Climate Change and Impacts
Oceans and Cryosphere

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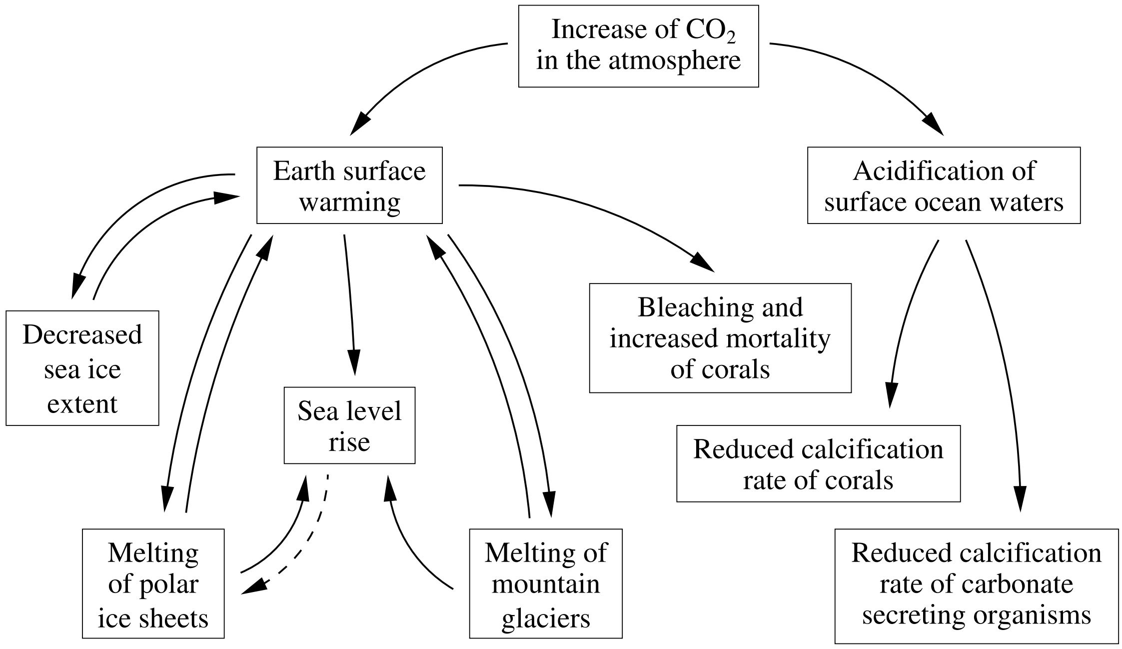
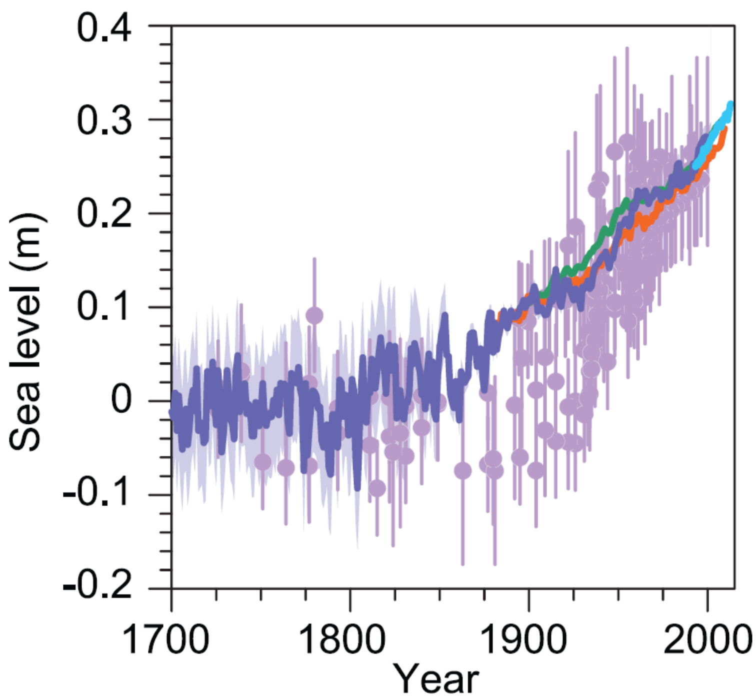
Plan

- Ocean
- Cryosphere
- Recent past and future
- Paleoclimate change
- Coastal oceans
- Surface ocean acidification

