GENIE MATHEMATIQUE ET MODELISATION

Année 2009/2010

RAPPORT DE STAGE DE 2ème ANNEE

Quantifying mixing by eddies around the Kerguelen Islands

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GMM2/2010

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Acknowledgements

First I would like to thank Emily Shuckburgh, my supervisor, for gave me the opportunity to carry out this internship at the British Antarctic Survey. Work under her orders within the Open Oceans Research Group was both an honour and a great pleasure, and her help for the redaction of this report was invaluable as well.

I also acknowledge Clare Enright, Ocean Model Manager, and Emma Thompson, PhD student in Mathematics, Physics and Oceanography joint with the University of Cambridge, for their help and their availability, especially during my first days.

Finally, I wish to acknowledge warmly Jorge Martinez-Rey, Master's student in Oceanography at the University of Bangor, Wales, who was like me a temporarily member of the Open Oceans Research Group through an internship. Work every day beside him was a pleasure and there is no doubt that our complicity should have improved our work.

Vocabulary

Altimetry

The measurement of height or altitude.

Baroclinic instability

Hydrodynamic instability of a jet that can occur in a rotating fluid.

Bathymetry

The measurement of the depths of sea bottom features in large bodies of water.

Effective diffusivity

Employed to characterise the strength of mixing by an eddy. Unit : metres^2 per second.

Phytoplankton

Drifting organism which use carbon dioxide, release oxygen, and convert minerals to a form animals can use. When present in high enough numbers, they may appear as a green discoloration of the water due to the presence of chlorophyll within their cells.

Southern Ocean

The south region of the Atlantic, Indian, and Pacific Oceans surrounding Antarctica.

Sverdrup

A unit of flow equal to one million cubic metres per second.

Topography

The relief (height variations) of the Earth's surface.

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BAS	British Antarctic Survey
MIT	Massachusetts Institute of Technology
NERC	Natural Environment Research Council
OORG	Open Oceans Research Group
PSPE	Polar Science for Planet Earth
SSH	Sea Surface Height
TMS	Time-Mean Streamfunction

I – INTRODUCTION

Helping to drive the overturning circulation of the ocean or allowing biological blooms to develop, water mixing by eddies plays a particularly important role in the Southern Ocean.

For that reason one of the axis of research of the Open Oceans Research Group (OORG) is the study of eddies. The OORG is a unit of researchers within the British Antarctic Survey (BAS). Indeed the BAS serves the British government being a world-leader in Antarctic research. It is based in Cambridge, United Kingdom.

The internship duration was to three months and a half. I worked for Emily Shuckburgh, the head of the OORG. Following her previous studies on estimating and understanding the eddy diffusivity in the Southern Ocean, my work focused on quantifying water mixing around the Kerguelen Islands [see appendix a to locate them]. Thus it forms part in the investigation of the role of eddies in ocean, which is Emily Shuckburgh's current research.

The previous studies have to be learn first, as all the necessary steps to get the effective diffusivity from satellite data. However adapting existing codes to be able to change easily of survey patch is the first real goal. Quantifying eddy activity around the Kerguelen Islands, whether in space or in time, are then the main aims and it is hoped to correlate some seasonal cycles with recorded biological blooms.

It is first necessary to put the context of the internship, both presenting the BAS and putting the study back in its context (II). Then eddies are introduced, with an explanation of the model framework (III). The most important part is dedicated to the results (IV) : space and temporal variability of the effective diffusivity and try to improve the calculations as well. Finally, a little assessment is done (V) before conclude (VI).

II – WORK ON EDDIES WITHIN THE BRITISH ANTARCTIC SURVEY

In this part, both the company where I worked and my survey concern are presented.

II.1 – From the British Antarctic Survey to the Open Oceans Research Group

The BAS is a component of the Natural Environment Research Council (NERC) and is based in Cambridge, United Kingdom.

It has its roots in Operation Tabarin, a secret World War II mission. Designed to deny Antarctic waters to enemy ships, Tabarin also had a scientific role, collecting data on Antarctic biology, geology and weather during the last two years of the war. After the end of the war in 1945, Tabarin's three bases and its scientific work were transferred to a new organisation – the Falklands Islands Dependencies Survey, which in turn was renamed in 1962 as BAS.

Since then, BAS has become a world-leader in Antarctic research. Indeed, it now employs over 400 staff, and operates five research stations, two royal research ships and five aircrafts in and around Antarctica. These 400 plus employees can roughly be divided in two principal parts, sciences staff and services staff [for more details about the BAS organisation see appendix b].

Thus BAS has, for over 60 years, undertaken the majority of Britain's scientific research on and around the Antarctic continent, through operations and science programmes executed and managed from Cambridge. Now, BAS shares that continent with scientists from over thirty countries.

The total BAS budget for 2009-2010 is £47.1 million, which comes mostly from an allocation by the NERC, its parent body. Of this, £11.1 million is spent on the science programme, and £36 million spent on supporting the science, which includes the costs of running the ships, aircraft and research stations. The high costs involved highlight the challenges BAS faces in operating within a harsh and remote environment.

In 2007, the NERC launched its new science strategy "Next Generation Science for Planet Earth, 2007-2012". The strategy recognises that the Antarctic and the Arctic are central components of the Earth system, and introduced different ways of working across the UK's environmental science community.

In order to better support and respond to the NERC strategy, BAS developed its new strategic science framework, Polar Science for Planet Earth (PSPE), which started on 1st April 2009. PSPE consists of six programmes linked to the NERC Science Strategy.

One of those is called *Polar Oceans*. It investigates the role of processes and changes both in the shelf sea and in open-ocean environment, and will further the understanding of polar control of the Earth System.

The Open Oceans Research Group (OORG) is one of two research groups within the Polar Oceans programme, the other being the Shelf Seas group. It uses a combination of theoretical studies, numerical modelling and analysis of observational data to better understand the dynamics of the ocean and thereby improve predictions of future climate change. The group is led by D^{r} Emily Shuckburgh and includes scientists with expertise in chemistry, physics, biology and earth sciences. Among the main scientific priorities for the group are: (i) to improve the understanding of the role of the polar oceans in climate change, including feedbacks associated with ocean carbon uptake, (ii) to improve predictions of sea level rise by improving understanding of ocean-ice interactions and (iii) to investigate ocean changes that may have implications for ocean ecosystems.

II.2 – The study : context and statement

The Antarctic Circumpolar Current (ACC) is the largest current in the world ocean, carrying about 135 Sverdrup (Sv) from west to east around Antarctica. The current flow is concentrated in a number of circumpolar fronts, which extend from the sea surface to the sea floor. The fronts also mark the boundaries between zones with distinct physical, chemical and ecological characteristics.

Eddies produced by dynamical instabilities of the fronts play an important part in the dynamics of the ACC. It helps drive the overturning circulation of the ocean that links the Southern Ocean with the North Atlantic and the ACC links the Pacific, Atlantic and Indian Oceans. These circulations transport heat and dissolved carbon dioxide around the global ocean and link the deep ocean with the atmosphere, and are therefore critical for determining the global climate.

Eddy mixing is also essential for local processes, for example, in supplying nutrients such as iron run-off from islands to phytoplankton in a manner that then generates phytoplankton blooms. In this way they have a key influence on biogeochemical processes.

That’s how I will use observational and model data to quantify the eddy mixing around the Kerguelen Islands, which is a region of particular physical and biological interest. The topography of the Kerguelen Plateau is irregular, which should enhance the eddy activity and, at the same time, one of the largest phytoplankton blooms of the Southern Ocean takes place every year above the Kerguelen Plateau.

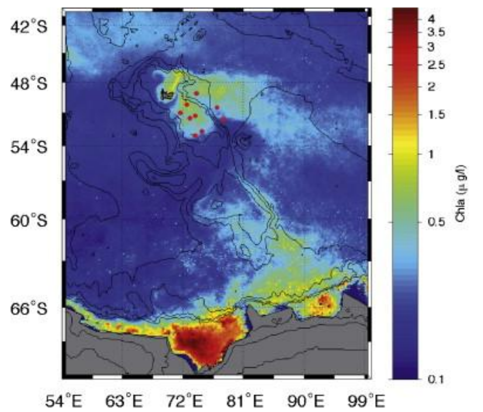


Figure 1 : Map of the Kerguelen plateau area, showing major topography and chlorophyll-a climatology (1997-2007) from the MODIS AQUA sensor

The overall aim of my survey is to quantifying mixing by eddies around the Kerguelen Islands including both the spacial and temporal variability. One of the greatest motivations for this is to understand the correlation of seasonal cycles of the eddy activity with chlorophyll blooms shown by ocean-colour satellite images.

This work follows Emily Shuckburgh's previous studies on estimation and understanding of eddy diffusivity in the Southern Ocean. At this time, the OORG had just access to satellite data for the year 1997, and used that to work on fixed size Southern Ocean's patch. As I need for my survey to work on several years data and to be able to change patches easily, adapting existing codes to different years and patch sizes constitute intermediate goals. Trying to improve the efficiency of the calculation is also an objective.

III – STORY OF EDDIES

Below I provide an overview of eddies, of the global model framework and of the theoretical basis for passing from a tracer to an eddy diffusivity.

III.1 – Eddies in the Southern Ocean

III.1.a – What are they ?

Eddies are usually thought of as anomalies to the (temporal or spatial) mean flow. In the ocean and the atmosphere, the term eddy has multiple connotations. Eddies can be rings, vortices that swirl water around their centres either cyclonically (clockwise in the southern hemisphere) or anti-cyclonically (counter-clockwise in the southern hemisphere). Eddies can also be the transient part of a current, as distinct from the time-invariant current. The role of transient ocean eddies is analogous to the role of storm systems in day-to-day weather fluctuations : they are responsible for the short time-scale variability in ocean currents.

Ocean eddies range in size from tens to hundreds of kilometres (km). Southern Ocean rings have been observed to have radii of between 30 and 100 km, and the predominant length-scale of other transient features is thought to be about the same size. This corresponds to the mesoscale, features that are large enough to be influenced by the Earth's rotation but small enough that many eddies can fit within one ocean basin.

III.1.b – Why they occur ?

As shown in figure 2 on the right, the ACC is composed by three main fronts. They are called, from north to south, the Subantarctic Front, the Polar Front and the southern ACC front, and are circumpolar in extent and found on any north-south transect across the Southern Ocean. Because the fronts extend to the sea floor and the stratification in the Southern Ocean is relatively weak, the position of the fronts is strongly influenced by the bathymetry.

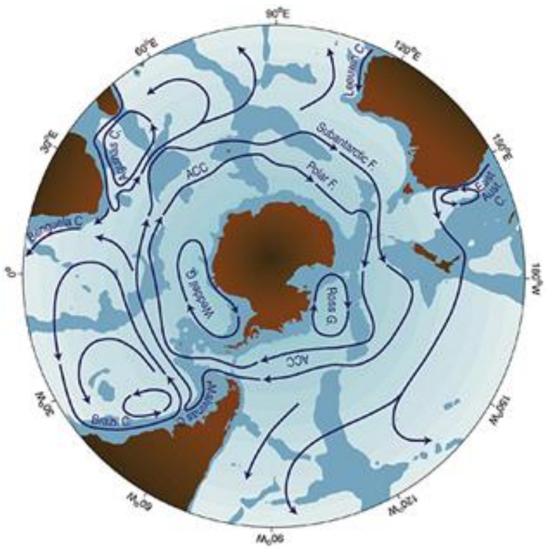


Figure 2 : The main Antarctic Circumpolar Fronts

But the ACC fronts posses variability as well, which is driven to a large degree by dynamical instabilities of the frontal jets. The instabilities cause the fronts to meander and spawn rings and eddy motions. The ACC has some of the most vigorous eddy activity observed in the ocean. Eddies are produced when dynamical processes release some of the energy stored in the sloping of density surfaces across the ACC, converting some of the energy in the mean flow into motions that vary with time, i.e. eddies. This process is called baroclinic instability, and thought to be responsible for most of the observed eddy variability.

Eddies may also occur because of topography, either as lee waves downstream of topography or as Taylor columns located directly over topography. Since seafloor topography does not change position, at least on the timescales of eddy motion, these are usually thought of as standing eddies. However, if standing eddies experience small displacements, then they can be associated with enhanced transient eddy variability in regions where topographic lee waves are predicted. These regions occur for instance eastward (or downstream following the flow of the Circumpolar Current) of Kerguelen in the southern Indian Ocean or of Drake Passage between South America and the Antarctic Peninsula.

III.1.c – What is their role ?

