



Ocean, Heat Reservoir

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On our watery planet, the ocean is the primary regulator of global climate by continuous radiative, mechanical and gaseous exchanges with the atmosphere. In particular, the ocean absorbs, stores, and transports through its flow motion (*i.e.*, currents) heat from the sun affecting atmospheric temperature and circulation around the world. Furthermore, seawater is the source of most precipitation. The ocean is way much more efficient at storing heat (93% of the excess of energy resulting from the human induced Green House Gases content in the atmosphere) than the continents (3%) and the atmosphere (1%). The upshot of this is that the ocean is the slow component of the climate system and has a moderating effect on climate changes. However, consequent to the continuous absorption by the ocean of the human induced excess of heat, ocean waters are warming, which has consequences on the ocean's properties and dynamics, on its exchanges with the atmosphere and on the habitats of marine ecosystems. For a long time, discussions of climate change did not take the oceans fully into account, simply because very little was known about them. To a considerable degree our ability to understand and anticipate what might happen to Earth's climate in the future, depends on our understanding of the role of the ocean in climate.

OCEAN - HEAT RESERVOIR

Our Earth is the only known planet where water exists in three forms (liquid, gas, solid), and in particular as liquid oceanic water. Due to its high heat capacity, radiative properties (gaseous) and phase changes, the presence of water is largely responsible both for our planet's mild climate as well as to the development of land life.

The oceans represent 71% of the surface of the planet. They are so vast that one can easily underestimate their role in the earth climate. The ocean is both a large reservoir, but at the same time continuously contributes to radiative, physical and gaseous exchanges with the atmosphere. These transfers and their impacts on the atmosphere and the ocean are at the core of the climate system.

The ocean receives heat from solar electromagnetic radiation, in particular in the tropics. It exchanges heat at its interface with the atmosphere at all latitudes, and with sea-ice in polar regions. The ocean is not a static environment: ocean currents are responsible for the redistribution of excess heat received at the equator towards the higher latitudes. At these latitudes transfers of water from the surface to the deep ocean take place as water loses buoyancy flowing poleward due to the effect of strong heat loss. The mechanism of this vertical dense water transfer related to an increase of seawater density (caused by a lowering of the temperature or an increasing of salinity) is the starting point for the global ocean thermohaline circulation (derived from the Greek *therme*: heat; *halos*: sea salt). The ocean also reacts dynamically to changing climatic conditions (*i.e.* wind, solar radiation...). The time scale of these processes

can vary from a seasonal or yearly scale in tropical areas to a decadal scale in surface waters, reaching several hundreds, even thousands of years in the deep ocean layers.

The atmosphere and ocean do not only exchange heat: water is also exchanged through the processes of evaporation and precipitation (rain, snow). The oceans contain 97.5% of the water on the planet, while continents contain 2.4% and the atmosphere less than 0.001%. Water evaporates virtually continuously from the ocean. Rain and river runoff compensate for evaporation, but not necessarily in the same regions as evaporation. Furthermore, the salt content in the ocean modifies the physical properties of seawater, particularly its density. Water exchange with the atmosphere, riverine input and melting of sea ice and ice caps thus contribute to variations in the density of sea water, and hence to the ocean circulation and vertical transfers within the ocean.

In addition, thanks to ocean circulation, the renewal of surface water, and in particular the exchanges with the deep ocean layers, play a very important role in carbon cycling as high latitude CO₂ enriched waters are drawn down towards the deep ocean.

THE TEMPERATURE OF THE OCEAN IS RISING

Recent warming caused by the emission of greenhouse gases related to human activity does not only affect the lower layers of the atmosphere and the surface of the continents. Measurements of sea temperature have been made during the past five to six decades over the 1000 to 2000 first meters of the ocean from ships, oceanographic buoys, moorings and more recently, autonomous profiling floats (the Argo project) that enable vertical sampling of the top 2000 m of the water column. They have allowed oceanographers to observe a significant increase in the temperature of the ocean over the studied period. On first hand, this recent warming of the ocean affects the surface layers (the first 300 to 500 meters). However at high