Processes and feedbacks

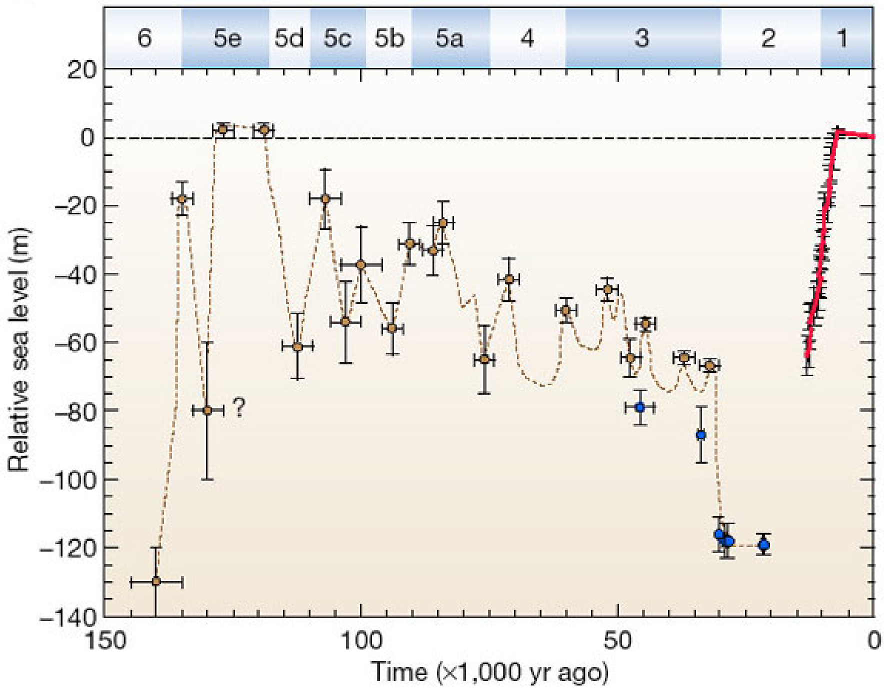


Historical Evolution of Sea Level



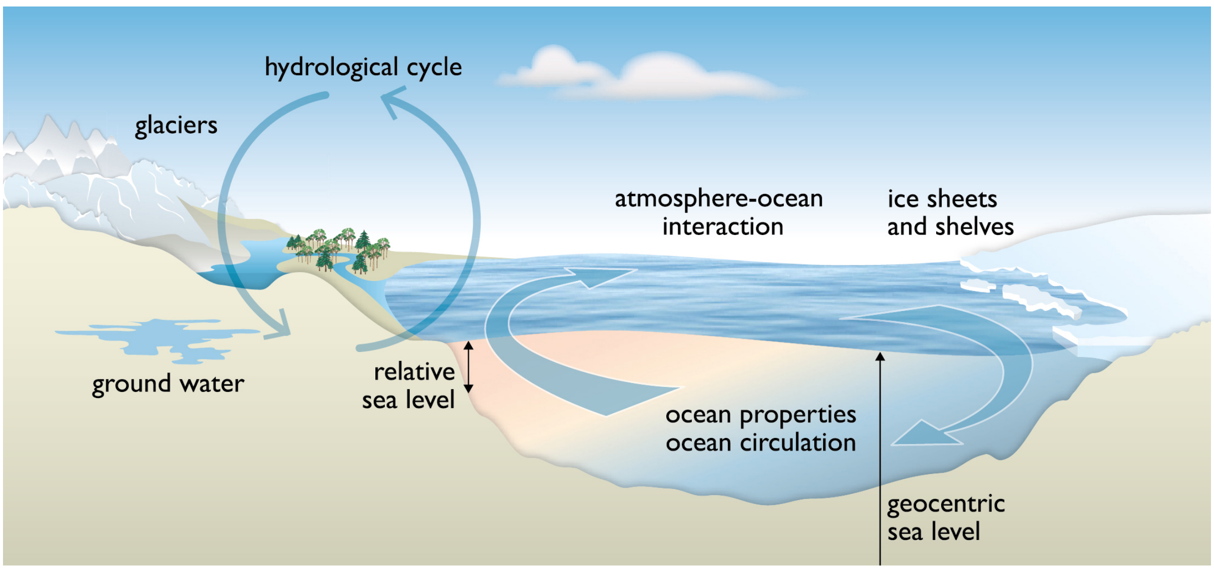
Source: IPCC-WG1 (2013, Fig. 13.3e)

Glacial-interglacial Sea Level Change



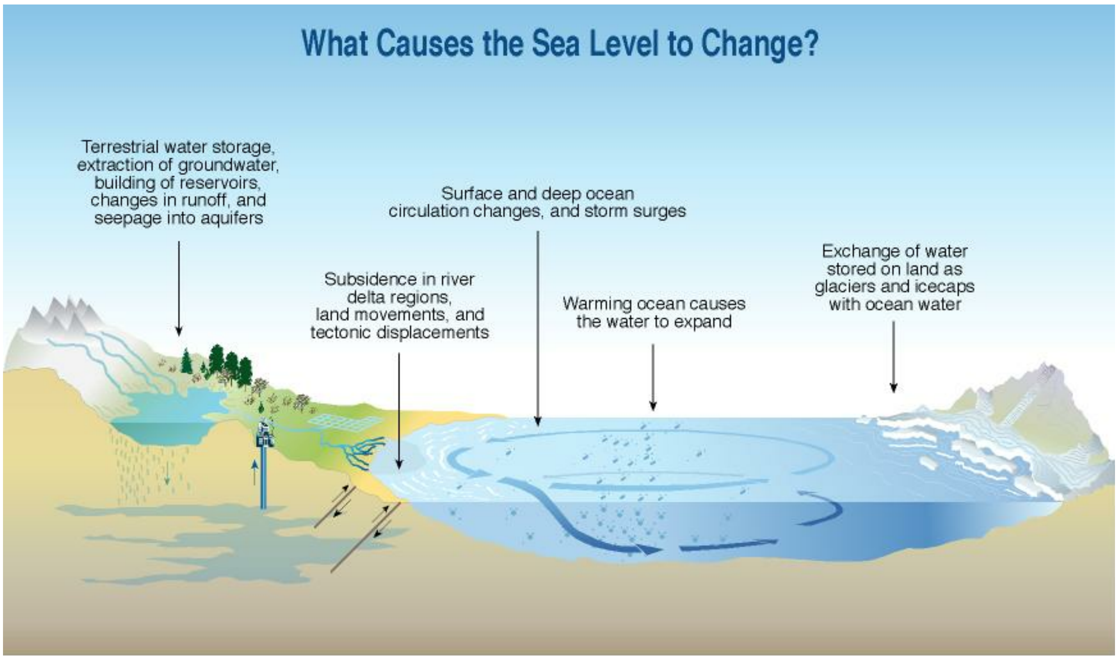
Source: Lambeck et al. (2002)

