Vortices in the ocean

Lecture 1: observations, measurements, structure and role
OBSERVATIONS
First, the wind driven circulation in the North Atlantic

Wind and current patterns (schematic)
Now, let's have a look at a few oceanic eddies...

Loop current eddies (Gulf of Mexico)
(1) Gulf-Stream rings
Fig. 2. (a) Diagrams showing the formation of cyclonic Gulf Stream ring Bob in February–March 1977 based on infrared images from the NOAA-5 satellite. Two anticyclonic (warm-core) rings were observed north of the Gulf Stream. (b) Vertical temperature section through ring Bob and the Gulf Stream on 12 March 1977. Ring Bob can be seen as the area of raised isotherms and cool surface temperatures.
On the other side of the basin, meddies and swoddies...

Mediterranean water outflow in the Gulf of Cadiz
(2) Meddy formation from the Mediterranean water outflow

Fig. 2. – Les eaux méditerranéennes entrent dans l’Atlantique au niveau du détroit de Gibraltar. Par un mécanisme qui reste à élucider, de grosses bulles sont lâchées. Celles-ci s’aplatissent et sous l’action de la force de Coriolis, qui dévie les mouvements vers la droite dans notre hémisphère, forment des tourbillons anticycloniques : les meddies.

(meddy = Mediterranean water eddy)
Vertical structure of meddies (T and S)
Observed distribution of meddies in the northeastern Atlantic

Fig. 5. – Recensement de tous les meddies observés. Noter le déplacement général vers le Sud-Ouest (source : Richardson et al, JPO 90).
(3) Surface eddy generation on the eastern boundary of the North Atlantic

The NAVIDAD current in winter around the northwestern and northern Iberian coast and in the Bay of Biscay (dark = warmer waters)

Two warm surface eddies detach from NAVIDAD: O98 near Cape Ortegal and F98 near Cape Ferret canyon
Sketch of time series of SST showing swoddy formation near Cape Ferret in 1990
Swoddies (Slope Water Oceanic eDDIES) in the Bay of Biscay
How do we measure oceanic vortices?

In situ measurements

Eulerian methods: from ship, moored
Lagrangian methods: acoustic or not, guided or drifting

Remote sensing (satellites)

SST, SSH, SAR, SSS?, Scat
Measurements from ship
Moorings

EQUIPMENT

Radio: s/n 9550
Freq: 156.425
Strobe: s/n A-1010

45" SYNTACTIC FLOAT (new)
150Khz ADCP S/N 600

300 M

3/16" WIRE 366-A = 47.70 m

SONOTEK C.M. s/n D-305

400 M

3/16" WIRE 366-B = 193.42 m

SONOTEK C.M. s/n D-300

600 M

5-17" GLASS FLOATS

3/16" WIRE 366-C = 193.29 m

800 M

5-17" GLASS FLOATS

3/16" WIRE 366-D = 80.70 m

SONOTEK C.M. s/n D-308

893 M

10-17" GLASS FLOATS

RELEASES: s/n 30202 ORE
s/n 30203 ORE

3/16" WIRE 366-E = 99.80 m

3/8" CHAIN 5.0 m

1000 M

ANCHOR 2500 lbs. Air (3 wheels)
Drogued surface drifters
SEMASE 99

Surof. buoy trajectories

* : Release position

AQSOS positioned buoys
26510 1400m
26511 900m
26512 900m
26513 1100m
26521 1200m
26522 1200m
26529 900m
Deep floats (isobaric/isopycnic floats) acoustically tracked: RAFOS
"Meddy" Formation off the Iberian Peninsula
Sea Surface Temperature and Sea Surface Height

Algerian eddy: SST, SSH, geostrophic velocity
A few numbers (scales):

- **Radii** from 10 to 120 km,
- **Thickness** from 100 to 1000m (or more)
- **Location**: surface, thermocline, bottom (cold dome) eddies
- **Velocities**:
  - Internal: up to 1 m/s horizontally (GSR), more often a few 10cm/s
  - External: 1 to 10 cm/s (beta-effect, topography, currents)
- **Temperature and salinity anomalies vs environment**: up to 4C and 1g/kg
- **Rate of formation**: GSR 10-15/year, meddies 15/year, swoddies more irregular
- **Life-time**: from a few weeks to about 4 years
STRUCTURE
Definition of oceanic vortices