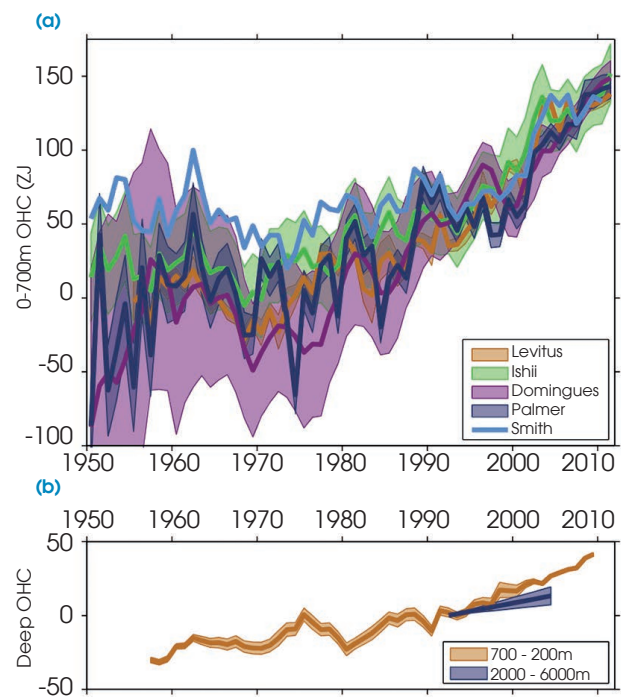


Fig.1 — (a) Evaluation of the yearly average of the heat content in ZJ (1 ZJ = 10²¹ Joules) calculated from observations in the surface layers of the ocean (between 0 and 700m depth). these estimates have been updated from Levitus *et al.* (2012), Ishii and Kimoto (2009), Domingues *et al.* (2008), Palmer *et al.* (2007) and Smith and Murphy (2007). Uncertainties are in grey, as has been published in the different aforementioned studies. **(b)** Estimates of the moving average of the heat content in ZJ over 5 years for the 700 to 2000m layer (Levitus 2012) and for the deep ocean (from 2000 to 6000m) during the 1992 to 2005 period (Purkey and Johnson, 2010). Figure adapted from Rhein *et al.*, 2013.

latitudes, the temperature increase has reached the deep layers of the ocean (Figure 1; Rhein *et al.*, 2013; Levitus *et al.*, 2012; Ishii and Kimoto, 2009; Domingues *et al.* 2008; Palmer *et al.*, 2007; and Smith and Murphy, 2007).

The temperature of the 0-300m layer has increased by about 0.3°C since 1950. This value is approximately half than the temperature increase at the surface of the ocean. Furthermore, although the average temperature of the ocean has increased less than that of the atmosphere, the ocean represents the greatest sink and reservoir of excess heat introduced into the climate system by human activities. This is due to its mass as well as its high

thermal capacity. Indeed, over 90% of the excess heat due to anthropogenic warming accumulated in the climate system during the past 50 years has been absorbed by the ocean (15 to 20 times higher than observed in the lower atmosphere and on land; Figure 2). This represents an excess energy storage by the ocean that is greater than 200 zeta-joules ($2 \cdot 10^{23}$; $1\text{ZJ} = 10^{21}\text{Joules}$) since the 1970s.

Recent results also show that the deep ocean has actually accumulated a larger amount of heat than had been estimated so far, which may explain, simultaneously with the impact of natural

climate variability such as the El Nino Southern Oscillation (ENSO), the recently observed slow-down in atmospheric warming (Durack *et al.*, 2014). This excess heat in the ocean is caused by direct warming from solar energy (e.g., this is the case in the Arctic due to an intensified reduction in the area of sea ice during summer) as well as thermal exchange enhanced by increasing infrared radiation due to rising concentrations of greenhouse gases in the atmosphere. The continuing or even increasing accumulation of heat in the deep layers explains that the ocean heat content kept rising during the last ten years, despite near-constant average surface ocean temperature (Balmaseda *et al.* 2013). Moreover, this climatic hiatus has been recently explained by an increase of the ocean heat content at depth (Drijfhout *et al.*, 2014). The random climate variability from one year to another is not surprising given the high nonlinearity and complexity of the Earth climate system. Temporary stagnations of global warming can be essentially related to ocean dynamics.

Ocean temperature rises induce side effects that could be of consequence, if not catastrophic, but that are yet still poorly understood. Amongst these effects, there is its contribution to the rise of average sea level, currently estimated to be over 1mm/year. (e.g., Cazenave *et al.*, 2014).

The oceans and seas produce another direct effect on climate change: it is likely that rising temperatures are progressively leading to an intensification of the global water cycle (Held and Soden, 2006; Allan *et al.*, 2010; Smith *et al.*, 2010; Cubash *et al.*, 2013; Rhein *et al.*, 2013).

Water vapor being a greenhouse gas, it has a role in accelerating global warming, and consequently water evaporation. Changes in the water cycle can be observed using the variations in salinity as a proxy. An assemblage of recent data shows that surface salinity has changed over the past five decades, with an increasing contrast between the North Atlantic and the North Pacific basins (Durack and Wijffels, 2010; Hosoda *et al.*, 2009; Rhein *et al.*, 2013).

