# The ocean, a heat reservoir

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The ocean's ability to store heat (uptake of 94% of the excess energy resulting from increased atmospheric concentration of greenhouse gases due to human activities) is much more efficient than that of the continents (2%), ice (2%) or the atmosphere (2%) (Figure 1; Bindoff *et al.*, 2007; Rhein *et al.*, 2013; Cheng *et al.*, 2019). It thus has a moderating effect on climate and climate change. However, ocean uptake of the excess heat generated by an increase in atmospheric greenhouse gas concentrations causes marine waters to warm up, which, in turn, affects the ocean's properties, dynamics, volume, and exchanges with the atmosphere (including rainfall cycle and extreme events) and marine ecosystem habitats. For a long time, discussions on climate change did not take the oceans into account, simply because we knew very little about them. However, our ability to understand and anticipate changes in the Earth's climate depends on our detailed knowledge of the oceans and their relationship to the climate.

## THE OCEAN: A HEAT RESERVOIR AND WATER SOURCE

Earth is the only known planet where water is present in its three states (liquid, gas and solid) and in particular in liquid form in the ocean. Due to the high heat capacity of water, its radiative properties and phase changes, the ocean is largely responsible for the mildness of our planet's climate and for water inflows to the continents, necessary for developing and sustaining life.

The ocean, which has a very thin layer of salty water, contains more than 96% of the Earth's water, covers 7% of its surface, and acts as a thermostat, warming the atmosphere and exchanging water with it to form clouds and distribute precipitation (rain, snow, etc.) around the world.

It is therefore the key element of the climate system since it mitigates the ongoing changes due to anthropogenic greenhouse gas emissions by absorbing almost all the excess heat (94%: Cheng *et al.*, 2019) and a quarter of the $CO_2$ emissions (Le Quéré *et al.*, 2018). Without the ocean, the atmospheric warming observed since the early 19th century would be much more intense.

Our planet's climate is governed to a significant extent by the ocean, which is its primary regulator thanks to the ocean's ability to fully absorb any kind of incident radiation on its surface and its continuous radiative, mechanical and gaseous exchanges with the atmosphere. These exchanges and their consequences are at the heart of the climate system.

The ocean receives heat from solar electromagnetic radiation, mainly in tropical regions, but its surface also exchanges extensively with the atmosphere, at all latitudes where it is not covered with ice. The ocean is not static, and marine currents distribute the excess heat received in the tropical regions towards higher latitudes and the ocean depths, especially through high-latitude transfers in areas where surface waters become denser and sink, mainly due to significant heat losses. It also reacts dynamically to changes in climatic conditions (winds, sunlight, etc.). Transfer and redistribution times are highly variable, on timescales ranging from seasons to years in tropical regions, decades in surface layers, and even up to hundreds or thousands of years in deep waters.

The atmosphere and the ocean exchange not only heat, but also water through evaporation and precipitation (rain, snow, etc.). The oceans store 97% (1,338 billion $km^3$) of the world's total water resources (1,386 billion $km^3$), while continents only contain 2.4% and the atmosphere less than 0.001% (Gleick, 1996). Water on Earth circulates continuously in a cycle, referred to as the water or hydrological cycle. In simple terms, water enters the atmosphere through evaporation from the ocean surface (which provides 90% of the water) and continents. Water vapor rises, forms clouds, then water falls back to Earth as rain, hail, or snow. Some of the precipitation remains on plant foliage and returns to the atmosphere through evaporation. Some of the precipitation that reaches the ground also evaporates; the remaining water seeps into the ground where it enters water tables or flows downstream, feeding lakes and rivers, which ultimately carry the water to the oceans.

Water is continuously evaporating from the ocean. Rainfall and river runoff compensate for evaporation, but not necessarily in the same areas.

The salt contained in seawater modifies its physical properties, especially its density. Water exchanges with the atmosphere, river runoff and melt water from sea ice or polar ice caps contribute to variations in seawater density, and hence to ocean circulation and vertical transfers in the ocean. Renewal of surface water through ocean circulation and, in particular, water exchanges with the deep ocean also play a significant role in the $CO_2$ cycle, moving carbon dioxide-enriched surface waters from high latitudes towards the deep ocean.

