Factsheet

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Climate Systems

National Environmental Science Program

Oceans and Coasts

Explaining sea-level rise

Sea levels fluctuate due to various factors, even in the absence of climate change. These include land movements, tides, local weather patterns, seasonal cycles and year to year changes due to phenomena like the El Niño–Southern Oscillation. The interaction of these factors creates a highly complex system (Figure 1). Climate change is causing an acceleration of sea-level rise through amplifying some of these factors.

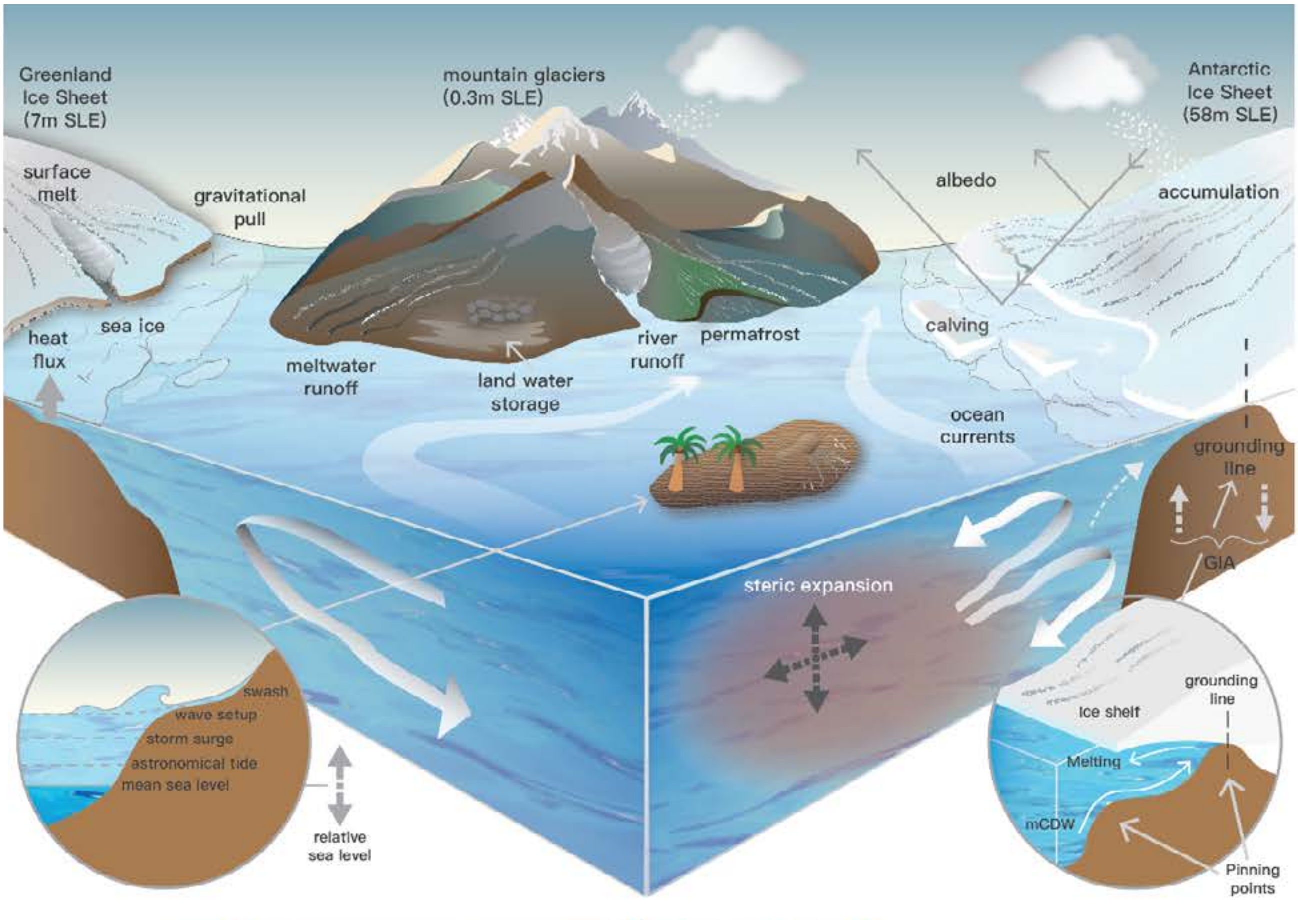

Figure 1. Climate-sensitive processes and components that can influence global and regional sea level. Image adapted from Fox-Kemper et al., 2021.

