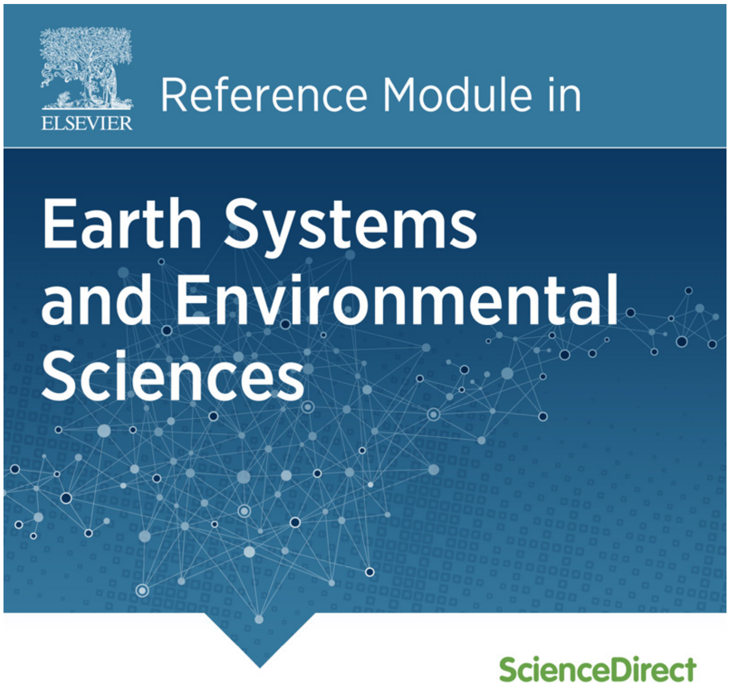

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Rotating Gravity Currents☆

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Introduction

The term gravity current refers to unidirectional flow of fluid with a free surface in a field of gravity. The free surface commonly separates that fluid from a second fluid of different density, although it is possible that the second fluid has negligible effect on the flow, as in the case of water flowing under air. Such currents are also called density currents or buoyancy currents. The distinguishing feature of a gravity current is that the force of gravity acts on the density variation to create a buoyancy force that produces the motion. Additional effects due to earth rotation are frequently found upon such currents in the ocean.

Much knowledge of buoyancy-driven currents in the ocean comes from studies that originated in engineering, and in natural sciences for which earth rotation is not important. When a door is opened between rooms with different air temperatures, a flow and counter flow quickly start to transport heat from the warm to the cold room. In mines, the presence of gas or differential heating can lead to buoyant forces and can produce an intense outflow through narrow openings at higher elevations of the mine. During fires, hot gas can accumulate under ceilings and ascend stairwells as an inverted density current. In rivers, bores and fronts can become intense enough to produce very rapid changes in water elevations and velocity during floods or, in some cases, during extreme tide events. In the atmosphere, strong local effects produce katabatic winds, fronts, sea-breezes, and outflows of chilled air from thunderstorms. In some cases suspended particles cause density variation of the bulk fluid. Thus, such currents are found during dust storms, as avalanches, and as downflows of pyroclastic suspensions during volcanic eruptions. They can also be found as turbidity currents on mountains and within the ocean.

Gravity currents in the ocean come in many similar forms, with density differences arising from turbidity, salinity, or temperature variations. They usually originate in constricted regions that separate waters of different density. Thus they frequently originate near river mouths, at the openings of estuaries, at sea straits, and near saddle points separating deep ocean basins.

Roughly speaking, the most rapidly occurring currents have lifetimes of less than a day. Density difference between the density current and surrounding ocean water ranges from 1% to 10% and is usually produced by sediment or salinity differences. The thickness is limited by the fact that the water rapidly flows away from the source region. It is thought typically to range from ten to a few hundred meters. These large and energetic currents are usually formed in response to sudden triggering events such as floods, sudden shifts in high winds, earthquakes, landslides, or volcanic eruptions. Good measurements are often lacking owing to the extremely rapid nature of the events. The relation of such currents to surface weather or tectonic events means that they are usually located near land, from the coast to the bottom of the continental slope or even within bays and estuaries. Examples range from great sediment currents emerging from landslides or from the mouths of rivers and estuaries to fresh water layers in fjords and bays. Both are found more commonly during flood seasons.

