intergovernmental Panel on Climate Change, IPCC, whose incredible job takes a whole year of their career of exhaustive review) the necessity to be up to date about the current research by reading publications must be faced collectively. This cooperation is necessary and the lab team is the ideal frame, in my opinion. We are able to provide an enlightened point of view about the interest of every paper and each review leads to a series a question we try to solve together. This is the opportunity to learn about one's own field of investigation but also to get some knowledge about other fields, especially the ones in which the other fellows of the laboratory are.

4.3.3 English in Science

The laboratory was extremely cosmopolitan and I consider it as a wealth too. There were many English speakers coming from all over the world like United-Kingdom, South-America, New-Zealand, United-States, Singapore and Australia of course but also many non-native English speakers coming from Germany, China, Croatia, India etc. The importance of English to communicate and share opinions was crucial. This is why I wish we, French people, had had an instruction in English more focused on oral expression and comprehension, especially "in the field". In my opinion exchanges of students between our country and English speaker ones should be encouraged and developed. Moreover as I was first writing my report in French, I realised how much I was isolating myself from the advice my supervisors, my colleagues or even my housemates could give me. It led to make me do double amount of work. This is why, even if I am quite proud to write science in French, I think that writing the report in English should rather be encouraged than dissuaded. This is a good way to improve our skills as well.

4.3.4 Life in Melbourne

Finally I just want to mention that this internship gave me the opportunity to visit and live in Australia, which I value extremely. I am particularly satisfied to have met so many interesting and worthy Melbournians, especially my housemates and their friends, and to have begun to discover the incredible city of Melbourne. Moreover, the internship is extremely formative as it allows us to experience the life in laboratories, to face our future job and to get into the scientific community. I also made the most of being on a lively campus by taking part to the Wholefoods cooperative. This is a vegetarian/vegan restaurant held and run by the students, using local production and offering varied range of meals. This good alternative to the fast food restaurants around also allows us also to get to know other students of the university better. Eventually, I wish to add that Monash University has allowed students to make grow a permaculture garden on its campus of Clayton and this led to a fruitful experience for the people involved. The project is that it would eventually supply Wholefoods with fresh vegetables and aromatic herbs. This kind of initiative, collective and innovative, makes definitively sense within the projects of the associative community of a university. I look forwards to seeing such cooperative or projects on my own campus and I will do my best in this aim.

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Appendix

Determination of the height of the dynamical tropopause

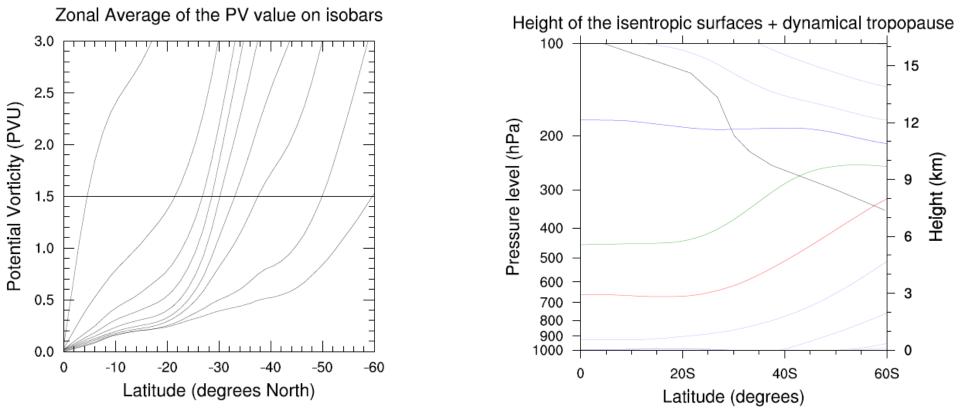

Figure 11: To determine the height of the dynamical tropopause we plotted the zonal average of the pv value on isobar surfaces. From left to right, the curves correspond to 100, 125, 150, 175, 200, 225, 250, 300, 350 hPa isobars. The threshold defining the dynamical tropopause (border between troposphere below and stratosphere above) is here $P = 1.5$ PVU. Indeed we find lower values of pv in troposphere and higher in stratosphere. For each isobar, we note the latitude corresponding to 1.5 PVU. Then we are able to add the position of the dynamical tropopause on the chart of the Right, respresenting the position of the isentropic surfaces along a meridian in summer (here in January 2000).

