

On Spiral Eddies in the Ocean

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Preface

Small cyclonic spiral eddies with a scale of 10 km are very frequently observed, both from satellites and space shuttles, at the ocean surface. In the “mesoscale revolution”, weather and baroclinic instabilities were attributed to the ocean. This line of research is continued herein. It is suggested that spiral eddies may possibly be the sea surface signature of the “bad weather” below. The spiral-like cyclones generated and evolving in this baroclinic model regime are found to be consistent with the observed spatial and temporal scales. Both modelled and observed spiral eddies are associated with streaks of strong cyclonic shear and convergence. The numerical experiments presented indicate that spiral eddies are restricted to the very upper ocean, and that they are a source of kinetic energy for the mean flow.

The bad weather generated from ageostrophic baroclinic instabilities is prone to strong cyclonic lows. This is a cornerstone in the spiral model put forward, and has to be taken into account when choosing a model ocean. In particular, the ability of the so-called variable-temperature layer model to produce oceanic “bad weather” as defined herein, is found to be limited.

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This research was conducted under the supervision of Professor Kristian B. Dysthe. Although science today is much characterized by its specialists, it has been my privilege and pleasure to work with one of its remaining “Renaissance men”. I can only hope that some of Kristian’s knowledge and broad approach to science have rubbed off on me.

I am also indebted to the other members of the Hydrodynamics group of the Department of Mathematics, University of Bergen. In particular I thank Professor Jarle Berntsen for introducing me to numerical ocean modelling, and Dr Inge K. Eliassen for our many discussions.

One part of this thesis (paper 3) is the result of a stay at the School of Mathematics, University of New South Wales, Sydney, Australia. I thank Professor Michael A. Banner for inviting me, and Dr Brian G. Sanderson for discussing his research with me, and for letting me use his numerical ocean model. I am very grateful to Greg and Guilaine Buckley, and to Simon and Kylie Evans for their genuine hospitality, and for the many good times “Down Under”. Even though I never got to see the Great Barrier Reef, I have been to the Royal both in Randwich and in Leichhardt.

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Introduction

When I returned to Scripps Institution at the end of W. W. II as a student of Harald Sverdrup, physical oceanography was still practiced in the tradition of the “Challenger” expedition, with a few isolated research vessels probing the world oceans. As a result, we were studying ocean climate rather than ocean weather.

Munk (1997)

Going back to the seminal papers of Charney (1947) and Eady (1949), the synoptic highs and lows in the extratropical atmosphere are understood to be the result of baroclinic instabilities. At the time Charney and Eady published their theories, weather forecasting had been treated as an initial value problem of mathematical physics for almost half a century (c.f., Eliassen 1994). There was no such complex approach to dynamical oceanography. The dynamics of the ocean were thought to be characterized by gyre scale ($O(1000\text{ km})$) circulations, and by western boundary currents like the Gulf Stream and the Kuroshio. Then came the “mesoscale revolution”.

1. The mesoscale revolution

The phrase “mesoscale revolution” is due to Munk (1997). He dates the revolution to the discovery of the Gulf Stream meanders in the fifties (c.f., Stommel 1965), and the revelation of strong variable currents in the deep waters during the 1959–60 R/V *Aries* campaign (c.f., Swallow 1971). This started off huge measurement programs. The MODE Group (1978) found that the kinetic energy level associated with the mesoscale eddies is two orders of magnitude larger than that of the gyre scale mean flow! The mesoscale denotes the oceanic dynamic equivalent to the atmospheric synoptic scale, that is the scale of the weather. Thus, the existence, and importance, of an oceanic counterpart to the atmospheric weather was established. As cyclonic lows and anti-cyclonic highs constitute the synoptic weather in the atmosphere, mesoscale eddies in the ocean may be termed “oceanic weather”. The fundamental length scale of the baroclinic flow that forms the weather is the internal radius of deformation. The mesoscale therefore refers to horizontal variability on a scale from tens to some hundreds of km. The lower range is referred to as the submesoscale. Weather is herein restricted to mean the weather of middle and high latitudes.

