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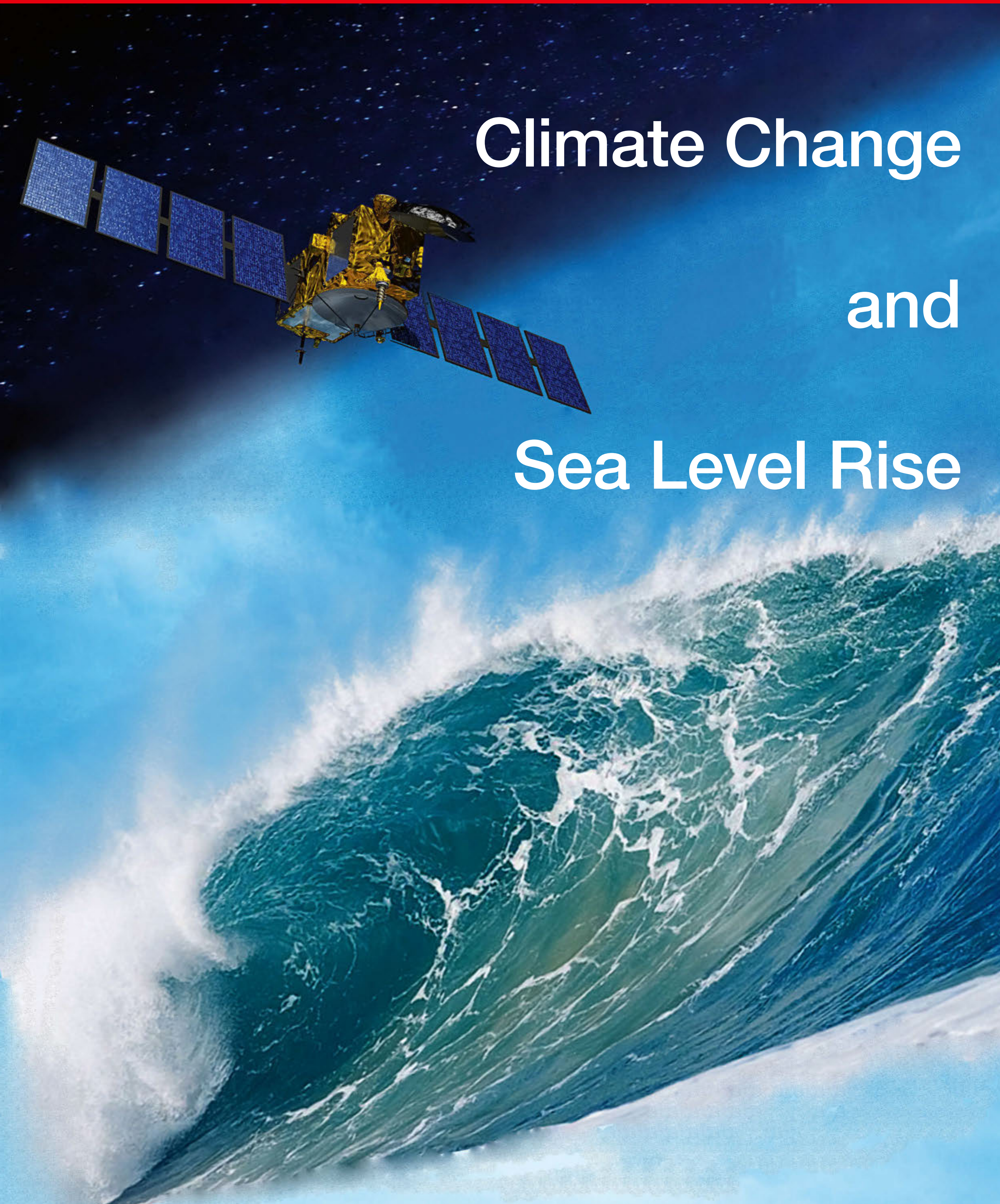

Climate Change and Sea Level Rise

Editorial

The climate on our planet Earth is changing, recently at an accelerated pace. As more than 70% of our planet is covered by water, surely one of the most sensitive indicators of this change is the state of the global ocean.

The sea level, for example, varies on a large number of temporal and spatial scales, driven by forces due to wind, tides, atmospheric pressure differences, temperature, salinity, gravitational differences and so forth.

In order to quantify and distinguish between these variations, precise measurements are necessary. Investigating changes of the sea level requires a reference, and a mean sea level can be defined as an average over a long time series of measurements, such that changes due to tides and wind effects are eliminated. The global mean sea level refers to a spatial average over the entire ocean. In the absence of any external forces, the mean sea level would follow an equipotential surface of the Earth's gravitational field. This surface is called the geoid (e.g. see *Spatium* 31) which does not resemble a simple sphere or ellipsoid but varies significantly from one place to another due to the Earth's uneven mass distribution. The difference between mean sea level and the geoid is referred to as the ocean surface topography. Precise measurements of the ocean surface topography have been possible since the launch of advanced satellite altimeters, sensors that measure the sea surface height via the return travel time of a radar signal sent to the ground below their path. Between the years 1900 and the early 1990s, the sea level rose by about 15 cm. Recent satellite altimeter data reveal an accelerating rise of 9.5 cm from 1993 to 2020. This acceleration is due to an increased heat content in the global ocean driving thermal expansion of the seawater and to the melting of land-based ice sheets and glaciers. Estimating the future developments is not easy, for example in 2007, the Intergovernmental Panel on Climate Change (IPCC) projected a maximum rise of 60 cm until 2099, their report of 2013 already projected between 70 cm and just below 100 cm.

Anny Cazenave, the author of this edition of *Spatium*, is an expert in the field of geophysics and in particular in space geodesy. She has pioneered the use of satellite-borne instrumentation to investigate the Earth's mantle and crust and very early on developed methods to compute ocean topography using satellite altimetry. In a fascinating talk within the ISSI lecture series on 30th October 2019, she shared her recent results on sea level rise and its role within climate research.

Anuschka Pauluhn
Mönthal, September 2020

Impressum

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Association Pro ISSI
Hallerstrasse 6, CH-3012 Bern
Phone +41 (0)31 631 48 96
see
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for the whole *Spatium* series

President
Prof. Dr. Adrian Jäggi,
University of Bern

Editor
Dr. Anuschka Pauluhn
CH-5237 Mönthal

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Title Caption
Artist's impression of the Jason-3 satellite ("Joint Altimetry Satellite Oceanography Network 3") which is a collaboration project of several European and US American partners (EUMETSAT, CNES, NASA, NOAA). Its mission is to supply data for scientific, commercial, and practical applications to sea level rise, sea surface temperature, ocean circulation, and climate change.

Climate Change and Sea Level Rise

Anny Cazenave, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France and ISSI, Bern, Switzerland

1. Introduction

Planet Earth is currently in a state of energy imbalance: it reemits less energy into space than it receives from the Sun. This energy imbalance is estimated to be around 1 W/m^2, a small quantity compared to the 342 W/m^2 received from the Sun[1], but significant enough to cause important changes to the global climate. The cause of this energy imbalance is well known and attributed to so-called greenhouse gases (GHG), mostly carbon dioxide (CO_2), emitted by human activities as a result of fossil fuel combustion and of land use change, mostly deforestation. GHG absorb part of the infrared radiation re-emitted by the Earth causing an additional heating effect that superimposes on the natural greenhouse effect. **Figure 1** and **Figure 2** show the global GHG emissions since 1960 and the emissions by regions.