Quasi horizontal recirculating fluid motions

horizontal motion --> importance of Coriolis force and of thermohaline stratification
recirculating --> internal motion (rotation) >> external motion (translation, deformation)
recirculating --> often close to circular or elliptical (mode 2 def)
recirculating --> traps water masses with specific characteristics

Long lived

internal motions >> external motions (water trapped)
usually distant, except in formation areas
dissipative processes are slow and act mostly on periphery (or thermal exchanges with the atmosphere)
but a few processes (e.g. topographic interaction) can be rapid and very destructive
Definition of oceanic vortices

Of size comparable to the internal deformation radius
  baroclinic processes are often important (BCI, vortex stretching)
  or geostrophic adjustment
  but other processes may be important (barotropic instability,
  coastal or topographic effects)
  high vertical modes (intrathermocline vortices) --> smaller Rd

Play an important rôle in heat and momentum transfer across the ocean
  trap water masses with important T and S anomalies
  large (50-100km radii), energetic and long-lived (0.1-4 years)
  cover significant distances across the ocean (up to 4000km)
  e.g. T and S anomalies due to meddies cover half the width of the Atlantic ocean at 1000m depth and meddies about 1/3 of total transport of MW
Essential quantity for ocean vortex dynamics: Potential Vorticity

Since motion dominated by rotation and stratification, recirculation and trapped water masses, Ertel PV, defined by

\[ PV = \frac{(\zeta + f)}{\rho} \cdot \frac{d\rho}{dz} \]
\[ \zeta = \frac{dv}{dx} - \frac{du}{dy}, \quad f = f_0 + \beta y \quad (\text{beta-plane approximation}) \]

is conserved by fluid columns between isopycnals in the absence of diabatic processes.

In fact, anomaly of Ertel PV is useful for vortex dynamics:

\[ PVA = PV - \text{mean PV} \quad (\text{surrounding water at rest}) \]

\[ \text{mean PV} = \frac{f}{\rho_0} \frac{d\rho_0}{dz}, \quad \rho = \rho_0 + \rho' \quad (\text{related to motion}) \]
Potential Vorticity and its anomaly (2)

In Shallow-water models, PV is $q = (\zeta + f) / h$
where $h$ is thickness of homogeneous layer

PVA is $\Delta q = q - (f/H)$
Differences between Oceanic Eddies and Turbulence (+ links)

Turbulence can occur in homogeneous or stratified fluids, with/without rotation, and be 2D or 3D. Even if governed by rotation and stratification, turbulence can produce vortices if there is an inertial zone between forcing and dissipation scales, if beta effect is weak and stratification moderate. If so, turbulence is made of vortices of all sizes, some transient, some more durable, and of filaments. Turbulence can have more 3D motions (in particular in filaments). But then, vortices can be dominant in dynamics (and in particular via few-vortex interactions).

Oceanic eddies are coherent, nearly isolated structures, with strong PV anomaly, nearly 2D flow, distinct water masses. Thermodynamical effects may be important (mixing, heat exchange with atmosphere). Topography influences propagation and erosion (vs organisation of turbulence).
ROLE
Energy of rings: 1 to 20 $10^{15}$ J (for Gulf Stream rings, up to 50 $10^{15}$ J for Agulhas rings)

CCR occupy 15% of the Sargasso Sea surface and WCR 40% of the continental slope area. They account for 10% of the total energy input by the wind over the gyre.

Though they carry less than 5% of the energy flux of the GS away from the jet, they contribute substantially to the local APE. In fact, in the GS system, energy is concentrated in the vicinity of the jet --> ring interactions with the jet, and meanders are dominant features in terms of energetics.

For biology, rings can
- provide a means for recruiting populations while mean currents flush them away
- achieve vertical export of nutrients and carbon on their edges (filaments seem more efficient than rings for this purpose).