A useful framework for modelling the mesoscale is the quasi-geostrophic (QG) approximation, formalized by Charney (1948). The linear QG the-

ories of Charney (1947) and Eady (1949) successfully predict the scale of the synoptic weather. In a review paper, McWilliams (1979) reports that a variety of mesoscale features may be interpreted quasi-geostrophically. Examples are the meanders of the Norwegian Coastal Current, and open-ocean eddies.

Quasi-geostrophic instability, with its implicit requirement that the internal radius of deformation R is much larger than the inertial length scale L_0 , produces high and low pressure anomalies of equal strengths. Ageostrophic ($R \sim L_0$) baroclinic instabilities produce more dramatic events, i.e., bad weather. When the QG restriction on the scales is lifted, intense cyclonic lows is the result (e.g., Gill 1982, p. 575). For submesoscale baroclinic flow, R and L_0 are of comparable magnitude. Submesoscale baroclinic instabilities could therefore be expected to generate “oceanic bad weather”. This is supported by the linear stability analyses of Barth (1994), and Fukumachi et al. (1995). Bottom frictional torques (D’Asaro 1988; Ohshima and Wakatsuchi 1990), and the coastal ocean response to surface wind and stress variations (Shay et al. 1998), have also been suggested to generate submesoscale eddies.

2. Spiral eddies

Their (the spiral eddies’) almost ubiquitous occurrence... whenever submesoscale dynamics was revealed in the sun glitter, indicates that they are perhaps the most fundamental entity in ocean dynamics at this scale.

Scully-Power (1986)

The so-called spiral eddies are a distinct submesoscale surface pattern. Up to the eighties, they were considered to be rare dynamic features in the ocean. Photographs of the world’s oceans from space shuttles (Scully-Power 1986; Munk et al. 2000), and images of Norwegian coastal waters from radar satellites (Dokken and Wahl 1996), have shown that such eddies are indeed common. An eddy street made visible by the sun’s reflection from the surface of the sea is shown in Figure 1.

Surface convergence compacts naturally occurring surface active material into slicks. Both SAR and sun-glitter images of the ocean surface have a rather broad distribution of sea slicks, or streaks, with a spacing of the order of 1 km and a width of the order of 100 m (c.f., Figure 1). The streaks are domains of reduced surface roughness, making them visible to the remote instruments. It is the large-scale arrangement of these streaks that forms the images of the spiral eddies. A small minority of the streaks are shear

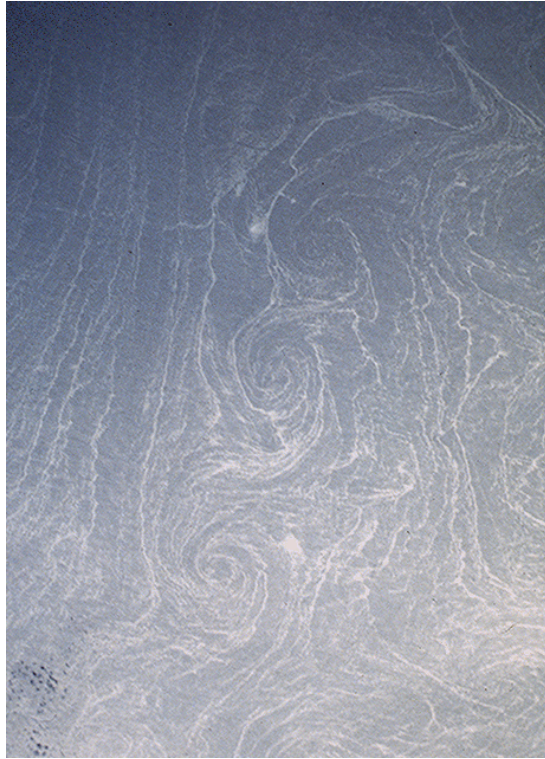


Figure 1: Photograph of a spiral eddy street in the Mediterranean Sea off the coast of the Egyptian/Libyan border (Scully-Power 1986). The diameter of the eddies is roughly 10 km.