- Ocean temperature, salinity and density are properties that influence and depend on ocean circulation (SLE=Sea-level equivalent, mCDW=modified Circumpolar Deep Water, GIA=Glacial Isostatic Adjustment).
- White arrows indicate ocean circulation.
- Pinning points (right lower corner) indicate where the grounding line is most stable and ice-sheet retreat will slow (source: Fox-Kemper et al., 2021).
- River runoff, and the Greenland and Antarctic ice sheets and mountain glaciers contribute to changes in the mass of the ocean whereas thermal expansion contributes to changes in ocean volume.
- Ocean currents and gravitational pull by the ice sheets contribute to regional variations in sea level.

Which contributors to sea-level rise are amplified by climate change?

Climate change is causing our planet to warm. This includes the warming of our oceans and changing the way our ocean currents and weather systems behave.

The main climate change factors affecting changes in sea levels are:

- **Expanding water:** As the ocean warms due to climate change, seawater takes up more space, which is called thermal expansion.
- **More water:** Melting glaciers, ice caps, polar ice sheets, and groundwater add more water to the ocean, making sea levels rise.

Locally, sea levels can also rise or fall because of:

- **Moving water:** Changes in ocean currents, waves, tides, and other factors due to ocean dynamics move water around.
- **Land changes:** The land itself can sink or rise, with these vertical land movements affecting relative sea levels in that area.

From 1901 to 2018, most of the rise in sea levels was caused by melting glaciers (41%), seawater expanding as it warms (38%), and melting from the Greenland ice sheet (25%). Smaller amounts came from water stored on land, such as groundwater (8%), and the Antarctic ice sheets (4%) (Figure 2).

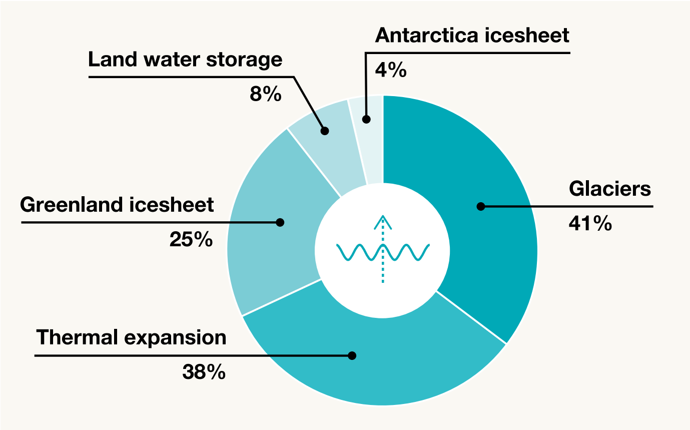

Figure 2. Percentage contributions to sea-level rise over the period 1901–2018.

Scientists are concerned about how fast the ice sheets are melting and expect this contribution to increase in the future.

All of these various factors must be considered in interpreting measurements of past sea-level change and projections of future sea levels. Predicting local hazards such as extreme sea levels caused by tides, storm surge and waves, must take into account how much the sea level is also rising from climate change.

A closer look at climate change and sea-level rise

Changes to the total global sea level can be understood by considering changes to water mass and volume. Locally, sea level can change as water is redistributed around the globe.

1. Mass changes

Ice sheet contributions

If the Antarctic and Greenland ice sheets, along with the world's other mountain glaciers, were completely melted, they would raise global sea levels by approximately 58m, 7m, and 0.3m respectively. This melting occurs due to rising temperatures of the air and oceans, which directly melt the ice, and reduced precipitation that limits ice formation.

Precipitation such as snow and rain add mass to glaciers and ice sheets, while increasing temperatures cause glaciers and ice sheets to lose mass through melting or calving at their edges, where ice meets lakes or oceans. The combination of this mass gain and loss is called Surface Mass Balance.

Warming ocean temperatures also contribute to rising sea levels by melting and thinning ice below the ocean surface. This reduces the structural support (buttressing effect) provided by ice shelves, increasing the likelihood of mechanical breakdown where ice meets ocean waters.

A particularly unstable configuration of ice sheets arises when the bedrock below an ice sheet slopes downwards towards the centre of the ice sheet. In this situation warmer water underneath the ice sheet accelerates ice sheet loss (Figure 3 a-c). This accelerated loss is referred to as Marine Ice Sheet Instability (MISI). Much of Antarctica has reverse-sloped bedrock, making it vulnerable to the process of Marine Ice Sheet Instability.