Since the ACC is continuous around the Antarctica, its mean flow provides no pathway to carry water southward from low-latitude subtropical gyres. Thus eddies play a critical role in explaining the transport of heat, freshwater, and other properties across the ACC. For the most part, eddy transports are thought to carry properties along isopycnals – surfaces of constant density – rather than mixing waters of different densities. Overall, air-sea heat fluxes and upper-ocean transport estimates suggest that eddies carry roughly 0.45×10^{15} watts of heat poleward across the ACC in order to maintain the heat balance of the high-latitude ocean. These estimates are obtained from current meter observations and autonomous subsurface floats. In most estimates, regions with high transient eddy variability are also associated with high eddy heat flux.

In addition to transferring heat, eddies also transfer momentum, both horizontally and vertically. Observations from altimetry and current now indicate that horizontal eddy fluxes are small and have comparatively little effect on the mean flow. However, eddy fluxes are thought to be largely responsible for carrying momentum downward from the surface, where it is input by the wind, to the sea floor, where it can be transferred to the solid Earth. Downward transport of momentum is carried out by “interfacial form stress”, the pressure work done by one layer of the ocean on the layer below. This pressure work can be expressed as a poleward eddy density flux, and it is commonly approximated as an eddy heat flux. Thus, eddies imply a clear link between the heat flux across the ACC and the dynamics required to balance wind forcing.

III.1.d – What are the principal consequences ?

Eddies can influence biological productivity, and in several distinct ways. They can help to transport nutrients into otherwise low-nutrients surface waters, either through cross-frontal horizontal exchanges or through vertical exchanges. For example, the centre of a cyclonic ring be a region of upward vertical velocity, which can help bring nutrients from the deep ocean. Nutrients can be trapped within an eddy's surface layer, increasing their residence time within a particular region and therefore allowing a biological bloom to develop. Eddy processes can also influence productivity if they permit a shallow mixed layer to develop, thus trapping nutrients and phytoplankton at depths where sunlight is readily available.

Comment *: Notice that although Southern Ocean eddies have significant impacts on circulation, temperature patterns, and biology, their small length-scales make them difficult to observe and also difficult to resolve in global-scale numerical ocean circulation models. As a result, eddy processes are parameterized in climate models, usually as diffusive processes.*

III.2 – From satellite data to tracer mixing

Satellite data gives the Time-Mean Streamfunction (TMS) and the Sea Surface Height (SSH) anomalies, every 7 or 10 days from 1993 to 2008. (All the pictures during the process of the methodology come from a patch in the north of Kerguelen, for the year 1997, and with every 10 days data. For instance step 28 means we are around the 280th day of the year, i.e. in 1997, early October.) [appendix c to know more about satellite data].

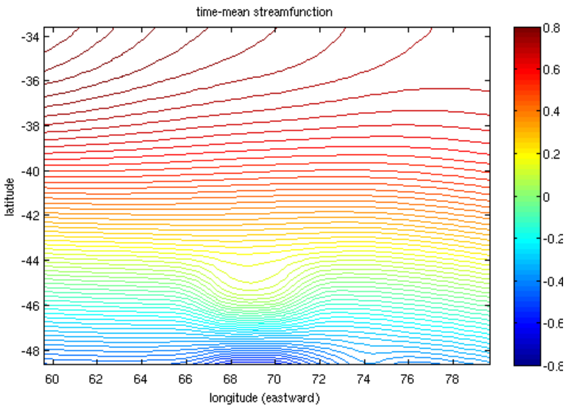


Figure 3 : TMS : example

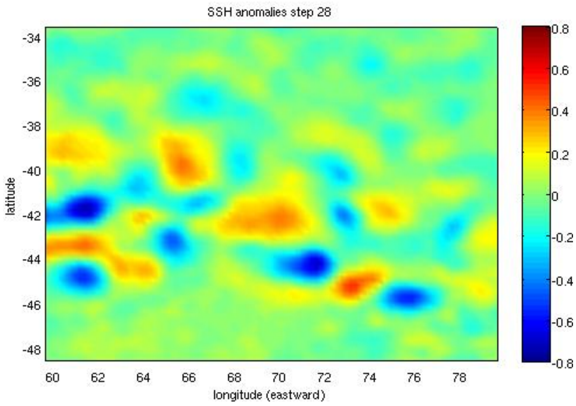


Figure 4 : SSH anomalies : example

Notice that the highest SSH anomalies are often found where values of the TMS change quickly, as these area have more instabilities, which seems rather intuitive.

Then these two datasets are superposed (figure on the right), and a velocity field is produced.

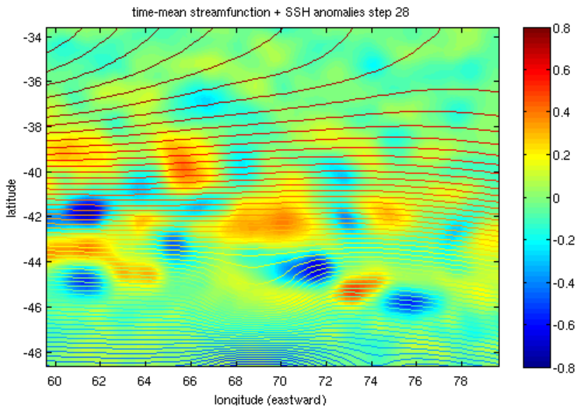


Figure 5 : TMS & SSH : example

To a good approximation, motion in the atmosphere and ocean is in geostrophic balance. In the atmosphere this is manifested as flow along pressure contours, with the magnitude being proportional to the horizontal pressure gradient, as seen on weather charts. In the ocean, the geostrophic flow can be deduced in a similar way from the sea surface height anomalies h (the streamfunction $\psi = gh/f$, where g is the acceleration due to gravity and $f = 2\Omega \sin(lat)$ is the Coriolis parameter (Ω angular velocity of the Earth)).

Then we initialize an idealized tracer to be aligned with the mean streamlines at the beginning of one year, and integrate that, using the advection-diffusion code from the Massachusetts Institute of Technology (MIT) general circulation model. The velocity field is modified slightly to create a re-entrant channel that is periodic in longitude and has no flow out of the north and south boundaries and therefore the patches are chosen in regions across which the mean streamlines are predominantly zonal. The tracer integration is continued for one year, and we obtain pictures of our tracer every 7 or 10 days of the surveyed year.

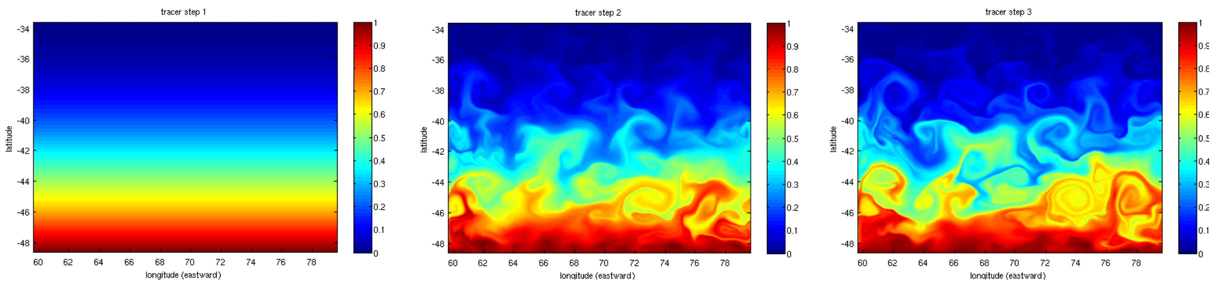


Figure 6 : 3 first pictures of the tracer

Now we need to pass from these tracer images to eddy diffusivity values, and that's what we will focus on.

III.3 – How to calculate the effective diffusivity

The link between tracer and effective diffusivity is intuitive : the longer the tracers contours are, the more mixing there is and so the higher the eddy diffusivity is. That's how the effective diffusivity diagnostic is based on identifying the enhancement of diffusion that arises through the effects of eddies stretching and folding tracer contours. In mixing regions, tracers are vigorously stretched into complex geometrical shapes with tight gradients, and this leads to large values of effective diffusivity.

We are concern with the problem of a passive tracer q, advected by a two-dimensional non divergent velocity field v, described by the evolution equation

$$\frac{\partial q}{\partial t} + v \cdot \nabla q = k\, \nabla^2 q\,,$$

where k is a constant of diffusivity, for which we will take 50 $m^2.s^{-1}$. We must also notice that $v \cdot \nabla q$ is the advection term whereas $k\, \nabla^2 q$ is the diffusion term.

This equation can be rewritten as a diffusion equation in area coordinates $\mathcal{A}$ [appendix d],

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial x}\left[\kappa_{eff}(\mathcal{A})\frac{\partial q}{\partial \mathcal{A}}\right],$$

with diffusion coefficient

$$\kappa_{eff}(\mathcal{A}) = k\frac{1}{\left(\frac{\partial q}{\partial \mathcal{A}}\right)^2}\frac{\partial}{\partial A}\int_{\mathcal{A}(q,t)} |\nabla q|^2 \, d\mathcal{A} \, .$$

Thus, q diffuses in $\mathcal{A}$ coordinates at rate κ_{eff} , which can be computed by summing up $|\nabla q|^2$ between adjacent q contours.

The effective diffusivity can be related to the length of q contours strained by the velocity field, as can be seen follows. Note that κ_{eff} has units of meters to the fourth power per second, that corresponds to a diffusivity times a length^2 ; the diffusivity in area coordinates is $k{L_{eq}}^2$, where L_{eq} , known as the equivalent length, is given by

$${L_{eq}}^2 = \left(\frac{\partial q}{\partial \mathcal{A}}\right)^2\frac{\partial}{\partial A}\int |\nabla q|^2 \, d\mathcal{A} = \frac{\partial \mathcal{A}}{\partial q}\underbrace{\frac{\partial}{\partial q}}_{\frac{\partial \mathcal{A}}{\partial q}\frac{\partial}{\partial \mathcal{A}}}\int |\nabla q|^2 \underbrace{\frac{dl \, dq}{|\nabla q|}}_{d\mathcal{A}} = \underbrace{\oint \frac{dl}{|\nabla q|}}_{\frac{\partial \mathcal{A}}{\partial q}}\oint |\nabla q| dl \, ,$$

where the relation

$$(\partial\mathcal{A}/\partial q) = (\partial/\partial q)\int d\mathcal{A} = (\partial/\partial q)\int (dl \, dq/|\nabla q|) = \oint (dl/|\nabla q|)$$

is used.

Because $L = \oint dl$, then ${L_{eq}}^2 = L^2$, the actual length of a q contour, if $|\nabla q| = const$ on dl. If $|\nabla q| \neq const$ on dl, then ${L_{eq}}^2 \geq L^2$. This can be seen follows. Writing

$$L = \oint |\nabla q|(dl/|\nabla q|) = (\partial/\partial q)\int |\nabla q| \, d\mathcal{A} = [1/(\partial q/\partial\mathcal{A})](\partial/\partial\mathcal{A})\oint |\nabla q| d\mathcal{A}$$

we see that

$${L_{eq}}^2 = \frac{1}{\left(\frac{\partial q}{\partial \mathcal{A}}\right)^2}\frac{\partial}{\partial A}\int |\nabla q|^2 \, d\mathcal{A} \geq L^2$$

$$= \left[\frac{1}{\left(\frac{\partial q}{\partial \mathcal{A}}\right)}\frac{\partial}{\partial A}\int_{\mathcal{A}} |\nabla q| d\mathcal{A}\right]^2 ,$$

because the "sum of the squares" is always greater the "the square of the sum".

To obtain the diffusivity with conventional units we define a quantity

$$\kappa_{eff} = \frac{kL_{eq}{}^{2}}{L_{min}{}^{2}},$$

where L_{min} is the minimum length of a q contour. Because $L_{eq}{}^{2} \geq L^{2} \geq L_{min}{}^{2}$, geometrically κ_{eff} may be interpreted as the enhancement of diffusion resulting from the enhancement complexity of the tracer contours. On a sphere, the minimum length of a tracer contour is given by $L_{min} = 2\pi r \cos\phi_e$, where ϕ_e is known as the "equivalent latitude", this being the slowest decaying mode of the diffusion equation on a sphere. For application to the Southern Ocean, the continental boundaries prevent this minimum from being reached and the slowest decaying mode of the diffusion equation system is not given by a simple analytic formula. We therefore obtain L_{min} numerically.

