Ocean eddy tracking with circlets

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Abstract. We present a new method for detecting circles on digital images. This transform is called the *circlet* transform and can be seen as an extension of classical 1D wavelets in 2D: each basic element is a circle convolved by a 1D wavelet. In comparison with other circle-detector methods, mainly the Hough transform, the *circlet* transform takes into account the finite frequency aspect of the data: a circular shape is not restricted to a circle but has a certain width. The transform operates directly on image gradient and does not need further binary segmentation. The implementation is efficient as it consists of a few Fast Fourier Transforms. We apply the method to detect eddies on remote sensing images of chlorophyll from the Gulf of Lion (North Western Mediterranean Sea). The results show the effectiveness of the method to deal with real images with blurry edges.

1 INTRODUCTION – EDDY DETECTION

In coastal oceanography, sub-mesoscale structures, e.g. eddies in the range of 20 to 100 km, appear to be a key element for the good understanding of surface circulation, but also for the marine ecosystems as eddies may drive phytoplankton blooms. Such small eddies are not caught by altimetry or in situ measurements. Tracers (e.g. ocean color) in a turbulent ocean may however reveal the sub-mesoscale circulation. Tracking motion of non-rigid targets such as eddies is a key step for subsequent data assimilation [6]. An estimation of the temporal deformation of ocean color image is indeed not simply linked to the horizontal velocity field and cannot be directly used for data assimilation. For example, a static eddy exhibits a permanent circular shape that does not reveal the strong azimuthal velocity. A combination of eddy detection (size, position and polarization) and vertical stratification assumptions may be used to estimate the sea level anomaly and to assimilate data. In the case of oceanographic remote sensing images, eddy detection is a complex task due to weak and blurry edges, and to large motion displacements and distortions between successive satellite images. In that context, we propose a new method for eddy tracking based on a 1D wavelet analysis of objects with circular shapes. Classical 1D wavelets are very useful to detect point singularities. Combined with a geometrical analysis, it potentially offers a powerful tool for the detection of objects with circular shapes.

We first review the classical techniques developed for eddy tracking. From a global perspective, eddies correspond to water masses with a rotating component around the same pivoting center [7]. They more or less have circular structures, possibly with a closed contour, but there is no unique simple characterization of eddies [4]. In the case of simulated data, the associated velocity field or sea-surface elevation is certainly the most relevant dynamical variable for describing eddies. The most popular features are (1) the Okubo-Weiss criterion [13] that aims at separating the velocity field into regions of high vorticity and strain, and (2) the Lyapunov exponents that quantify local stirring [5]. For remote sensing images, the velocity field is however not available and other techniques have been developed to automatically detect mesoscale eddy structures. They assume a high correlation between the sea-temperature and the velocity field [9]. The eddies are generally detected either on spatial or temporal satellite gradient maps [1]. We refer to [3] for a more complete review. One could distinguish between

1. Texture-based approaches [1]. [11] compute the singularity map by processing the wavelet projections on the modulus of the gradients. Singularity analysis is then used to uncover the circulation patterns in global ocean. In [10], eddy detection is based on curvature.

2. Shape fitting based methods. These geometrical approaches mainly consist of matching a given shape (circles, ellipses, circle arcs, ...) with pixel binary segmentation data. The Hough transform and several other circle or ellipse fitting algorithms have been applied to determine the radius and the central position of eddies on binary edge maps [8].

3. Automatic machine learning based approaches. These methods analyze the neighboring pixels to distinguish between eddies and non eddy structures [3].

Geometrical methods for detecting circles or more complicated shapes are usually applied on binary images obtained after segmentation. They are thus very sensitive to the selected threshold values. Automatic techniques are restricted to eddy center detection and are always followed by a geometrical method to estimate the eddy radius.

We propose in this paper a new transform for eddy detection. It is based on a modification of the wavelet analysis to detect objects with circular shapes. We first describe the transform and then present an initial application on chlorophyll data in the Gulf of Lion (North Western Mediterranean Sea) for remotely sensed data.

2 The circlet transform

In the proposed approach, there is no need for binary image segmentation. The method consists of decomposing any image into "circles" with different radii via a series of Fast Fourier Transforms (FFTs). These circles are called *circlets* as they can be seen as the convolution of a circle with a 1D wavelet, in the same way as *wavelets* relate to waves.

2.1 General frame work

The *circlet* elements are characterized by a central position (x_0, y_0), a radius r_0 and a central frequency content f_0 (Figure 1). This finite frequency f_0 provides a certain width to the *circlet* in the spatial domain. This is the main difference with the Hough transform, beyond the implementation aspects.