Additionally, processes like hydrofracturing—the repeated melting and freezing of water in crevices—cause ice shelf collapse into the ocean.

This phenomenon, known as Marine Ice Cliff Instability (MICI) – see Figure 3d-f – is still under research and not well understood.

Recent sea-level contributions from the Greenland ice sheet have primarily resulted from changes in surface mass balance and glacier retreat. In West Antarctica, increased ice flow, ocean-driven melting, and ice-shelf collapses, especially in the Antarctic Peninsula region, have contributed to sea-level rise.

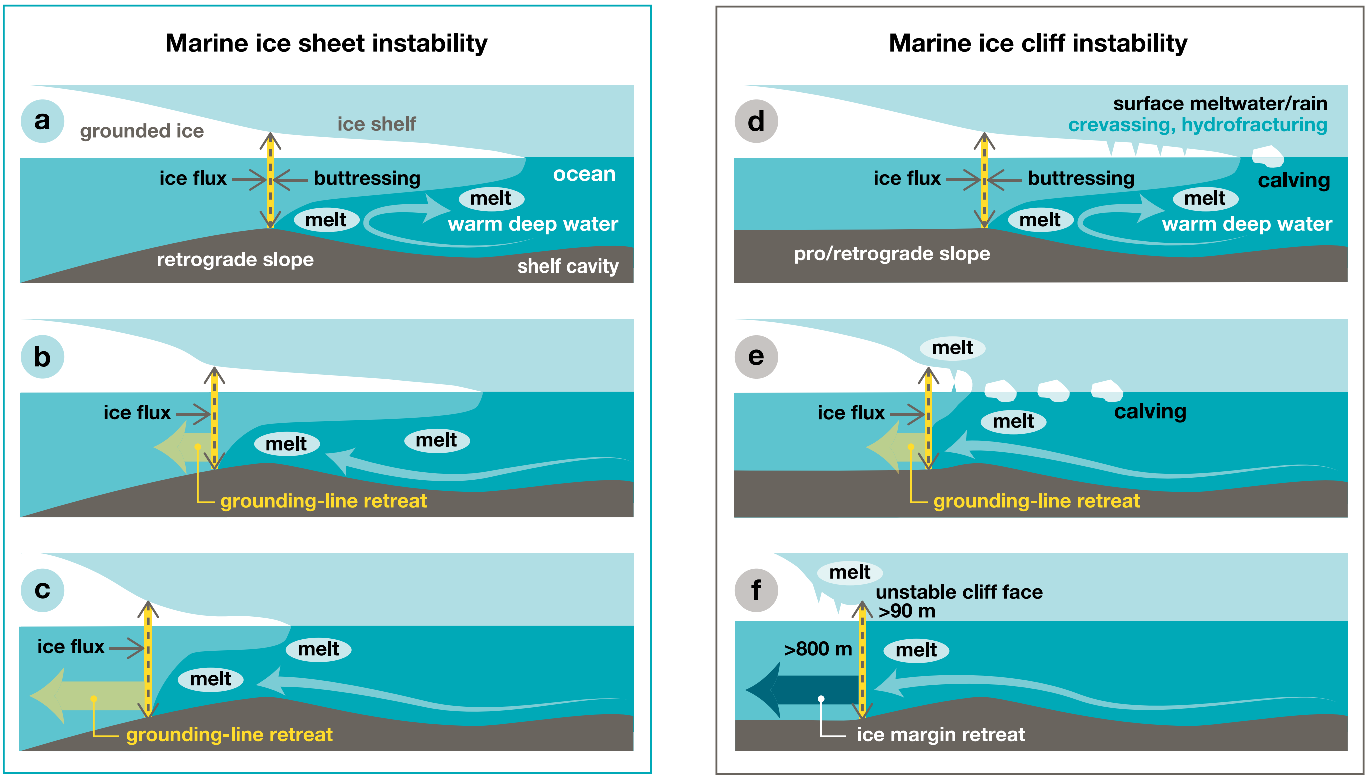

Figure 3. Schematic representation of the processes of Marine Ice Sheet Instability and Marine Ice Cliff Instability. Image adapted from DeConto and Pollard (2016).

Other mass change contributors

Terrestrial or land water storage refers to water held in dams and underground aquifers. During the 20th century, terrestrial storage slightly increased, which helped reduce sea-level rise that might have otherwise occurred. The main cause was dam construction, which trapped water that would otherwise flow to the oceans. However, dam building has largely ceased worldwide. On the other hand, groundwater extraction from aquifers for domestic, agricultural, and industrial purposes now contributes positively to sea-level rise. Once extracted and used, the water eventually drains back into the oceans. Increased groundwater use is a small but growing factor in sea-level rise.