Creation of potential vorticity dipole due to diabatic heating

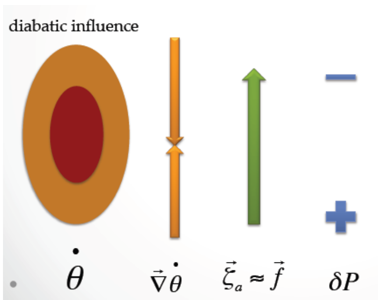

Figure 12: Extract of the presentation made on the occasion of Michael Reeder's lesson (Review of the article of Möller and Smith, 1993, [6]). It describes the diabatic creation of a dipole of potential vorticity due to the strong convection as the one in the eyewall of a cyclone. The equation of evolution is $\frac{D}{Dt}P = \frac{\vec{\zeta_a}\cdot\vec{\nabla}\dot{\theta}}{\rho}$. $\dot{\theta}$ represent the diabatic heating due to latent heat release during the convection. The heating function is represented here by the orange-red ovals, its gradient by the orange arrows. The scalar product with the vorticity vector (here in Northern Hemisphere, represented by the green arrow) leads to the potential vorticity dipole: cyclonic at the bottom and anti-cyclonic at the top. Similar reasoning in Southern Hemisphere leads to cyclonic disturbance of potential vorticity in the lower level too.

Other examples of Rossby wave breaking

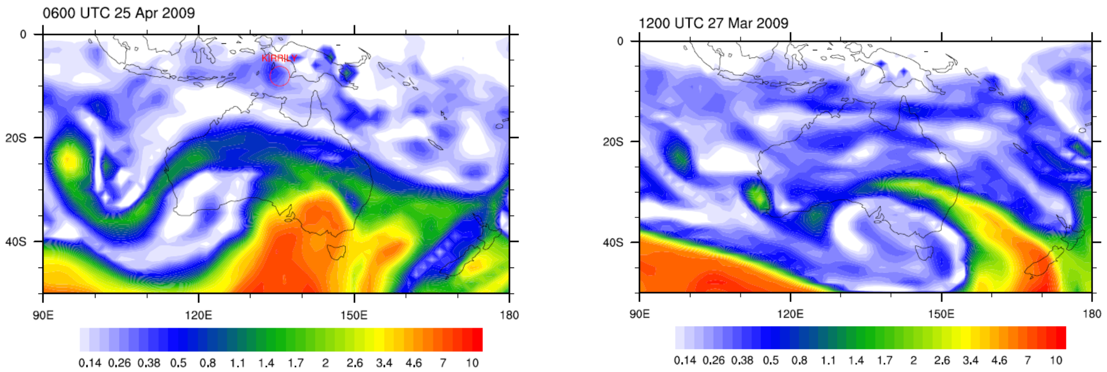

Figure 13: PV field at 6 am UTC on 25 April 2009 and at 12 pm UTC on 27 March 2009 on Left and Rigth respectively. We can clearly see the streching of a high potential vorticity streamer after a Rossby wave breaking. This streched area "on the top of the wave" got destibilized and left some spherical anomalies like on the Rigth picture. The aim of our project is to track those anomalies.

Evolution of the number of pv anomalies during two summery seasons

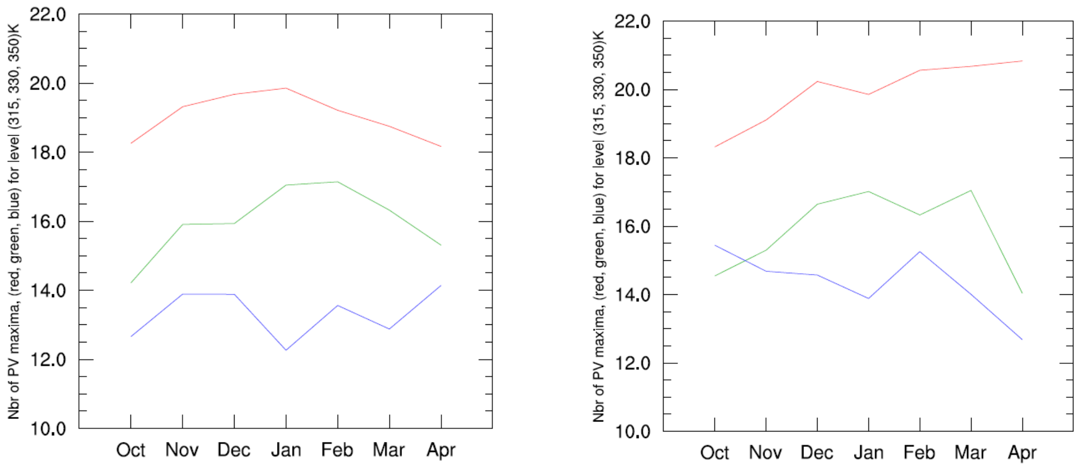

Figure 14: On Left for the year 2008 and on Rigth for the year 2001. The red, green and blue curves correspond respectively to the 315 K, 330 K and 350 K levels.