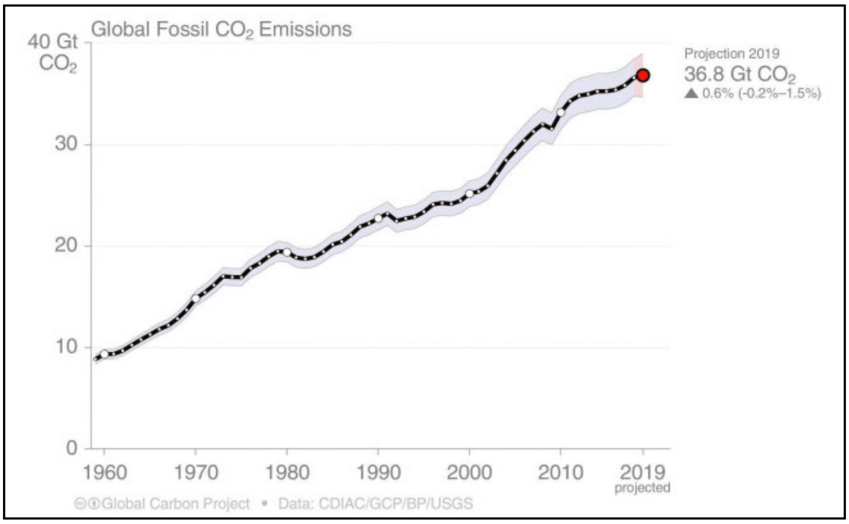
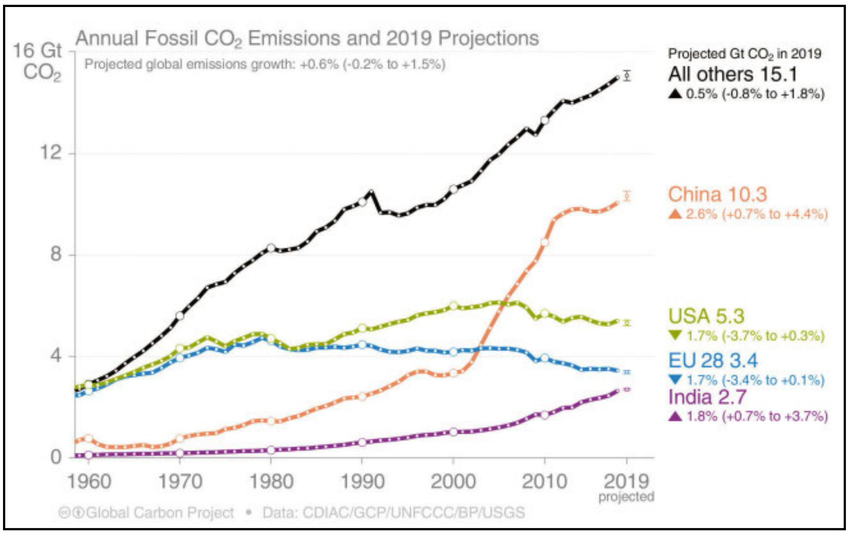


Figure 1: Total GHG emissions (in Gt/year equivalent CO_2) since 1960 (source: The Global Carbon Budget project, 2019).

Over the decade 2009 to 2018, emissions in CO_2 equivalent from fossil fuels and deforestation amount to 37.5 and 5.5 Gt/year, respectively. Only 44 % have stayed in the atmosphere because of two important sinks: the vegetation and the oceans that absorbed 29 % and 23 % of emitted CO_2, respectively. However, a negative side effect of the ocean sink is acidification of sea water, with potentially disastrous consequences on marine life and entire marine ecosystems. The CO_2 concentration in the atmosphere reached 410 ppm (parts per million) in 2019, a value 40 % higher than the highest concentrations encountered by planet Earth during the last 800 000 years.

Figure 2: GHG emissions (in Gt/year equivalent CO_2) per region since 1960 (source: The Global Carbon Budget project, 2019).



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[1] Of the 342 W/m^2 of solar radiation received on average by the Earth, about 30 % is directly reflected back to space by the atmosphere and the surface, in particular Arctic sea ice, leaving approximately 240 W/m^2 of solar energy available for warming the atmosphere, land surfaces and the oceans.

The ocean has the largest heat capacity (and thus thermal inertia) of all compartments of the climate system. Over the past 50 years, about 93 % of the energy excess due to human activities has been stored as heat in the ocean. The remaining 7 % have been equally shared to warm the atmosphere and the continents, and to melt sea ice and land ice.

Figure 3 shows the evolution of the global mean Earth temperature since 1850. The last decade (2010 to 2019) has been the warmest since the beginning of the record.

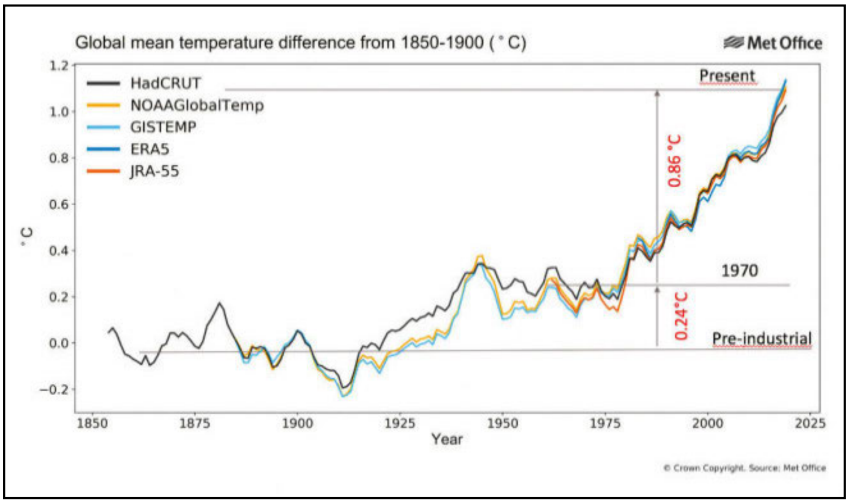

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Figure 3: Evolution of the Earth's global mean temperature since 1850 (source: WMO "State of the global climate 2019").

Warming of the ocean and melting of land ice (glaciers, and Greenland and Antarctica ice sheets) have another consequence: sea level rise.

During the Earth's history, sea level has varied over a broad range of temporal scales. On geological timescales (about 5 to 100 million years) large-amplitude (> 100 m) sea level changes primarily resulted from tectonics processes (e.g. large-scale change in the shape of ocean basins associated with seafloor spreading and mid-ocean ridges expanding). Growth and decay of polar ice sheets during the Quaternary glacial ages, driven by changes of the Earth's obliquity and orbit around the Sun, in particular its eccentricity, have also caused sea level variations of approximately one hundred metres. Other natural factors, e.g. change in solar irradiance and volcanic eruptions, can cause sea level fluctuations of a metre or less. Internal climate variability (e.g. related to El Niño events) is responsible for small sea level variations on interannual and decadal timescales (see below). Over the last few decades, sea level has also displayed a long-term increase caused by human-induced global warming. In the following, we essentially discuss the latter two effects.

El Niño: Span. for "the child" is the name given to a climate phenomenon observed mainly in the Pacific Ocean. In fact, the El Niño/Southern Oscillation (ENSO) cycle has causes and consequences on a rather global scale. It is a rather irregularly appearing, however quasi-periodic, variation (observed to happen on timescales between two and seven years) in winds and sea surface temperatures affecting much of the tropics and subtropics in the Pacific Ocean. The El Niño phase of the ENSO cycle corresponds to a mass of warm water transported from the western tropical Pacific Ocean eastward, superposing the cold nutrient-rich upwelling water along the South American west coast. The cooling phase of the cycle subsequent to El Niño is referred to as "La Niña". The warm phase is accompanied by high air surface pressure in the western Pacific and low pressure in the eastern Pacific and vice versa for the cold phase. Extreme events of this climate pattern can have strong effects on the weather, such as floods and droughts, in central and south America, as well as in other regions of the world. Developing countries dependent upon agriculture and fishing, particularly those bordering the Pacific Ocean, are the most affected. Mechanisms that cause this coupled atmosphere-ocean oscillation remain under study.

2. Measuring sea level changes

2.1 Tide gauges

On paleo timescales, spanning the last two millennia, sea level change is known indirectly from proxy indicators, such as records from sediments on the ocean floor, uplifted marine terraces or ancient corals.