lines. On the SAR and glitter images they can be identified when there is a crossing ship wake. The wake is then dislocated across the shear line consistent with a large cyclonic shear. In several cases (e.g., Scully-Power 1986; Munk et al. 2000) the shear has been estimated to be of the order 10^{-3} s^{-1} , ten times the magnitude of the planetary vorticity f at mid-latitude. Munk et al. (2000) find the shear lines to be exclusive to the spirals: "...spiral features, unlike other surface features, reveal strong cyclonic displacements of ship tracks". The lines seem to persist, still tracing out spirals, in SAR images at larger wind speeds when the regular slicks have been suppressed (e.g., Dokken and Wahl 1996; Johannessen et al. 1994). Thus, we associate these shear lines with the eddies.

Spiral eddies have been observed in many oceans in both hemispheres, but not within 6 degrees of the Equator. They are found both in coastal

areas and in the open ocean, generally in an interconnected pattern, but it should be noted that observed patterns are frequently somewhat more random than that of Figure 1 (c.f., Scully-Power 1986; Munk et al. 2000). A quite extreme example is pictured in Figure 2. Scully-Power (1986) describes spiral eddies to be always cyclonic, with a diameter of 12 to 15 km, while in the ERS SAR observations of Dokken and Wahl (1996) from the Norwegian coast, 85% of the eddies are cyclones and 15% anti-cyclones. The average diameter of the anti-cyclonic eddies was found to be more than three times that of the cyclones, which was estimated to be approximately 7 km. Munk et al. (2000) collected more than 400 photographs taken by astronauts containing spiral eddies, and found them to be “10–25 km in size and overwhelmingly cyclonic”. The reader is referred to Munk et al. (2000) for further observational characteristics and an historic account on the discovery of spirals. The latter is as an outline of the history of space oceanography in general. From the Apollo program of the 1960s, via the launch of the first ocean satellite in 1978, to the variety of space-borne instruments of today, remote sensing has been essential in revealing the complexities of the dynamic ocean.

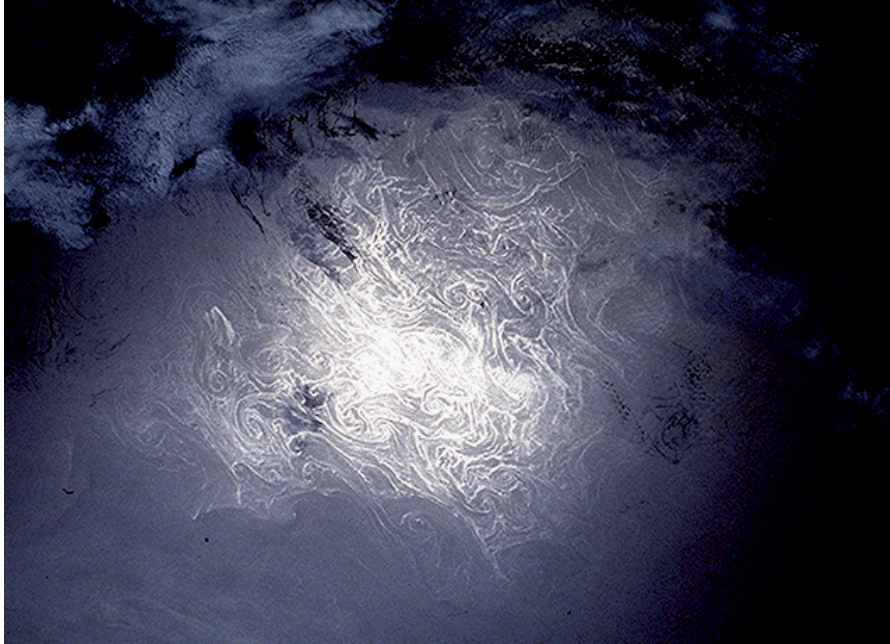


Figure 2: Photograph of a complex spiral eddy field in the Gulf Stream off Long Island, New York state, U.S.A. (Scully-Power 1986).

