Sea Level Rise

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Measurements from tide gauges and satellites have shown that the sea is rising globally at an average rate of about 1.7mm per year since the beginning of the 20th century, a direct consequence of human-driven global warming, although there is strong regional variability. This increase is mainly due to two factors: the increase in ocean temperature resulting in expansion of sea water, and the melting of continental ice sheets, glaciers and ice caps with an input of fresh water into the ocean. Despite uncertainties, proposed scenarios indicate that sea levels will continue to rise at a faster pace than during the 20th century, reaching an increase of more than 25cm (best case) and 82cm (worst case but likely underestimated) by 2100.

MAREGRAPHIC MEASUREMENTS DURING THE 20TH CENTURY

Direct observation of changes in sea level began with the industrial era and the systematic installation of tide gauges in a few harbours across northern Europe, then progressively in other areas of the world. These instruments, originally developed to measure the tides, provide us with precious data on the evolution of sea level during the twentieth century. Although few in numbers and poorly distributed over the globe, the historical tidal series indicates that since the beginning of the twentieth century, the sea has globally been rising at an average speed of about 1.7mm per year (Figure1, left).

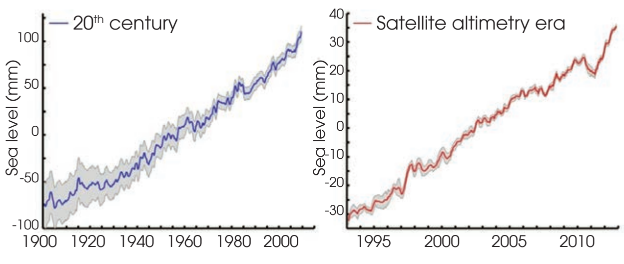

Fig.1— Evolution of the global average sea level, estimated from the reconstruction by Church and White (2011) over the twentieth century (left) and from satellite altimetry over the 1993-2012 period (source: AVISO). The uncertainty associated with each of the curves is in grey. The annual and semi annual cycles have been removed. Note the vertical scale difference between the two curves. From Cazenave & The Cozannet (2014).

THE OBSERVATION OF CHANGES IN SEA LEVEL FROM SPACE

Since the early 1990s, routine measurements of the rising sea levels have been made from space, thanks to high-precision altimetry satellites like Topex/Poseidon, Jason-1/2, ERS-1/2, Envisat and recently Saral/Alika and Cryosat (Ablain *et al.*, 2014). Satellite observations have a major advantage in comparison with the tide gauge: they provide a quasi-global observation of the entire ocean, with a revisit time of a few days. Figure 1 (right) illustrates the evolution of the sea level measured by altimetry satellites between 1993 and 2013. During this period, the rise in sea level was almost linear at a speed of 3.2±0.4mm/year (Cazenave *et al.*, 2014). This increase is the double of that recorded by tide gauges during the twentieth century, suggesting an acceleration of sea level rise since the early 1990s. Thanks to its complete coverage of the global ocean, satellite altimetry also revealed that the rise in sea level is not uniform. It presents a strong regional variability (see Fig.2) from regions such as Western Tropical Pacific where the sea level is rising 3 times faster than the global average, to other regions such as the western United States coastline, where the sea level is dropping at a rate of 1 to 2mm/year.

THE CAUSES OF THE CURRENT RISE IN THE GLOBAL MEAN SEA LEVEL

On a global average, the current rise in sea level is a direct consequence of anthropogenic global warming (Church *et al.*, 2013). It has two main causes:

1. Increasing ocean temperatures and associated thermal expansion (when the temperature increases, the sea water expands and sea level rises)
2. The melting of continental ice, glaciers and ice caps (freshwater flows to the sea due to melting continental ice lead to rising sea level). In addition to these processes, a small contribution also results from liquid water exchanges with the land (0.38mm/year over the 1993-2010 period).

- **Thermal expansion**

Thanks to sea temperature measurements collected from sensors dropped overboard from the stern of merchant ships during the past five decades and from the automatic floats from the international Argo project during the past ten years, oceanographers have observed that the ocean is getting warmer. Sea water expands with increasing temperature, thus leading to a rise in sea level. It is estimated that during the altimeter period (*i.e.* since 1993 and the beginning of satellite observations), this contribution can explain for 30% of the rise in global sea level (1.1±0.3mm/year between 1993 and 2010; Church *et al.*, 2013).

- **Melting glaciers**

Glaciers represent the whole of the continental ice masses, except for the two vast Greenland and Antarctic ice caps. There are more than 200,000 glaciers, covering about 730,000 km² of emerged lands. Since the end of the Little Ice Age around 1850, observations (from in situ measurements of glacier mass balance, altimetry and recently space gravimetry) have evidenced glacier retreat in almost all mountain ranges. This is partly explained by their delayed response to natural global warming following the Little Ice Age. However, the acceleration of glacier mass loss observed since the mid-1980s has been attributed to the recent anthropogenic warming (Marzeion *et al.*, 2014). During the altimeter period between 1993 and 2010, the glaciers are estimated to have contributed to a 0.9mm/year sea level rise (Church *et al.*, 2013).