More recent (i.e. roughly since the beginning of the 20th century) data on sea level variations have come from direct in-situ measurements by tide gauges, instruments located along continental coastlines and islands. Prior to the beginning of the 20th century, data are very sparse and based only on a few long records at sites mostly located in Western Europe. The largest tide gauge database of monthly and annual mean sea level records is the Permanent Service for Mean Sea Level (PSMSL, www.psmsl.org) which contains data for the 20th century from roughly 2000 sites. However, these records are often inhomogeneous in terms of data length and quality. For long-term sea level studies, only about 10% of this data set is usable (see **Figure 4**), due to data gaps and limited tide gauge distribution in the past.

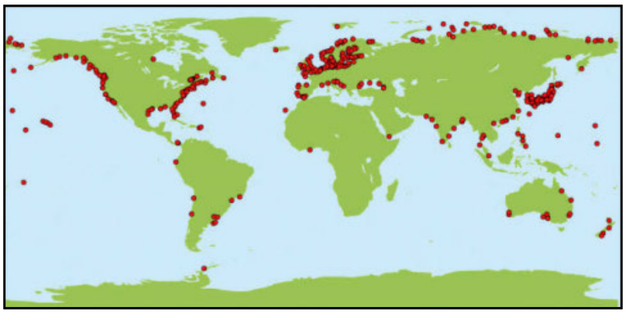

Figure 4: Tide gauge network (from the PSMSL) with more than 40-years of sea level records.

Tide gauges measure sea level relative to the ground, and as they are attached to the coast, thus also register the vertical ground motions, in addition to the climate-related sea level change. These vertical ground motions can result from a variety of factors caused by tectonic and volcanic processes, as well as other natural factors (e.g. sediment loading in river deltas) or human activities (ground water pumping and oil/gas extraction) causing ground subsidence. Post-glacial rebound, the viscoelastic response of the Earth's crust and mantle to the last deglaciation, also called "Glacial Isostatic Adjustment" (GIA) is another process that gives rise to vertical land movements.[2]

After the approximately 130 m sea level rise associated with the last deglaciation that started about 20000 years ago, geological, geochemical and archeological observations indicate that the mean sea level remained almost stable during the last two to three millennia, then started to rise about two centuries ago. A large number of studies have analysed tide gauge data from the PSMSL to provide a historical mean sea level time series. The most recent ones report a mean sea level increase of 15 cm over the 20th century, however with a large range of different values (from 12 cm to 19 cm). This large uncertainty results from many factors, e.g. uneven and restricted distribution of tide gauges, treatment of data gaps in the records, geographical averaging procedure, impact of vertical crustal motions and methods to correct them.

2.2 Satellite altimetry

Since the early 1990s, satellite altimetry has become the main tool for precisely and continuously measuring sea level with quasi-global coverage and a few days

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[2] During the last glacial period about 20000 years ago much of northern Europe, Asia, North America, Greenland and Antarctica was covered by ice sheets of up to three kilometres thickness during the glacial maximum. The enormous weight of this ice caused the surface of the Earth's crust to deform and warp downward, forcing the viscoelastic mantle material to flow away from the loaded region. When the glaciers retreated, the removal of this weight led to slow (and still ongoing) uplift or rebound of the land and the return flow of mantle material back under the deglaciated area. Due to the extreme viscosity of the mantle, it will take many thousands of years for the land to reach an equilibrium level.

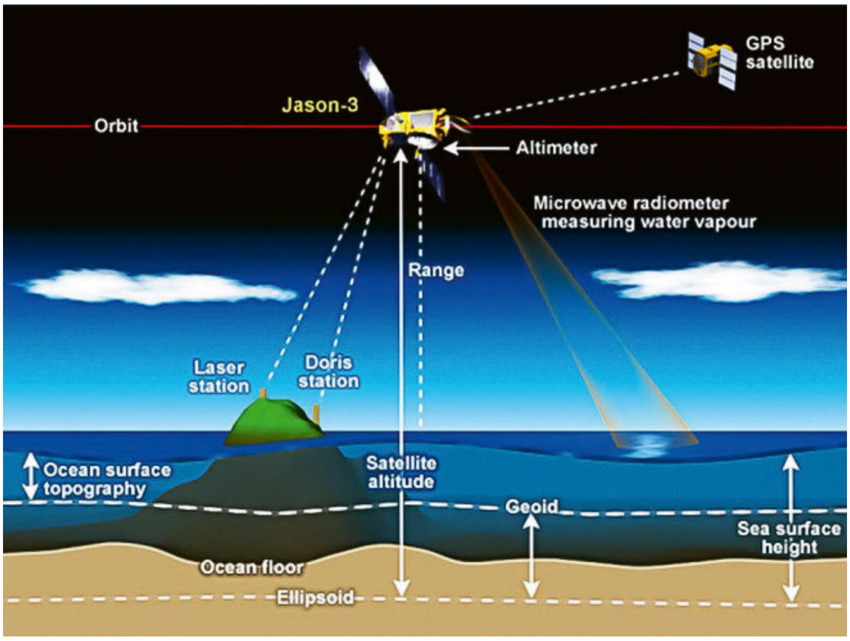

Figure 5: The principle of nadir satellite altimetry.

revisit time (called the "orbital cycle"). Compared to tide gauges that provide sea level relative to the ground, satellite altimetry measures "absolute" sea level variations. The concept of the satellite altimetry measurement is simple (see **Figure 5**): the on-board radar altimeter transmits microwave radiation towards the sea surface, which partly reflects back to the satellite. Measurement of the round-trip travel time of the signal provides the height of the satellite above the sea surface (called "range"). The quantity of interest in oceanography and sea level studies is the sea surface height above a fixed surface as a reference (typically a conventional reference ellipsoid or a mean sea surface). It is obtained by the difference between the height of the satellite above the reference (deduced from precise orbitography[3]) and the range measurement. A description of the reference surfaces like the geoid can be found for example in *Spatium* 31 (Earth Gravity from Space by R. Rummel).

Every single measurement of the signal travel time and thus the height needs to be corrected for various factors, such as atmospheric (ionospheric and tropospheric) delays generated by varying electron content and by the amount of water and dry gases in the atmosphere. Other corrections due to geophysical effects, such as the sea state bias (the sea is seldom calm), and the tides of the solid Earth and the ocean are applied as well. The final result of a coherent time series of the sea surface height has to take instrumental drifts and bias between successive altimetry missions into account.

High-precision satellite altimetry started in 1991 and 1992 with the launch of ERS-1 by the European Space Agency (ESA), and of the joint NASA (National Aeronautics and Space Administration) – CNES (Centre National d'Etudes Spatiales) satellite Topex/Poseidon (T/P), respectively. Since then, several high-precision altimetry missions have followed: Jason-1 (2001), Jason-2 (2008) and Jason-3 (2016), the successors of T/P with similar orbital characteristics. ESA also developed ERS-2 (1995), Envisat (2002), CryoSat (2010) and Sentinel-3A/3B (2016/2018). Cryosat and Sentinel-3A use new technology, i.e. Synthetic Aperture Radar (SAR) altimetry.[4] The Sentinel-3 missions contribute to the COPERNICUS operational programme of the European Union. SARAL/AltiKa (2013), a joint Indian-French mission, operates in the Ka-band (≈ 35 GHz), allowing a smaller radar footprint on the ground than other missions (T/P, the Jason series, ERS and Envisat being equipped with Ku-