Rainfall variations can also temporarily impact sea levels, particularly during widespread flooding over land. These short-term changes are often linked to climate events, such as the El Niño–Southern Oscillation. However, they generally have only a minor and temporary effect, typically on interannual time scales.

2. Volume changes

When water warms, it expands in volume. The oceans have absorbed more than 90% of the excess heat in the climate system due to global warming. This has contributed to ocean warming and thermal expansion, causing an increase in the volume of the ocean over and above that caused by the adding of mass to the ocean.

During the 20th century, about one-third of sea-level rise was caused by ocean water expanding as it warmed. From 1901 to 2018, this thermal expansion added around 6 cm to global sea levels. Most of the heat absorbed by the ocean is stored in the upper 700 meters, though warming happens at all depths.

The ocean does not warm evenly. Some regions, including some around Australia, show increases in ocean heat several times faster than the global mean (Figure 4).

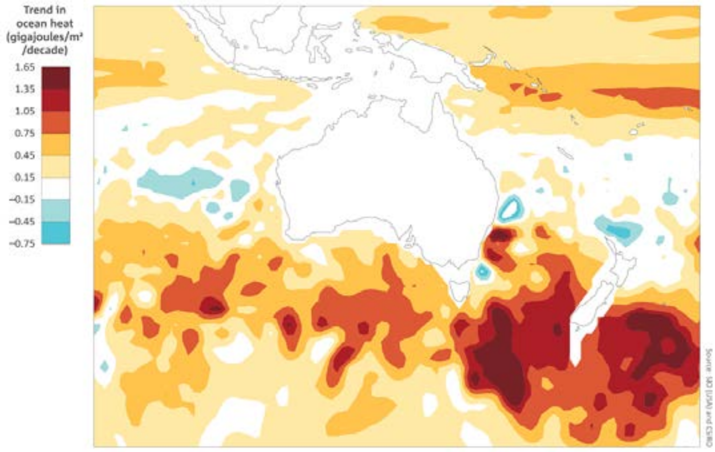

Figure 4. Estimated trend in ocean heat content in the upper 2,000 metres between 2005 and 2023. The highest uptake of heat occurred in regions where the circulation draws heat into the deep ocean, such as the Southern Ocean. Image from State of the Climate 2024, CSIRO and Bureau of Meteorology.

3. Sea-level redistribution

Sea level is not level around the globe. Even though the total global sea level is rising, at any location sea levels may be falling or experiencing even higher rates of sea-level rise. Factors that cause sea level to rise or fall in one location relate to the weather, local ocean currents, gravity and Earth rotation changes and movement of the land up or down.

Atmospheric regions of high and low pressure

Atmospheric circulation creates areas with higher or lower pressure around the globe, which directly impacts sea levels. This effect is called the inverse barometer effect.

Sea levels rise by 1 cm for every hectopascal drop in atmospheric surface pressure compared to the global average, and they fall by the same amount for an increase in pressure. Regions of high pressure typically occur near 30° latitude in both hemispheres and at the poles, while low-pressure areas are found near the equator and between 50° and 60° latitude.

Severe storms, such as tropical cyclones, low-pressure systems, and fronts in mid-latitudes, also create regions of low pressure. Combined with strong onshore winds, these conditions can lead to storm surges.

Ocean currents

Ocean currents move warm or cold water and can impact local sea levels. For example, Figure 5 shows how the strengthening of the southward-flowing East Australian Current raises sea levels on the seaward side of the current due to ocean dynamics, a process called geostrophy. These dynamic factors may explain why sea-level rise rates measured by satellite altimeters over the ocean differ from those recorded by nearby coastal tide gauges.

Changes in Earth's gravity field and rotation

Sea levels are affected by the mutual gravitational pull between ice sheets and the ocean. As the mass of land-based sea ice decreases, this gravitational attraction weakens. Changes in ice sheet mass also influence the Earth's rotation, contributing to regional variations in sea-level patterns.

Additionally, shifts in ice sheet mass can deform the solid Earth, causing vertical land movement—either upward or downward—known as an elastic response.
These combined effects of rotation, gravity,
and deformation create a unique spatial pattern called a sea-level fingerprint. This fingerprint results in lower sea levels near the coastlines of melting ice sheets and higher sea levels across the oceans on the opposite side of the planet from the ice sheets.