Finally, we can see the eddy diffusivity from a tracer picture getting this :

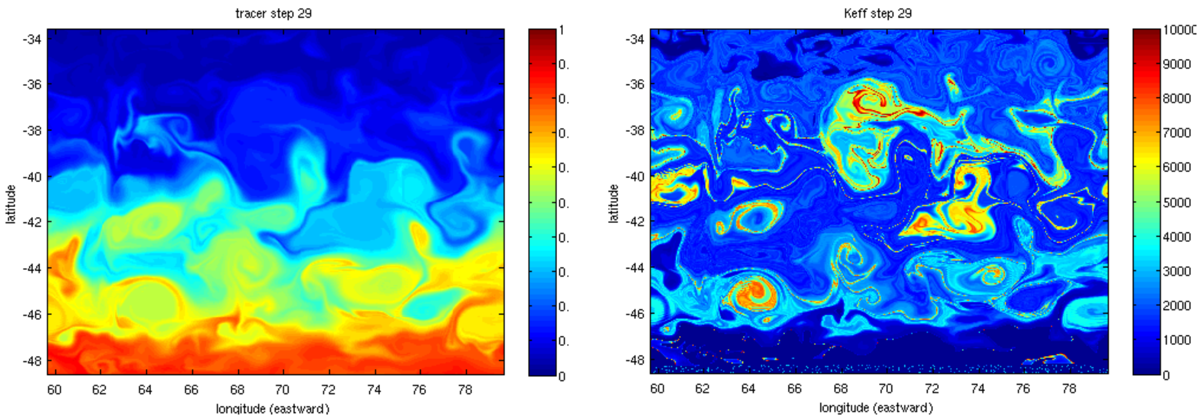


Figure 7 : A tracer picture (left) and the associate eddy diffusivity picture (right)

IV – MIXING BY EDDIES AROUND THE KERGUELEN ISLANDS

My work has been led by the data we obtained and all the observations made as the work was advancing. Thus the direction of research was frequently re-evaluated in light of new results. This is described below.

IV.1 – Spacial variability : the year 1997 around the Kerguelen Islands

At the beginning we just only had data which gave us the altimetry every 10 days for the year 1997. Thus I divided the ocean around Kerguelen in 4 principal parts : north, south, west, east, in the aim to find differences or similarities in term of eddy diffusivity around the Kerguelen Islands.

In order to identify relevant features, the MIT general circulation model was run over the 12 following patches :

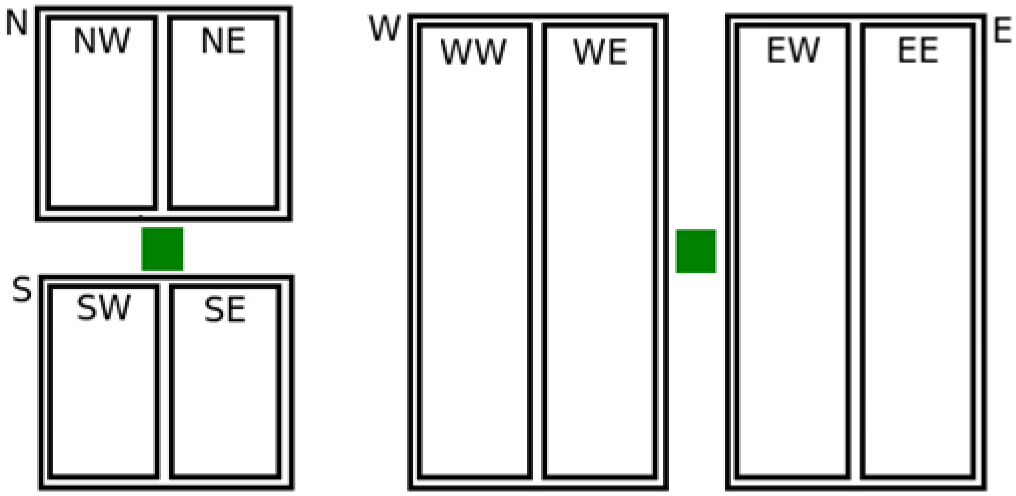


Figure 8 : Survey patches around Kerguelen Islands

The green square is the island, which is excluded from the patches to avoid misleading values for the diffusivity in that region. The letters stand as N : North, S : South, W : West, E : East. [see appendix e for the precise coordinates of the patches].

The upper limit for the patches is the boundary of the model data, around 30° south. The lower limit for the patches is Antarctica itself. In order to leave a safety margin, the limit was set to either 57° or 55° south. In this way, the patch size was always a multiple of five. Further calculations within the model can be easily handled with these numbers.

The Kerguelen Islands are, as for them, defined by the coordinates : Latitude : from 48.5° to 50° south, Longitude : from 68.5° to 70.5° east.

At last, notice that for all the patches, the effective diffusivity is obtained following the steps described before (III.2, III.3). When the scale is from 0 to 200 $m^2.s^{-1}$, the values must be multiplied by 50 to get the real values of effective diffusivity.

The features of all the 4 principal patches are presented below, clockwise from south to west.

IV.1.a – The south

The three following pictures are enough to emphasize the weak eddy diffusivity in the south of Kerguelen.

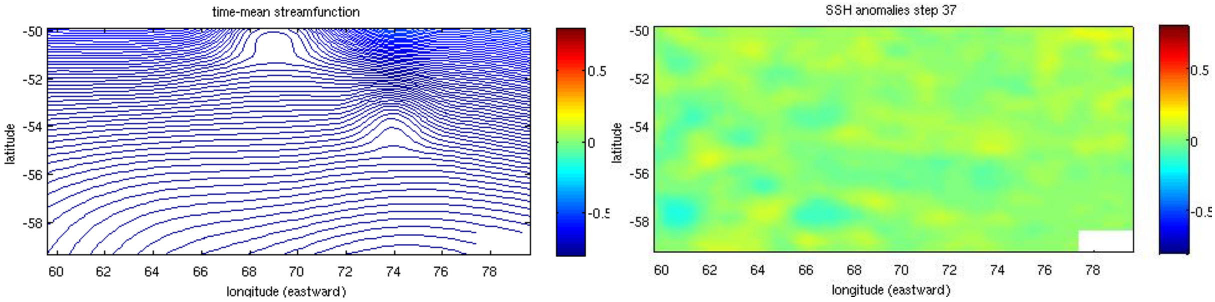


Figure 9 : TMS (left) and SSH anomalies (right) from the patch S (last step)

Indeed, the TMS values are almost the same everywhere in the patch, which involve weak SSH anomalies.

As a consequence, the effective diffusivity is very low, with more or less 250 $m^2.s^{-1}$.

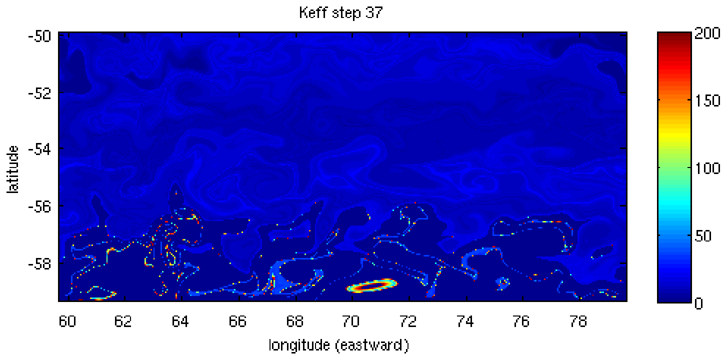


Figure 10 : Effective diffusivity from the patch S (last step)

IV.1.b – The west

We can see hereunder, through the example of the step 10, that SSH anomalies are the most important where the values of the TMS change strongly and the flow is subject to baroclinic instability generating eddies.

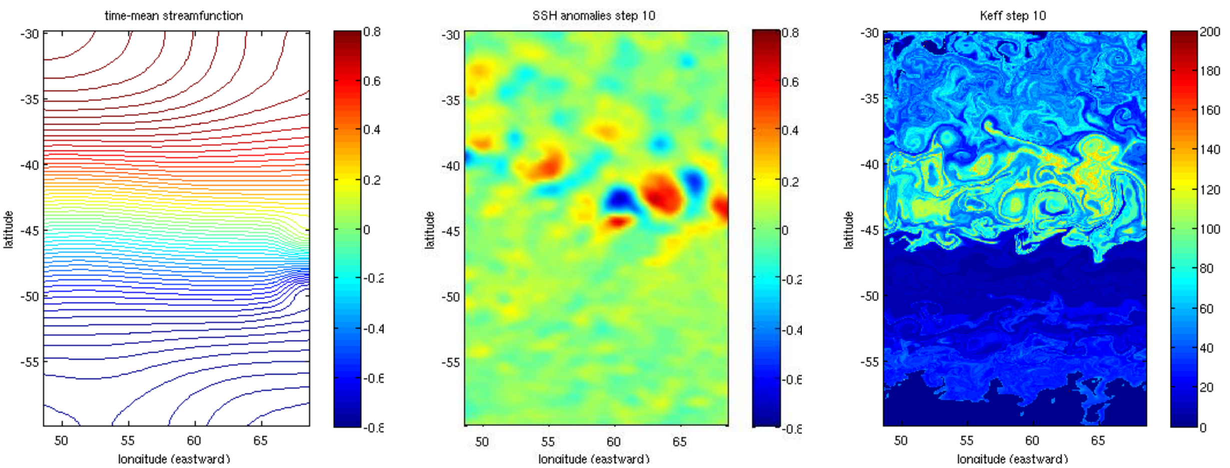


Figure 11 : TMS (left), SSH anomalies (middle) and effective diffusivity (right) from the patch W (step 10)

The values of effective diffusivity are weak below 45° south, which corresponds with the values seen below for the patch S. Notice also that the highest values are around 600 $m^2.s^{-1}$ and are all found in a band from 40° to 45° south.

The pictures of the patches WW and WE, as those of SW and SE before, are not shown because they are respectively quietly similar to the patches W and S. They therefore can't be used for identifying interesting features.

IV.1.c – The north

First look at the TMS of the patch N and the effective diffusivity picture at the last step of the year.

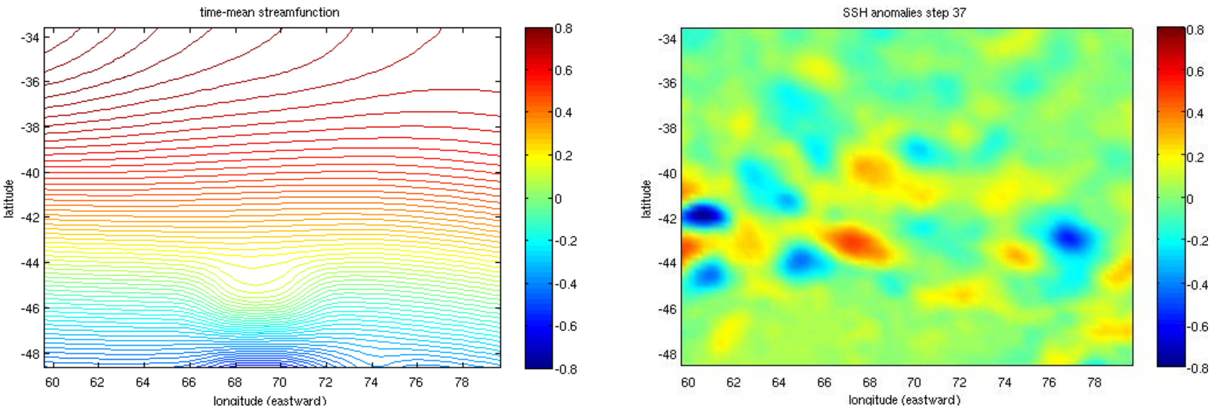


Figure 12 : TMS (left) and SSH anomalies (right) from the patch N (last step)

Most of the effective diffusivity values fluctuate between 2000 and 6000 $m^2.s^{-1}$.

But what is interesting here is to compare the divisions NW and NE of the patch N.

Indeed, looking the effective diffusivity from this 2 divisions at the same step, a big difference can be observed. Thus, effective diffusivity values are higher from NE than from NW.

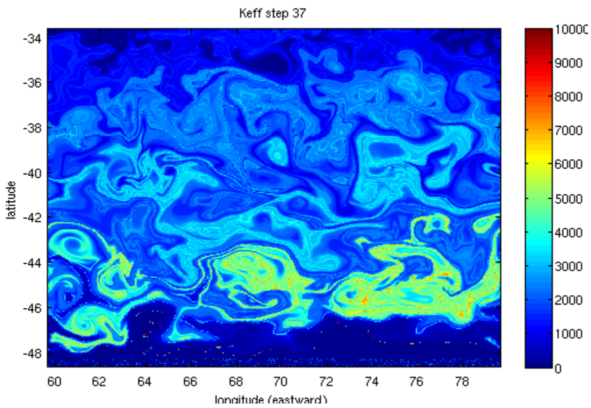


Figure 13 : Effective diffusivity from the patch N (last step)

We know that ACC goes eastward, and topographic obstacles are known to enhance the eddy diffusivity.

