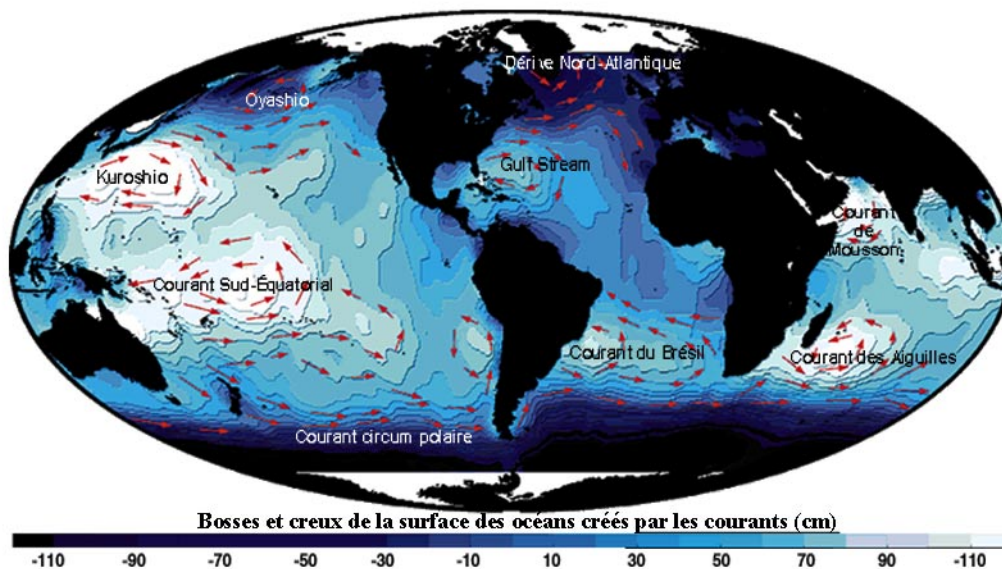


Ocean circulation

The surface of oceans is never still. Huge quantities of water and energy are transported around the world through an ocean circulation system. Surface currents and deep currents flow within oceans like rivers, some fast and turbulent, others slow and meandering. This circulation is the result of a combination of wind and differences in both temperature and salinity induced by the atmosphere and rivers. The Earth's rotation and underwater geography also play an important role in determining the path taken by water masses.

Ocean circulation in the surface zone

The Sun does not warm the Earth uniformly. The oceans spread its heat throughout the world by transporting heat from warmer regions (the tropics) to colder regions (the poles). The oceans may be compared in some ways with a thermostat, regulating the climate. It is thanks to the Gulf Stream and the North Atlantic Drift, for example, that Europe's climate is milder than that of towns on the same latitude along the East coast of the United States. The oceans also play an important role in long-term climate change (over several dozen years or even over several thousand years).



Map of bumps and hollows on the surface of the sea created by major ocean currents (credit: CLS, Toulouse)

Ocean currents are like long rivers. They can range from several dozen metres to hundreds of kilometres wide. They consist of a series of meanders and form bumps or hollows on the surface of the oceans. The typical amplitude of ocean surface relief due to currents (known as dynamic topography) is around one metre. The speed of these currents is proportional to the gradient of the bumps and hollows on the surface of the water. What is more, they are subject to the Coriolis effect arising from the Earth's rotation. In the northern hemisphere, currents turn clockwise around bumps and anti-clockwise around hollows. The reverse is true in the southern hemisphere. (This also applies to air masses, resulting in the cyclones (around low pressure) or anticyclones (around high pressure) mentioned during weather forecasts). The enormous masses of water in these currents take with them the heat stored by the ocean, acting as a thermal control system. Any variation in the quantity of water transported or in the direction of flow therefore affects meteorological phenomena (precipitation and evaporation) and even climatic phenomena in the case of major, long-term change.

Ocean stratification

The vertical structure of oceans may be likened to a series of superimposed layers each with its own characteristics. These layers are usually identified by three parameters: temperature, salinity and pressure. Using these three quantities, we can calculate density, which is another important parameter in understanding ocean circulation (especially vertical circulation).

- Temperature

Ocean temperature is mainly influenced by the atmosphere which warms up or cools down the surface waters. The Sun's rays warm up surface waters throughout the year in tropical regions but during the summer only at higher latitudes. The surface layers in contact with the atmosphere are separated from the deep ocean by a layer several hundred metres deep in which the temperature drops rapidly with depth. This layer is known as the "thermocline" (or "metalimnion"). The temperature of deeper layers does not vary as much as surface temperatures.

- Salinity

Salinity is the amount of salts contained in water. Salts constitute 3.5 % of sea water, the main one being sodium chloride (more commonly known as table salt). If we consider the total volume of the world's oceans to be 1,460 million cubic kilometres, salt represents 48 million tonnes, or around 35 grams per kilogram of water. If we were to spread this salt over the surface of the Earth, we would have 95 tonnes of salt on each square metre. Salinity varies little in the surface zone, but it is enough to affect the circulation of water masses. Salinity is

itself affected by surface evaporation and the contribution of fresh water by the atmosphere (in the form of rain or snow), by rivers or by the melting of sea ice. Just like temperature, salinity also varies by the mixing up of distinct water masses.