Correlation between *cyclone number* and two parameters

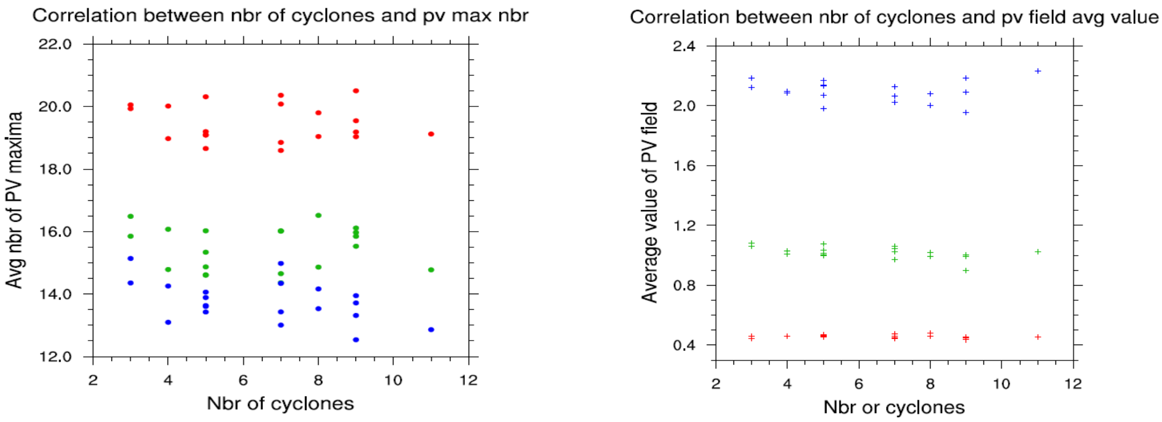

Figure 15: On Left: Average number of pv anomalies over Australia during a summery period over number of **cyclones** the same season. Red, Green, Blue for 315 K, 330 K and 350 K levels. On right: Average value of the pv field during a summery period over number of cyclones the same season. Here the cyclones have been count within the database of http://weather.unisys.com/hurricane website. No correlation has been found.

Correlation between *tropical storm number* and two parameters

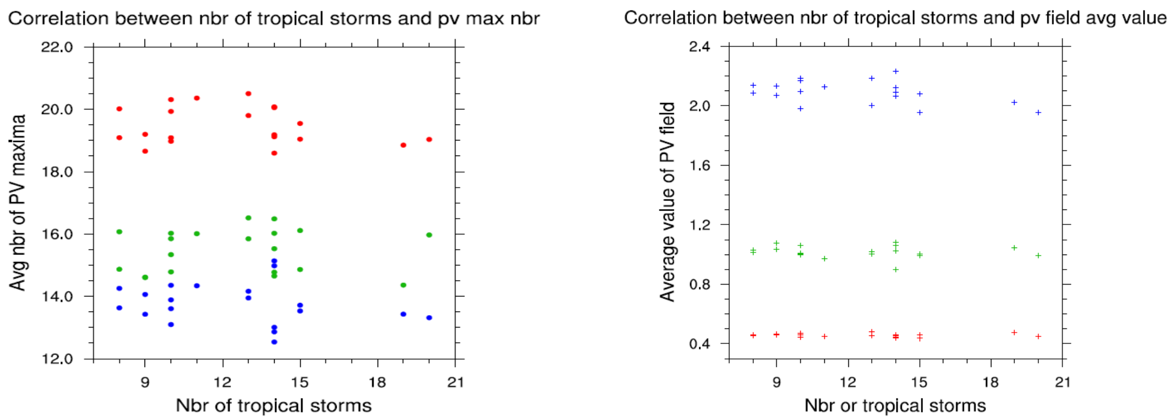

Figure 16: On Left: Average number of pv anomalies over Australia during a summery period over the number of **cyclones and tropical storms** the same season. Red, Green, Blue for 315 K, 330 K and 350 K levels. On Right: Average value of the pv field during a summery period over the number of cyclones and tropical storms the same season. Here the cyclones and tropical storms have been count within the database of http://weather.unisys.com/hurricane website. No correlation has been found.