To sum up: Spiral eddies are cyclonic eddies with a horizontal scale of the order of 10 km. The slicks that trace them out are associated with both convergence and large cyclonic shears. Observations from space platforms suggest spiral eddies to be plentiful in the world's oceans.

Modelling spiral eddies

Even though spiral eddies are frequently observed, it seems that surprisingly little effort has been put into finding a model for their generation and life. We are aware only of the contributions of Eldevik and Dysthe (1999, 2000), and Munk et al. (2000). Apart from the need to understand the phenomenon, there are several other important reasons to study such submesoscale dynamics. It may have significance for the understanding of the larger scale system. In a similar way that the “mesoscale revolution” introduced (quasi-geostrophic) weather to dynamical oceanography, submesoscale dynamics can introduce the equivalent of bad (ageostrophic) weather, as suggested in the introduction.

The submesoscale is rarely resolved by the spatial and temporal resolution used in numerical ocean models today. The parameterization of sub-grid scale physical effects in such models is often essential for their performance.

Eddies are important in the distribution of passive tracers like plankton patchiness, both in the real ocean (e.g., Pingree 1978; Pingree et al. 1979), and in ocean models (e.g., Abraham 1998). Models of how spiral eddies are generated could also improve the interpretation of data from remote sensing. This is particularly important as snapshots of spirals from space are plentiful. There seems to exist no *in situ* measurements of the spirals, and only one observation of temporal evolution (i.e., Flament and Armi 1985).

1. The Margules front (Paper 1, Eldevik and Dysthe 1999)

Spiral eddies have been described as cyclonic eddies with a horizontal scale of $O(10\text{ km})$, that is in the low range of the internal radius of deformation in the ocean. Adding to this the absence of spirals in the vicinity of the Equator makes a compelling argument that the phenomenon is baroclinic and ageostrophic. A simple geostrophic flow that is both baroclinic and has a surface shear line of strong cyclonic vorticity is the so-called Margules density front. An example of a Margules front can be found in Figure 2 of

Eldevik and Dysthe (1999).

The importance of such fronts for the development of intense low pressure zones/cyclones in the synoptic weather, was put forward by the Bergen school of meteorology (e.g., Bjerknes 1919; Solberg 1928). The generation of spiral eddies through cyclogenesis at density fronts could be a common denominator of the observations. Both Scully-Power (1986) and Munk et al. (2000) believe strong cyclonic shears to be a characteristic of the spirals. Dokken and Wahl (1996) find eddies to be “situated exactly at the border between, in all probability, two different water masses” in several of the images along the Norwegian Coast.

Eldevik and Dysthe (1999) investigate the possibility that the spirals are generated due to instabilities at a Margules type front (c.f., their Figure 2). The linear stability of such a simple two-layer geostrophic equilibrium has been studied by several authors (e.g., Iga 1993, and references therein). The findings of Iga (1993) suggest that the preferred length scale of an unstable frontal wave can be submesoscale. In the nonlinear, three-dimensional numerical experiment, Eldevik and Dysthe (1999) use as the initial condition a slightly disturbed Margules type front that is diffused so that the frontal width is a few kilometers. Initially, small scale frontal disturbances grow according to the ageostrophic predictions of Iga (1993). In the nonlinear stage of development, the frontal wave winds up cyclonically into spirals of dimension less than half its wavelength (c.f., Figure 5 of Eldevik and Dysthe 1999). It has a clear similarity to the eddy street in Figure 1. Associated with the curl-up is a relatively strong convergence that is seen to accumulate passive surface floats in the spirals. The instability is found to be predominantly baroclinic and the dimension of the spirals is of the order of 10 km.