Sea Level: Processes and Contributions



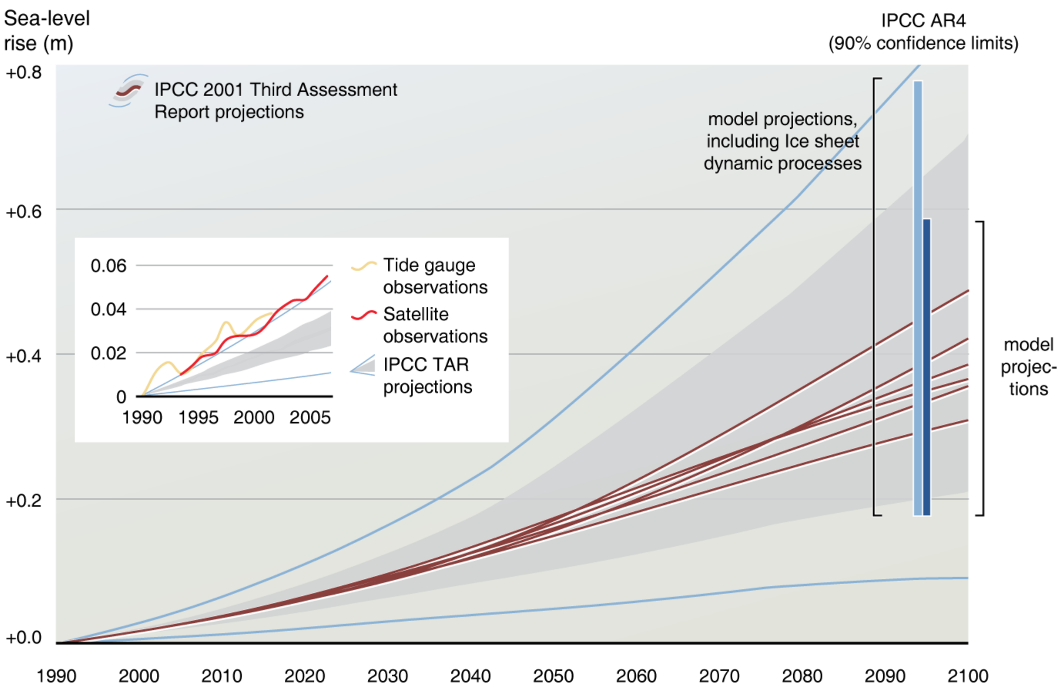
Source: IPCC-WG1 (2013, Fig. 13.1)

Sea Level: Processes and Contributions



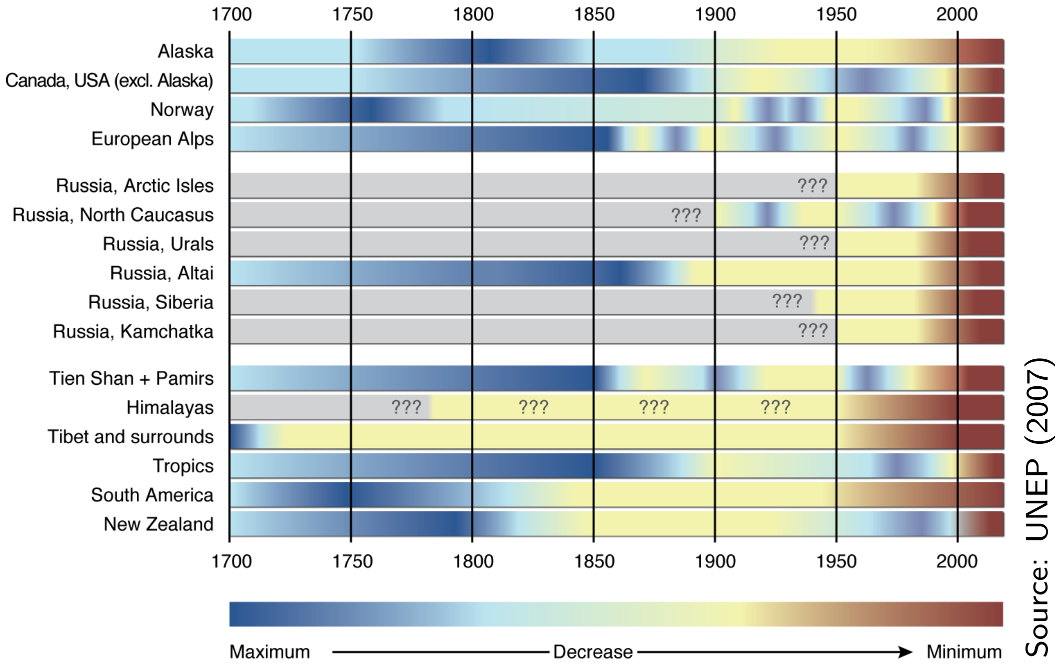
Source: UNEP (2007)

Future Sea Level Change: Projections



Source: UNEP (2007)

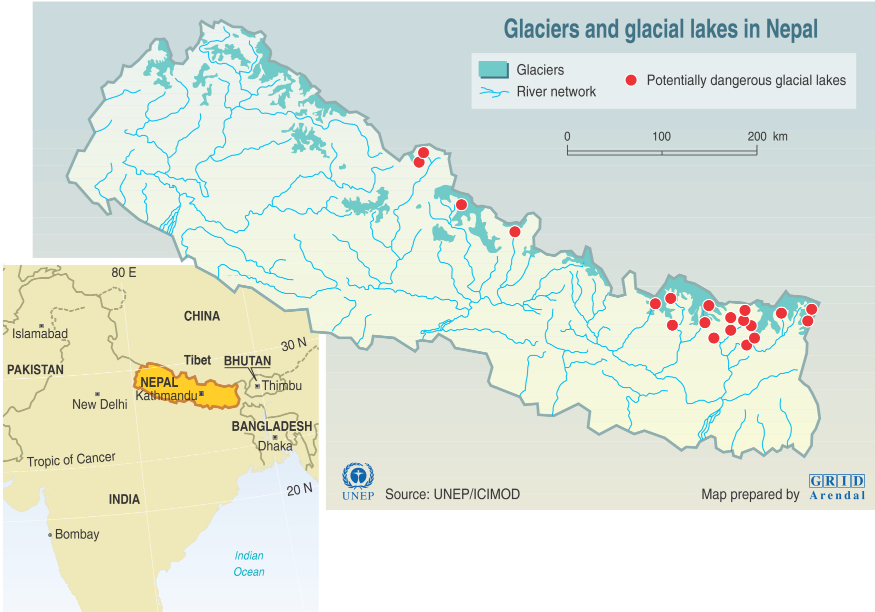
Glaciers: Fluctuations Since the Little Ice Age



Mountain Glacier Retreat: Impacts

- short and medium term
  - rise of glacial lake levels
  - risk of mountain lake overflow
  - risk of rupture of moraine (natural) and artificial dams
  - Glacial Lake Outburst Floods (GLOF) or flash floods
  - reduced drinking water resources (next 20 to 30 years)
- long term
  - perturbation of the water cycle
  - contribution to global sea level rise
  - reduced hydroelectric power potential
  - reduced river discharge