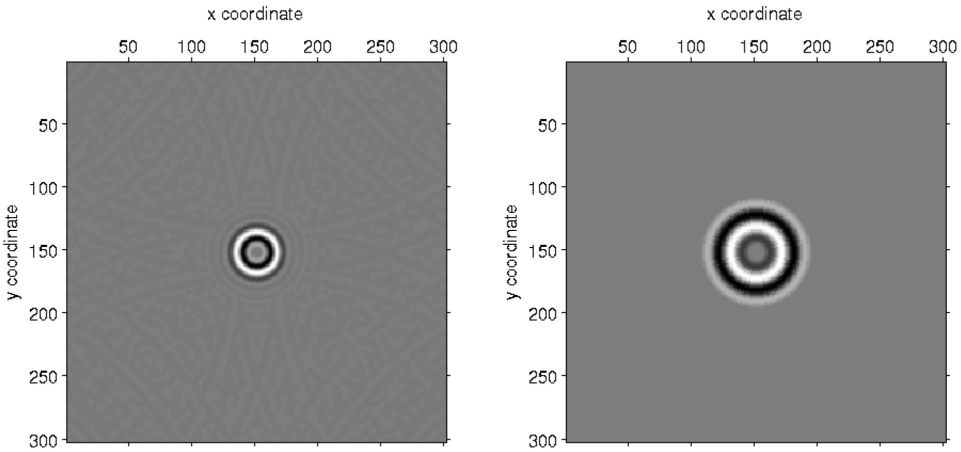

Figure 1: Representation of a single *circlet* (left) and its 2D Fourier transform (right). By construction, it is well-localized in the Fourier domain.

The decomposition and reconstruction processes are similar in essence to the curvelet transform [2]. The objective is to decompose any 2D image $f(x, y)$ into a sum of basic functions c_μ called *circlets*:

$$f(x, y) = \sum_{\mu} A_\mu \cdot c_\mu(x, y). \tag{1}$$

For curvelets, the basic elements have elongated shapes, similar to the representation of local plane waves. For *circlets*, the basic functions are circular. We first construct a tight frame, so that the associated amplitudes A_μ are obtained by a scalar product

$$A_\mu =< f, c_\mu >= \iint \mathrm{d}x\mathrm{d}y\, f(x, y) \cdot c_\mu(x, y). \tag{2}$$

From a practical point of view, the *circlet* transform is constructed in the 2D Fourier domain. The key step consists of defining appropriate filters to get basic functions c_μ with circular shapes.

2.2 Definition of filters

The construction of the filters is obtained in a two-step process: first we define 1D filters F_i and then 2D filters G_i. Both filters F_i and G_i are defined in the frequency domain and form a partition of it: for all ω and (ω_1, ω_2), we have $\sum_i |F_i(\omega)|^2 = 1$ and $\sum_i |G_i(\omega_1, \omega_2)|^2 = 1$. This condition is important to ensure a perfect reconstruction scheme. First define $\omega_i = \pi(i - 1)/(N - 1)$ where N is the number of filters. For

$|\omega \pm \omega_i| \leq \pi/(N-1)$, $F_i(\omega) = \cos(\omega \pm \omega_i)$, otherwise $F_i = 0$. Note that the F_i filters are symmetric. One can easily check that the F_i filters form a partition of the 1D frequency domain. The G_i filters are defined from the F_i filters by introducing a phase delay in order to create a circular shape in the space domain,

$$G_i(\omega_1, \omega_2) = e^{i|\omega|r_0} \cdot F_i(|\omega|), \tag{3}$$

where $\omega = (\omega_1, \omega_2)$, $|\omega| = \sqrt{\omega_1^2 + \omega_2^2}$ and r_0 determines the radius of the *circlet*. It is also easy to see that the G_i filters also form a partition of the 2D frequency domain. By using polar coordinates, it is also possible to prove that the 2D inverse Fourier Transform of G_i is circular, meaning that the basis functions $c_\mu(x, y)$ have circular shapes.

2.3 Algorithm description

The algorithm is defined as follows:

- As a pre-processing step, apply a spatial gradient (discrete Laplacian operator) to the original image in order to emphasize the discontinuities in the data. In addition to this, satellite images classically suffer from missing information due to the presence of clouds. In that case, we interpolate the data by a geostatistical filtering method (kriging) that provides results spatially consistent with the original data [12].

- Perform the forward *circlet* transform consisting of (1) a 2D Fourier transform of the original image $f(x, y)$ to obtain $\hat{f}(\omega_1, \omega_2)$, and (2) for all filters and for all selected r_0 values, the inverse Fourier transform of $\hat{f} \cdot G_i$. The result provides all the *circlet* coefficients related to scale i and radius r_0.

- Select the *circlet* coefficients with the highest absolute values.

If needed, to reconstruct the image from the coefficients, first apply a 2D Fourier transform for all scales and selected radii, multiply by the conjugate of G_i and sum all results. The final image is obtained by applying a 2D inverse Fourier transform. From a practical point of view, we rather select a single scale (i.e. single F_i filter) and a series of radii, with expected values from $r_{min} > 0$ to r_{max} to potentially select circular forms with some specific spatial sizes.