Trajectories of the pv anomaly backtracks

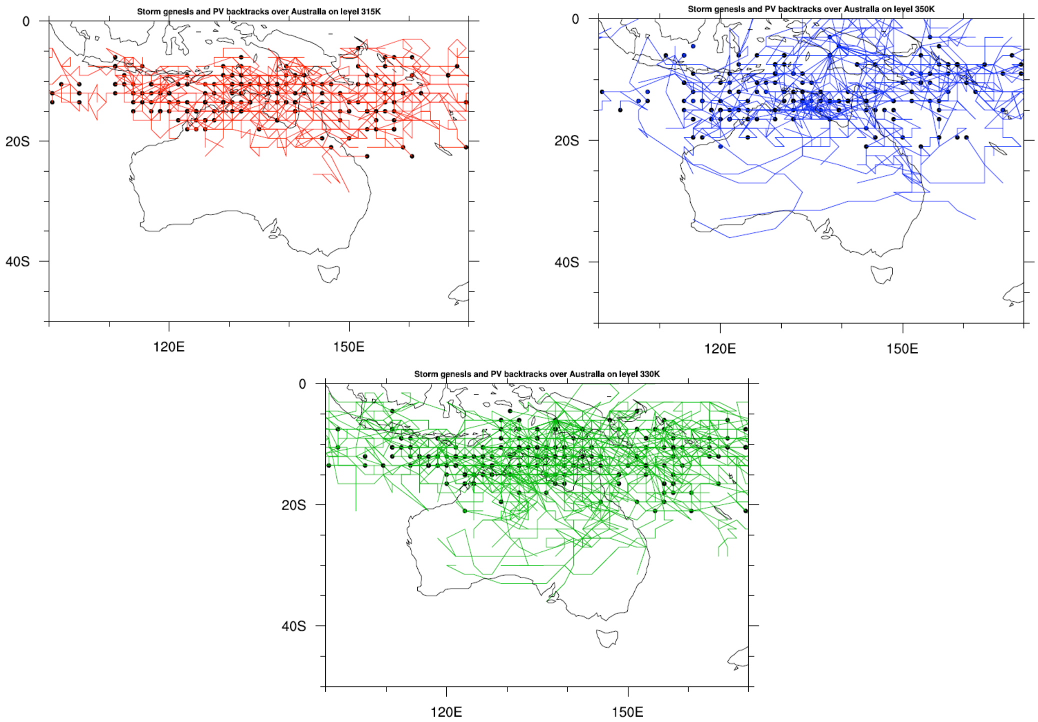

Figure 17: The backtraks of the pv anomalies leading to storms are represented for each level: in red for the 315 K level, in green for the 330 K level and in blue for the 350 K level.

Statistics on latitude of earliest dection of the anomalies

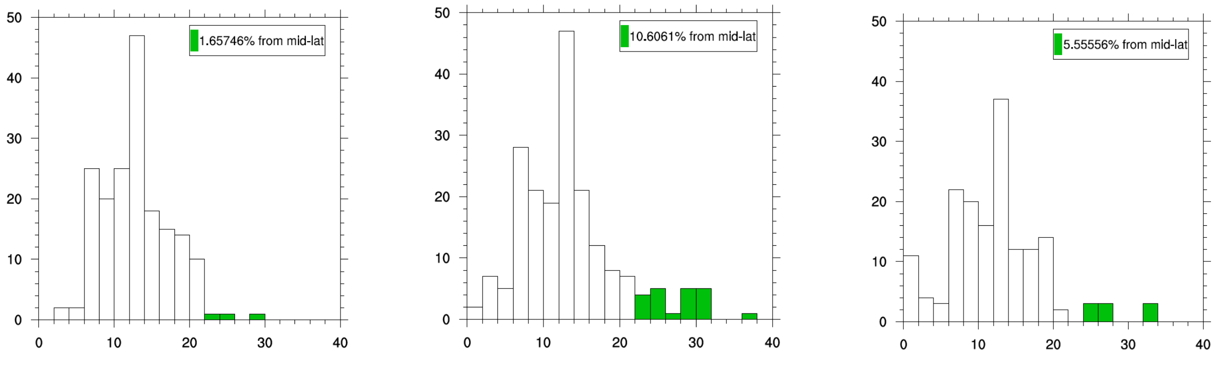

Figure 18: **Number of anomalies over latitude** (in degrees South). This is the statistics on the latitude of earliest dection for each anomaly associated with a storm over Australia those past twenty years. From Left to Right the anomalies are found on the 315 K, 330 K and 350 K levels respectively.