Here the obstacles are quiet simply Kerguelen Islands themselves (cf. figure 8).

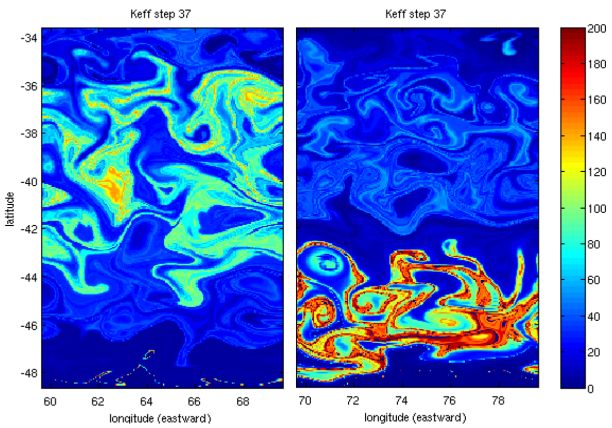


Figure 14 : Effective diffusivity from patches NW (left) and NE (right) (last step)

IV.1.d – The east

Pictures are presented in the same order as for the patch N.

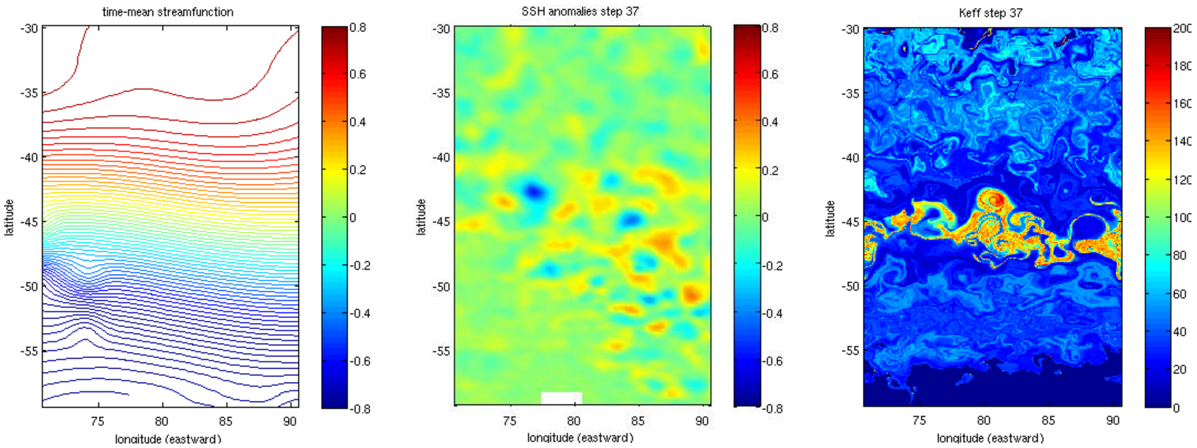


Figure 15 : TMS (left), SSH anomalies (middle) and effective diffusivity (right) from the patch E (last step)

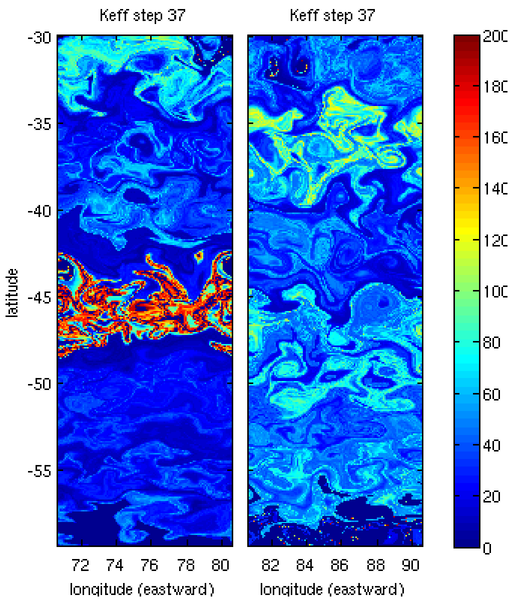


Figure 16 : Effective diffusivity from patches EW (left) and EE (right) (last step)

Looking the effective diffusivity from the patch E, we can see that the values seem to be relatively high in a little band around 45° south. Conversely, they are low again in the south part of the picture.

The effective diffusivity pictures of the last step from the patches EW and EE are also shown on the right and we can see the effect of the Kerguelen Islands again. Thus eddy diffusivity has very high values in EW whereas values in EE are lower than values from E.

We can therefore deduce that there is more mixing just “after” the islands than further in the east.

<u>Conclusions</u> : The effective diffusivity is particularly weak in the south of the Kerguelen Islands, and more generally in the southern part of the Southern Ocean. The survey of the year 1997 to emphasized the link between topography and eddy activity as well. Indeed, parts situated just on the east of Kerguelen Islands (NE and EW) seem to have higher eddy activity than others.

Later I obtained new data which run from 1993 to 2008 and every 7 days. I was now able to calculate eddy diffusivity all along 16 years. Nevertheless I then focused on the year 1993 and all the examples of the following part are from the patch N. Thus in IV.2 it is a matter of improving the calculations.

IV.2 – Interpolations' tries to improve the calculations

Recall that as said in III.3, the velocity field is modified slightly to create a re-entrant channel that is periodic in longitude. The problem with this approach is that there is therefore a jump when it passes from the end of a step to another one (symbolised below by the arrows and arcs).

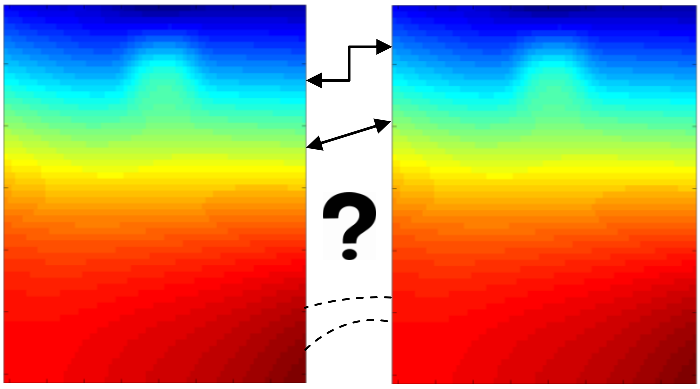


Figure 17 : Discontinuity illustrated by juxtaposing two TMS

The first idea we have had for correct this kind of discontinuity is to add what we can call a buffer area, for both the TMS and the SSH. Its role is to make a link between each step, smoothing the transition from one step to the following.

IV.2.a – With two edges

The principle is the following : for a patch which measures 20 degrees in longitude (it corresponds to 80 points), 10 degrees on each side are added (40 points). Then, a simple interpolation on these edges should avoid the discontinuity seen before for the TMS.

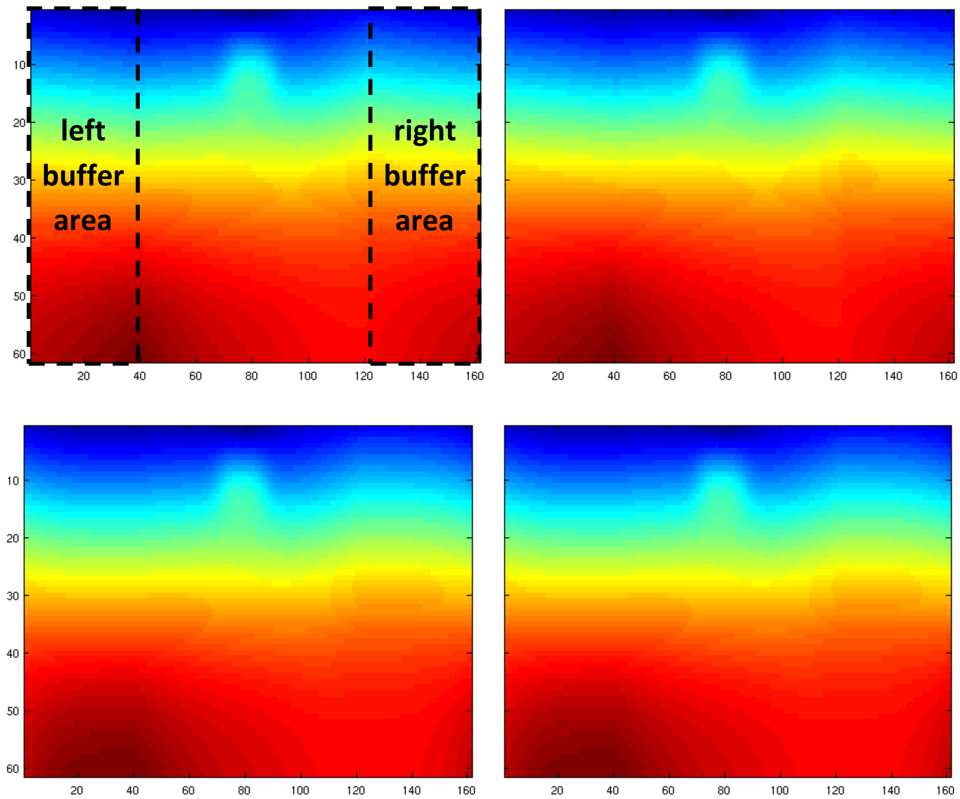


Figure 18 : 2 TMS with buffer juxtaposed : with linear interpolation (at the top) and with cubic interpolation (at the bottom)

Thus 2 interpolations have been computed, a linear interpolation and a cubic one. We can easily see that the cubic interpolation seems better than the linear one, even if there still are unsatisfactory things, especially around the column 121.

In parallel, the SSH anomaly has been changed as follow, and with the same concern of link steps. Thus 2 buffer areas are used and the SSH anomalies drop to zero. Different SSH anomalies have been tried, dropping to zero in 5 degrees (columns 21 to 40 and 122 to 141) or in 10 degrees (columns 1 to 40 and 122 to 161).

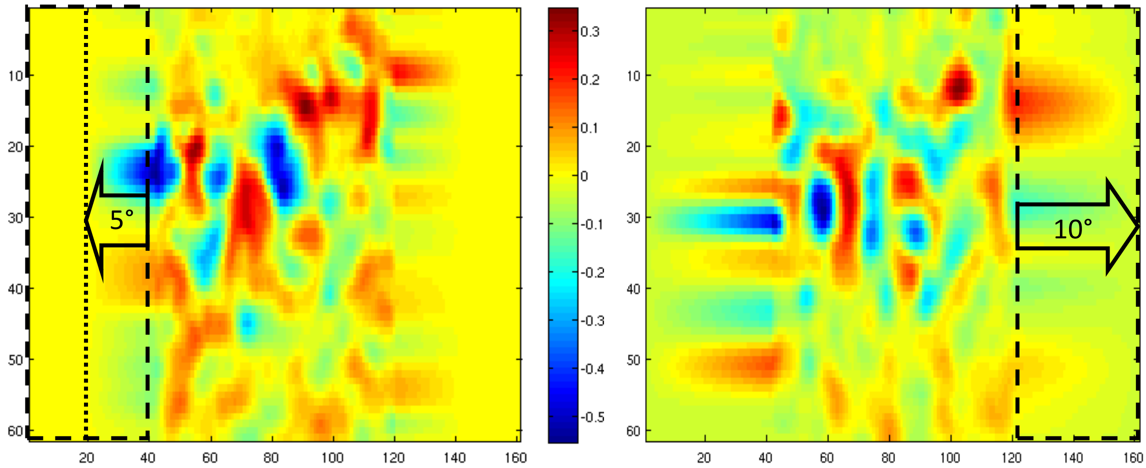


Figure 19 : SSH anomalies : dropping to zero in 5 degrees (left) and in 10 degrees (right)

Then we run the MIT general circulation model tracer advection on our 40 degrees of longitude patch. We therefore obtain the tracer on this extended patch, whereas the goal is to compare the eddy diffusivity in our initial patch. The eddy diffusivity values are only calculated for the initial patch, and differences from the classical calculation are explored.

Before we compare the results, we present the other interpolations which have been tried.

IV.2.b – Flipping the original data

Rather than add two lateral areas, we try here to add just one area, which is the east west symmetry of the initial patch. Thus there is no discontinuity and, using this method on both the TMS and the SSH, we also permits the eddies to develop.