## THE OCEAN IS WARMING UP

The recent warming caused by anthropogenic greenhouse gas emissions affects not only the lower atmospheric layers and continental surface. The fourth and fifth assessment reports of the IPCC Working Group (hereinafter "IPCC AR4 and AR5") highlighted the critical role played by the ocean both in the long-term response of the terrestrial system to global warming and in short-term projections (IPCC, 2013). Changes in heat and freshwater content can influence the predictability of relevant societal information on a decadal timescale. 94% of the global warming associated with human-induced climate change results in ocean warming (Figure 1; Bindoff *et al.*, 2007; Rhein *et al.*, 2013; Cheng *et al.*, 2019). Climate simulations show that global change in ocean heat content becomes the predominant factor in the global thermal balance on a timescale of several months and provides a more reliable indication of the Earth's net radiative forcing than changes in global surface temperature (Palmer *et al.*, 2011; Palmer & McNeall, 2014; von Schuckmann *et al.*, 2016).

The thermal expansion associated with ocean warming accounts for about 30-40% of the observed sea level rise (WCRP Global Sea Level Budget Group, 2018; Church *et al.*, 2011) and is expected to substantially contribute to future projections for the 21st century (Church *et al.*, 2013). The spatial pattern of the change in ocean heat content exerts a strong influence on local sea level changes and remains a key uncertainty in regional projections of sea level rise (*e.g.*, Slangen *et al.*, 2014; Cannaby *et al.*, 2016; Carson *et al.*, 2016). In addition, scientists are beginning to understand the importance of the spatial pattern of ocean heat uptake in relation to climate feedback and climate sensitivity (Rose *et al.*, 2014; Rose & Rayborn, 2016). In fact, this parameter determines the extent of surface warming generated by a given amount of greenhouse gas emissions.

Changes in the global water cycle, such as variations in water availability, droughts and floods, are a major concern as Earth's climate changes. The ocean accounts for 97% of the water stored in all water reservoirs worldwide, and 80% of the Earth's surface freshwater fluxes occur at the ocean-atmosphere interface (Durack, 2015). Ocean waters contain simple salts (*e.g.* Pawlowicz *et al.*, 2016). During the evaporation process, these salts remain in the ocean. As a result, as water passes from the ocean to the atmosphere, and vice versa, salinity anomalies persist and accumulate, providing indications on the variability or changes in the water cycle.

The changes observed in ocean heat and freshwater content are calculated based on available *in situ* measurements of subsurface temperature and salinity. Although the earliest global survey of ocean subsurface temperature dates back to the H.M.S *Challenger* expedition in the late 19th century (Roemmich *et al.*, 2012), it was not until the late 1960s that widespread measurements of ocean temperature were obtained in the first 300-700 m of the water column (Abraham *et al.*, 2013).

Historical observations of the ocean during the second half of the 20th century were highly concentrated in the northern hemisphere, since these measurements were associated predominantly with research vessels and shipping activity, which was particularly significant in these regions. However, it is only since the mid-2000s, with the advent of the Argo International Program's array of free-drifting profiling floats (www.argo.net), that regular and near-global ocean samplings has become available over the first 2,000 m of the water column (Roemmich *et al.*, 2012; Riser *et al.*, 2016). Argo also provides co-located observations of salinity, from which changes in ocean heat and freshwater content can be deduced.

These co-located temperature and salinity observations allow scientists to calculate the density field and its influence on regional sea level variations (Willis *et al.*, 2008), as well as the related changes in ocean flow (Gray & Riser, 2014). They also provide mechanistic insights into the observed changes through water mass analysis (Desbruyères *et al.*, 2016).
The advent of remote sensing in 1978 with the Seasat Earth-orbiting satellite marked the beginning of a new era in global ocean studies. This first remote platform included a radar altimeter to measure satellite height above the ocean surface, a microwave scatterometer to measure wind speed and direction, a microwave radiometer to measure sea surface temperature, and visible and infrared radiometers to identify clouds, land and water features. The usefulness of these remote space platforms for measuring sea surface temperature was demonstrated in the early 1980s (*e.g.* McConaghy,

