

# The Role of the Mediterranean Outflow

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## Outline

Mixing and entrainment in the descending Mediterranean outflow plume

Baseline case study for friction and mixing in the deep ocean

Friction determines how fast the plume descends

Entrainment determines how deep the plume reaches

Meddy Formation

Meddies are coherent submesoscale lenses of Mediterranean Water remnants

Regularly formed at Cape St. Vincent as outflow rounds the corner

Rapid clockwise rotation with periods of about 5 days

Long-lived (>2 years) if they do not collide with a seamount

Northward flow of Mediterranean Water

Clear signal on Iberian continental slope to 44°N

Does Mediterranean Water directly flow into the Nordic Sea?

Overturning in the eastern Atlantic MedBox

Descending Mediterranean Water plume entrains near surface Atlantic waters

3 Sv inflow in upper 300 m, 3 Sv outflow in intermediate layers 300-2000m

Entrainment in MedBox drives deep Azores Current

Overturning sequesters substantial amount of anthropogenic CO<sub>2</sub> to deep ocean

How does Mediterranean outflow affect the saltiness of the Atlantic Ocean?

High salinity tongues extend westward and southward from Gibraltar in the intermediate and deep waters of the Atlantic

Is the outflow responsible for the Atlantic basis for the global thermohaline circulation?

## Descending Mediterranean Outflow from the Strait of Gibraltar

High salinity, dense Mediterranean water piles up in the Mediterranean behind the sill of the Strait of Gibraltar. The Mediterranean water is about 2 parts per thousand saltier and denser than any other Atlantic water. Gibraltar sill depth is about 300 m so the dense water exiting the Mediterranean cascades down into the Atlantic Ocean, mixing and entraining ambient Atlantic waters until it settles at a depth of about 1000 m and spreads out into the Atlantic. Just west of the sill the outflow turns to the right following the Iberian continental slope, descends rapidly to 800 m depth and much of the entrainment occurs within 200 km of the sill as the core salinity drops below 37‰. The descending outflow provides a valuable process study on mixing and entrainment in the ocean. How fast should an overflow plume descend, how much mixing should there be? The rate of descent depends on friction, so the observed descent provides an estimate of bottom friction. The depth the overflow plume reaches depends on entrainment so the observed settling depth provides an estimate of entrainment. Entrainment is thought to be related to the strength of the density anomaly and the speed of the plume but it is uncertain what the exact relationship is. Observations of the Gibraltar overflow plume then provide a baseline case study of entrainment and mixing for combination with observations of

other outflow plumes from other sills such as Denmark Straits and Faroe Bank Channel to understand mixing and entrainment processes in the ocean.

## **Meddy Formation**

When the Mediterranean outflow turns the corner at Cape St. Vincent to head north along the Iberian continental slope, a remarkable type of eddy is sometimes formed. It is a clockwise rotating lens of remnant Mediterranean water of about 500 m vertical thickness in the middle of the water column around 1000 m depth. These meddies are rapidly rotating (3-7 day rotation period), weakly stratified sub mesoscale features that can remain coherent over several years as they move mostly westward and southward in the eastern Atlantic. Some are destroyed when they encounter a seamount but others only slowly mix away due to interleaving and double diffusive processes. Various attempts have been made to estimate how much of the salinity flux is carried by meddies into the Atlantic, with values ranging from 10% to 60% of the total salinity flux depending on how many meddies are formed each year. In a targeted deployment of floats in the Mediterranean Water plume at Cape St. Vincent, 14 out of 44 floats ended up in Meddies formed near the Cape.

## **Northward Flow of Mediterranean Water**

Along the Iberian continental slope, there is a high salinity signal at about 1000m depth that extends seaward about 500 km representing a core of Mediterranean water flowing northward. The fate of this northward flow in the Bay of Biscay and further north is uncertain. Some (e.g. Iorga and Lozier, 1998) trace the Mediterranean water core into the Rockall Trough and over the Iceland-Scotland Ridge, providing the salinity preconditioning required to form Nordic Sea deep and intermediate waters and ultimately North Atlantic Deep Water. Others (e.g. McCartney and Mauritzen, 2001) deny that such a direct pathway of Mediterranean Water into the Nordic Seas exists.

## **Spreading of Mediterranean Water across the Atlantic**

At intermediate depths, Mediterranean water remnants can be identified as high salinity-high temperature intermediate waters across the Atlantic. Charts of salinity on potential temperature surfaces from the database of historical hydrographic stations show a tongue of Mediterranean Water spreading westward and northward away from the Strait of Gibraltar. On shallower surfaces, the spreading appears to be mainly westward and northward, whilst at deeper surface the spreading appears to be west-southwest. Such charts have been used in the past to assess the relative roles of advection and diffusion in the intermediate waters of the Atlantic. The discovery of meddies, however, complicates the simple advective-diffusive balance, as coherent but isolated small-scale features appear to carry a significant amount of Mediterranean water westward and southward over long distances and times.

## **Role of Mediterranean Water in Atlantic Circulation**

The Mediterranean outflow contributes high salinity to the intermediate and deep layers of the North Atlantic. The Atlantic is the saltiest of the world's oceans but it is a difficult problem to quantify the extent to which the Mediterranean outflow contributes to the saltiness of the Atlantic. The evaporation over the Mediterranean (which leads to the high Mediterranean outflow salinity) is small compared to the net evaporation over the subtropical Atlantic and smaller than the freshwater carried by the atmosphere from the Atlantic to the Pacific across Central America. Yet the visual

penetration of high salinity Mediterranean waters across the Atlantic provides a powerful emotional argument that the Mediterranean water must make a major contribution to the Atlantic salinity. Reid (1979) asserts that the saltiness of the Mediterranean outflow ultimately leads to the formation of North Atlantic Deep Water and without the Mediterranean outflow the global thermohaline circulation would be completely different. Johnson (1997) claims the Mediterranean outflow is a contributing factor in causing ice ages and argues for damming the outflow at Gibraltar now to prevent the coming ice age. Models suggest that the Mediterranean outflow salinity does ultimately mix into the Gulf Stream and North Atlantic Current, contributing to the high salinity waters entering the Nordic Seas. But how much overall effect the Mediterranean outflow has on the high salinity of the Atlantic and on the thermohaline circulation has not been reliably quantified.

## Overturning in the Eastern Atlantic

## MedBox

For the MedBox defined by zonal sections at 42°N and 25°N and a meridional section at 20°W, enclosing the eastern Atlantic and Mediterranean Sea, there is a net flow of waters above 300m depth into the Box of 3 Sv and a net outflow of waters from the Box between 300 to 2000 m depth of 3 Sv. 1 Sv of dense Mediterranean outflow exiting the Strait of Gibraltar at 200 to 300 m depth entrains about 2 Sv of upper Atlantic waters as it descends into the interior Atlantic. This creates the overall overturning circulation within the MedBox of 3 Sv. This entrainment process with associated vortex stretching mechanism has dynamical effects in generating the Azores Current and possibly the Azores Countercurrent. The entrainment of upper Atlantic waters with high anthropogenic carbon dioxide content represents an important process sequestering anthropogenic CO<sub>2</sub> into the deeper layers of the Atlantic Ocean (Alvarez et al., 2005).

## Additional Reading:

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