Glacial Lakes in the Himalayas: Nepal



Source: http://www.grida.no

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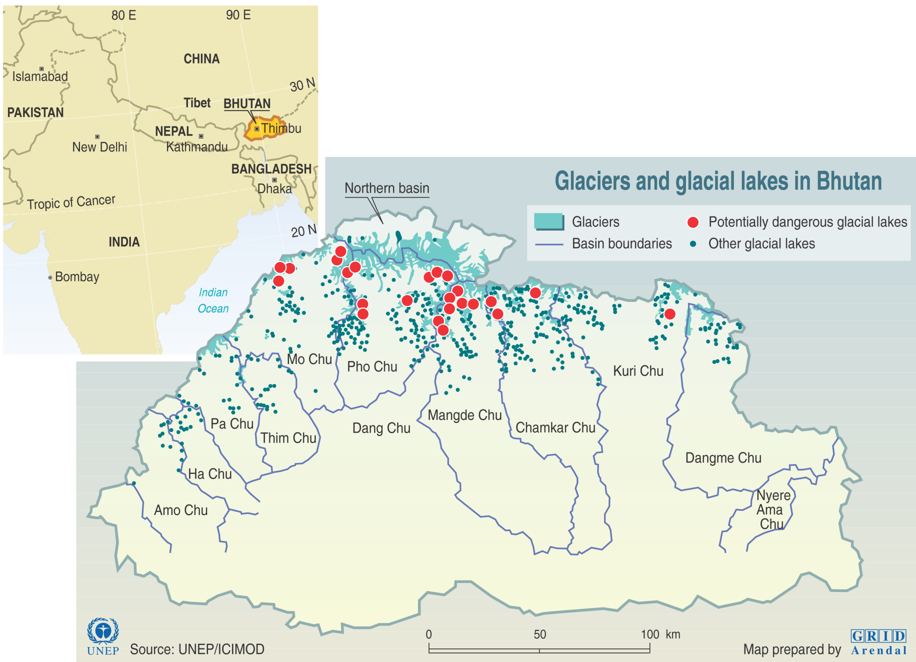
Glacial Lakes in the Himalayas: Bhutan



Source: http://www.grida.no

Mountain Areas: a Few Guidelines

- ca. 500 million people live in mountain areas or on high plains
- about half of the World's population relies on drinking water supplied by mountain areas
- in arid and semi-arid zones, 70 to 95% of surface waters come from mountain areas
- mountain tourism represents 15 to 20% of the World tourism
- mountain ecosystems are inherently fragile

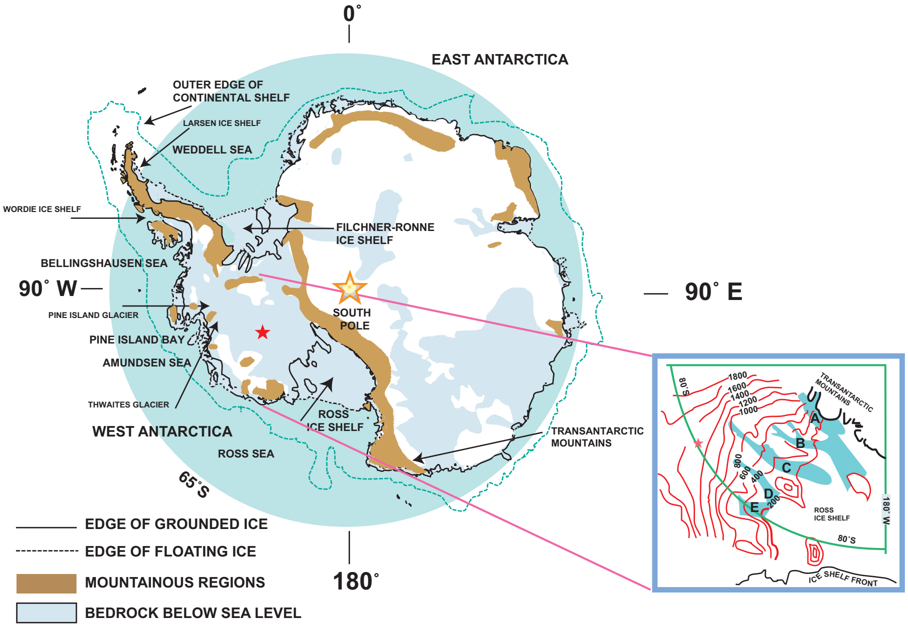
Source: UNESCO (2002, `http://www.unesco.org/bpi/fre/unescopresse/2002/02-87f.shtml`)

Ice Sheets and Potential Sea Level Rise

	Volume (10^{15} m^3)	Surface Area (10^{12} m^2)	Equiv. Δh (m)
Greenland	2.9	1.7	~ 7
East Antarctica	26.039	10.354	~ 60
West Antarctica	3.262	1.974	~ 6

Source: UNEP (2007), IPCC (2001)

Antarctic Ice Sheet

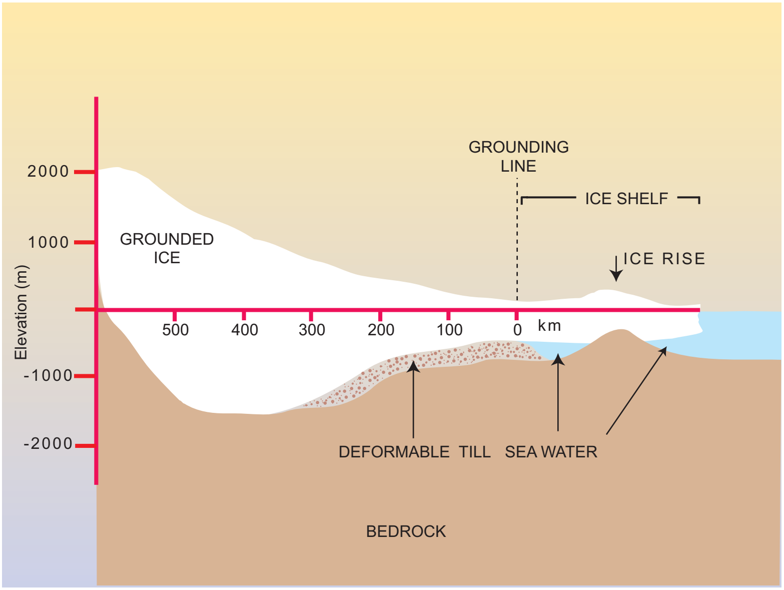


Source: Oppenheimer (1998)