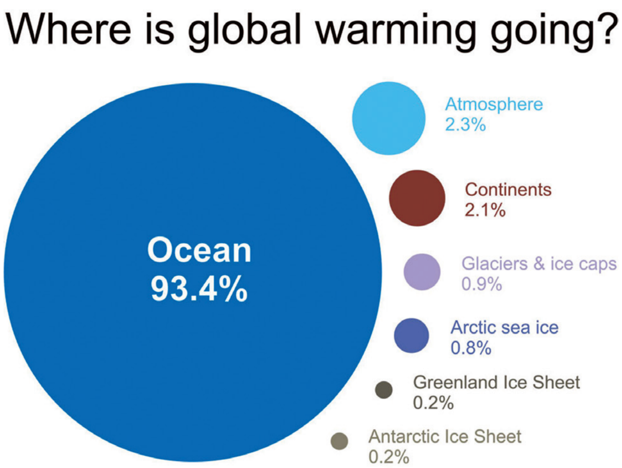



Fig.1 — Visual depiction of the amount of heat associated with anthropogenic global warming that is going into the various components of the climate system for the 1993-2003 period, calculated from IPCC AR4 (Bindoff *et al.*, 2007, section 5.2.2.2.3). This estimate was later confirmed by the IPCC's AR5 (Rhein *et al.*, 2013). Today, the ocean value has been revised upwards: (94% in Cheng *et al.*, 2019). This value is likely be taken up by the IPCC AR6, as well as that of other components of the climate system. It should be noted that focusing on air temperature on the Earth's surface misses more than 90% of the overall warming of the planet. As a result, indexing global warming based on the Earth's surface temperature tends to underestimate this value by 90% (adapted from https://skepticalscience.com/Infographic-on-where-global-warming-is-going.html).

1980); in the early 1990s, the integrated quantity of sea surface height was established (*e.g.* Le Traon *et al.*, 1998; Ducet *et al.*, 2000), and the first satellite measuring sea surface salinity was launched in November 2009 (the ESA's SMOS satellite measuring soil moisture and ocean salinity). Several other missions were launched shortly thereafter (*e.g.* Berger *et al.*, 2002; Lagerloef *et al.*, 2008; Fore *et al.*, 2016). Satellite observations provide an exceptional, high-resolution view of surface ocean dynamics in terms of temperature, sea levels and surface salinity.

Satellite data ideally complement *in situ* ocean observations by providing a spatial and temporal context for measurements carried out in a scattered fashion by oceanographic vessels and Argo floats. Thus, satellite measurements help solve scale problems or monitor regions that are not adequately sampled or covered by *in situ* observations, as is the case, for example, for variations in coastal oceans and marginal seas associated with river plumes influencing freshwater content at the regional level (*e.g.* Fournier *et al.*, 2016).

*In situ* measurements are usually much more accurate, ensuring reliable ground conditions to calibrate and validate satellite data. The combined use of these data provides estimates of ocean heat and freshwater content on both global and regional scales (Reynolds *et al.*, 2007; Guinehut *et al.*, 2012; Xie *et al.*, 2014).

## OBSERVED CHANGES IN HEAT CONTENT (*I.E.* ENERGY)

Prior to the Argo program, much of the assessment of global ocean variability was limited to annual and seasonal climate cycles (Levitus, 1984, 1986, 1989; Boyer & Levitus, 2002; Kara *et al.*, 2003; de Boyer Montegut *et al.*, 2004), or five-year periods for deep seabeds (Levitus, 1989). Thanks to the Argo international program, much more comprehensive studies on ocean variability during the modern era have been made possible.

Most of the historical measurements took place in the upper ocean layers (0-700 m deep). Our knowledge of long-term change is therefore most robust at these depths (Figure 2; Abraham *et al.*, 2013). Since the first assessments of ocean warming became available, a consistent picture of ocean changes caused by human activities over timescales of several decades has been highlighted through ocean observations (*e.g.*, Levitus *et al.*, 2000). Subsequently, a clearer picture of the ongoing changes has emerged, showing an evident warming of the upper ocean from 1971 to 2010 at an average rate of 107 TW (these estimates range from 74 to 137 TW according to five independent studies), and a weaker warming trend between 1870 and 1971 (Rhein *et al.*, 2013), broadly consistent with our understanding of changes in terrestrial radiative forcing (*e.g.* Myhre *et al.*, 2013).