The simulation demonstrates how a front with cyclonic shear will curl up into cyclonic spiral eddies having the right dimension. The question of why cyclonic shear seems to dominate in ocean fronts is not addressed, and simply taken as a fact as static stability requires the shear across a Margules front to be cyclonic. Whether a Margules front is a likely geostrophic flow is questionable. Since the work of Charney (1947) and Eady (1949), extratropical fronts have been considered to be intrinsic to the evolution of baroclinic instabilities in a continuously stratified atmosphere.

2. Oceanic “bad weather” (Paper 2, Eldevik and Dysthe 2000)

In addition to their observational material, Munk et al. (2000) offer a model for the generation of spiral eddies. The preference for cyclonic shears is ad-

dressed. They present a sequential process consisting of two essentially two-dimensional stages. First there is an ageostrophic frontal preconditioning phase, producing strong cyclonic shears. Then they assume a shear instability to wind up spirals in the established shear zone. Separating the problem into these two distinct phases, Munk et al. (2000) give the reader an appealing image of the generation of ocean spirals. What is excluded, however, are the details on the transition between, and the possible coexistence of, the two phases. In meteorology, sharp fronts and cyclones are understood to be generated in the same baroclinic instability process (e.g., Garnier et al. 1998). As an unstable frontal wave evolves, there is both sharpening of horizontal gradients perpendicular to the wave and nonlinear windup of the wave to produce cyclones. An estimate of the preferred length scale of the corresponding oceanic frontal waves is therefore required in order to apply such a model to the spiral eddies.

Along these lines, Eldevik and Dysthe (2000) find that spiral eddies may possibly be described as oceanic bad weather. They suggest that buoyant geostrophic jets in the upper ocean are prone to produce unstable frontal waves that provide a suitable horizontal restriction for the spirals, and with an ageostrophic growth rate in agreement with the temporal evolution estimated from Flament and Armi (1985). The argument, that is based on dimensional analysis and a variety of previous relevant research on baroclinic instability, is strengthened by the results of the accompanying numerical experiments.

A number of different experiments were conducted. The initial geostrophic flow of the reference experiment, displayed in Figure 5 of Eldevik and Dysthe (2000), has a weak horizontal stratification with a corresponding wide surface velocity jet. There is no external forcing present. Emerging anomalies must draw their kinetic energy from either the mean kinetic energy or the (available) potential energy of the flow. As the disturbance grows, frontogenesis sets in, and the velocity shear is strongly amplified by convergence on the cyclonic side of the jet. In Figure 6 of Eldevik and Dysthe (2000), the frontal wave is seen to wind up nonlinearly to reveal a cyclonic spiral. Due to the accompanying convergence, passive surface floats accumulate to delineate the eddies in their Figure 13. The horizontal dimension and the time scale for the windup of eddies displayed in the numerical experiments, as well as the associated shear and convergence, are in good agreement with estimates from observations. Eddy motion extends down to the model thermocline, but the actual spiral eddies are seen to be concentrated in the upper 20–40 meters (c.f., their figures 9, 10, and 12).

Secondary instabilities eventually set in to produce a more complex pattern of similar cyclones (c.f., their figures 17 and 18). For relevance to observations, the reader should compare their figures 13a–c and 18 with the sun glitter images in figures 1 and 2.

In agreement with Eldevik and Dysthe (1999), but contrary to the instability model of Munk et al. (2000), the generation and life of spiral eddies are found to be of baroclinic nature. For large periods of the simulations, the kinetic energy of the mean flow is found to feed on that of the eddies. In other words, the spiral eddies accelerate the mean flow. Orlandi and Cox (1973), Qiu et al. (1988), and Wang (1993), all find a similar transfer of energy in their numerical studies of larger scale baroclinic instabilities of ocean currents. As the observational material suggests spiral eddies are abundant in the ocean, they may be an important source of kinetic energy for the meso- and larger scale flow. In most non-eddy-resolving experiments, this “up the gradient” transfer of energy is not possible because energy is continuously dissipated from the flow through eddy viscosity.