The greatest documented rapid currents are the giant ocean turbidity currents that course down the continental shelf break into the abyssal ocean. Not only are these believed to erode the continental rise, but they also propagate hundreds of kilometers over flat terrain (principally the abyssal plains) and supply sediment to cover these sedimented regions. Large currents from volcanic ash settling in ocean water are also known indirectly from the sediment record. Although these may involve relatively immense amounts of mass flux, none has been directly measured. Unusually large amounts of fresh water may flow out of bays under certain meteorological conditions. The outflow of fresh water from the Baltic occasionally increases enormously during storms and propagates along the coast of Norway as a gravity current. The current has, at times, endangered oil platforms with its intensity. There is speculation that large outflows of fresh water may have occurred at the end of some ice ages.

Currents with intermediate timescales from one day to a few months have layer depths from 10 to 100 m. These are usually associated with salinity variations in the sea water with density variations ranging from 0.1% to 1%. These currents are often unsteady, ebbing and waning in periods ranging from days to months or even years. Many are found at the outlets of rivers, bays, or marginal seas. Surface currents have lower salinity than the ambient ocean.

They tend to flow along coastlines owing to the influence of the earth's rotation. These currents often radiate waves along their outer edge, and are bounded offshore by a semipermanent front that separates the fresh water from the ocean water. Bottom currents have higher salinity than the ambient water. The dense salty water descends over the sloping continental shelf and slope, and occasionally selects pathways determined by submarine canyons.

☆*Change History*: December 2015. JA Whitehead updated the text in the "Concluding Remarks" section and further readings.

The slowest to change are the largest density currents with widths of 20–1000 km and layer depths from 100 m to 1 km. They typically vary in intensity over periods of a few months to many years. These too can be composed of a layer of warmer or fresher water lying above deep denser water, or, alternatively, of a layer of colder or saltier dense water that sinks below the ambient warmer water into the deep ocean. Such currents are associated with temperature changes of 1° or 2°, or salinity variations of 0.1–1 ppt or less.

Observations

A large turbidity current was triggered by an earthquake near the Grand Banks Newfoundland in 1929. Submarine cables were sequentially broken at progressively greater depths for a lateral extent of over 300 km during an interval of 13 h. Later geological surveys yielded estimates of volumetric displacement over a thousand times greater than any recorded on land. Despite the importance of turbidity currents, their direct observation is limited to occasional reports because of their rapid dispersion time and the lack of forecasts of the earthquakes that start them. The fossil evidence of the sedimentary record indicates they are a major mechanism for dispersion of sediment on the deep ocean floor. Such rapid turbidity currents have also been found on a smaller scale in canyons on the continental rise and offshore of islands. They are a principal mechanism for erosion of young ocean islands. And finally, they are candidates for tsunami production after an earthquake, since their energy release and volume displacement can greatly exceed the energy of the earthquake itself.

Low-salinity plumes flowing along coastlines are probably the best-studied of all ocean gravity currents. Their offshore edge is easily seen by airplane and satellite. Some freshwater density currents, for example, the Norwegian Coastal Current have been known by fishermen for centuries. A similar kind of current is found flowing eastward out of the Tsugaru Strait between Hokkaido and Honshu, Japan. The current veers to the south and forms a warm eddy during certain seasons. This eddy is well known to the fishermen.

If the layer is only slightly larger than 10 m in depth, wind events, with periods of a few days, may have an important effect. An example is the outflow of fresh water from Chesapeake Bay. The plume of fresh water frequently curves to the right as it leaves the mouth of the bay and flows along the coast of Virginia toward Cape Hatteras. A flow to the right is consistent with the direction that theory and laboratory models have indicated would be produced by earth rotation. At some stage wind is seen to blow the freshwater plume offshore and the current breaks up, probably owing to the lack of a coastline to support the pressure field of a unidirectional gravity current with the earth's rotation. Similar effects have been seen offshore of the mouth of Delaware Bay.