Nevertheless this is not smooth on the symmetry axis, so we decide to add a small intermediate band in which a cubic interpolation is made.

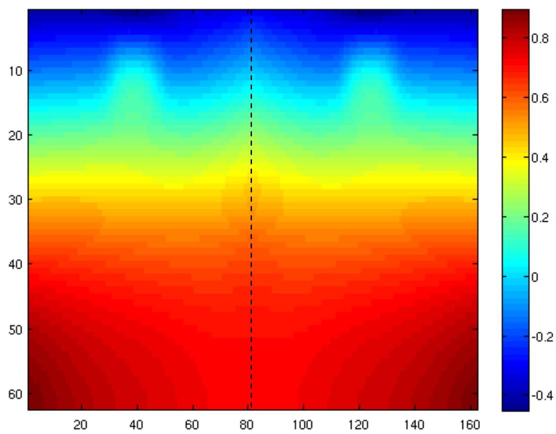


Figure 20 : Flipped TMS in 2D

On the right is the same TMS but in 3D.

We will need a thinner mesh, with n times more points than the on the old one, with n the number of columns wished for the intermediate band. The new values of the mesh are fixed with a cubic interpolation. Finally we get the mesh below.

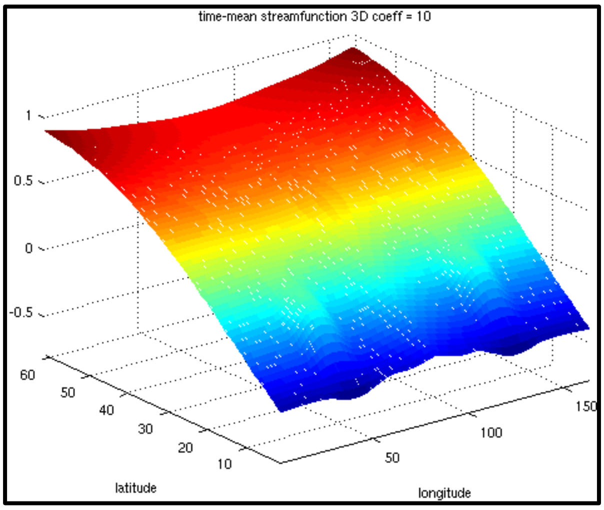


Figure 22 : Flipped interpolate TMS in 3D

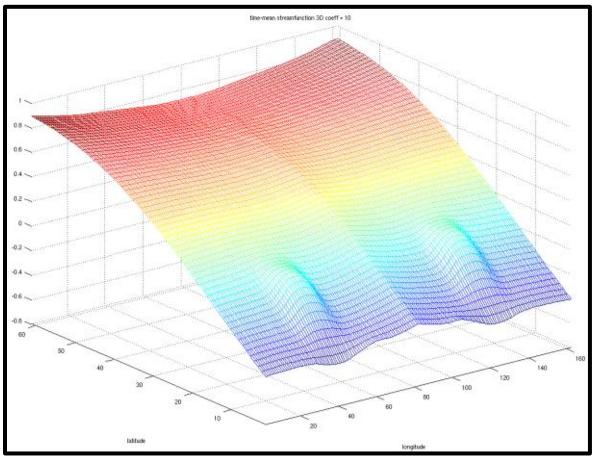


Figure 21 : Flipped TMS in 3D

Then the old mesh is taken, and the n-1 interpolate values in the middle are replaced in the intermediate band after a little adjustment.

Hereunder the results of this interpolation on the TMS seen in 2D for n=10 and n=50.

For both the flipped TMS is shown before and after the interpolation. Let's start with n=10.

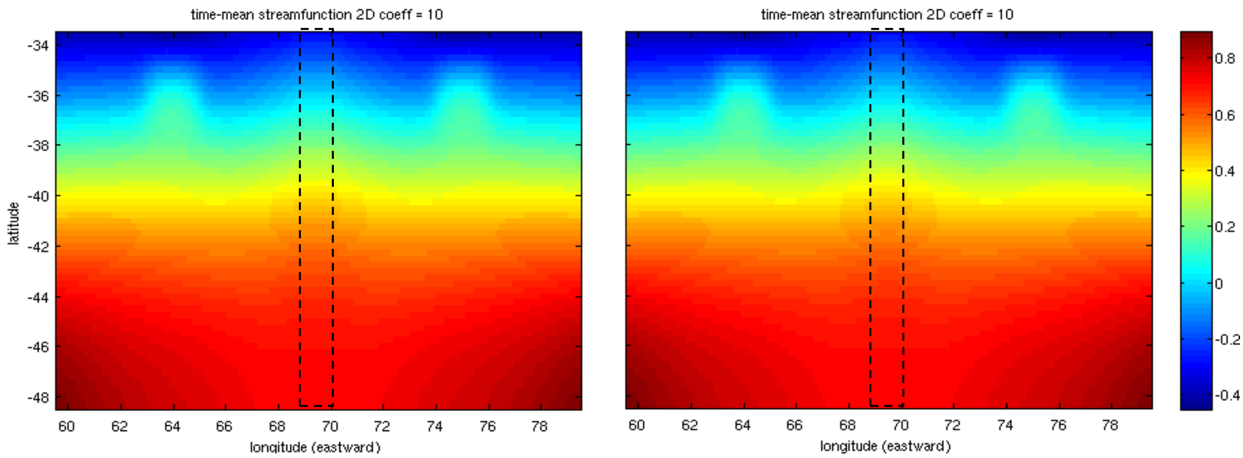
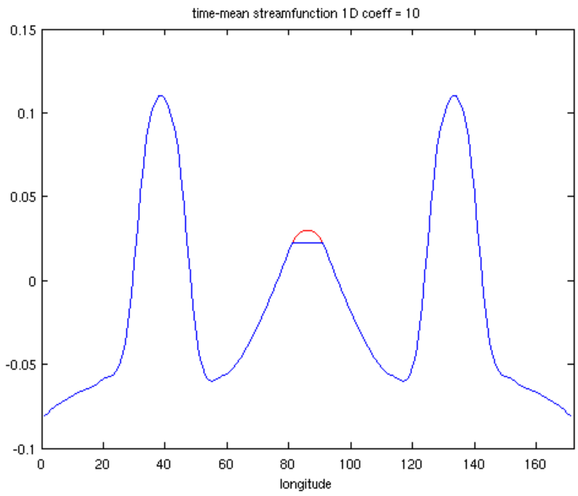


Figure 23 : Flipped TMS in 2D with n=10 before (left) and after the interpolation (right)

Now see the effect on values of two precise latitudes (the interpolate values are in red). The first row is around 36° south and the second is situated around 46° south.



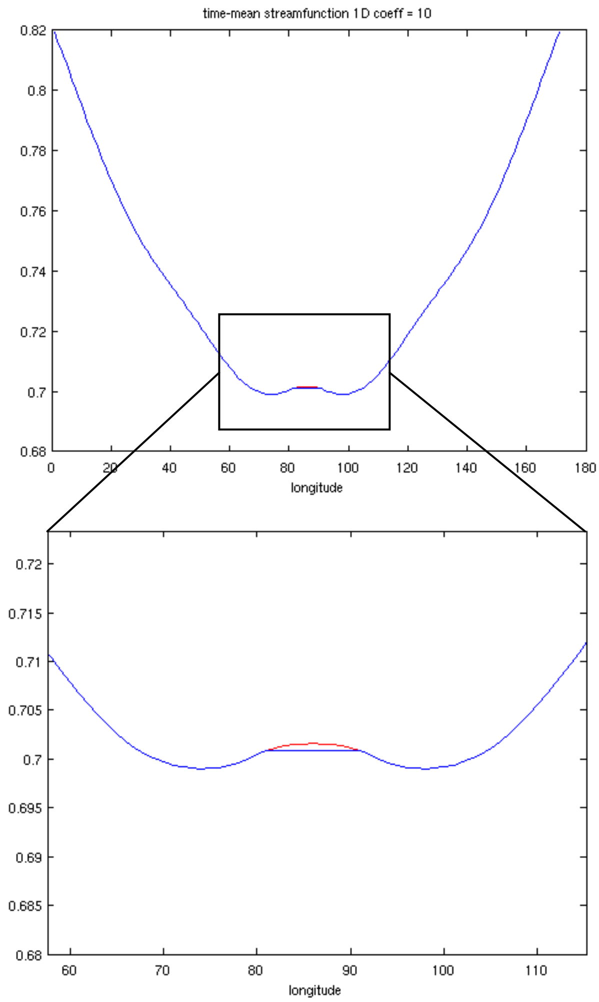


Figure 24 : The effect of the TMS interpolation with n=10 on values of 2 precise rows : around 36° south (above on the left) and 46° south (right)

Now look at the results for n=50.

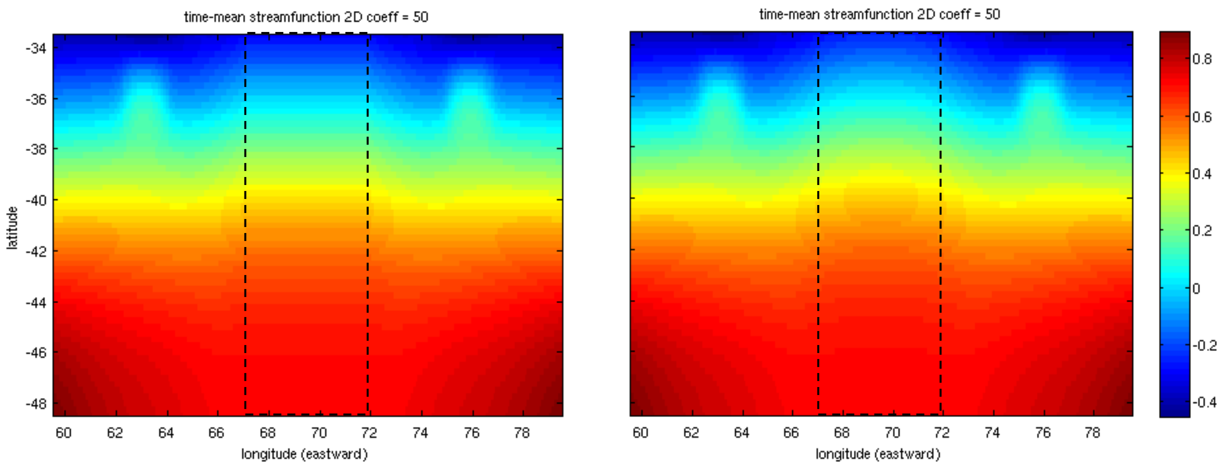


Figure 25 : Flipped TMS in 2D with n=50 before (left) and after the interpolation (right)

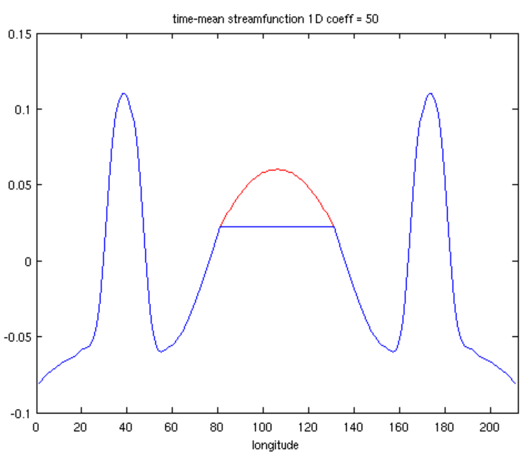


Figure 26 (on the left) : The effect of the TMS interpolation with n=50 on values of a row around 36° south

The method is clearly efficient to smooth the TMS. The same thing is used on the SSH anomalies.

Then, compare the results on eddy diffusivity to understand the effects of the interpolations described above. We have tried buffer areas of 10 and 20 degrees, with two kinds of SSH at each time. That's how for instance 10/10 means a TMS extended by 10 degrees on each side (the buffer areas) and a SSH anomalies dropping to zero in 10 degrees whereas 20/5 means 20 degrees for the buffer areas and a SSH anomalies dropping to zero in 5 degrees.