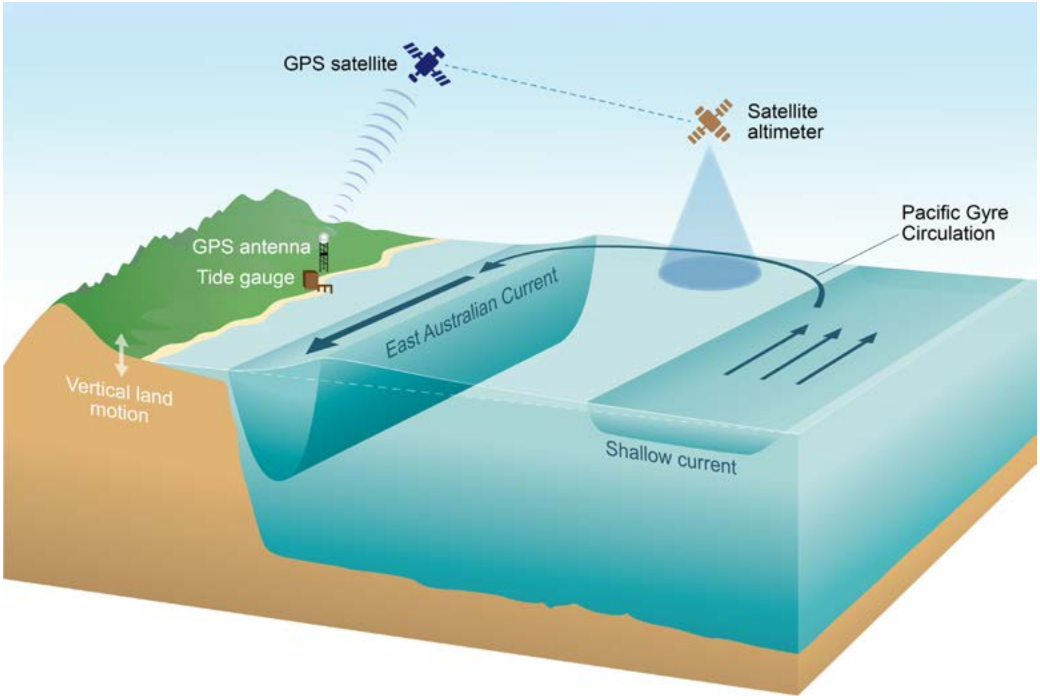

Figure 5. Diagram explaining how differences between rates of sea-level rise measured by satellite altimeters and tide gauges can arise. (1) Changes in ocean dynamics, such as the strengthening southward flow of the East Australian Current, cause an increase in the sea-surface height seaward of the current direction so that the rate of sea-level rise measured by the satellite altimeter would be greater than the rate at the nearby coastal tide gauge. (2) Tide gauges may move vertically – a common local cause is groundwater extraction which causes land subsidence – so that rates of sea-level rise from the tide gauge would appear greater than the rates of sea-level rise in the nearby ocean measured by satellite altimeters. Vertical movement of tide gauges can be measured using Global Positioning System (GPS) Satellites. Image from CSIRO

Vertical land movement

Sea-level changes can be influenced by vertical movement of coastal land, either sinking or rising. If the land is sinking, the relative sea-level rise in that area will be greater.

The measurement of sea-level changes varies depending on the method used. Tide gauges measure relative sea levels at the coast, while satellite altimeters measure sea levels relative to the Earth's centre (Figure 5). In regions where vertical land movement is occurring different rates of sea level change can therefore be measured.

Vertical land movement results from several processes. One major cause is the Earth's slow adjustment to the melting of ice sheets from the last ice age, known as glacial isostatic adjustment. Present-day melting of land ice also contributes to these global adjustments.

On shorter timescales, urban development, sediment compaction, groundwater extraction, and oil or gas removal can lead to land subsidence, increasing relative sea-level rise.

Tectonic activity, such as earthquakes or volcanic eruptions, can cause ongoing or sudden changes in land levels.

In Australia, weak land subsidence (0 to -2 mm per year) is observed in most locations. This subsidence is primarily due to large-scale melting of glaciers and polar ice sheets after the last ice age, along with the sea-level fingerprint effect caused by contemporary land ice mass changes.

More information

This explainer is delivered in conjunction with the National Environmental Science Program's Climate Systems Hub Oceans and Coasts project.

Visit www.nesp2climate.com.au
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To understand more about sea-level rise impacts and response options visit the CoastAdapt website www.coastadapt.com.au

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