The fresh water outflow through straits from large interior seas is found to be great enough that the current persists for weeks or months even in the face of wind fluctuations. The Norwegian coastal current mentioned above is a good example. The Baltic current empties about 15,000 $m^3\ s^{-1}$ of fresh water into the Skagerrak. The water mixes with salt water, turns northward in association with the Jutland current coming from the south, and flows along the coast of Norway. This coastal current moves northward for many hundreds of kilometers. Fluctuations take days or weeks to move from their source in the Skagerrak to the northern end of the coastal current.

Two well-known currents driven by salinity difference are produced by the salinity-driven exchange flow through the Strait of Gibraltar. The Mediterranean Sea is about 10% saltier than the surface Atlantic water owing to the aridity and consequent evaporation of the Mediterranean region. In the Strait, there is a surface inflow of fresher Atlantic water (known even in ancient times) and an underlying outflow of saltier Mediterranean water that was detected in 1870, after more than two centuries of speculation that it existed. The eastward-flowing inflow encircles a clockwise (anticyclonic) gyre in the Alboran Sea by flowing around the northern edge of the gyre. The current then veers southward along the eastern portion of the gyre and encounters the coast of North Africa. It then curves eastward and proceeds along the coast of Africa as the Algerian current. This current is also found to meander offshore and back again with wavelengths lying between 25 and 100 km. The current has seasonal and monthly fluctuations and the gyres expand and contract accordingly. The westward flow of deeper salty water leaves the Mediterranean and descends roughly to 1 km depth in the Atlantic. Part of the Mediterranean water breaks up and forms internal eddies that spread from their origin throughout the eastern North Atlantic and contribute to a salinity maximum at that depth. The remainder continues to flow northward along the continental shelf break at roughly a depth of 1000 m along the coast of Portugal and Spain.

There are numerous other currents of lower salinity that flow along the coastlines of the continents. The Gaspe current flows seaward along the coast of the Gaspe Peninsula of Quebec, driven by the river runoff from the St. Lawrence estuary. The East Greenland current conveys lower salinity water southward along the shelf and shelf break of Eastern Greenland. This large current contributes to the salt/freshwater balance of the Arctic. The Labrador Current flows southward along the East Coast of Canada, bringing icebergs southward into the shipping lanes.

Submerged gravity currents are associated with important deep and bottom water circulation. Flows from one deep ocean basin to another produce intense localized flows at the sill between the two deep basins. This sill is thought to be located at the col, or shallowest point of the deepest saddle point between basins, although some frictional effects may move the location of the most important regions downstream. Measurements of temperature, salinity, and velocity have been taken in the localized vicinity of about a dozen large oceanic sills in all the oceans. The most thoroughly studied is the Denmark Straits overflow between Greenland and Iceland. Cold water from the Nordic seas flows over the 650 m deep sill and descends to about a depth of 3 km to form the lower North Atlantic Deep water. A second overflow from the Nordic seas crosses a sill south of the Faeroe Islands at about 800 m depth and enters the eastern North Atlantic. Overflows are also found at a number of other sills at locations shown in Figure 1. The North Atlantic overflows are important contributors to meriodonal overturning of the ocean and thus to climate. Thus they