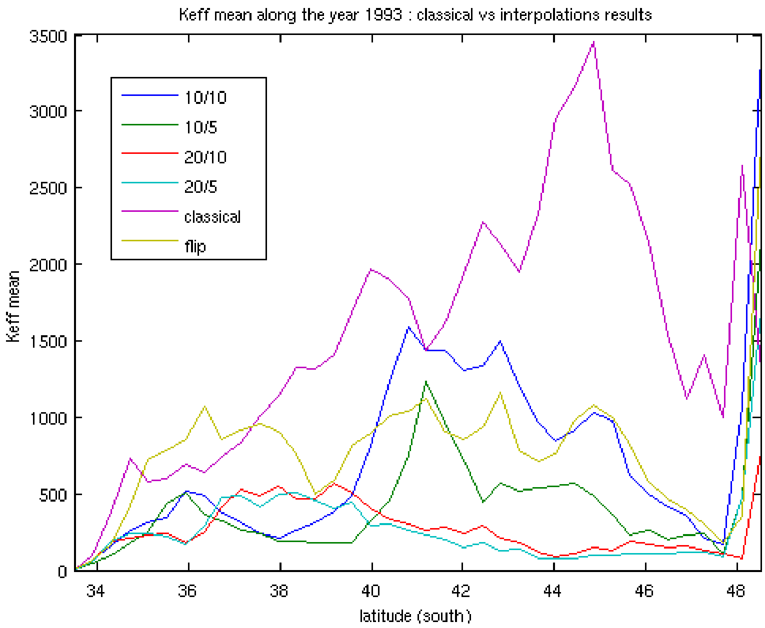


Figure 27 : Effective diffusivity average along the year 1993 : classical against tries results

Conclusions **:**

- *First it is evident that every effective diffusivity average along the year 1993 due to the new techniques is lower than the classical one, and by far. Although the effective diffusivity at the end is calculated from the tracer just on the original patch, extend the TMS and SSH fields decreases the effective diffusivity values. Thus effective diffusivity due to 20/10 and 20/5 tries are particularly weak.*

- *Without taking account of the scale of the values, the shape of the new technique curves are different to the classical curve as well. The peak between 43° and 46° south is relocated between 40° and 43° south for the 10/10 and the 10/5 tries whereas there is no apparent peak for the others tries.*

- *Effective diffusivity values from the 10/5 try are lower than from the 10/10 try and in the same way the 20/10 try's values are lower than the 20/5's. As it could be expected, keeping the SSH anomalies at zero longer prevents the eddies from developing and finally decreases the eddy mixing.*

- *What would be a clue of the robustness of our method is to see similar effective diffusivity values whatever the buffer areas' sizes. These sizes should not affect the results, which is not the case here. Other techniques need to be explored.*

IV.3 – Temporal variability : seasonal cycle research throughout 16 years

The effective diffusivity is generated for all the 16 years from 1993 to 2008, using the satellite data of TMS and SSH every 7 days. To make up for time constraints, we will focus on the patch N which is an interesting region in terms of eddy activity.

IV.3.a – Treating each year separately

The first approach is simple. First the eddy diffusivity for every 16 year is generated independently of other years. Then, the results are gathered together and at last a curve of the eddy diffusivity evolution during the 16 years is plotted.

Thus the first results are the following :

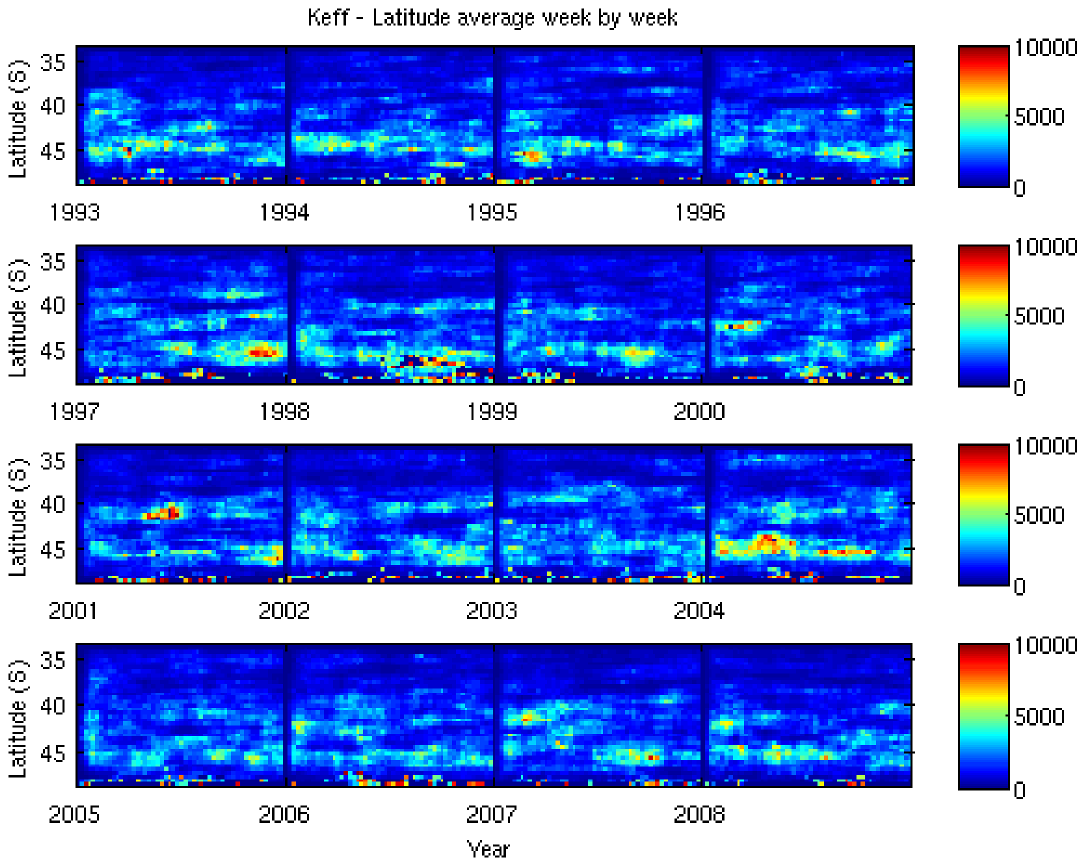


Figure 28 : Effective diffusivity average by latitude every week from 1993 to 2008

For each step, the average of each latitude has been calculated and put in a column. In this way, one column on the figure above corresponds to one step and each year is divided in 52 or 53 steps (= week).

The few blue columns at the beginning of each year render the model's need to do several steps before getting interesting eddy activity. This lack of eddies can also be seen on the next figure.

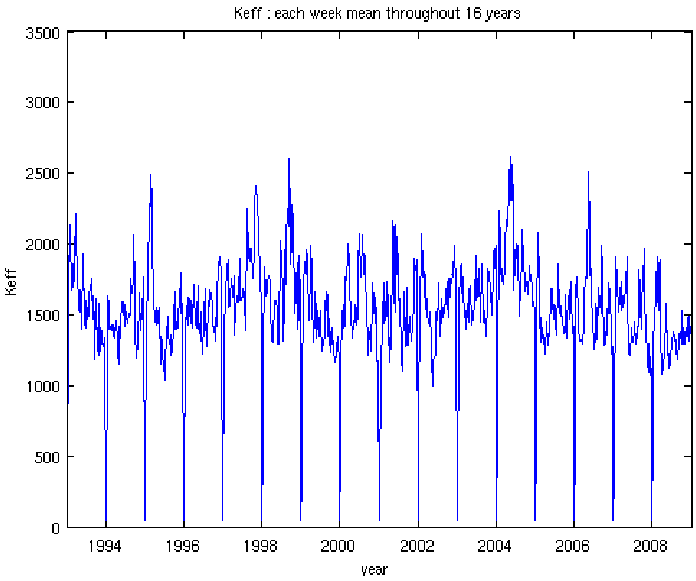


Figure 29 : Effective diffusivity average from 1993 to 2008

We here do not take account of the latitude anymore. The curve is the effective diffusivity average each week from 1993 to 2008.

Now see the effective diffusivity average on the 16 years according to the latitude (below on the left). From now on we want to work on the latitude band which has the highest values, and to remove the strange results around 48° south to have more explicit results. That's what is taken below on the right.

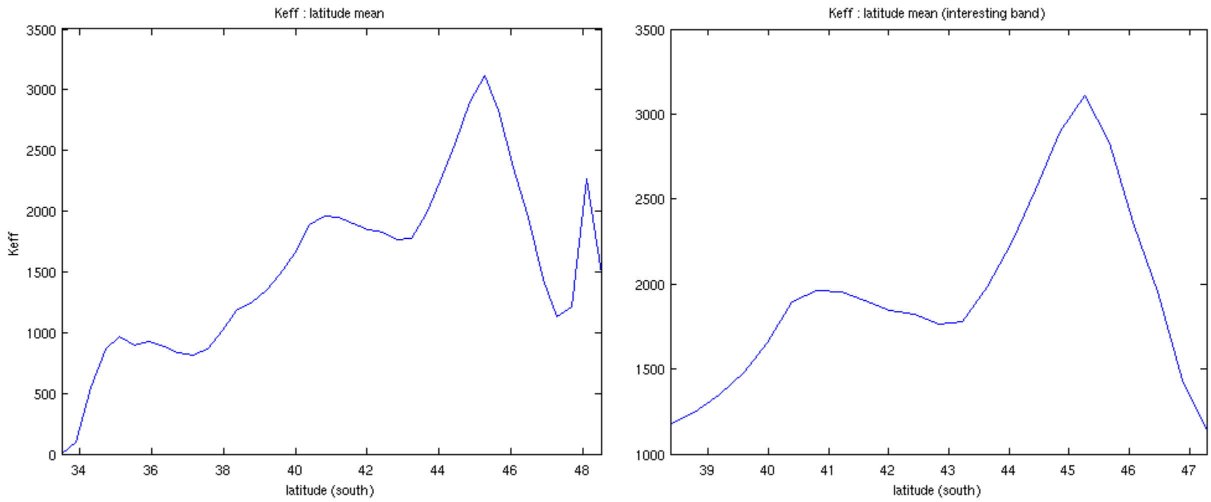


Figure 30 : Latitude mean of the effective diffusivity for the whole patch N (left) and only for the interesting band (right)

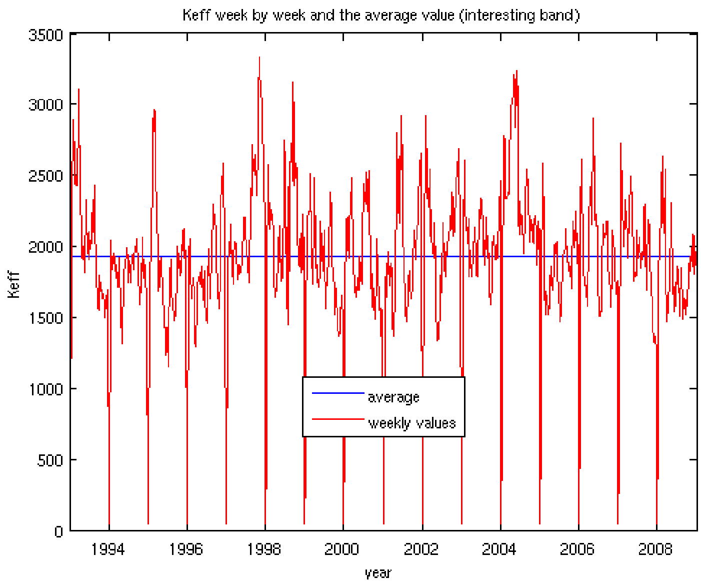


Figure 31 : Effective diffusivity average from 1993 to 2008 and its absolute average (interesting band only)

The effective diffusivity average of each week throughout the 16 years is now printed but only for the interesting band (in red), and with the absolute average (in blue). We can easily see that the curve is largely similar with the previous one in figure 29. It shows that the distribution of the eddy diffusivity is broadly similar, whatever the latitude. Only the magnitude change.

To show the eventual cycles and their amplitude more easily, we relocate the curve above to make it fluctuate around zero. To erase the important noise of the data, we also apply a simple algorithm to them, which consists in removing every old value by the mean between this value and its *n* neighbouring values (*n* is a parameter equal to 20 below).