Statistics on the length of the backtracks

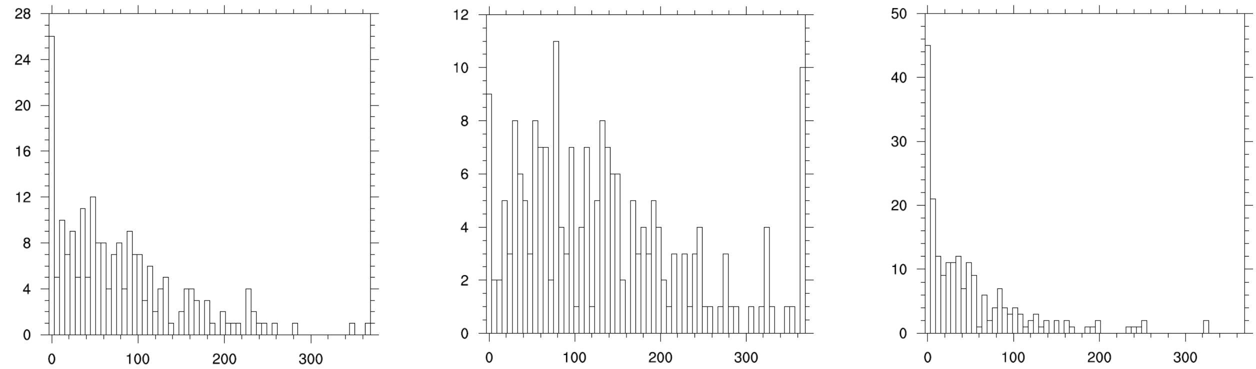

Figure 19: **Backtrack number over their length in hours**, for all the storms over Australia those past twenty years. On the 315 K, 330 K and 350 K levels respectively from Left to Right.

Full Table about the statistics of the geographic origin of the pv anomalies

Basin	Level	Mean latitude of origin	Std deviation	Ratio from the mid-latitudes
Timor	315 K	12.5° S	4.46°	1.74 %
Timor	330 K	13.0° S	6.52°	10.6 %
Timor	350 K	12.3° S	6.71°	6.80 %
Coral	315 K	13.2° S	4.32°	1.52 %
Coral	330 K	13.3° S	6.54°	10.7 %
Coral	350 K	10.9° S	6.33°	3.39 %
Both	315 K	12.7° S	4.42°	1.66 %
Both	**330 K**	13.1° S	6.53°	**10.6 %**
Both	350 K	11.8° S	6.61°	5.56 %

Correlation between storm number and pv anomaly number/intensity in the *box*

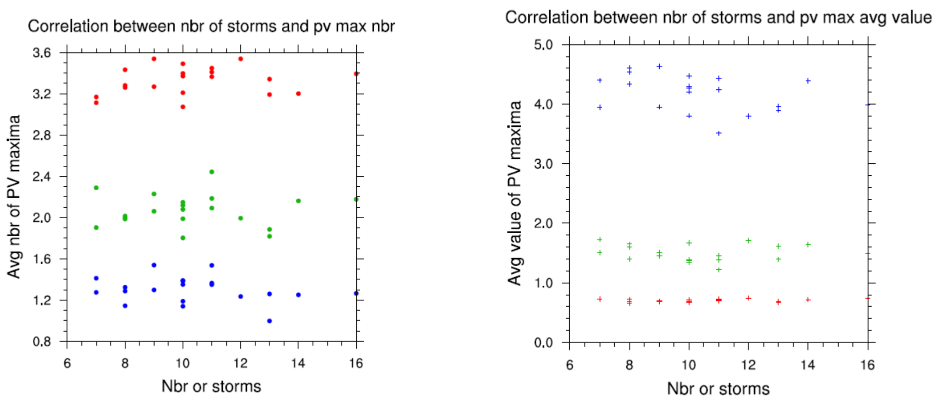

Figure 20: On Left: Average number of pv anomalies in the considered *box* during a summery period over the number of storms the same season. Red, Green, Blue for 315 K, 330 K and 350 K levels. On Right: Mean intensity of the pv anomalies during a summery period over the number of storms the same season. No correlation has been found neither.