Marine Ice Sheet Instability

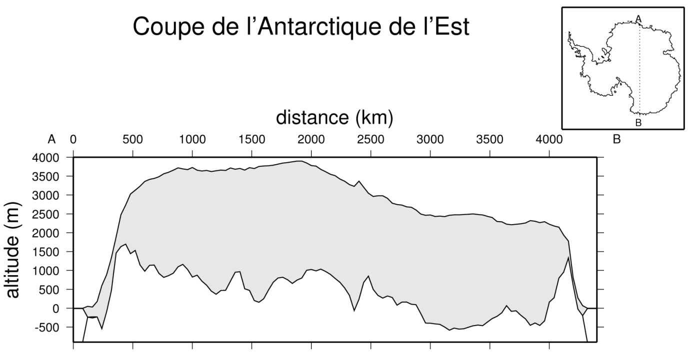
- Ice flux at the grounding line (*ligne d'ancrage* or *ligne d'échouage* in French) of a marine ice sheet increases with the ice sheet's thickness at that place
- Sea level change may possibly perturb the position of the grounding line
  $\Rightarrow$ Archimedes' principle – buoyant force acting onto the floating part
- If the ice sheet rests upon bedrock sloping towards the continental interior a sea level rise may trigger an ice sheet instability
- Other possible perturbation: viscosity change due to temperature change

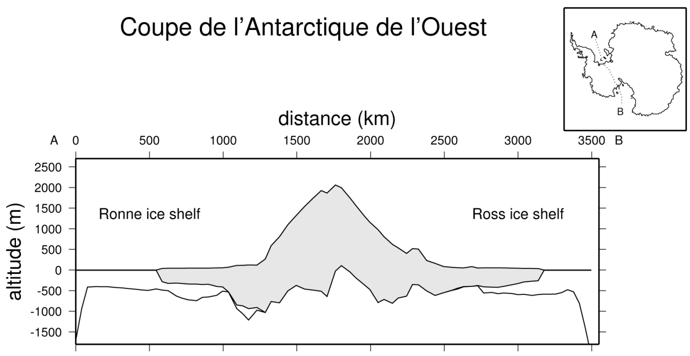
Marine Ice Sheet Instability



Source: Oppenheimer (1998)

West-Antarctic Ice-Sheet Instability



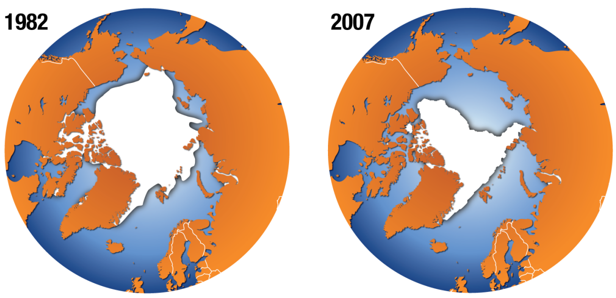


Source: Dumas (2002)

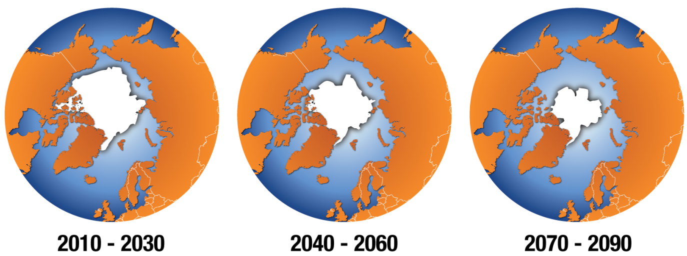
Sea Ice Decrease

- Reduced extent
  - maximum extent
  - minimum extent
- Thickness changes (volume)
- Reduced multi-annual sea ice