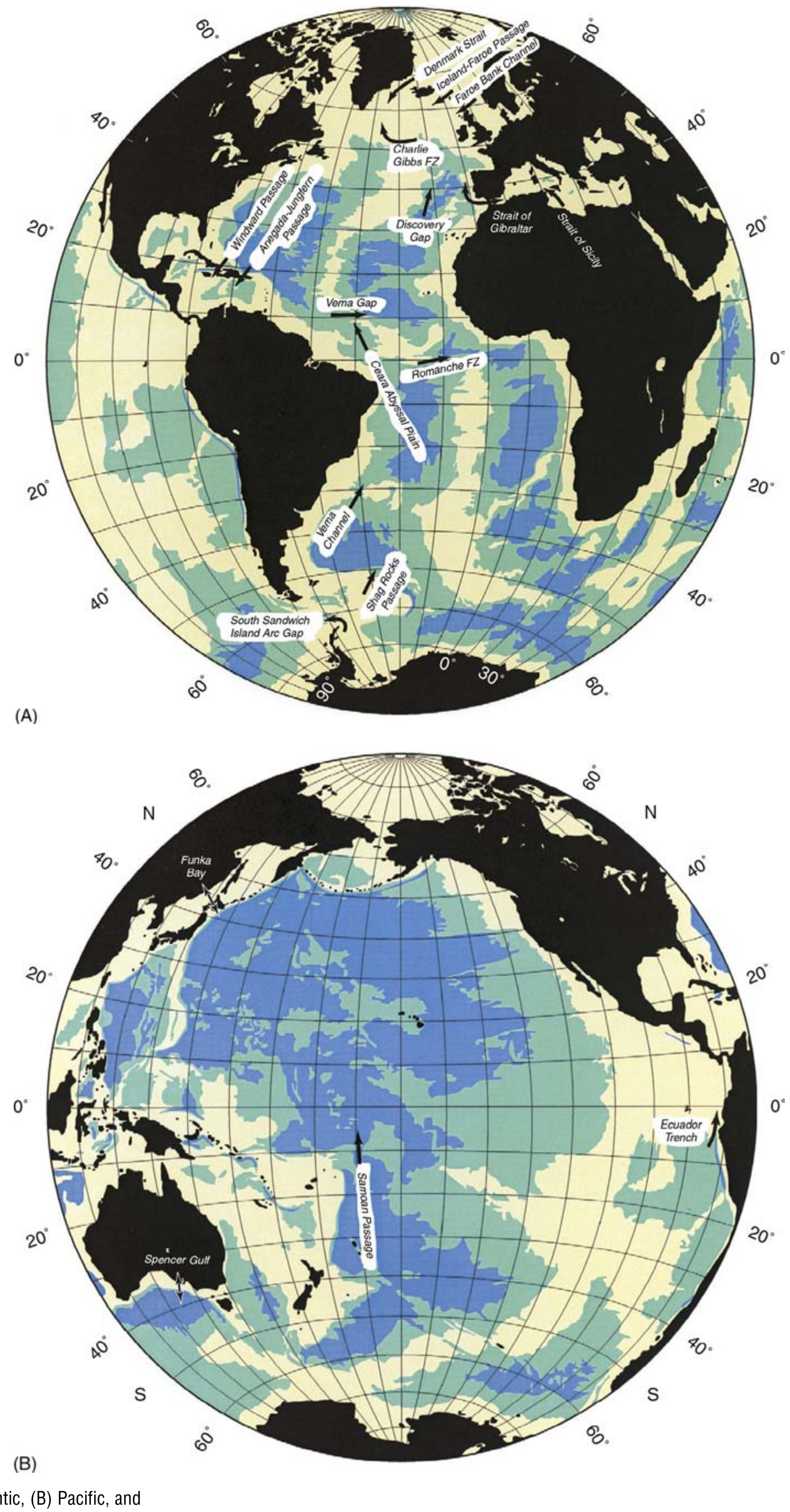
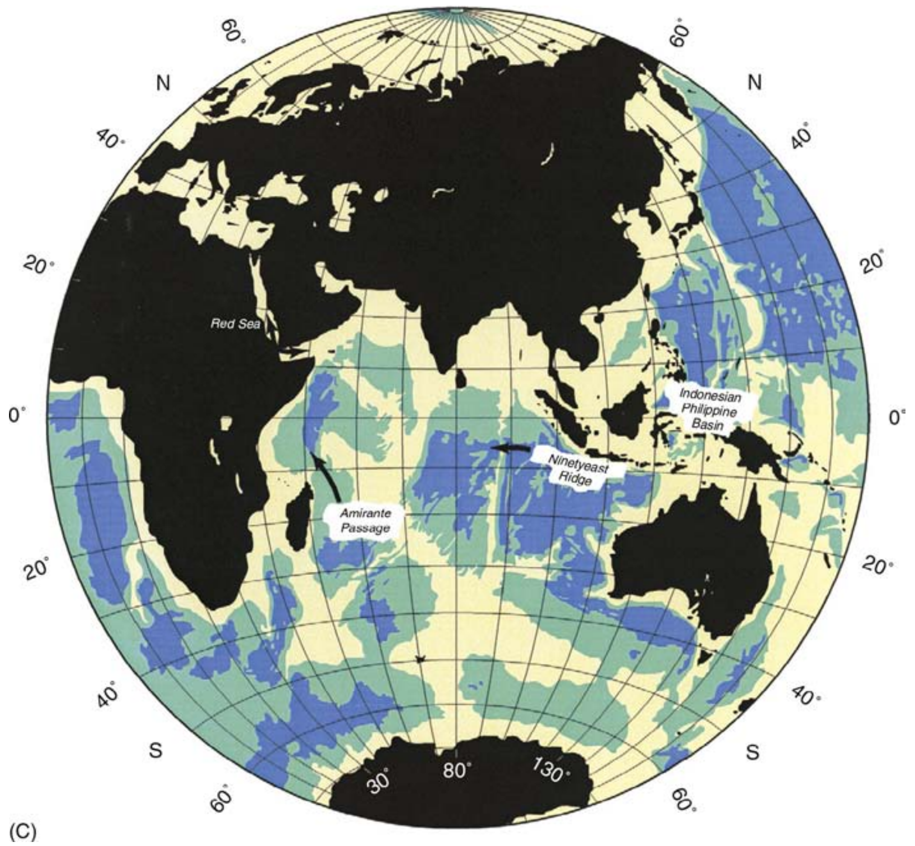