Salinity measurements at different depths also reveal changes (Durack and Wijffels, 2010; Rhein *et al.*

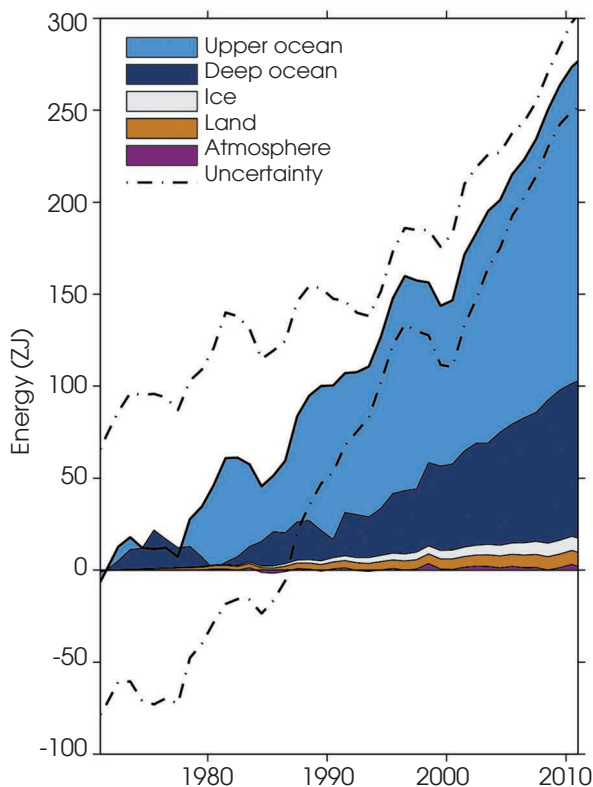


Fig.2— Energy accumulation curve in ZJ with reference to the year 1971 and calculated between 1971 and 2010 for the different components of the global climate system. The sea temperature rise (expressed here as a change in heat content) is significant. The surface layers (light blue, 0 to 700m deep) contribute predominantly, while the deep ocean (dark blue; water layers below 700m) is also a significant contributor. The importance of the role of the melting of continental ice (light grey), the continental areas (orange) and the atmosphere (purple) is much smaller. The broken line represents the uncertainty of estimates. Figure adapted from Rhein *et al.*, 2014.



al., 2013). The most noteworthy observation has been a systematic increase of the contrast in the salinity between the subtropical gyres, that are saltier, and high latitude regions, particularly the Southern Ocean. At a global scale, these contrasts point to a net transfer of fresh water from the tropics towards the poles, thus implying an intensification of the water cycle. In the North Atlantic, a quantitative assessment of the thermal energy storage and freshwater flux over the past 50 years confirms that global warming is increasing the water content of the atmosphere, thus leading to the intensification of the water cycle (Durack *et al.* 2012).

The sea temperature rise also modifies its dynamics as well as the transfers of heat and salt, thus locally disrupting the surface exchanges of energy with the atmosphere. Thermohaline circulation can also be disturbed and may affect the climate at a global scale by significantly reducing heat transfer towards the Polar Regions and to the deep ocean. According to the IPCC (Intergovernmental Panel on Climate Change), it is very likely that the thermohaline circulation will slow down during the 21st century, although it should be insufficient to induce a cooling of the North Atlantic region. Increasing ocean temperature also has a direct impact on the melting of the base of the platforms of the continental glaciers surrounding Greenland and Antarctica, the two major continental water reservoirs (Jackson *et al.*, 2014; Schmidko *et al.*, 2014; Rignot *et al.*, 2014). Hence, although it was known that global warming is enhancing glacial melt, it is now proven that the heating of the oceans is contributing primarily to the melting of ice shelves that extend the Antarctic ice cap over the ocean. For example, considering that Antarctica holds about 60% of the world's fresh water reserves, recent studies show that the melt of the base of the Antarctic ice caps has accounted for 55% of the total loss of their mass between 2003 and 2008, representing a significantly large volume of water (Rignot *et al.*, 2014).

Ocean warming affects the biogeochemical mass-balance of the ocean and its biosphere¹.

Although most of these aspects have been documented, it is noteworthy to mention that the warming of the oceans can also impact the extent of their oxygenation: the solubility of oxygen decreases with increasing water temperature: the warmer the water, the lower the dissolved oxygen content. The direct consequences involves losses of marine life and its biodiversity and restrictions in the habitats (e.g. Keeling *et al.* 2010).

Compared to the atmosphere, the ocean presents two characteristics that confer it an essential role in the climate system:

1. Its thermal capacity is more than 1000 fold that of the atmosphere and allows the ocean to store most of the solar radiation flux and surplus energy generated by human activities.
2. Its dynamics are much slower than in the atmosphere, with a very strong thermal inertia; at time scales that are compatible with climate variability, the ocean therefore keeps a long-term memory of the disturbances (or anomalies) that have affected it.

However, the world ocean is still poorly known due to its great size and to the inherent technical difficulties encountered in oceanographic observation (e.g. the difficulty of high precision measurements at pressures exceeding 500 atmospheres; the need to collect *in situ* measurements everywhere in the ocean aboard research vessels that are operated at great costs). In addition, ocean dynamics can be very turbulent and subsequent interactions with the atmosphere, extremely complex. To unveil these unknowns and uncertainties will be an essential step to predict the future evolution of the climate in a more reliable manner. Observations and measurements are irreplaceable sources of knowledge. It is therefore necessary to improve the nature and quantity of ocean observations with the aim to establish a long-lasting, internationally coordinated, large-scale ocean-observation system.

¹ In particular refer to « The ocean carbon pump » and « the ocean acidification and de-oxygenation » scientific sheets



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