Sea Ice Decrease in the Arctic

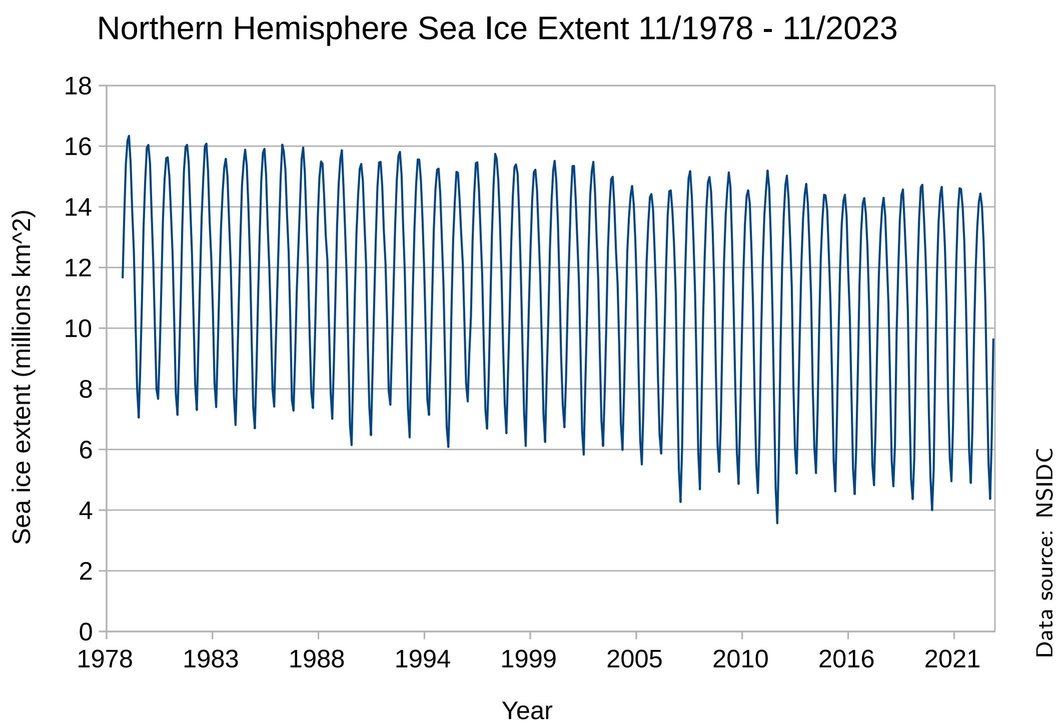


National Snow and Ice Data Center, 2007

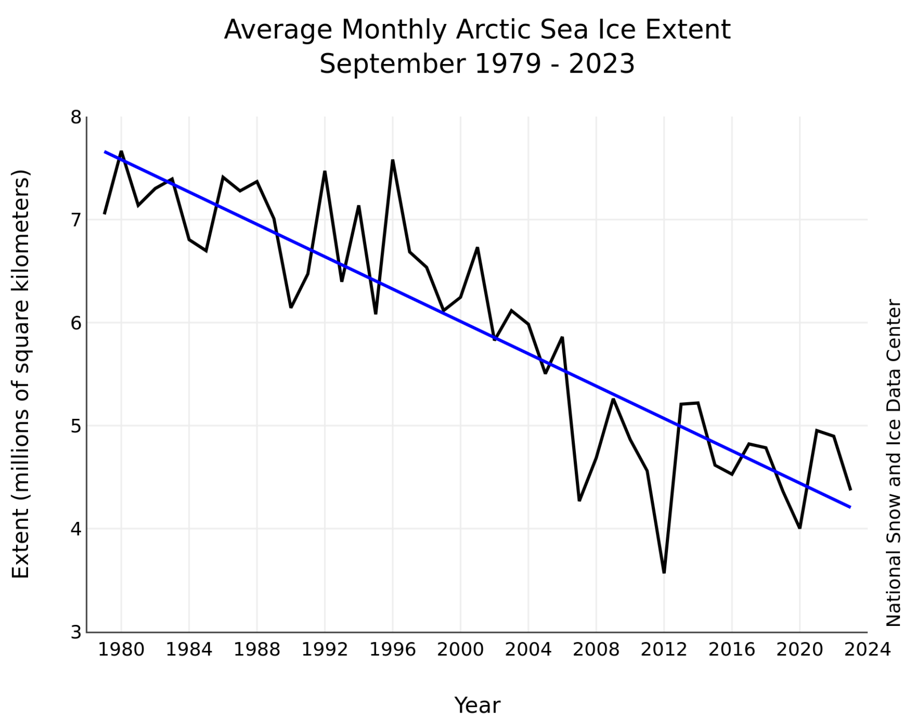


Arctic Climate Impact Assessment, 2004

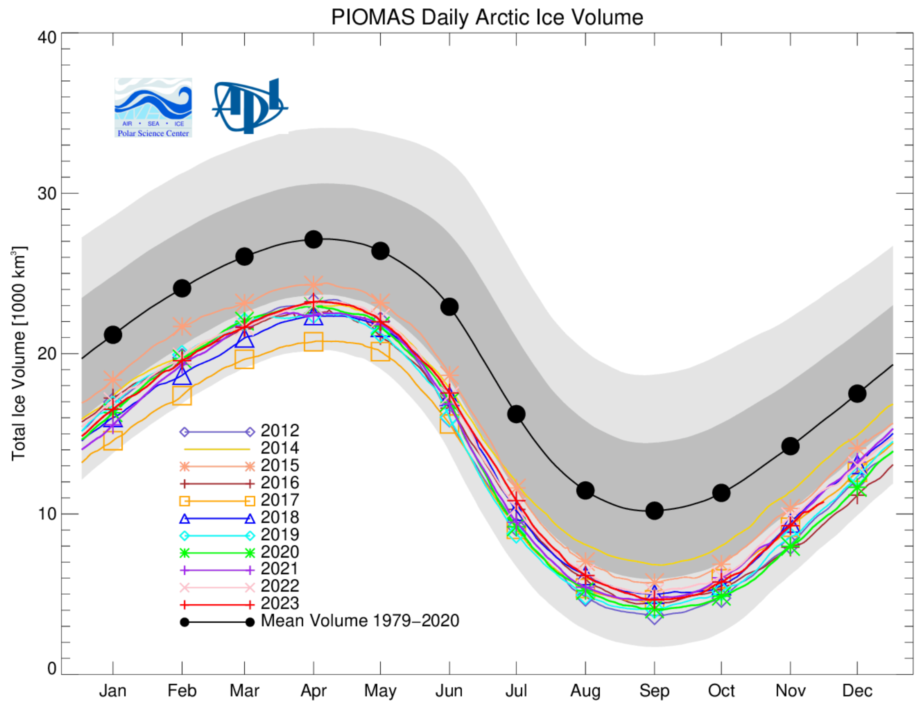
Arctic Sea Ice: Evolution of the Extent



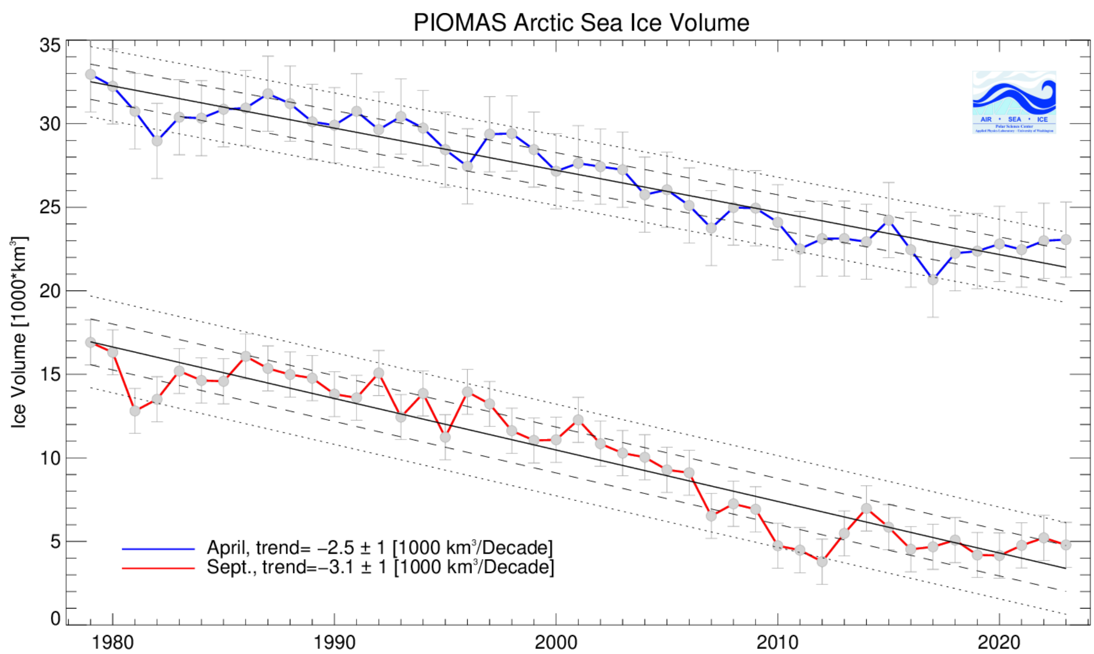
Arctic Sea Ice: Annual Extent in September