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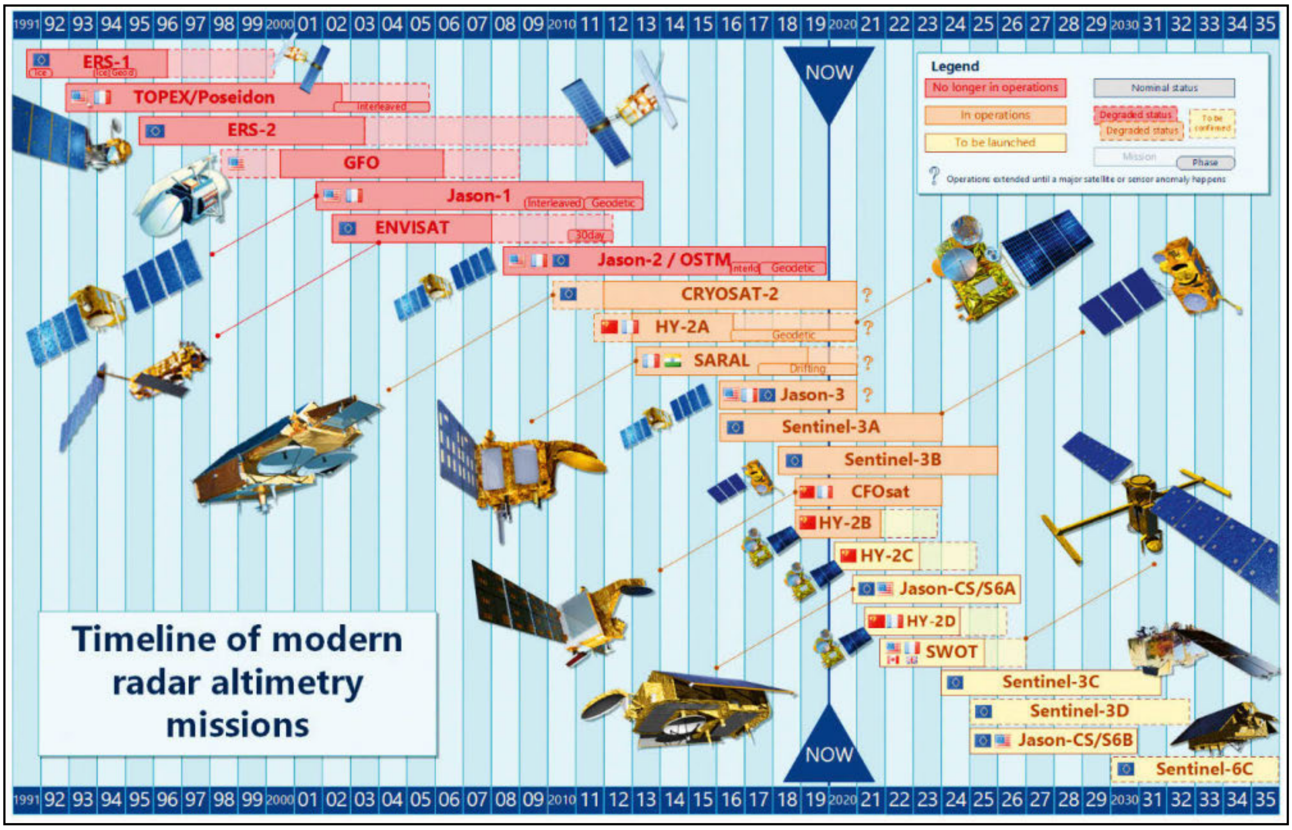
[3] Also called Precise Orbit Determination, POD. The determination of precise satellite orbits by means of geodesy techniques like GNSS (Global Navigation Satellite Systems, e.g., GPS, GLONASS or Galileo), DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite, where ground-based radio beacons emit signals that are received by the monitored satellite), or Satellite Laser Ranging.

[4] In the Synthetic Aperture or delay-Doppler processing method, additionally the Doppler shifts of the return echo of the radar signal from a little in front and behind of the nadir point are recorded. This enhances the resolution.

Figure 6: Constellation of modern radar altimetry missions.



band (13 GHz to 17 GHz) radars). A wide-swath interferometric altimetry mission (SWOT- Surface Waters Ocean Topography) able to study the mesoscale ocean circulation is currently being developed by NASA and CNES for a launch in 2022. Altimeter satellites have also been launched by the Chinese Space Agency (HY2A and HY2B). The T/P and Jason series have an orbital cycle of 10 days but a large spacing between satellite tracks (roughly 300 km at the equator). They cover the 66°S to 66°N latitude domain. The orbital cycle of the ESA missions and SARAL/AltiKa is 35 days, but the spacing between tracks is smaller and the latitudinal coverage reaches up to 82°, allowing a large portion of the Arctic Ocean to be covered.

Figure 7: Geographical coverage of satellite altimetry missions.

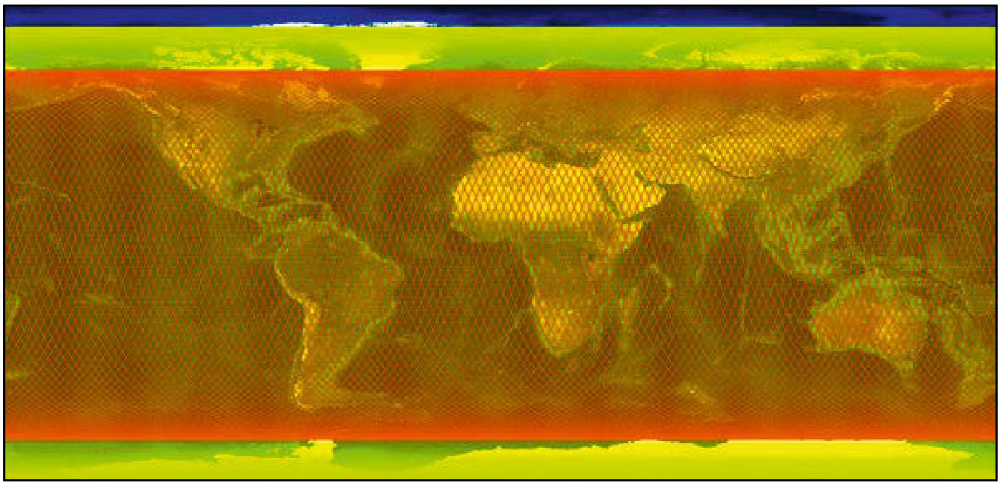


Figure 6 shows the status of the constellation of high-precision altim-

eter satellites while **Figure 7** shows the geographical coverage of the altimetry missions.

In altimetry, the global mean sea level (GMSL) is estimated by geographically averaging all sea surface height measurements performed by the satellite during an orbital cycle. The GMSL evolution is deduced from successive orbital cycles. During the past 27 years, at least two altimeter satellites have been operating simultaneously, and during some periods, even more than two. Such data are combined to compute the GMSL change over time. This is shown in **Figure 8**.