Even though the measurement coverage area decreased at intermediate depths (700-2,000 m) before Argo, scientists were able to calculate five-year estimates dating back to 1957 (Levitus *et al.*, 2012). These, too, show strong warming over the observed period, but at a slower rate than in the upper ocean. The ocean is therefore accumulating energy at a rate of 4 x $10^{21}$ Joules per year, equivalent to 127,000 nuclear power plants (with an average production of 1 Gigawatt) discharging their energy directly into the world oceans.

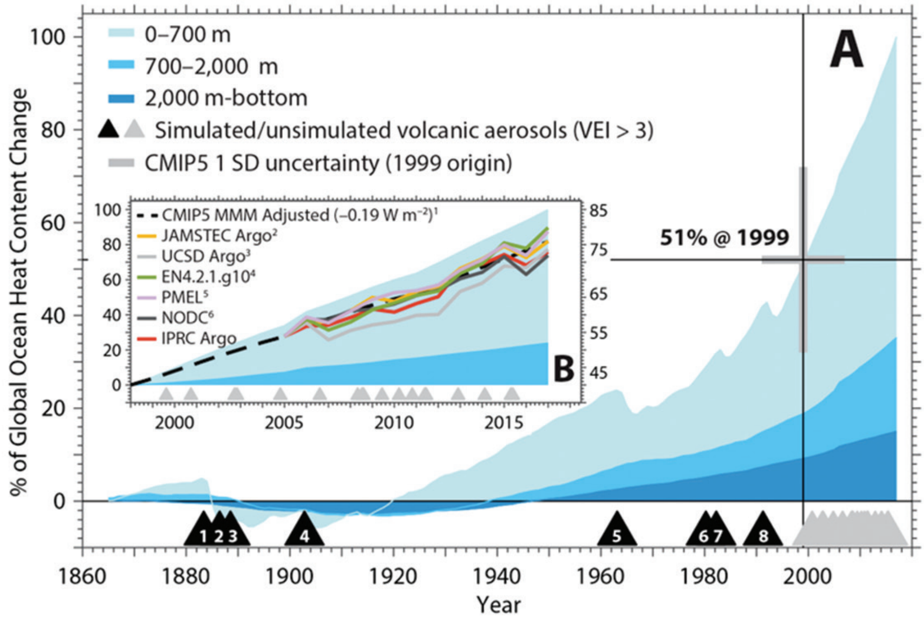
Although all available analyses show a significant historical warming, the patterns and rates differ due to measurement coverage limitations and the different methods used to reconstruct global changes from sparse observations (*e.g.* Boyer *et al.*, 2016; Palmer *et al.*, 2017). This issue has virtually disappeared in the upper and intermediate ocean since the Argo era (Figure 2; Roemmich *et al.*, 2015).

Deep-water measurements (at > 2,000 m in depth) are even rarer than those carried out in the intermediate layer (700-2,000 m deep) and are performed during oceanographic research campaigns using highly accurate and calibrated measuring platforms (GO-SHIP, Sloyan *et al.*, 2019).

Deep-sea layers have also undergone statistically significant warming since the 1990s, with a large regional variability. Seabed monitoring is currently limited to deep hydrographic sections, based on a sparse network of ship tracks that are usually repeated every two to three years, and on moored arrays in the Atlantic Basin (Figure 2; Frajka-Williams *et al.*, 2019).

Deep ocean warming results from downwellings of surface waters between subtropical and polar latitudes. Waters sink down to various depths (200-400 m at subtropical latitudes, 400-1,000 m at subpolar latitudes and down to ocean abysses at polar latitudes), due to heat and freshwater exchanges with the atmosphere that drive the global ocean circulation.

Based on available observations, the deep ocean (below 2,000 m) and the abyssal zone (below 4,000 m) are estimated to have accumulated heat at a rate of 22.3 ± 23.7 TW and 10.7 ± 3.4 TW, respec-




[1]Ridley et al., 2014; [2]Hosoda et al., 2008; [3]Roemmich & Gilson, 2009; [4]Good et al., 2013; [5]Johnson et al., 2018; [6]Levitus et al., 2012