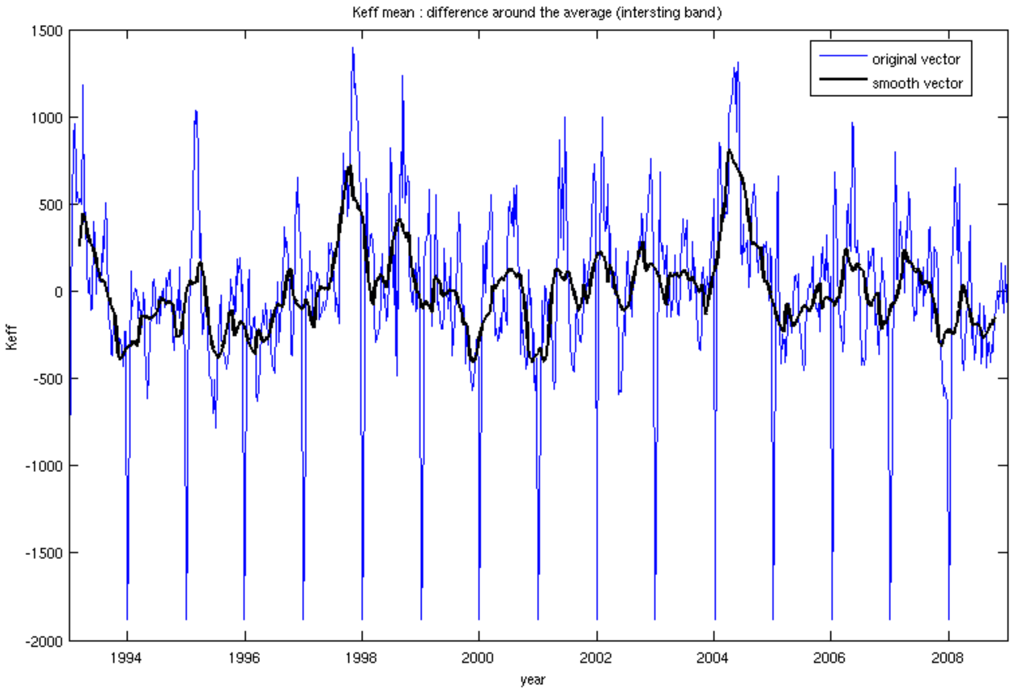


Figure 32 : The oscillation of the effective diffusivity throughout 16 years (interesting band only)

Even if extreme values are erase with this method, the same pictures have been produced again, after a try to improve the way they are obtained.

IV.3.b – Trying to link the years

The idea is to create shifted years (starting in October of the prior year, rather than January). This is to fill in the gaps at the start of the unshifted calculations during which the eddy features in the tracer are developing (the `spin up period'). The MIT general circulation model is run over these shifted years and as the 3 months which interest us are here the 3 last, the eddy activity of this 3 months has time to develop. Finally, the obtained effective diffusivity of our 3 months from the shifted calculation is put instead of the unshifted one.

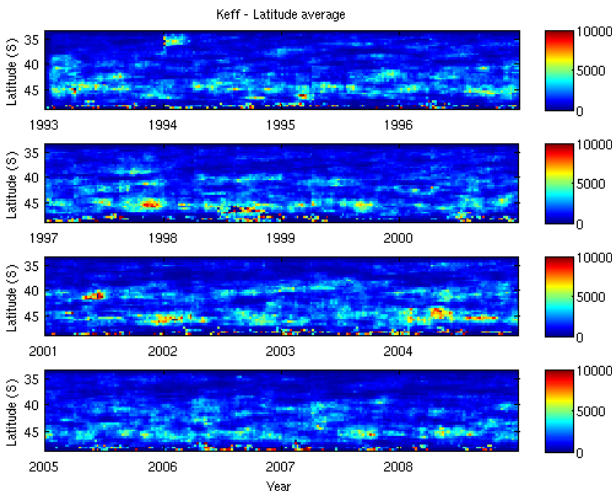


Figure 33 : Effective diffusivity average by latitude every week from 1993 to 2008 (retouched)

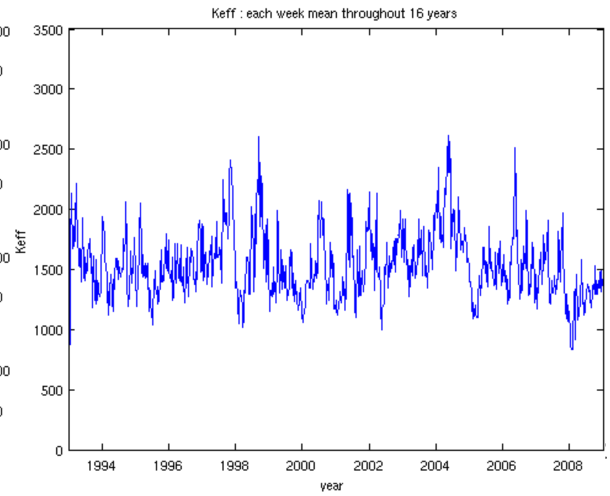


Figure 34: Effective diffusivity average from 1993 to 2008 (retouched)

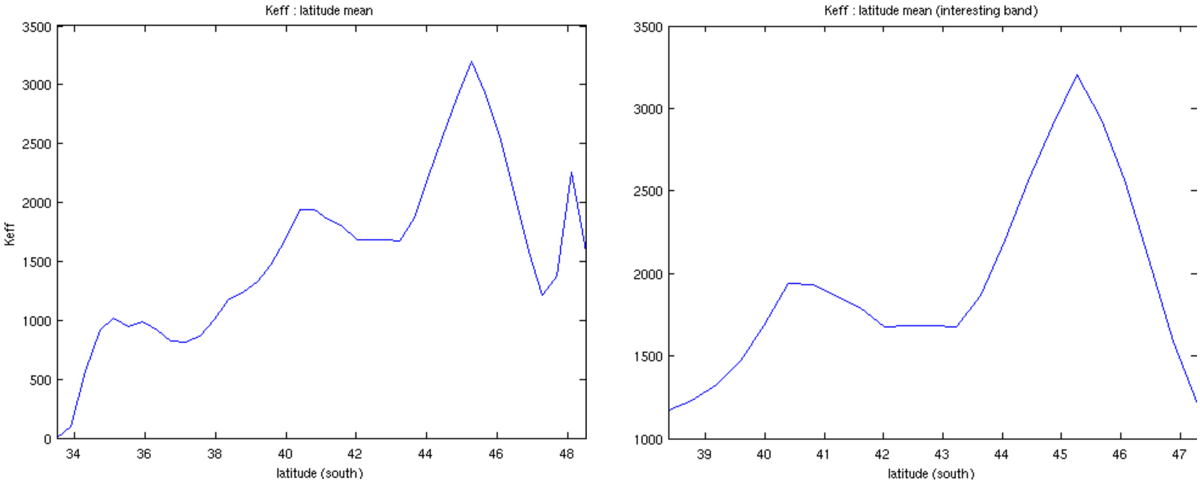


Figure 35 : Latitude mean of the effective diffusivity for the whole patch N (left) and only for the interesting band (right) (retouched)

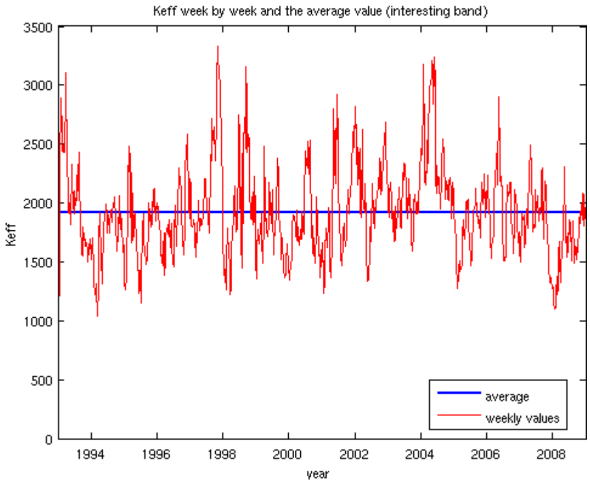


Figure 36 : Effective diffusivity average from 1993 to 2008 and its absolute average (interesting band only) (retouched)

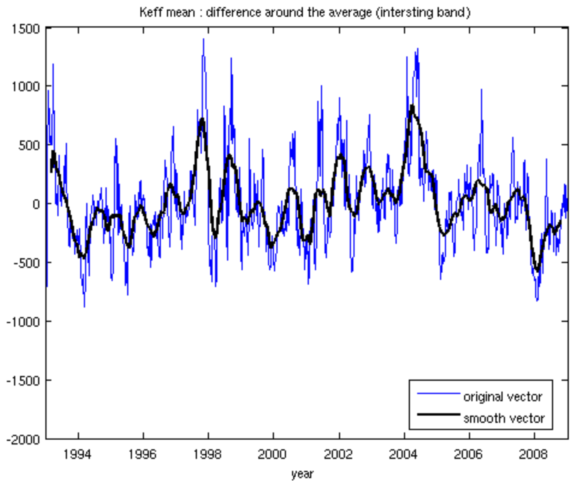


Figure 37 : The oscillation of the effective diffusivity throughout 16 years (interesting band only) (retouched)

The final picture of the effective diffusivity oscillation (figure 37) is almost the same as in figure 32. We can notice the presence of two clear peaks, during the second semester 1997 and the first semester 2004.

<u>There are a number of avenues for future work. These include</u> :

- *Do the work above (IV.3) on the patches W, E and S to see if the curve of the effective diffusivity oscillation still have the same appearance. Then produce a curve of the effective diffusivity oscillation which would render of the eddy activity all around the Kerguelen Islands.*
- *Look for some correlation between the last mentioned curve and bigger scale phenomena like the Antarctic Oscillation or El Niño. It could tell us if these global events influence mesoscale eddy activity, what is expected according to knowledge on the overturning circulation.*

- *We already know that the eddy mixing should enhance the biological productivity. Find some correlation between the effective diffusivity curve and the chlorophyll bloom observed by ocean-colour satellite images is found would be a new clue of the correctness of the MIT general circulation model.*
- *Combining the two previous points, predictions in term of biological productivity could be improved.*
- *Studies of other areas of the Southern Ocean are also necessary before draw important conclusions.*

V – ASSESSMENT

Although the aim was clearly defined at the beginning, the studies throughout the weeks have been mostly oriented by the results in progress, at the same time as new ideas were appearing. This enriched the study even if some of the original avenues of research had to be left in progress in order to reach the principal aim in time.

The time was indeed the most important constraint. Working for research for almost four months showed me difficult it is to obtain relevant results in a definite period. One can't know when interesting results will fall. I also must to mention material constraint, or more precisely computing constraints. Running the MIT general circulation model, among other things, is of course not instantaneous.

I also would like to emphasize some knowledge which I have acquired in my course and developed in my internship. I particularly think about the experience of working on a UNIX environment. The initiation of both meshes and diffusion problems during my course were also advantages for a faster understanding of the problem. More generally, the skills of flexibility and adaptability were important. Indeed, I had needed, for example, to get absorbed in oceanographic books, just to be able to understand my supervisor. At last, the programming skills largely helped me to write several codes, especially with the intention of correcting the lack of scalability of codes and of readability of results.

Regarding the results now. The obtained results are only intermediate results, thus conclusions have to be drawn with prudence. Nevertheless, the research continues and my results will serve for future studies. That's why a blog has been created and kept up-to-date, showing the principal results of the OORG and the most important things which have been learned.

VI – CONCLUSION

Quantifying mixing by eddies around the Kerguelen Islands in order to find some seasonal cycles was the main aim of the study.

After learning a few things about eddies in the Southern Ocean and understanding how the effective diffusivity could be obtained from satellite data, a comparison of the eddy activity all around the Kerguelen Islands on the year 1997 has been made. It seems to confirm the enhancement of water mixing in presence of irregular topography. A number of avenues to improve the calculations have also been explored. This is work in progress, but gives promise for future studies. Finally, the effective diffusivity oscillation around its average for a patch in the north of the Kerguelen Islands and throughout 16 years still need to be correlated with chlorophyll blooms or already known large scale phenomenon before drawing important conclusions.

Thus the study needs to be continued, and it should be easily possible leaning on the blog created to this end.

I hope finally that the present study will be able to help Emily Shuckburgh in her research. Working for her in the BAS taught me a lot, and being able to apply my skills and knowledge to a such exciting science as oceanography was for me both a bit of luck and a pleasure every day.