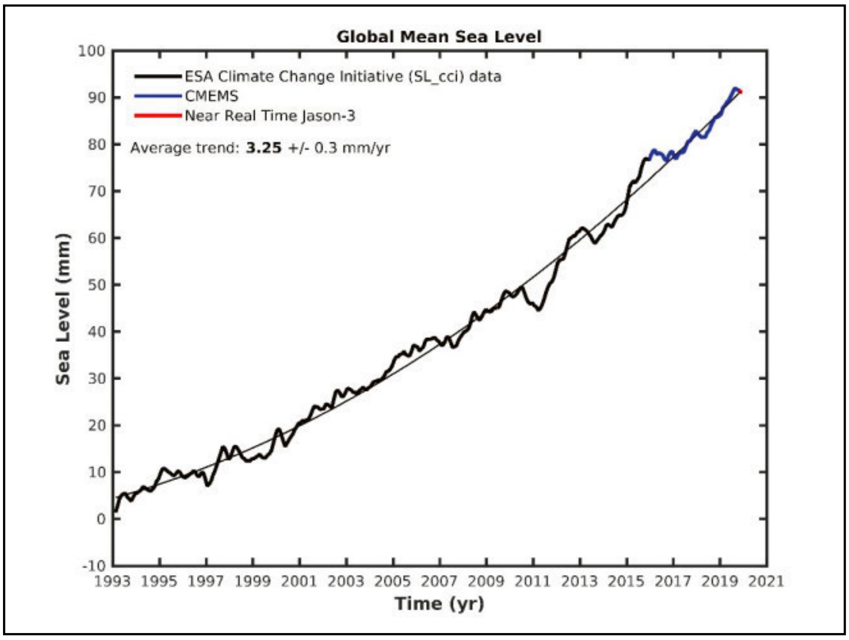
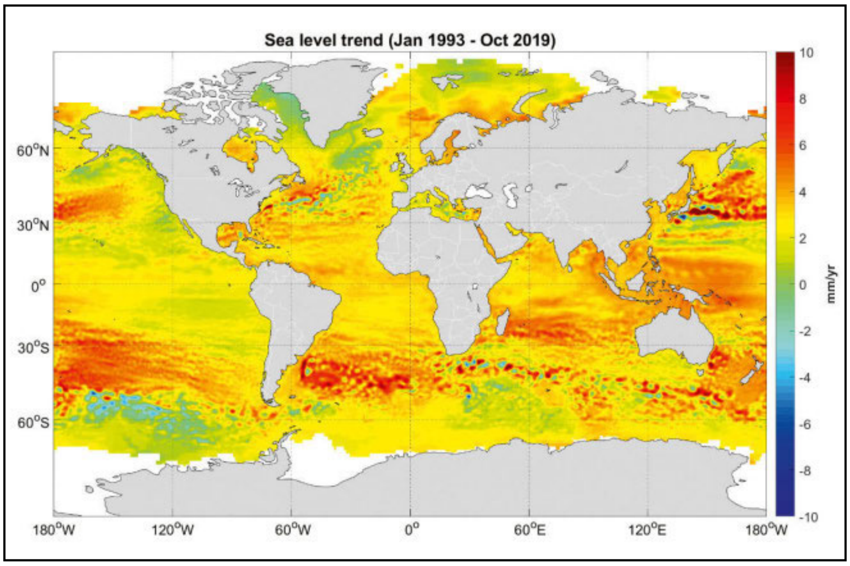


Figure 8: Evolution of the global mean sea level from January 1993 to May 2020 based on satellite altimetry data (source: LEGOS).

The curve shown in **Figure 8** shows that the GMSL is rising and that the rise is even accelerating. Over the period 1993 to 2020, the mean rate of rise is (3.25 +/- 0.3) mm/year. The acceleration is estimated to 0.1 mm/year^2. The precision of a single sea surface height measurement has now reached the 1 cm to 2 cm level allowing the precision of the mean rate of rise to reach about 0.3 mm/year. This level of precision is also confirmed by comparison with tide gauges and assessments of all sources of errors affecting the altimetry system.

Figure 9: Regional trends in sea level over 1993 to 2019 from satellite altimetry (source: LEGOS).



Owing to its quasi-global coverage of the oceans, satellite altimetry also allows mapping of sea level change on a regional scale. This is shown in **Figure 9**. In some regions, sea level trends are two to three times larger than the global mean rise. This is particularly clear in the northern and western tropical Pacific, as well as in the southern ocean.

3. Understanding sea level change

3.1 Causes of present-day global mean sea level rise

In terms of global mean, sea level change mostly results from ocean thermal expansion and ocean mass increase due to melting of glaciers and ice mass loss from the Greenland and Antarctica ice sheets. A small contribution comes from changes in land water storage and atmospheric water content. As the oceans warm in response to anthropogenic forcing, sea waters expand, thus sea level rises. When mountain glaciers melt in response to increasing air temperature, sea level rises because of fresh water mass input into the oceans. Similarly, ice mass loss from the ice sheets causes sea level rise. Modification of the land hydrological cycle and associated land water storage due to combined natural and man-made climate variability and change also lead to sea level change.

Ocean warming

Since the middle of the 20th century, in-situ ocean temperature (and to a lesser extent salinity) data has been collected by various devices, e. g. expendable bathythermographs (XBT) from ships, buoys and moorings, and since the beginning of the 21st century by the automatic profiling floats from the Argo system[5]. During the 1990s, temperature measurements of the upper ocean were collected down to a depth of about 700 m along commercial shipping routes. Although the coverage was improved compared to the previous decades, large regions remain un-sampled, in particular in the southern hemisphere and in the Arctic. Besides, salinity measurements were very few. The Argo project has totally revolutionized the situation, with its 4000 automatic floats providing systematic temperature and salinity measurements down to a depth of 2000 m at 10 day intervals, with quasi global coverage (though not yet over the Arctic Ocean). Full deployment of the Argo floats was effective in around 2005. **Figure 10** shows the Argo floats coverage at the time of writing.

The ocean temperature data collected over a few decades have clearly shown that the oceans are warming, as illustrated in **Figure 11** by the ocean heat content increase.

Figure 10: Argo floats coverage.

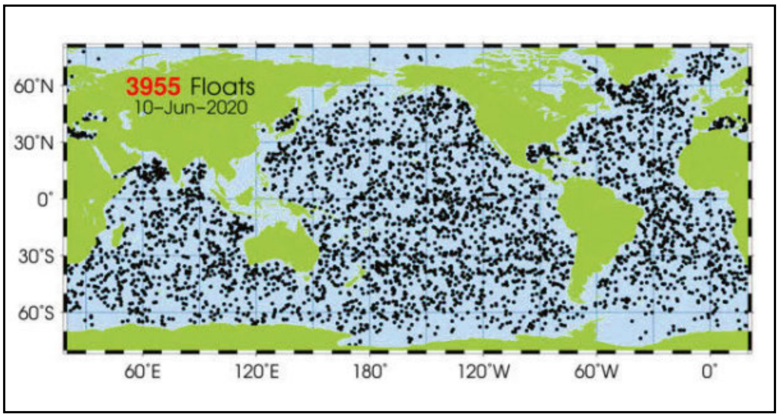
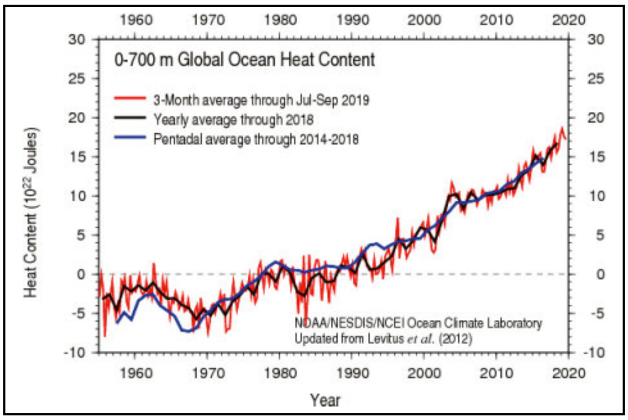


Figure 11: Ocean heat content since 1955 (source: WMO State of the global climate 2019).



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[5] Argo is an international programme that uses profiling floats to measure temperature, salinity, surface currents, and, recently, bio-optical properties in the Earth's oceans. The fleet consists of about 4000 drifting floats deployed worldwide.

The main land ice contributions to sea level come from glacier melting and ice mass loss from the Greenland and Antarctica ice sheets.

Ice sheets

If totally melted, Greenland and West Antarctica (the unstable part of the continent) would raise sea level by about 7 m and 5 m, respectively. Clearly, even a small amount of ice mass loss from the ice sheets can produce substantial sea level rise, with adverse impacts on vulnerable low-lying coastal regions.

