SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year …2013…………………………………………………….

Project Title: Using Lyapunov covariant modes for atmospheric predictability

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Computer Project Account: ……………spfrlape……………..……

Principal Investigator(s): ……Guillaume Lapeyre…………………………….……

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Affiliation: Laboratoire de Météorologie Dynamique, Paris….……

Name of ECMWF scientist(s) collaborating to the project (if applicable) …Bernard Legras……………………………….……

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Start date of the project: ……01/01/2012……………………………….……

Expected end date: ……31/12/2014……………………………….……

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	10000	3821	10000	0
Data storage capacity	(Gbytes)	100	35	100	30

Summary of project objectives

(10 lines max)

The scientific objective of this project is to make use of the Lyapunov covariant modes for atmospheric predictability studies. Until now, only singular vectors and bred vectors have been used for predictability studies of the atmosphere. The covariant modes describe the intrinsic instabilities in the vicinity of each trajectory in the phase space so that they are the more relevant to describe the error dynamics near a given prevision. Slow modes, which have a growth rate close to 0 should be less susceptible to saturate and may carry the extended range predictability. We aim to examine the properties of these modes and the predictability within this framework.

Summary of problems encountered (if any)

(20 lines max)

The project was aiming at first to make a review paper on current status on predictabilities issues using Lyapunov vectors (either covariant, backward vectors or breeding modes) and to use the numerical simulations done at ECMWF as examples. During the year, such a review was published (Kuptsov and Parlitz, 2012). Nonetheless the most interesting part in the study of these vectors is not already published/addressed by other groups, i.e. the case of barotropic quasi-geostrophic turbulence. Another problem was that we did not succeed to recruit a PhD student to work on that subject, which delayed our work.

Summary of results of the current year (from July of previous year to June of current year)

This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

Lyapunov vectors can be decomposed into three classes: forward vectors which correspond to linear perturbations which are orthogonal to each other for some particular norm and grow exponentially with time (at rates called the Lyapunov exponents). These forward vectors are the limit at infinite time of the well-known singular vectors used at ECMWF. On the contrary, backward vectors are vectors orthogonal to each other that have grown exponentially in the past (with rate equal to the Lyapunov exponents). They are related to the well-known bred vectors as discussed by Legras and Vautard (1995). Both types of vectors share the same properties to be norm-dependent and not to be time invariant (in the sense that if we let evolve these vectors over a finite time, we do not obtain the corresponding vectors at the new time). Because of these flaws, these two families of vectors do not characterize the intrinsic properties of the dynamical system. However, from these two classes of vectors, one can derive another class (the Covariant Lyapunov Vectors, CLVs) that satisfies both the norm independence and the invariance in time. These CLV (and the Lyapunov exponents) fully characterize the natural instability of the system. Recently, new techniques have been proposed to compute the CLVs, which present the advantage to be tractable numerically.
At the moment, no study of these vectors was done for atmospheric flows with high number degrees of freedom, only simplified systems for other applications were studied. Our aim is to compute these CLVs and use them to characterize the intrinsic instability properties of atmospheric flows and evaluate the potential of these vectors for long-range predictability.

The first part of the project was to adapt one typical model of the atmosphere, the quasigeostrophic barotropic model to the HPCF and to implement a parallel version of the method to compute these different vectors (using a method proposed by Ginelli et al. 2006). We were able to compute 256 CLVs for a numerical simulation of 256*256 degrees of freedom with a spectrum of Lyapunov exponents that includes both positive and negative exponents. This is quite challenging since we need to compute both the trajectory and backward Lyapunov vectors and the high number of perturbations was necessary in order to capture the perturbation with Lyapunov exponent close to zero. Also only a long time period allows the Lyapunov exponents to converge slowly in time and we need the precise knowledge of these exponents in order to sort the CLVs as a function of these exponents. At first, we have checked that the CLVs that were computed were norm-independent and time-invariant and we have examined the convergence rate of the technique to compute these vectors.

Figure 1 shows a typical snapshot with the background flow in gray shadings and the Lyapunov covariant modes (each mode with a different color). The background flow is presented as its relative vorticity, with high positive values in white, and high negative values in black. One can see the presence of numerous vortices and filaments in between, corresponding of the standard picture of two-dimensional turbulence. The CLVs are represented in colors, showing only regions of absolute value in vorticity larger than a certain threshold. We observe that CLVs are mainly located inside eddies and filaments (when plotting the vorticity of these perturbations). A difficulty when plotting the CLV spatial structures is that we have to choose a particular quantity (kinetic energy, streamfunction, vorticity) to show them, while they are not dependent on the related norm.
Nonetheless, what is striking in figure 1 is that CLVs bear some similarities between each other: some part of one CLV can overlap with another part of another CLV (see for instance the blue and green contours on the top left of Figure 1). We hypothesize that this is a manifestation of “collective” behavior of CLVs (which has been reported in the literature for simpler systems), but here this behavior occurs only in some particular regions of the background flow (here mostly eddies and filaments).
One difficulty in analysing such a flow is that there are too many interactions between vortices, so each CLV projects on many vortices at the same time (see the numerous red structures in figure 1 which correspond to only one CLV). This issue can be overcome by examining more idealized situations of 2 or 3 vortices interacting between each other. These situations occur frequently in fully turbulent flows. However, in this case, the Lyapunov exponents are zero or negative (since a flow without forcing cannot sustain any instability). Nonetheless, for periods of time long enough but not too long, we observe the superposition of CLVs for the case of rotating or translating vortices (Figure 2a and b), which is consistent with what occurs in the fully turbulent simulation of Figure 1.
An analysis of the evolution in time of CLV and the basic flow confirms the robustness of these findings in the different cases.