- *Pressure*

To simplify matters, we can consider that pressure at a given ocean depth is the effect (felt at this depth) of the weight of the water mass between the surface and the particular depth. Consequently, pressure increases with depth. In fact it increases proportionally to the weight of water layers (water being a nearly incompressible fluid). The mean depth of the oceans is 3,800 metres. Its total mass comes to 1.4 billion tonnes, which is 300 times the mass of the atmosphere. At a depth of 11 kilometres, which is the deepest point of the ocean, the pressure is 10 times greater than the pressure needed to compress a block of wood to half its original volume.

- *Density*

Density is by definition the mass (or weight) of water in a given volume of water. To take an example, we have a mean of 1 kilogram of water in 1 litre, making a density of 1,000 kilograms per cubic metre. Low-density water masses are light, and high-density masses heavy. Density increases with depth. Temperature, salinity and, to a lesser extent, pressure determine the density of sea water. When temperature drops, density increases. When salinity drops, however, density also drops.

Variations in density over time and between two geographical regions trigger movements in water masses. Two mechanisms may be distinguished. First, when a water mass becomes denser the water becomes heavier and drops downwards. (This phenomenon occurs during the winter in the Gulf of Lions—Mediterranean Sea—and in some polar regions). In polar regions, the drop in temperature associated with winter and the formation of sea ice lead respectively to a drop in water temperature and an increase in salinity, which increases density. The water can then sink as much as 2,000 metres. The second mechanism occurs over much greater areas: variations in density between two areas of the ocean can lead to differences in pressure. If the Earth did not revolve, the water masses would move directly from high pressure areas (anticyclones) to low pressure areas (cyclones). However, the effect of the Earth's rotational movement, combined with the pressure, modifies the trajectory of these water masses. When the different forces balance each other out, we have "geostrophic equilibrium". The resulting currents are known as geostrophic currents.

Global circulation

The combined action of horizontal and vertical movements lead to planet-wide circulation. Exchanges of mass and heat between the ocean and atmosphere alter

the water's temperature and salinity. They drive the ocean circulation known as "thermohaline circulation". On a global scale, it is composed of a set of currents which connect the superficial layers to deep layers and the major ocean basins - the Atlantic Ocean, the Arctic, the Pacific, the Antarctic and the Indian Ocean. We often represent this circulation by a "conveyor belt". Currents are actually more turbulent and behind this picture lies a complicated network of currents about which we know very little. The conveyor belt image represents a slow, "average" kind of current. It would be more accurate to superimpose onto this mean circulation a complex set of currents and eddies which are far more variable over time. Some eddies only last a few days !

The mean global thermohaline circulation can be summarised as follows: water in the North Atlantic is cooled down in the winter and its salinity increases due to the evaporation caused by wind and the formation of sea ice. These water masses, now denser than before, sink before being caught up and dragged along towards the equator. They then head towards the Indian Ocean between the Arctic and Antarctica before splitting in two. One current enters the Indian Ocean while the other heads eastwards, reaching the Pacific in the northern hemisphere. During this long journey, the water masses get mixed up and their temperature rises. The return journey for this circulation is through the warm currents near the surface. This is why water masses in the Indian Ocean and the North Pacific lie close to the surface and are driven by a surface current heading towards the North Atlantic. The process then begins again. The water takes about one thousand to years to complete this cycle.

The Gulf Stream



The Gulf Stream is one of the most powerful "rivers" in the world. It is also the most well-studied ocean current as it plays a major role in the determination of the climate (particularly the climate of Western Europe). The Gulf Stream is mainly born in the Gulf of Mexico then heads northwards off the shores of four North American states (Florida, Georgia, South and North Carolina) before turning eastwards. A main branch of the Gulf Stream, called the North Atlantic Drift, crosses the Atlantic to Scandinavia. Secondary branches reach Europe, where they head downwards off the French coastline to reach the Tropical Atlantic along the African continent. Thus they form a large loop in the North Atlantic. The Gulf Stream and its secondary branches transport relatively warm water, warming up the atmosphere and therefore the climate of Western Europe. This explains why winters in Bordeaux are much milder than winters in New York, even though the two towns are on the same latitude. The current's mean speed is about 7 kilometres an hour, the speed of somebody at a fast

walk. At times it extends across 150 kilometres and is 1500 metres deep. Its rate of flow is about the equivalent of all the planet's rivers put together, in other words around 100 billion litres per second. It is formed of meanders and eddies ranging from a few dozen kilometres to a hundred kilometres across.

As early as the 16th century, some navigators had mentioned the existence of such a current having had difficulty going against it. Late in the 18th century, the first maps of the Gulf Stream were compiled. They showed a very regular current. For the past twenty years or so, we have been able to study the numerous variations in this current from space: its flow rate, position and tortuous nature (revealed by the formation of numerous meanders and eddies).

Bibliography

Satellite Altimetry and Earth Sciences, a handbook of techniques and applications, edited by Lee-Lueng Fu and Anny Cazenave, International Geophysics Series, Volume 69, 2001.

L'océanographie physique, by Maxence Revault d'Allonne, Editions PVF, Collection Que sais-je ? n°438.

La machine océan, Jean-François Minster, Flammarion, Collection Champs n° 427.

Océanographie régionale, by Paul Tchernia, éditions ENSTA.