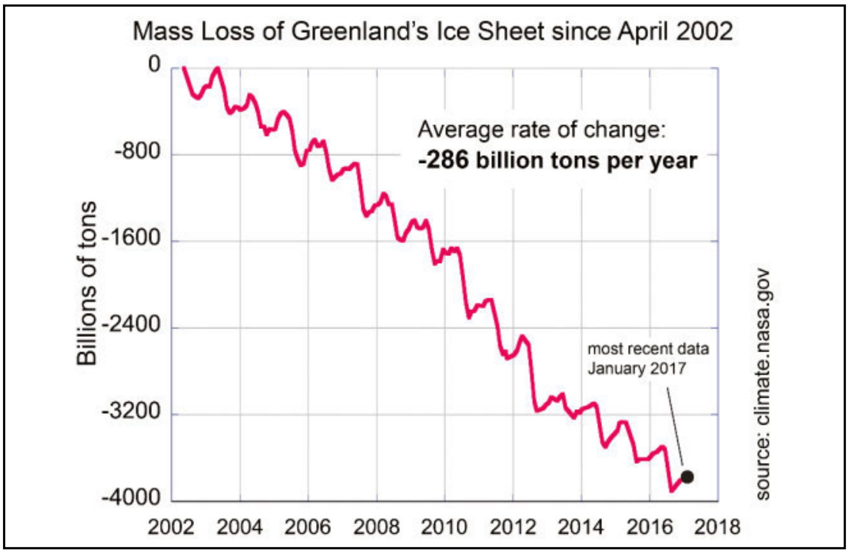


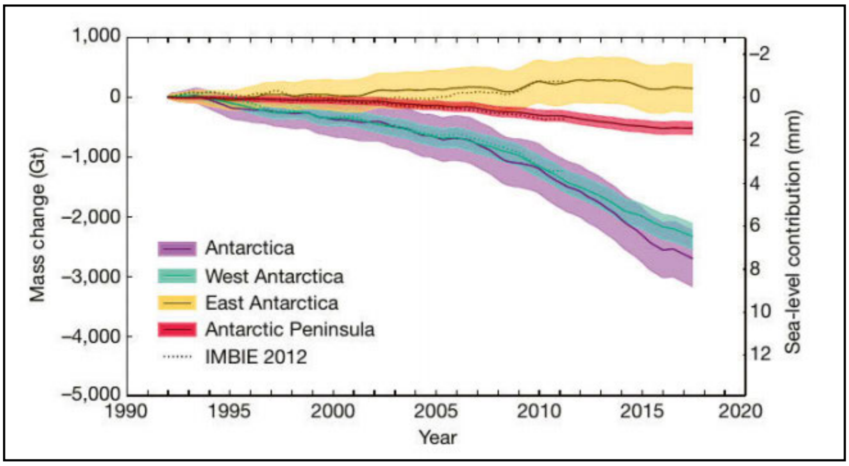
Figure 12: Ice mass loss from the Greenland ice sheet (source: NASA).

Since the early 1990s, different remote sensing observations have provided important observations of the mass balance of the ice sheets. These include airborne, satellite-based laser and radar altimetry, synthetic aperture radar interferometry –InSAR, and since 2002, space gravimetry from GRACE (gravity recovery and climate experiment).

GRACE is a space mission developed by NASA and the German Space Agency. It consists of two twin satellites flying on the same orbit and measuring their mutual distance using a microwave device with 1 micrometre accuracy (cf. also *Spatium* 31).

The first GRACE mission covered the period 2002 to 2017. A GRACE follow-on mission with similar characteristics was launched in 2018. GRACE measures temporal changes of the Earth's gravity field with a ground resolution of approximately 300 km at monthly intervals. On timescales from a few months to several years/decades, changes in the gravity field mostly result from mass redistributions in the Earth surface fluid envelopes related to changes of land hydrology and of the cryosphere. However, GRACE also measures solid Earth processes such as earthquake-related crustal deformations and post-glacial rebound, the so-called GIA described before. Over Greenland and Antarctica, GRACE directly provides the changes of mass of the ice sheets. This is illustrated in **Figure 12** and **Figure 13**, showing that Greenland and West Antarctica are losing mass at an accelerated rate.

Figure 13: Ice mass loss from the Antarctica ice sheet (credit: IMBIE 2 Project).



It is now well established that the recent ice sheet mass loss partly results from accelerated glacier flow along some coastal margins of the ice sheets and further iceberg discharge into the surrounding ocean. This results from short-term dynamical instabilities occurring in regions where coastal glaciers are grounded below sea level (this is especially the case in West Antarctica). Thinning and subsequent break-up of floating ice tongues or ice shelves that buttressed the glaciers result in rapid grounding-line retreat and accelerated glacier flow. Several recent observations have shown that warming of subsurface ocean waters triggers these dynamical instabilities. For Antarctica, this process explains almost all ice mass loss, while for Greenland it only accounts for about half, the other half being due to surface melting.

Glaciers

Being very sensitive to global warming, mountain glaciers and small ice caps have retreated worldwide during the 20th century, with significant acceleration since the early 1990s. Volume and mass balance studies of a significant number of glaciers, based on various in-situ observing methods and modelling, have been proposed, and estimates of the contribution of glacier melt to sea level rise have been deduced. Because of high year-to-year variability in glacier melting, in-situ based mass balances are generally provided as 5-year averages, a strong limitation when the period of investigation is short. For a few years, remote sensing techniques have also been used to estimate glacier mass changes.

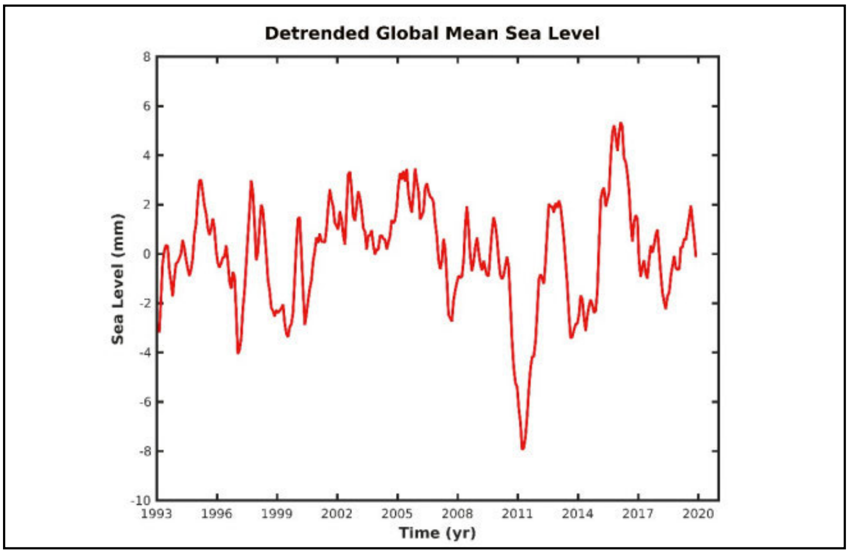
Terrestrial waters

Change in land water storage due to natural climate variability has contributed little to the GMSL long-term trend during the past few decades. On the other hand, on an interannual timescale, in particular during ENSO (El Niño-Southern Oscillation) events, fluctuations in water storage on land cause temporary anomalies of the global mean sea level of several millimetres (**Figure 14**).

During an El Niño or a La Niña event, the GMSL presents positive or negative anomalies of one to two years duration due to an excess or deficit of precipitation over the tropical Pacific (causing an increase or decrease of ocean mass). Because the atmospheric reservoir cannot contain an important amount of water mass over a multi-year timescale, change in ocean mass is nearly compensated by change in land water storage in tropical river basins and vice versa.

Human activities (i. e. anthropogenic changes in the amount of water stored in soils, reservoirs and aquifers as a result of dam building along rivers, underground water mining, irrigation, urbanisation, deforestation, etc.) represent another potential contribution of terrestrial waters to sea level change. The dominant contributions come from two factors of opposite sign: dam building, causing sea level drop, and ground water depletion, causing sea level rise. For the last few decades, ground water pumping has considerably increased while the building of

Figure 14: Detrended global mean sea level. The largest anomalies are driven by ENSO events. This is the case for the large negative anomaly in 2011 due to a La Niña event (source: LEGOS).



dams has decreased, so that there is a net slightly positive effect on the global mean sea level. Its exact contribution, however, remains highly uncertain.