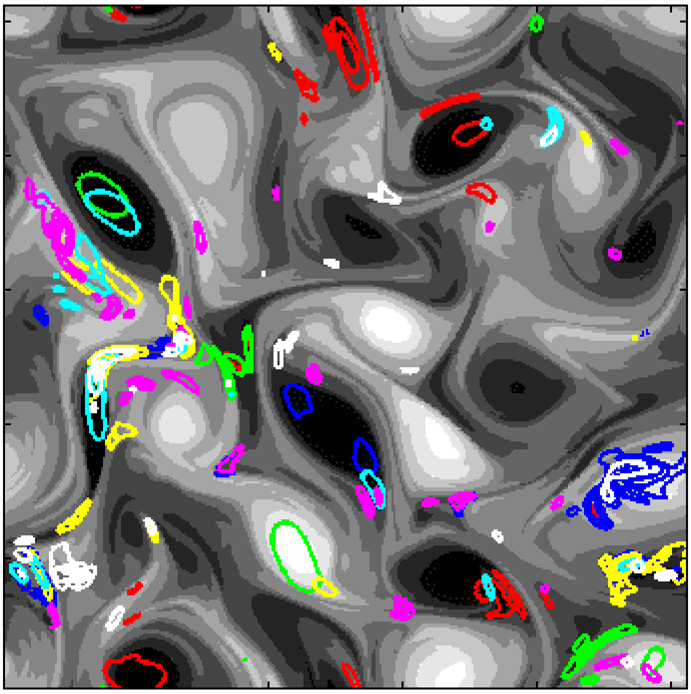

Figure 1: In gray shadings, horizontal field of relative vorticity showing numerous coherent vortices. In color, covariant Lyapunov perturbations (in term of vorticity perturbation). Each different color represents one particular perturbation associated with one Lyapunov exponent.

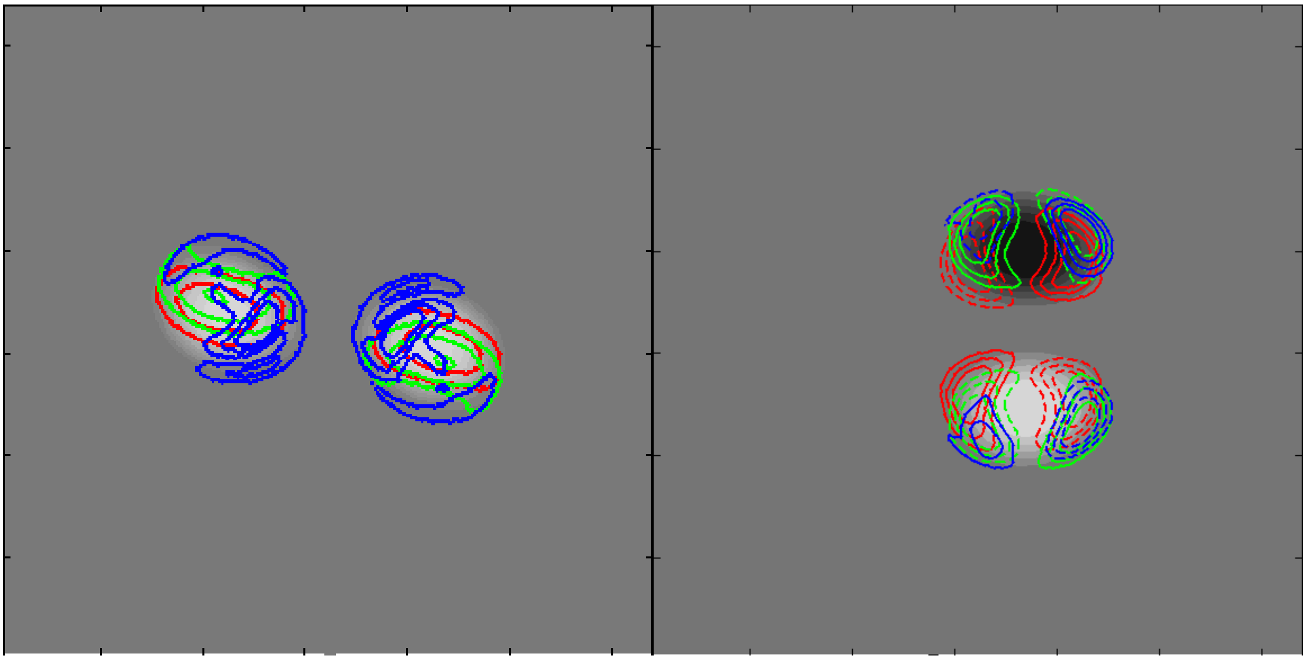

Figure 2: Case of (a) two rotating vortices, (b) translating vortex dipole. In shadings, horizontal vorticity field of the background flow. Blue, red and green contours correspond to the 3 first CLVs which correspond to positive Lyapunov exponents (when computing during the first part of the simulation).

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List of publications/reports from the project with complete references

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Summary of plans for the continuation of the project

(10 lines max)

We are now planning to implement a second technique (Kuptsov and Parliv 2012) to compute the covariant Lyapunov vectors, which would allow us to ascertain the accuracy of the computation of these vectors and to compare the advantages and the drawbacks of the two existing methods. A next step will be more theoretical since we need to provide a way to compare the CLVs with the appropriate norm in spatial space. Finally, we will examine how these CLVs may help in determining long-range predictability by examining the dynamics associated with the vectors associated with Lyapunov exponents near zero.

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