- **Mass loss of the polar ice caps**

The mass loss of the polar ice caps can be observed and estimated primarily with three techniques: Radar or laser altimetry (which measure changes in the elevation of ice sheets since 1991), Spatial gravimetry (which provides direct mass changes of the ice cap with time) and the flux method (calculation of the difference between climate model estimates of surface snow accumulation and the flow of ice reaching the ocean at the grounding line of the ice caps) (Rignot *et al.*, 2014). An assessment of these observations over the past 20 years (Shepherd *et al.*, 2012) indicates a very strong mass loss in the coastal regions of Greenland and West Antarctica. Together, these losses represent an increase in sea level of 0.6mm/year over the 1993-2010 period (Church *et al.*, 2013).

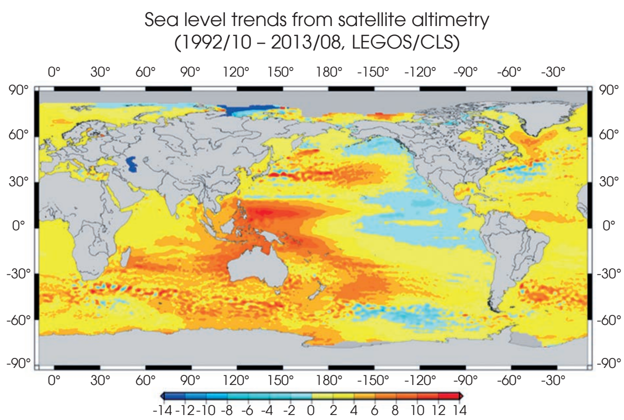

Fig.2— Global map of the geographical distribution of rates of sea level change (1993-2013) according to altimeter measurements from Topex/Poseidon, Jason-1/2, ERS-1/2 and Envisat (source: LEGOS).

REASONS FOR THE REGIONAL VARIABILITY OF SEA LEVEL

At a regional scale, the heat accumulation in the ocean and its associated thermal expansion generate most of the variability in sea level. The heat in the ocean is redistributed irregularly by ocean circulation (Stammer *et al.*, 2013) in response to atmospheric forcing (in angular momentum, heat and freshwater). Depending on the region, different processes are at work. For example in the western tropical Pacific, the intensification of trade winds observed for twenty years have caused a deepening of the thermocline in the western part of the basin, inducing the formation of a thicker layer of warm surface water and therefore a marked rise in sea level (Timmermann *et al.* 2010; Stammer *et al.*, 2013.).

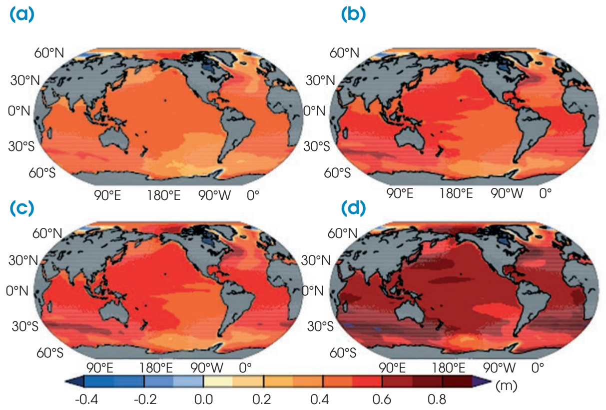

Fig.3— Overall average (21 CMIP5 models) of the change in relative sea level for RCP2.6 scenarios (a), 4.5 (b), 6.0 (c) and 8.5 (d). The impact of thermal expansion of the oceans, the mass of continental ice, continental stocks of liquid water and post-glacial rebound have been taken into account (adapted from Church *et al.*, 2013).

SEA LEVEL RISE IN THE FUTURE

In response to past and future emissions of greenhouse gases, global warming will continue in the future. Consequently, the increase in sea level will also continue, largely due to the melting of land ice and thermal expansion of the oceans. The challenge is to estimate the magnitude of this increase, with the regional disparities, and associated uncertainties. The uncertainties derive from two major sources: firstly, the lack of understanding of certain climatic processes that affect changes in sea level (*e.g.* this is the case for the ice flowing from the polar ice caps to the ocean) and secondly, the uncertainty concerning future gas emission scenarios for the anthropogenic greenhouse effect. Indeed, different scenarios involving emissions of greenhouse gases (expressed in terms of radiative forcing: RCP2.6, RCP4.5, RCP6.0 and RCP8.5, IPCC 2013) and the response of the climate system (expressed as the increase in the global temperature of the Earth) can occur for the coming decades (IPCC 2013). Each scenario indicates a rise in sea level between 1986 and 2000 and between 2080 and 2100, as they all forecast an increase in sea temperature and the melting of land ice. The extent of the sea level rise would vary between 25cm (best case scenarios RCP2.6) and 82cm (worst-case scenarios RCP8.5). In all cases, a simulation of the rise of the level of the sea between now and 2100 indicates that it will be faster than during the twentieth century. By 2100, the rate of sea level rise would reach 8-16mm/year for the RCP 8.5, which is similar to that during the last deglaciation. Moreover, in the same way that present changes in the current sea level are not uniform, it is expected that changes in sea level at the end of the XXI[st] century will display significant regional differences (Figure 3, Yin *et al.*, 2010). For example, considering the RCP8.5 scenario, the sea level could drop slightly in certain areas of the Arctic, while it could increase by more than 70cm along the east coast of the United States. It is therefore essential to take these differences into account and to model them correctly in order to anticipate future rises in sea level in coastal areas. At the moment, this is a very active research topic.

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