3.2 The sea level budget

A large number of studies have tried to close the sea level budget, i. e. to compare the observed rate of sea level rise with the sum of contributions estimated independently. Studying closure (or non-closure) of the sea level budget is important as it provides constraints on missing or poorly-known contributions such as the deep ocean under-sampled by current observing systems, or still uncertain changes in water storage on land due to human activities (e. g. groundwater depletion in aquifers). Global mean sea level corrected for ocean mass change allows independent estimates of changes in total ocean heat content over time, from which the Earth's energy imbalance can be deduced.

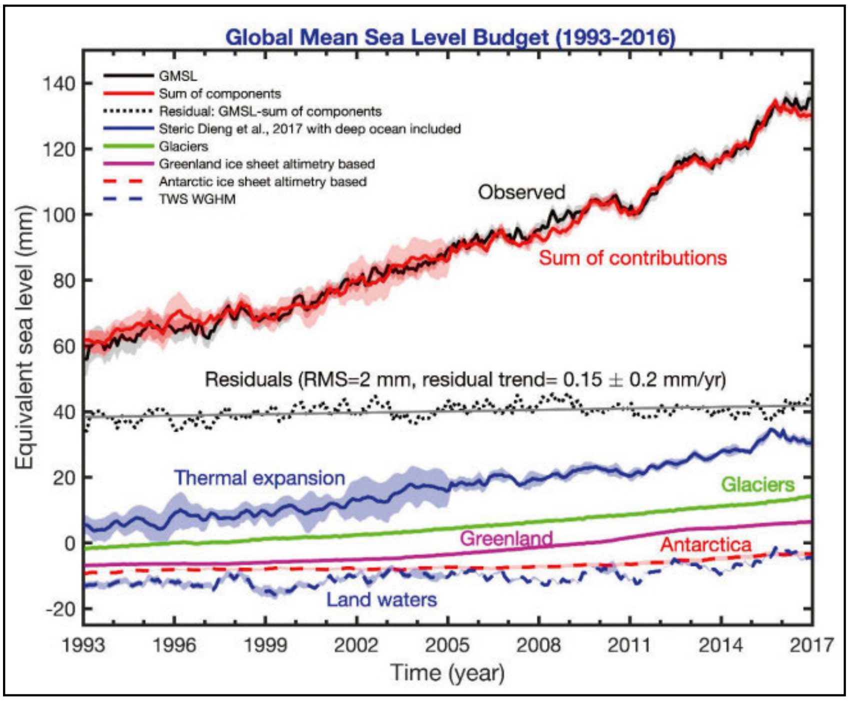
Figure 15 shows time series of individual components contributing to the GMSL as well as the sum of the components compared to the observed global mean sea level from 1993 to present. It is obvious that the sea level budget is almost closed over the study period within the respective uncertainties. Annual residuals remain below the 2 mm level. In terms of trends, the sea level budget since 2005 is closed to better than 0.3 mm/year, an order of magnitude similar to the uncertainty of the mean sea level rise. Quasi closure of the budget over the altimetry era suggests that any non-assessed component (i. e. deep ocean heat content below 2000 m) does not yet significantly contribute to the GMSL rise. Besides, this indicates that no systematic errors affect the different observing systems used to quantify the components of the sea level budget.

3.3 Regional scale

The regional variability in sea level trends is mainly due to large-scale changes in temperature and salinity-related density structure of the oceans, in response to forcing factors (e. g. heat and fresh water exchange at the sea-air interface and wind stress) and their interaction with the ocean circulation. Increase in wind stress and associated deepening of the thermocline explain the strong sea level trends observed in the western tropical Pacific during the altimetry era. This is illustrated by **Figure 16** which compares spatial trend patterns in altimetry-based observations **(left panel)** and thermal expansion **(right panel)** during the period 1993 to 2015 over the western tropical Pacific (global mean trend removed in both cases). Altimetry-based sea level and thermal expansion trends show very good agreement.

While in most regions regional changes in sea level trends essentially result from ocean tempera-

Figure 15: Sea level budget from 1993 to 2016. The individual contributions are shown at the bottom of the panel. The altimetry-based sea level and sum of contributions are shown by the black and red curves, respectively (source: ESA Sea Level Budget Closure Project 2019).



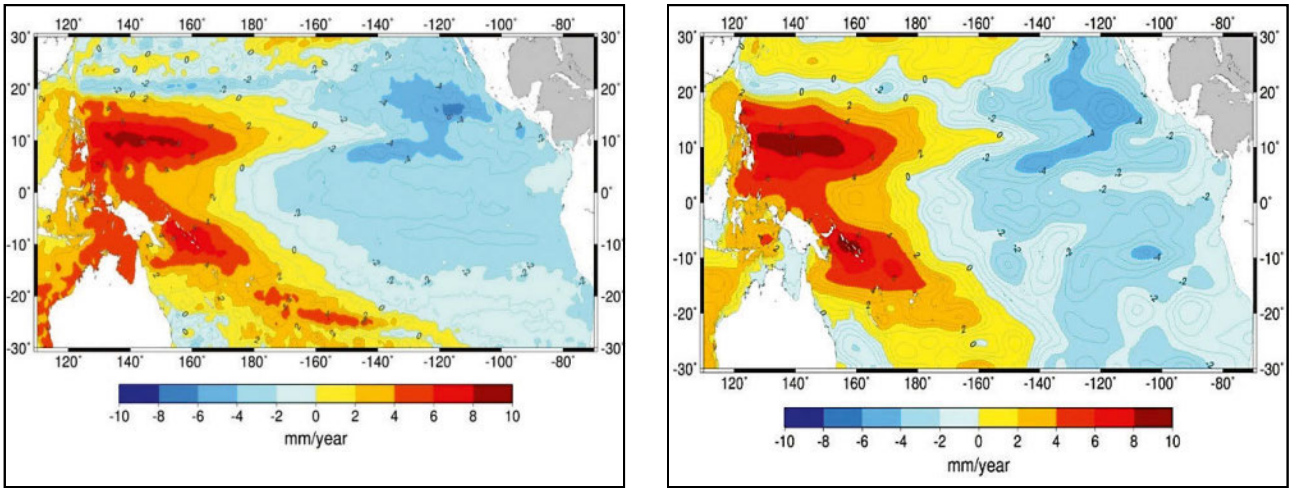


Figure 16: Spatial trend patterns in sea level over 1993-2015. **Left panel:** from altimetry; **right panel:** from thermal expansion (thermal expansion is estimated by vertically integrating in-situ temperature data from depth to the surface).

ture change, in a few others (e.g. in the Arctic) the change in salinity can also be important.

In addition to changes in sea water density due to changes in temperature and salinity, other processes can cause regional trends in sea level, e.g. atmospheric loading,[6] and solid Earth deformations and associated gravitational changes in response to mass redistributions caused by land ice melt and land water storage changes. The land ice melt related factor has two components: one associated with the last deglaciation (the GIA phenomenon), and the other due to on-going land ice melt. These factors – mostly known from modelling – give rise to complex regional patterns in sea level change (often called "fingerprints"): sea level drop in the immediate vicinity of the melting bodies but sea level rise in the far field (e.g., along the North East coast of America and in the tropics). The GIA effect depends on Earth's mantle viscosity and deglaciation history while the response of the solid Earth to on-going land ice melt essentially depends on lithosphere elasticity as well as on the amount and location of the current ice mass loss. Regional effects of both GIA and present-day ice melting are small compared to ocean thermal expansion and still hardly detectable in the satellite altimetry observations.