<u>**References**</u>

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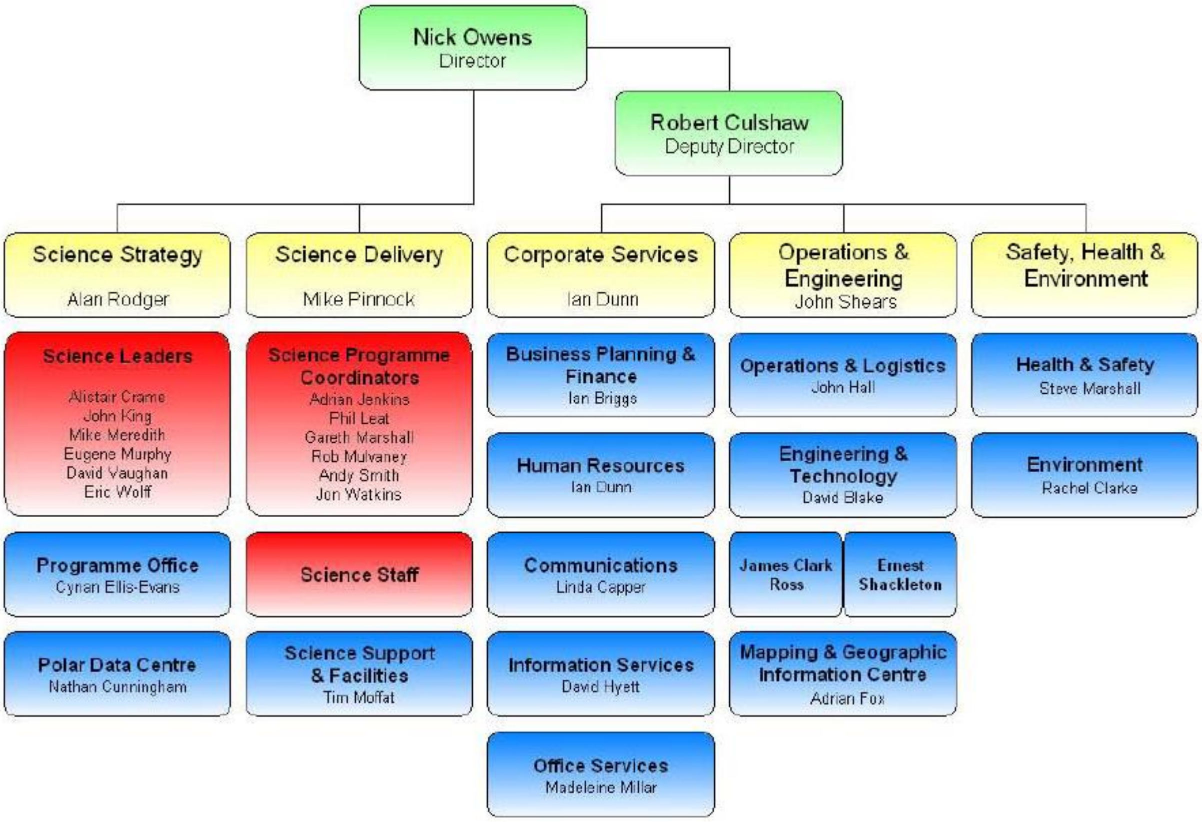
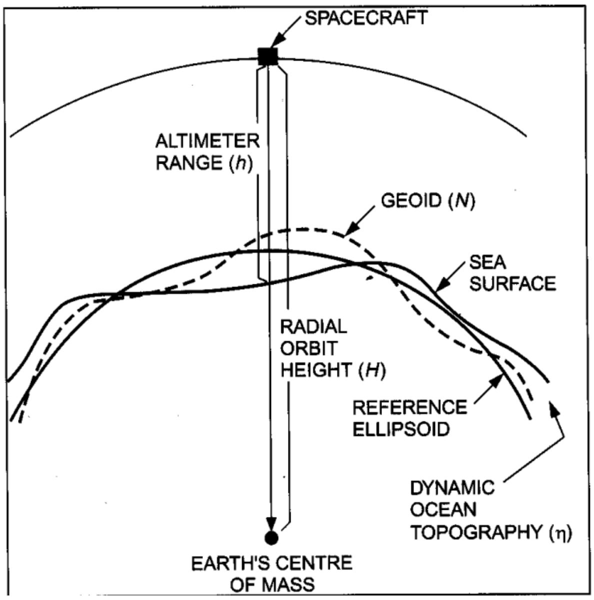
Table of appendixes

The Kerguelen Islands, in French commonly called Îles Kerguelen but officially Archipel des Kerguelen, are a group of islands in the southern Indian Ocean.

The islands are a territory of France without indigenous inhabitants, but France maintains a permanent presence of 50 to 100 scientists, engineers and researchers.

Appendix b : Appendix b : British Antarctic Survey Organisation Chart (01/04/2010)





On the left is shown the geometry of satellite altimetry. There are three components in the determination of ocean topography, η : the altimeter range measurement, h ; the radial height of the orbit, H ; and the geoid height, N. They are related as follows :

$$\eta = H - h - N \ .$$

The measurement of h is affected by uncertainties from sources including imperfect knowledge of the interaction of electromagnetic waves with the rough seas, the delay in the propagation of electromagnetic waves through the atmosphere and the ionosphere, as well as the calibration of the instrument's electronics. The determination of H is made by computations that rely on a precise knowledge of the earth's gravity field, the ability to model the non-gravitational forces such as radiation pressure and atmospheric drag, and the ability to track the location of the spacecraft precisely. The knowledge of N has to obtained from independent approach and its accuracy is a major issue in using altimetry for studying ocean circulation.

First, rewrite

$$\frac{\partial q}{\partial t} + v \cdot \nabla q = k\, \nabla^2 q$$

in the form

$$\frac{\partial q}{\partial t} = -\nabla \cdot \left(N_q + qv\right),$$

where N_q is the nonadvective (diffusive) flux of a q contours,

$$(A1):\ N_q = -k\, \nabla q\,.$$

The volume across q contours, defined by

$$a = \oint \left(v - v_q\right) \cdot n_q dl\,,$$

where $n_q = (\nabla q/|\nabla q|)$ is a unit vector normal to q contours and $v_q = \left(n_q/|\nabla q|\right)(\partial q/\partial t)$ is the velocity of a q contour normal itself, can only be associated with nonadvective fluxes (because the advecting velocity field is nondivergent. This volume flux can be related to diffusive fluxes as follows :

$$(A2):\ a = \frac{\partial \mathcal{A}}{\partial t} = -\frac{\partial D}{\partial q},$$

where D is the diffusive flux across a q contour given by

$$D = \oint N_q \cdot n_q dl = \oint N_q \cdot \frac{\nabla q}{|\nabla q|} dl = \frac{\partial}{\partial q} \int N_q \cdot \nabla q\ d\mathcal{A}\,,$$

using the following identity (a generalized form of Leibniz theorem) :

$$(\partial/\partial q) \int_{\mathcal{A}} c(x,t) d\mathcal{A} = \oint_L c(x,t) |\nabla q|^{-1} dl\,.$$

For an N_q given by Eq. $(A1)$, then

$$D = -k \frac{\partial}{\partial q} \int |\nabla q|^2 d\mathcal{A}\,,$$

and Eq. $(A2)$ becomes

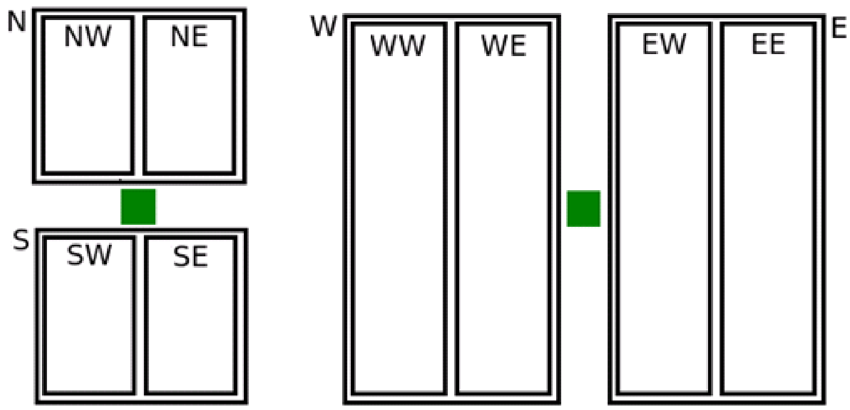
$$\frac{\partial \mathcal{A}}{\partial t} = -\frac{\partial D}{\partial q} = k \frac{\partial}{\partial q} \frac{\partial}{\partial q} \int |\nabla q|^2 d\mathcal{A}\,.$$

Now, since $\mathcal{A} = \mathcal{A}(q)$, then $(\partial\mathcal{A}/\partial t) = (\partial\mathcal{A}/\partial q)(\partial q/\partial t)$; $(\partial/\partial q) = (\partial\mathcal{A}/\partial q)(\partial/\partial\mathcal{A})$ and the above may be written as a diffusion equation in area coordinates, thus,

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial x}\left[\kappa_{eff}(\mathcal{A})\frac{\partial q}{\partial \mathcal{A}}\right],$$

with diffusion coefficient

$$\kappa_{eff}(\mathcal{A}) = k\frac{1}{\left(\frac{\partial q}{\partial \mathcal{A}}\right)^2}\frac{\partial}{\partial A}\int_{\mathcal{A}(q,t)} |\nabla q|^2\, d\mathcal{A}\,.$$



Patches	Latitude		Longitude		Size
	Upper limit	Lower limit	West limit	East limit	Lat x Lon
N	33.5° S	48.5° S	59.5° E	79.5° E	15° x 20°
NW	33.5° S	48.5° S	59.5° E	79.5° E	15° x 10°
NE	33.5° S	48.5° S	59.5° E	79.5° E	15° x 10°
S	50° S	59.5° S	59.5° E	79.5° E	10° x 20°
SW	50° S	59.5° S	59.5° E	79.5° E	10° x 10°
SE	50° S	59.5° S	59.5° E	79.5° E	10° x 10°
W	30° S	60° S	48.5° E	68.5° E	30° x 20°
WW	30° S	60° S	48.5° E	58.5° E	30° x 10°
WE	30° S	60° S	58.5° E	68.5° E	30° x 10°
E	30° S	59.5° S	70.5° E	90.5° E	30° x 20°
EW	30° S	59.5° S	70.5° E	80.5° E	30° x 10°
EE	30° S	59.5° S	80.5° E	90.5° E	30° x 10°

Notice that the Kerguelen Islands area is therefore defined by the following coordinates :
Latitude : from 48.5 to 50 south ; Longitude : from 68.5 to 70.5 east.

RESUME

Au sein du British Antarctic Survey, j'ai eu pour mission de quantifier le mélange des eaux dû aux tourbillons océaniques autour des Îles Kerguelen, en étudiant notamment les variabilités dans l'espace et dans le temps. Ce stage s'inscrit dans les recherches actuelles du D[r] Emily Shuckburgh sur le rôle des tourbillons dans l'océan. Les Îles Kerguelen constituent une région particulièrement intéressante sur les plans physique et biologique, présentant entre autres une topographie irrégulière et l'une des plus importantes efflorescences de phytoplanctons dans l'Océan Austral. Ainsi, une des principales motivations est de comprendre la corrélation entre cycles saisonniers d'activité tourbillonnaire et efflorescences de chlorophylle. C'est l' « effective diffusivity » qui reflète cette activité. Elle est obtenue en utilisant le modèle d'advection-diffusion du Massachussets Institute of Technology et à partir de données satellite qui renseignent sur les lignes de courants moyens et les anomalies du niveau de l'océan.

Il semble que l'activité tourbillonnaire soit la plus élevée juste à l'est des Îles Kerguelen. Cela confirme l'augmentation du mélange des eaux en présence de topographie irrégulière, le plateau de Kerguelen constituant un véritable obstacle sur le chemin du courant circumpolaire antarctique. En ce qui concerne la variation temporelle, notons que l' « effective diffusivity » oscille autour d'une valeur moyenne proche de 2000 $m^2.s^{-1}$, et avec deux pics notables fin 1997 et début 2004.

Mots clés : Îles Kerguelen, mélange des eaux, Océan Austral, océanographie physique, tourbillon.

ABSTRACT

Within the British Antarctic Survey, my work focused on quantifying water mixing by eddies around the Kerguelen Islands, including both the spacial and temporal variability. It forms part in the investigation of the role of eddies in ocean, which is D[r] Emily Shuckburgh's current research. The Kerguelen Islands is a region of particular physical and biological interest with among things an irregular topography and one of the largest annual phytoplankton blooms of the Southern Ocean. Thus an important motivation is to understand the correlation of seasonal cycles of the eddy activity with chlorophyll blooms. That is the effective diffusivity, obtained from satellite data of time-mean currents and sea surface height anomalies and using the advection-diffusion code from the Massachusetts Institute of Technology general circulation model, which reflect this activity.

The eddy activity seems to be the highest just on the east of Kerguelen Islands. It confirms the enhancement of water mixing in presence of irregular topography, indeed the Kerguelen Plateau constitutes a real obstacle on the way of the eastward Antarctic Circumpolar Current. In terms of seasonal variability, notice that the effective diffusivity from 1993 to 2008 fluctuates around an average value close to 2000 $m^2.s^{-1}$, however with two important peaks in the end of 1997 and in early 2004.

Keywords : eddy, Kerguelen Islands, physical oceanography, Southern Ocean, water mixing.