Fig.2 — Ocean models provide us with an overview of how the deep ocean reacts to radiative forcing. When compared with data coverage of the current Argo International Program of profiling floats (www.argo.net) and corrected for the forcing deviations observed since the 2000s, the rate of change in ocean heat content is similar to the observed estimates. Ocean heat uptake (percentage of total 1865–2017 change) for the CMIP5 Multi-model Mean (MMM) layers are presented in the blue wedges for the deep (dark blue), intermediate (blue), and upper (cyan/light blue). The three shaded wedges are combined in the same way as the variation in the global energy inventory performed in IPCC AR5 (Rhein *et al.*, 2013; box 3.1, Fig. 1). The thick vertical gray bar represents 1 Standard Deviation (SD) with respect to the CMIP5 simulations for the year (1999) in which the MMM heat uptake reaches 51% of the net increase (1865-2017) observed during the industrial era, The thick horizontal gray bar indicates 1 SD with respect to the CMIP5 simulations for the year in which the total accumulated heat is 50%. The black (including forcing) and gray (excluding forcing) triangles represent the major volcanic eruptions of the 20th and 21st centuries, the symbol size being proportional to their magnitude. Figure reproduced from Durack *et al.*, 2018 and adapted from Gleckler *et al.*, 2016.

tively, mainly because the Southern Ocean's deep waters have warmed 10 times faster than the North Atlantic's deep basins (Purkey & Johnson 2010; Desbruyères *et al.*, 2016).

## CLIMATE CHANGE, OCEAN WARMING AND EARTH'S ENERGY IMBALANCE

The Earth's climate is a solar-powered system. Throughout the year, approximately 30% of the incoming solar radiation is scattered and reflected back into space by clouds and the planet surface. The remaining solar radiation (about 240 W/m²), absorbed in the climate system, is converted into energy (internal heat, potential, latent, kinetic or chemical energy), then moved, stored and sequestered, mainly in the ocean, but also in atmospheric, terrestrial and glacial components of the climate system. Finally, it is sent back into space as outgoing long-wave radiation (OLR: Trenberth & Stepaniak 2003a, b; 2004). In a balanced climate, there is a global balance between the radiation absorbed by the planet and that emitted into space. This balance determines the Earth's radiative balance (Trenberth & Stepaniak, 2003-a, b).

Disruptions to this balance due to internal or external climate changes create a global energy imbalance, causing a radiative flux imbalance at the top of the atmosphere, shaped by several climate forcing factors.

Any variation in the Earth's climate system affecting the incoming or outgoing amount of energy changes the planet's radiative balance and can force temperatures to rise or fall. These destabilizing influences are called climate forcing factors. Natural climate forcing factors include changes in the sun's brightness; Milankovitch cycles (small variations in the shape of the Earth's orbit and its rotation axis that occur over thousands of years), and major volcanic eruptions that inject light-reflecting particles at altitudes as high as the stratosphere. Anthropogenic forcing factors include pollution by particulates (aerosols), which absorb and reflect incoming sunlight; deforestation, which changes the way the surface reflects and absorbs sunlight, and increasing atmospheric concentrations of carbon dioxide and other greenhouse gases, which reduce the amount of heat emitted from Earth into space. A forcing factor can trigger feedbacks that increase (positive feedbacks) or weaken (negative feedbacks) the initial global forcing. Polar ice loss is an example of positive feedback because it makes the poles less reflective. Recent studies show that the Earth is energetically imbalanced – the energy within the climate system is higher than that emitted into space – and this imbalance is increasingly influenced by the atmospheric concentrations of $CO_2$ and other greenhouse gases. In fact, these gases promote the accumulation of excess heat and cause global warming (Loeb *et al.*, 2009; Hansen *et al.*, 2011; Myhre *et al.*, 2013; Abraham *et al.*, 2013; Trenberth *et al.*, 2014; Allan *et al.*, 2014) (Figure 3).

The most recent studies show that 94% of this positive radiative imbalance causes an (observed) increase in ocean heat content (Abraham *et al.*, 2013; Rhein *et al.*, 2014; Figures 1 and 3a).

A small proportion (a few percent) of this energy contributes to the melting of sea ice and land ice in the Arctic (glaciers, Greenland) and Antarctica. The remaining energy contributes to land and atmosphere warming (Figure 3a), with changes in kinetic and chemical energy making a negligible contribution (Trenberth & Stepaniak, 2003; Trenberth *et al.*, 2002).