3 APPLICATION

Due to the property of the ocean, mainly the density stratification, the size of the turbulent structures is not uniformly spread. Therefore for realistic applications, a range of eddies with physically consistent sizes is selected. The application is carried out on real satellite chlorophyll maps. A chlorophyll filament is trapped by a small cyclonic eddy (Figure 2) and describes a spiral. The *circlet* algorithm applied to the gradient map provides a family of circles in agreement with the spiral shape of the filament. The larger one provides the horizontal scale (10 km) and the position of the eddy. For spiral, the main shape is not strictly circular. However, only few *circlet* coefficients (around 10) are sufficient for a good representation of the spiral (Figure 3).

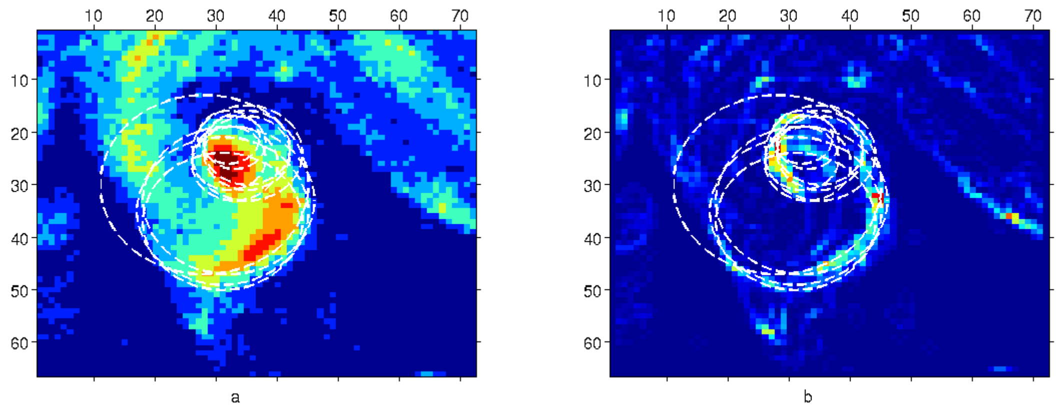

Figure 2: Original chlorophyll image (a) and spatial gradient image (b). The circles indicate the geometrical positions of the *circlets*.

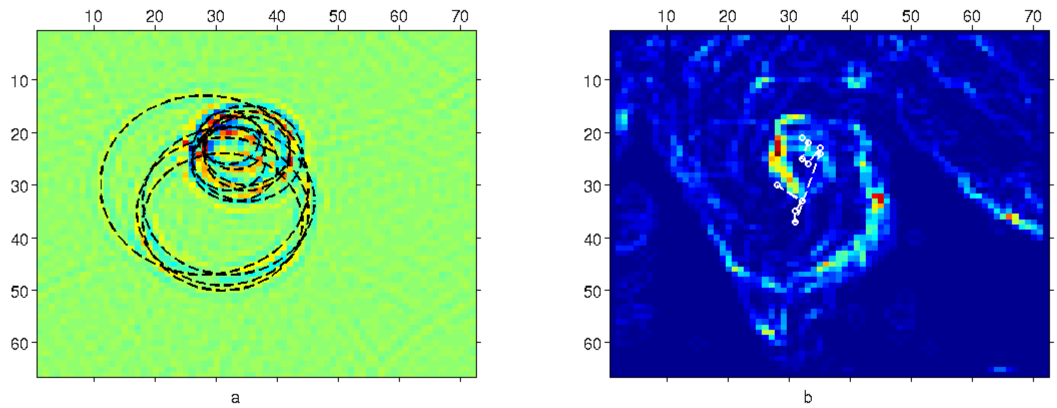

Figure 3: Reconstructed image (Figure 2) with the highest *circlets* coefficients (a), and central positions of the *circlets*, connected with decreasing radii (b).

4 Discussion

The applications are not restricted to chlorophyll images but could be used for sea-surface temperature data whenever images contain objects with circular shape. The 1D wavelet analysis implicitly contained in the *circlet* transform is very helpful for the detection of weak or blurry contrasts. Remote sensing patterns are not only the results of the circulation. The tracer behavior is obviously not conservative and depends for instance on the sunshine for the sea-surface temperature or on the biological activity for the chlorophyll. Expected spurious eddies can potentially be removed by applying the transform on a series of dynamical images. As a circle-detector, the *circlet* transform can be used in many other fields such as e.g. in medical imagery to detect and track eyes.

The *circlet* transform is a redundant transform in the sense that the number of coefficients is larger that the size of the input data. In the application, the selection of the *circlet* coefficients was done by a simple hard-thresholding, but more advanced methods such as soft-thresholding should be considered to select the most representative *circlets*.

5 CONCLUSION

We have presented a new method for detecting discontinuities with circular shapes on 2D images. The key property of the transform is certainly the finite frequency aspect of the basis functions. The transform is efficient due to its implementation in the Fourier domain. It can be used to evaluate the performance of numerical simulations with respect to the behavior of eddies (position, size, motion) observed on satellite images. We believe that the *circlet* transform could be used for a large number of applications not restricted to eddy detection in oceanography.

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