Figure 1 (A) Atlantic, (B) Pacific, and

(Continued)



(C)

Figure 1 **Con't** (C) Indian Ocean locations of deep ocean sills. The *arrows* show the direction of flow. *Light shading* indicates depths between 4 and 5 km; *dark shading* is deeper. Some surface straits that produce gravity currents (*bidirectional arrows*, eg, the Strait of Gibraltar) are also shown. The volume flux for these flows have estimates ranging from 0.01 to 10 Sv.

continue to be monitored. Recently, the upstream currents for the Denmark Strait overflow has been documented to have two branches, one North of Iceland and the other along the Greenland shelf break.

Theory

The primary balance in any density current, rotating or not, is between the buoyant force of gravity and change in momentum of the fluid. This leads to the velocity scale given by Bernoulli's principle of the form $v = \sqrt{g'D}$, where $g' = g\delta\rho/\rho$, is commonly called reduced gravity, D is vertical layer thickness, g is the acceleration of gravity, and $\delta\rho/\rho$ is the relative density difference due to thermal or salinity content between a layer and surrounding sea water. Frequently, such a current is set up as the layer of water flows away from a source region. Such currents can be either transient or steady. One way to measure the effect of Earth rotation is to express a timescale that is given by the number of seconds in a day divided by 4π times the sine of the local latitude. The formula for this timescale is thus $\tau(\mathrm{secs}) = 6876/\sin\theta$, a time duration that is about 2.7 h at 45 degree. For currents of longer duration than such a timescale, the flowlines will curve toward the right in the Northern hemisphere, and to the left in the Southern hemisphere from the Coriolis force of the earth's rotation. The only way for gravity currents to move large distances thereafter is to curve around and flow next to a coast or front. In such a case, the width of the current is limited to v_τ. Thus the volumetric flux is limited to size $v^2 D\tau = g' D^2\tau$. Gravity currents flowing along a coastline like this have a balance between a pressure gradient at right angles to the flow and the Coriolis force. For example, a current produced by a salinity change of 1.4 ppt and a depth of 100 m has the velocity scale 1 m s^{-1}, lateral width of about 10 km, and a volume flux of about 10^6 m^3 s^{-1}.

Inviscid "rotating hydraulics" theory has been developed to enlarge the understanding of a variety of nonlinear rotating flows. If the flow is fed from a region in which the layer of water is elevated by height H, velocity along the wall scales with $v_w = \sqrt{2g'(H-D)}$ in the absence of friction. Many gravity currents have been monitored by satellite data or with fixed arrays of instruments in the ocean. Flows through many of the deep ocean sills shown in Figure 1 have been found to follow the above scaling within a range of about a factor of 2 or 3. The effects of bottom friction, interfacial mixing, and complex ocean floor topography remain poorly understood at present. The upstream currents feeding overflows are known from laboratory and numerical work to be principally on the right (looking upstream in the Northern hemisphere).