Thus, the absolute value of Earth's radiative imbalance is the most important factor defining the state of global climate change and is much more scientifically robust than using the global surface temperature. In fact, it is a measure of the global energy involved in ongoing climate change, whereas the global surface temperature measures only a small fraction of that energy, because the ocean absorbs this surplus of climate energy and retains most of it. Consequently, the best estimate of the Earth's radiative imbalance is the measurement of ocean heat content, supplemented by radiation measurements carried out from space, at the top of the atmosphere (Von Schuckmann *et al.*, 2016).

## IMPACTS OF A WARMING OCEAN: SALINITY, FRESHWATER CONTENT AND WATER CYCLE INTENSIFICATION

In parallel with ocean warming, consistent salinity changes have also been observed in both the surface and the lower water layers (Boyer *et al.*, 2005; Hosoda *et al.*, 2009; Durack & Wijffels, 2010; Helm *et al.*, 2010; Mulet *et al.*, 2018). The salinity structure at the ocean surface reflects evaporation and precipitation patterns. Regions with high evaporation rates (such as subtropical atmospheric convergence zones, the Mediterranean Sea and the Red Sea) are characterized by higher salinity concentrations than those receiving high rainfall (such as tropical and subpolar regions). Observations show that salinity differences in these regions are increasing due to an intensification of the land water cycle (Durack *et al.*, 2012; Huntington *et al.*, 2006).

In fact, a warmer climate increases the atmosphere's ability to store water vapor, since this parameter increases with temperature according to the Clausius-Clayperon formula.

The accepted theory is that as atmospheric temperature rises, more water evaporates, mainly over the ocean. As a result, rainfall increases, essentially over land. Moreover, the processes by which clouds and precipitation form in the atmosphere largely depend on the amount, distribution and type of aerosols, because these small atmospheric particles directly influence cloud formation. They can also change the radiation properties of the atmosphere when it is cloud-free. Variations in the water cycle can also be caused by changes in the evaporation properties of soil surface and plants, thus impacting the soil's water storage capacity. If the water cycle intensifies, then all its components are amplified, *i.e.* more evaporation, precipitation and runoff (*e.g.* Williams *et al.*, 2007; Durack *et al.*, 2012; Lago *et al.*, 2016).

Despite this complexity, recent studies suggest that changes in the water cycle are closely linked to an increase in ocean heat content. A warmer ocean provides more heat and water vapor to the atmosphere, thus influencing rainfall patterns worldwide (Held & Soden, 2006; Allan *et al.*, 2010; Smith *et al.*, 2010; Cubash *et al.*, 2013; Rhein *et al.*, 2013).

Salinity analysis as a function of depth also reveals changes (Durack & Wijffels, 2010; Rhein *et al.*, 2013). The most remarkable observation is a systematic increase in salinity contrast between salty subtropical gyres and high-latitude regions, particularly the southern hemisphere. At the scale of the world ocean, contrasts indicate a net freshwater transfer from the tropical regions to high latitudes, showing an intensification of the water cycle.
In the North Atlantic Ocean, the quantitative assessment of heat storage and freshwater inflows over the past 50 years, is consistent with warming that increases the atmospheric water content, leading to an intensification of the water cycle (Durack *et al.*, 2012).

As with the increase in heat content in the deep ocean, salinity anomalies spread throughout the ocean with the global ocean circulation. The most important signal observed is an increase in ocean freshwater content in the Southern Ocean's abyssal and intermediate zones (they have desalinated at a rate equivalent to a freshwater inflow of 73± 26 Gt/year: Purkey & Johnson, 2012; Yao *et al.*, 2017; Silvano *et al.*, 2018), while freshwater content in subtropical and Mediterranean waters is decreasing (Palmer *et al.*, 2019).

The impact of ocean warming on the water cycle induces a feedback affecting climate change. Indeed, water vapor is a greenhouse gas and contributes to accelerating climate warming, and thus water evaporation.

## IMPACTS OF A WARMING OCEAN: SEA LEVELS

Current changes in sea levels are the result of various contributing factors caused by changes in the ocean, terrestrial hydrosphere, cryosphere and solid Earth. In fact, changes in the global mean sea level result from ocean thermal expansion (a warmer ocean occupies a larger volume) and changes in ocean mass due to ice mass loss from the Greenland and Antarctica ice sheets, melting glaciers and changes in land water storage (WCRP Global Sea Level Budget Group, 2018). At the regional level, spatial trends in sea levels result from several overlapping phenomena: changes in seawater density are due to changes in temperature and salinity (known as "steric" effects), atmospheric loading, solid Earth deformations and gravitational changes, generated by the mass redistribution associated with land ice melt and changes in land water storage (known as "static" effects; Stammer *et al.*, 2013).