3. Choosing a model ocean (Paper 3, Eldevik 2000)

Numerical modelling has for the last thirty years been an integrated part of dynamical oceanography. There exists a variety of numerical model oceans. They vary in both physical and numerical complexity (c.f., Kowalik and Murty 1993; Røed 1996). Orlandi and Cox (1973) were probably the first to model baroclinic instabilities in the ocean with a full three-dimensional numerical model. The approach to mesoscale modelling is quite similar today (e.g., Samelson and Chapman 1995; Erasmi et al. 1998). The major difference is the increased spatial and temporal resolution allowed for by the increase in computer power.

The proper representation of submesoscale dynamics in numerical ocean models requires a horizontal resolution of 1 km or less. Eldevik and Dysthe (1999, 2000) used the primitive equations, σ -coordinate numerical model of Berntsen et al. (1996) for the modelling of spiral eddies. Even such idealized process studies are computationally expensive at the required resolution. A typical experiment took 48 hours of CPU on an SGI Origin 2000.

Vertically homogeneous variable-temperature layer (VTL) models, originally due to Lavoie (1972), are often used as an alternative to three-dimensional primitive equations models. This is motivated by the fact that the upper ocean is often relatively well-mixed and separated from the underlying heavier water by a well-defined thermocline. In particular, it has been argued that VTL models are suitable for describing the dynamics

of ocean jets and fronts (c.f., Røed and Shi 1999, and references therein). In the widely used isopycnic-coordinate numerical ocean model MICOM, the upper layer is frequently chosen to be a VTL as described by Bleck et al. (1992). For a given computational cost, two-dimensional VTL models can resolve smaller horizontal scales than full three-dimensional primitive equations models, making the former amiable for the study of mesoscale ocean dynamics.

For the above reasons, the numerical experiments of Eldevik and Dysthe (2000) were originally planned to be performed in a VTL model ocean. The results of the preliminary simulations were surprising. Contrary to the expected scenario, i.e., spiral eddies as a surface signature of bad weather in the ocean (c.f., section 2 of Eldevik and Dysthe 2000), the unstable frontal wave emerging from any given initially geostrophic jet showed no preference for cyclones. Staggered rows of cyclonic and anti-cyclonic vortex pairs analogous to the Karman vortex street was the result (e.g., Figure 4 of Eldevik 2000). Thus, the VTL model ocean was discarded.

The seeming failure of the VTL model to produce spiral eddies, and the oceanic bad weather associated, is addressed by Eldevik (2000). The VTL model is based on the three-dimensional primitive equations model. The former model is the result when a suitable mixing of horizontal momentum is prescribed to the latter. See section 2 of Eldevik (2000) for details and the assumptions required. Through simple manipulations of the governing equations and numerical experiments, Eldevik (2000) finds that the added mixing dominates the VTL vortex dynamics. Conservation of potential vorticity, a key element in describing and understanding baroclinic dynamics, appears to fail in particular. This explains why staggered rows of vortices, and not the expected spiral-like cyclones, emerge from the initial geostrophic flow; compare figures 3 and 4 of Eldevik (2000).

Concluding remarks

In the “mesoscale revolution”, weather and baroclinic instabilities were attributed to the ocean. This line of research has been continued herein. The findings of Eldevik and Dysthe (1999, 2000) suggest that spiral eddies may possibly be the sea surface signature of the “bad weather” below. The spiral-like cyclones generated and evolving in this baroclinic model regime are found to be consistent with the observed spatial and temporal scales. Both modelled and observed spiral eddies are associated with streaks of strong cyclonic shear and convergence. The numerical experiments indicate

that spiral eddies are restricted to the very upper ocean, and that they are a source of kinetic energy for the mean flow.

The bad weather generated from ageostrophic baroclinic instabilities is prone to strong cyclonic lows. This is a cornerstone in the spiral model put forward, and had to be taken into account when choosing a model ocean. In particular, the ability of the so-called variable-temperature layer model to produce oceanic “bad weather” as defined herein, was found to be limited (i.e., Eldevik 2000).

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