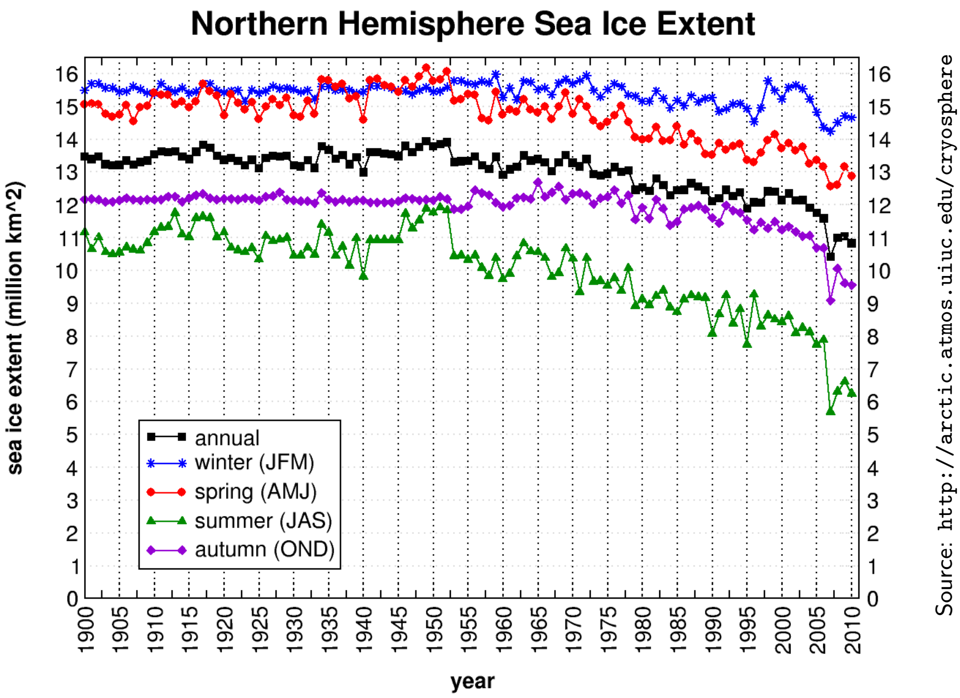
Arctic Sea Ice: Annual Volume Change



Arctic Sea Ice: History of Volumes From 1979 to 2023



Arctic Sea Ice: Seasonal Extents



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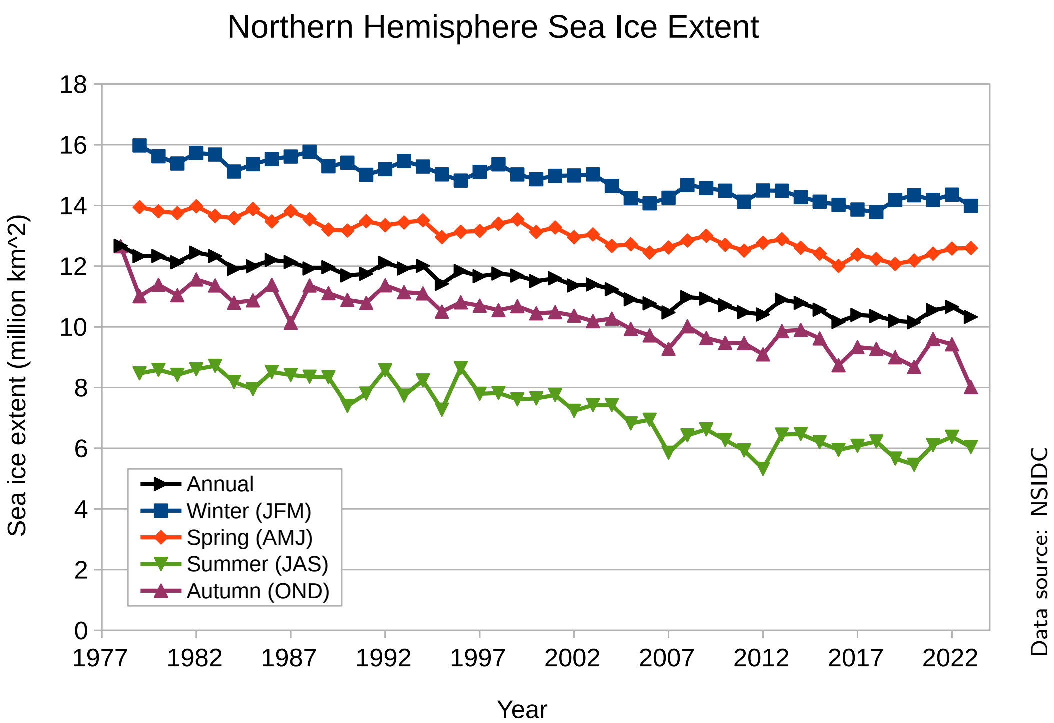
Arctic Sea Ice: Seasonal Extents