Increased ocean heat is estimated to be responsible for 35-40% of the total sea level rise, estimated at 3 mm/year since satellite measurements became available (Cazenave *et al.*, 2014; 2018).

## IMPACTS OF A WARMING OCEAN: OCEAN DYNAMICS AND TRANSPORT

Ocean warming also changes ocean dynamics, as well as heat and salt transport, thus locally disturbing energy exchanges with the atmosphere at its surface.

Global circulation can also be disrupted and affect the climate on a global scale by significantly reducing heat transport to high latitudes and the deep ocean. The IPCC considers it very likely that global circulation will slow down during the 21st century; but not enough to induce cooling in the North Atlantic regions. However, observations made over the past decade do not show a clear trend, but rather strong variations over very different timescales (ranging from weeks to decades: Meinen *et al.*, 2018; Frajka-Williams *et al.*, 2019). However, much longer time series are needed to support any change in ocean circulation. These changes are important, because they also affect changes in the transport of chemical ($CO_2$, oxygen, nutrients) and biological constituents (planktonic species, fish larvae).

## IMPACTS OF A WARMING OCEAN: ICE CAP MELT

Global ocean warming also has a direct impact on the melting of the base of ice shelves and continental glaciers surrounding Greenland and Antarctica, the two main reservoirs of water stored on continents (Jackson *et al.*, 2014; Schmidko *et al.*, 2014; Rignot *et al.*, 2014; Silvano *et al.*, 2018). Thus, while it was already known that global warming was increasing glacier melt, it is now proven that ocean warming significantly contributes to melting the ice shelves extending the Antarctic ice cap over the ocean. For instance, if Antarctica accounts for about 60% of the world's freshwater reserves, studies show that the melting of the base of its ice caps represented 55% of their total mass loss between 2003 and 2008 (Rignot *et al.*, 2014).

## ADDITIONAL IMPACTS OF A WARMING OCEAN

Ocean warming also affects the biogeochemical balances of the ocean and its biosphere. While most of these points are noted in the other scientific fast sheets, it can be mentioned that warming is also likely to have an impact on water oxygenation since oxygen solubility decreases as water temperature rises: The warmer the water, the less oxygen it contains. The consequences are marine biodiversity asphyxiation and habitat reduction (Keeling *et al.*, 2010).

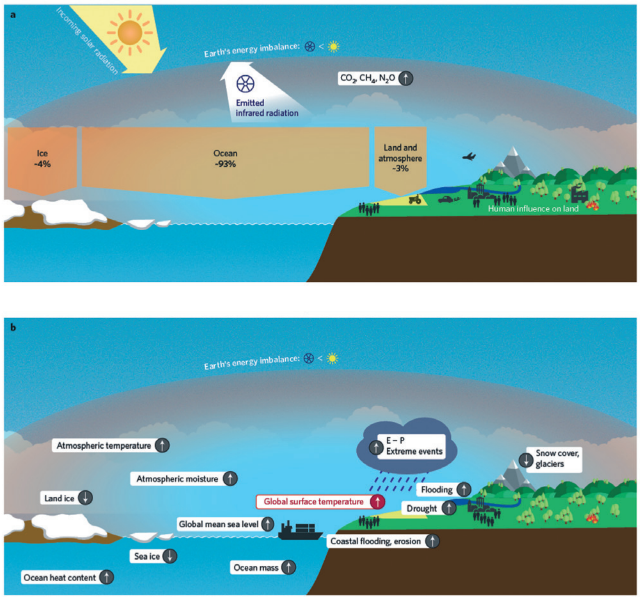



Fig.3 — Schematic representations of energy flow and storage in the Earth's climate system and related consequences. a) Earth's energy imbalance (Earth Energy Imbalance, EEI) resulting from human activities. The world ocean is the main heat reservoir, storing approximately 90% of EEI. The remaining heat warms up the Earth's surface and atmosphere, and melts ice (as indicated). b) The "symptoms" associated with positive EEI, including rises in the Earth's surface temperature, ocean heat content, ocean mass, global mean sea level, atmospheric temperature, and moisture, drought, flooding and erosion, increased extreme events, and evaporation-precipitation (E-P), as well as a decrease in land and sea ice, snow cover and glaciers. Adapted from von Schuckmann *et al.*, 2016.