Concluding Remarks

The velocity scale $v = \sqrt{g'D}$, timescale $\tau(\text{secs}) = 6876/\sin\theta$, and width scale $v\tau$ are the scales of gravity currents of oceanic flows in a variety of settings for the widths, durations, and depths within certain ranges. For water shallower than roughly 100 m, the frictional effects of turbulent boundary layers modify the flows substantially. The detailed response of gravity currents to this drag remains poorly understood. Currents wider than about 100 km begin to be influenced by the effects of a spherical earth or large variations in bottom shape. The radiation of shelf waves can attenuate gravity currents by leaking the momentum into shelf modes in front of the nose of the gravity current. The illustration in Figure 2 shows dye displacement from a shelf wave current next to a fresh water density current. This current is viewed from above in an experiment performed on a rotating turntable over a sloping bottom. In contrast to the photograph of the Norwegian Coastal Current in Figure 3, where eddies are visible at the outer edge of

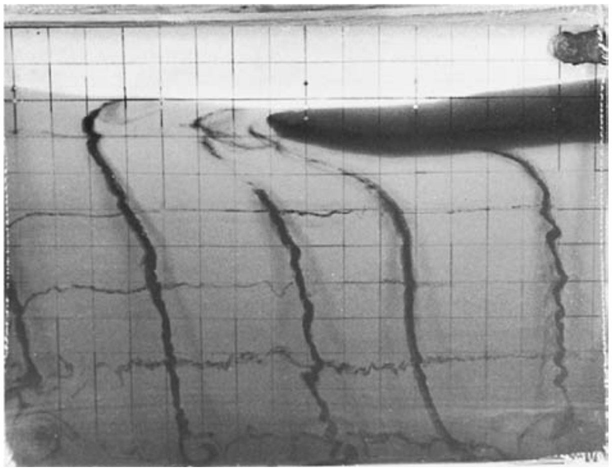


Figure 2 Top view of a dyed surface fresh water gravity current on a rotating turntable. The current flows over and around clear salt water above a flat tilted bottom with a slope of 30 degree from the horizontal. The coastline is located at the top of the picture; the deep region is located at the bottom. The turntable is rotating counterclockwise, which corresponds to a model of the Northern hemisphere. The fluid was fed with a source at the right. Density of the fluid and turntable rotation are adjusted to make a width scale $v\tau$ of about 0.1 m, which is the spacing of the grid lines. Distorted lines of dye show displacement around the current. Some of the displacement is made by shelf waves that propagate ahead of the nose of the gravity current.

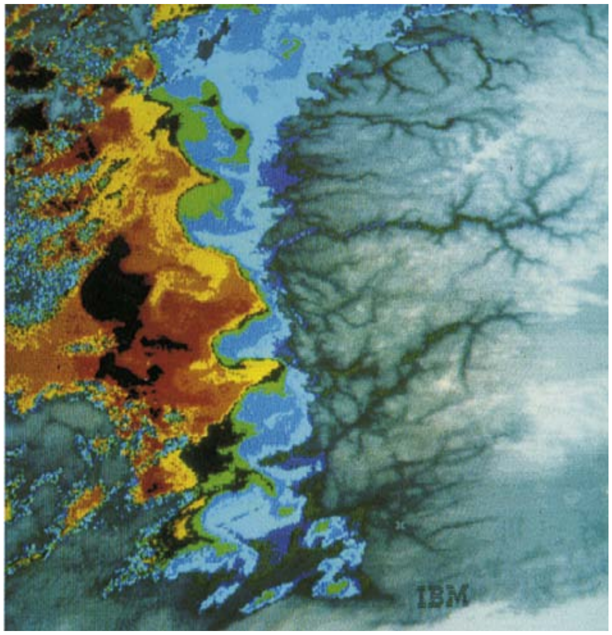


Figure 3 The Norwegian Coastal Current. The colors reveal variations of surface temperature with blue colder and yellow-red warmer. However the current itself has a density change from salinity variations that are much greater than those due to temperature. The current flows northward along the coast of Norway as a gravity current of lower-salinity water from fresh water outflow along Norway and the Baltic. Eddies along the outer edge are frequently visible. In some cases, an energized current has been seen as a northward-propagating nose.

the current, the bottom slope seems to stabilize this current but also allows smoother and more wavelike currents in the clear water surrounding the dark intrusion. In climate studies, equatorial Kelvin waves and internal Rossby waves are all important possible features of the gravity current component of tropical oscillations such as El Niño and ENSO (El Niño Southern Oscillation).

Further Reading

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