Overview of the datasets and data storing files

Short name	Description
e	Contains physical field data provided by ERAI
i	Contains storm information recorded by IBTrACS
c	Contains the number of pv maxima for each time step on each level
a	Records only stoms over Australia those past twenty years
b	Tracks pv anomalies associated with each storm of *timor* or *coral* matrix

Short	File name	Generating code	Input
e	ERAI dataset	N/A	N/A
i	Allstorms.ibtracs_all.v03r02.nc	N/A	N/A
c	pv_counter_compiled.nc	pv_max_multiple_detector.ncl	e
a	austorms_named.nc	ibtracs_timor_coral_named.ncl	i
b	all_backtracks.nc	basin_all_backtracks_newyear.ncl	a

Overview of the programs

Figure no.	Generating code	Input file(s)
frontpage	plot_pv_with_tctracks.ncl	e i
1 and 11	isentrops.ncl and isobars.ncl	e
2	ibtracs_timor_coral_named.ncl	i
3 and 13	track_pv_test.ncl	e
4, 10, 14	diagrams_plotter.ncl	c
5, 15, 16, 20	year(_manual)_evolution.ncl	a c
19	check_allwaves_backtrack_stat.ncl	b
6, 7, 8	storm_precursors_named.ncl	a b
9 and 17	summary_australia.ncl	b
18	statistical_lat_origin.ncl	b

Calendar

Week	Activities	Section
18 April	learning NCL, understanding Gareth's code `track_match_tc.ncl`	2.2.1
25 April	administrative duty, begining Michael's lesson *Advanced Dynamical Meteorology*	2.1.1
2 May	noticing systematic association tc/pv on `track_match_tc.ncl` output	2.1.4
9 May	review of Möller and Smith's article [6] for Michael's lesson	Figure 12
16 May	noticing association tc/pv again, checking tracking method	2.2.3
23 May	determining control parameters for pv anomaly tracks	2.2.3
30 May	storing charateristics of storms only *over Australia*, first backtracks	3.1
6 June	loop version of backtracking code, observation of backtrack trajectories	3.5
13 June	statistics on backtrack length, mean position of earliest detection	3.6
20 June	statistics on latitude of earliest detection, counting pv anomalies	3.7
27 June	writing report in French, seasonal fluctuation of pv anomaly number	3.3
4 July	study of Larry case, checking pv anomly number before a storm	-
11 July	translating and completing report	4.3.3
18 July	correlation of stormy seasons and pv field characteristics	3.4
25 July	chart of isentropes' height, last study focused on mid-latitudes pv	3.8

Here *tc* stands for tropical cyclones and *pv* for pv anomalies.

Abstract

This study focuses on one of the possible causes for tropical cyclogenesis in the Australian region during summer. Rossby wave breaking in the mid-latitudes could play a role in their formation by providing precursor vortices, which are subsequently transported towards the tropics where they promote organized convection. A detection method has been developed with the NC Language. Several statistical analyses have been used to determine the extent to which precursor anomalies have played a part over the past twenty years in the formation of tropical cyclones and tropical storms. The calculations are based on the ERAI dataset. About 10% of all tropical storms and cyclones are associated with potential vorticity anomalies from the mid-latitudes and, on average, those anomalies are detectable 5 days before the storms form. Despite the simplicity of the tracking method, which is potentially improvable, the results are encouraging, particularly for tropical weather forecasting.

Au cours de cette étude, nous nous sommes intéressés à une des causes possibles des cyclones tropicaux frappant l'Australie durant l'été. Le déferlement d'ondes de Rossby observé aux moyennes latitudes pourrait participer à leur formation via la dispersion vers les tropiques de parcelles d'air transportant une haute vorticité potentielle. Une méthode de détection de ces parcelles, appelées anomalies de vorticité potentielle, a été mise au point grâce au langage de programmation NCL. Plusieurs analyses statistiques ont été menées pour déterminer dans quelle mesure ce phénomène intervient dans la formation des tempêtes tropicales et cyclones tropicaux de ces vingt dernières années. Les données météorologiques utilisées proviennent principalement de la base de données ERAI. Il en ressort qu'environ 10% des cyclones et tempêtes tropicales sont associés à des anomalies de vorticité potentielle provenant des moyennes latitudes et que celles-ci sont détectables en moyenne 5 jours avant la genèse des tempêtes. Bien que la méthode de détection soit particulièrement simple, et donc potentiellement améliorable, ces résultats sont encourageants, notamment d'un point de vue prévisionnel.