## CONCLUSIONS

Compared with the atmosphere, the ocean has two characteristics that give it an essential role in climate regulation:

1. Its thermal capacity is more than 1,000 times higher than that of the atmosphere, allowing it to store the major part of solar radiation and the excess energy generated by human activities.
2. It has much slower dynamics than the atmosphere and a very high thermal inertia. The ocean is therefore likely to store the disturbances (or anomalies) affecting it over longer timescales, compatible with climate variability.

3. Despite the ocean's slow dynamics, its warming is already affecting the global water cycle, sea levels, polar glacier melt, chemical properties and marine ecosystems (Figure 3b).
4. Recent results suggest that ocean warming has a significant impact on some extreme events, such as tropical cyclones (Trenberth *et al.*, 2018; Emmanuel, 2017; 2018) and potentially affects storm intensity at higher latitudes.
5. The most recent estimates based on observations of the amount of heat accumulated in the ocean in recent decades (*i.e.*, 94% of the excess energy generated by human activities) are in close agreement with the results of numerical simulations of the Earth system (those used in IPCC AR5) over the same period (Cheng *et al.*, 2019). This gives scientists confidence in the results of numerical climate simulations. However, these models predict that if the current trajectory of anthropogenic greenhouse gas emissions (8.5 scenario in IPCC AR5, aka the "worst case" scenario) remains unchanged, the amount of heat stored in the ocean will grow exponentially (Cheng *et al.*, 2019; Figure 4), thus, increasing global warming, extreme events, continental and sea ice melt, and sea levels, as well as drastically affecting marine ecosystems and food availability.

However, we still know very little about the ocean because of its vastness and the technical difficulties inherent in ocean observations (very accurate measurements at pressures exceeding 500 atmospheres, the need for *in situ* measurements aboard vessels involving very high operating costs, long measurement duration and completion times in such a vast ocean, etc.). Moreover, ocean dynamics are very turbulent and interactions with the atmosphere and climate are very complex. Reducing these unknowns and uncertainties is essential to be able to make more reliable predictions about future climate change. Observations and measurements are irreplaceable knowledge sources. There is therefore a need to improve the nature and quantity of ocean observations and to set up a large-scale, long-term observing system, coordinated internationally. This was one of the main objectives set by the international scientific community for the next decade during OceanObs'19, a conference on ocean observations that is held every ten years (http://www.oceanobs19.net; Speich *et al.*, 2019).

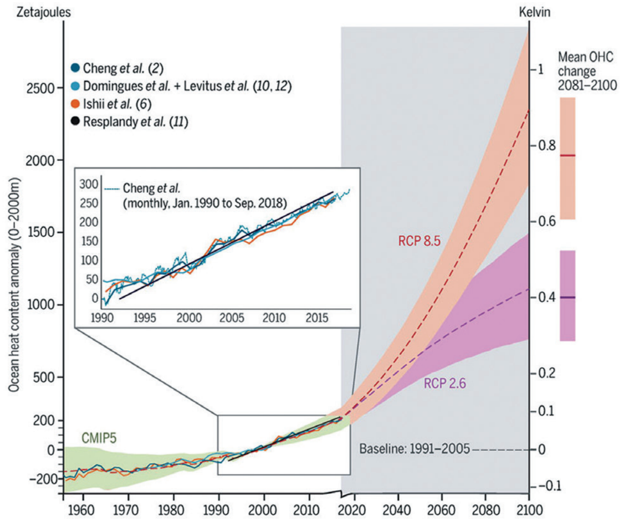



Fig.4 — Past and future changes in ocean heat content. The observed annual changes in heat content are consistent with the different estimates (Cheng *et al.*, 2019; Domingues *et al.*, 2008; Levitus *et al.*, 2012; Ishii *et al.*, 2017; Resplandy *et al.*, 2018) and with the ensemble means of models simulating the Earth's climate system used in IPCC AR5 (defined as CMIP5 models: IPCC, 2013). These results apply to historical simulations prior to 2005 and projections from 2005 to 2017 (supported by recent observations), thus giving confidence in future projections up to 2100 (RCP2.6 and RCP8.5: IPCC, AR5, 2013).

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