4. Changes and impacts in coastal regions

At local scales, in particular in coastal areas, additional small-scale processes superimpose on the global mean and regional sea level components and can make coastal sea level substantially different from open-ocean sea level rise. For example, changes in small-scale currents, as well as freshwater input in river estuaries, can modify the density structure of sea waters, hence the coastal sea level. Changes in wind, waves, shelf bathymetry, along-shore and cross-shore sediment transport, vertical land motions, land use change, and urbanisation are additional forcing factors able to modify sea level variations in the coastal zone. Unlike global mean and regional sea level measured by satellite altimetry

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[6] Changes of the weight of the column of atmosphere due to variations of pressure result in vertical changes of the sea surface.

missions, coastal sea level changes remain poorly known. Coastal zones are indeed highly undersampled by tide gauges and currently un-surveyed (within 15 kilometres of the coast) by conventional altimetry missions because of land contamination on the radar signal. However, dedicated reprocessing of the data from these missions now helps to estimate sea level change very close to the coast. In the near future, systematic use of new SAR technology implemented in recent ESA missions (e.g. CryoSat-2 and Sentinel-3A/B) will also allow estimating of sea level changes in the coastal areas.

Sea level rise is generally considered as a major threat of current global warming for the world's low-lying coastal regions. Coastal zones are indeed the most densely populated and economically active areas of the world. They concentrate important infrastructures such as harbours and industries. Today, about 600 million people live near the sea, at an altitude less than 10 m above sea level and mostly concentrated in several of the world's largest megacities. This number is expected to double by 2060.

Compared to extreme events, sea level rise is a slow process but it has long-term consequences. Adverse effects of sea level rise in coastal areas include permanent and temporary inundation, shoreline erosion, increased flooding during storm surges, salinisation of wetlands and aquifers, and loss of coastal ecosystems.

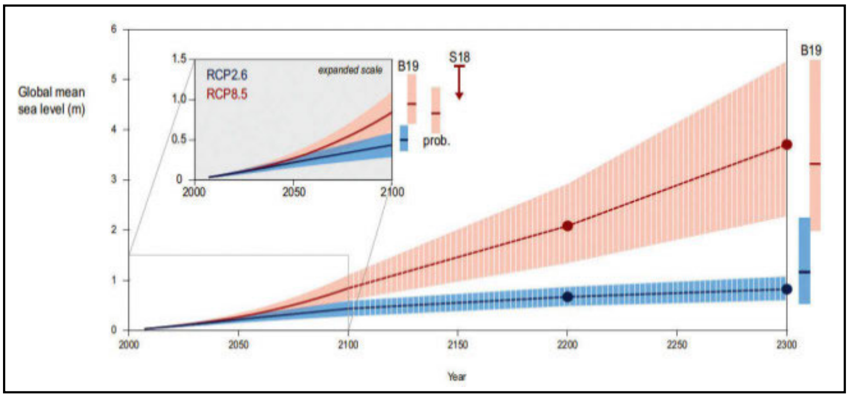
At the coast, in addition to climate-related sea level rise, another non climatic factor is vertical ground motion. Withdrawal of water from aquifers can produce dramatic ground subsidence, and hence relative sea level rise, especially in coastal megacities. During the second half of the 20th century, Tokyo, Shanghai, Bangkok and Jakarta subsided by several meters because of groundwater withdrawal. Ground subsidence is also widely observed in highly-populated deltaic areas, in particular in Asia. Ground subsidence amplifies the climate-related sea level rise and its negative impacts.

It is now well established that at a local scale, the coastal response to sea level rise depends on several non-linearly-related factors such as coastal morphology, near-shore bathymetry, sediment supply from rivers, changing waves and currents, etc. For the 20th century, shoreline erosion and retreat mostly resulted from multiple drivers, in particular extreme events like winter storms and urbanisation. By the end of the 21st century and beyond, however, the expected sea level rise will make it the dominant forcing factor of future coastal system changes.

5. Future changes

In the recently published (September 2019) special report on the oceans and the cryosphere (SROCC) from the Intergovernmental Panel on Climate Change (IPCC), projections of future sea level rise based on ensemble means of process-based climate models indicate that at the end of the 21st century, global mean sea level would have increased relative to today by 40 cm to 85 cm, depending on the radiative forcing scenario (**Figure 17**). The moderate forecast of 40 cm corresponds to a climate scenario that fulfills the

Figure 17: Projections of the global mean sea level rise (in m) until 2100 and 2300 for two global warming scenarios expressed in terms of representative concentration pathways (RCP). (Source: SCROCC, IPCC, 2019).



2015 Paris Agreement, i.e. a 2 °C target for the global mean Earth temperature in 2100 (compared to pre-industrial). This scenario would require drastic reductions of GHG emissions in the coming two to three decades and zero emission around 2070. The forecast of 85 cm corresponds to a high warming scenario, more or less pursued by the current GHG emissions. In this scenario, a global mean sea level elevation of +1 m compared to the year 2000 is not excluded.

In the high warming scenario (RCP 8.5), ocean warming, glaciers melting, and Greenland and Antarctica ice sheet mass loss would contribute by about 37 %, 23 %, 18 % and 17 %, respectively, the remaining 5 % being attributed to land water storage change. Summing the contributions of glaciers and ice sheets shows that land ice melt would contribute with nearly 60 %. Recent model calculations suggested the existence of a new type of ice-sheet instability in Antarctica (as yet unobserved), which would lead to approximately 1 m of global mean sea level rise by 2100 for Antarctica alone. But such a possibility is still controversial.

In addition, as is already the case today, future sea level rise will not be uniform, deviation from the global mean being expected in several oceanic regions, in particular in the tropics where an amplification of the global mean rise of 20 % to 30 % is expected.

6. Conclusion

Today, sea level rise is one of the best indicators of climate change. This is due to the fact that it integrates changes occurring in the Earth's climate system in response to system-inherent climate variability, as well as external forcing factors of natural and anthropogenic origin. These changes include ocean warming, land ice melt, and changes in water storage in continental river basins.

Measuring sea level rise and understanding its causes has considerably improved in the recent years, essentially because new in-situ and remote sensing observations have become available. Sea level is presently rising at a sustained rate of more than 3 mm/year and its rise is accelerating. These observations are of major importance for process understanding and validation of climate models developed to forecast future changes. It is indeed almost certain that sea level rise will continue in the future decades and centuries because of expected continuing global warming, thereby affecting a large number of world coastal regions. Sustained observations of sea level changes, as well as observations of the various factors that cause these changes, are of high priority in climate change research in order to provide improved sea level predictions from global to local scales. In the coastal zones, sea level observations and predictions will provide invaluable information to decision-makers in charge of developing adaptation and mitigation strategies to face environmental risks associated with climate change and human activities.

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SPATIUM

The Author

Anny Cazenave received her Ph.D. in geophysics in 1975 from the University of Toulouse. Subsequently, working at the French space agency CNES, she went into space geodesy, the use of satellites to track changes in Earth's surface, gravity field and orientation in space. She first focused on the dynamics of the oceanic crust and the mechanically strong layer of the uppermost mantle below it. Among other things, she used early spaceborne radars to show that the ocean surface is not flat, but follows the topography of the ocean floor. In other early work, she addressed questions about the rotation of Venus and the origins of the Mars moons, Phobos and Deimos.

Towards the end of last century, European and American space agencies launched a new series of satellite radar altimeters capable of monitoring sea level everywhere in the world oceans in more or less real time. By the early part of the 21st century, it had been determined that global sea level was rising by at least about three millimetres a year. As one of the leading scientists in the joint French/American satellite altimetry missions, TOPEX/Poseidon, Jason-1, and the Ocean Surface Topography Mission, Anny has contributed to a greater understanding of this sea level rise and its dependence on global warming.

Besides a large number of publications, Anny was lead author of the sea level sections of the Intergovernmental Panel on Climate Change's most recent full reports, in 2007 and 2014.

Since 2013, she has been director of Earth sciences at the International Space Science Institute.

In 2020, she received the prestigious Vetlesen Prize, often referred to as the Nobel Prize in geophysics, for her pioneering work in using satellite data to chart and quantify rises in the surface of the oceans, and related changes in ice sheets, landmasses and freshwater bodies.