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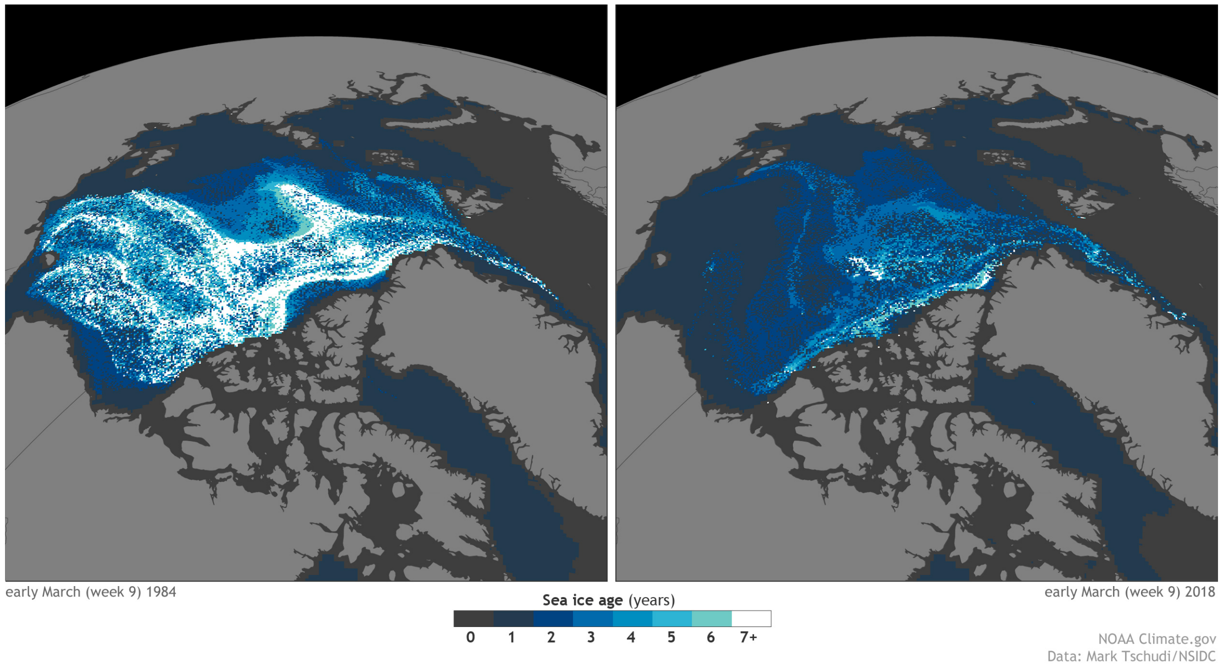
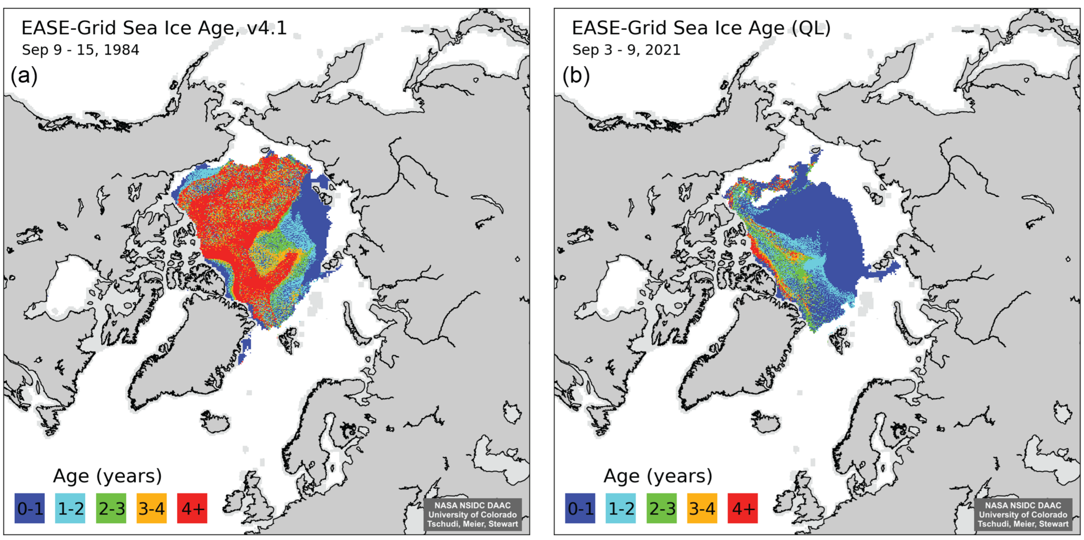
Arctic Sea Ice: Age Distribution



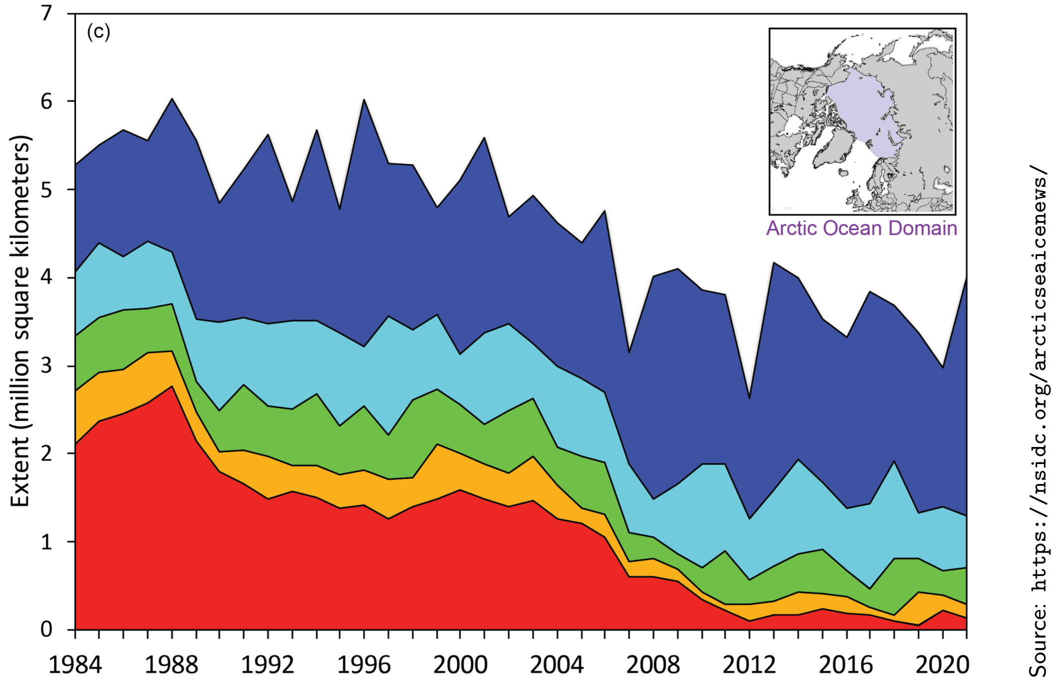
Source: https://www.climate.gov

Arctic Sea Ice: Age Distribution

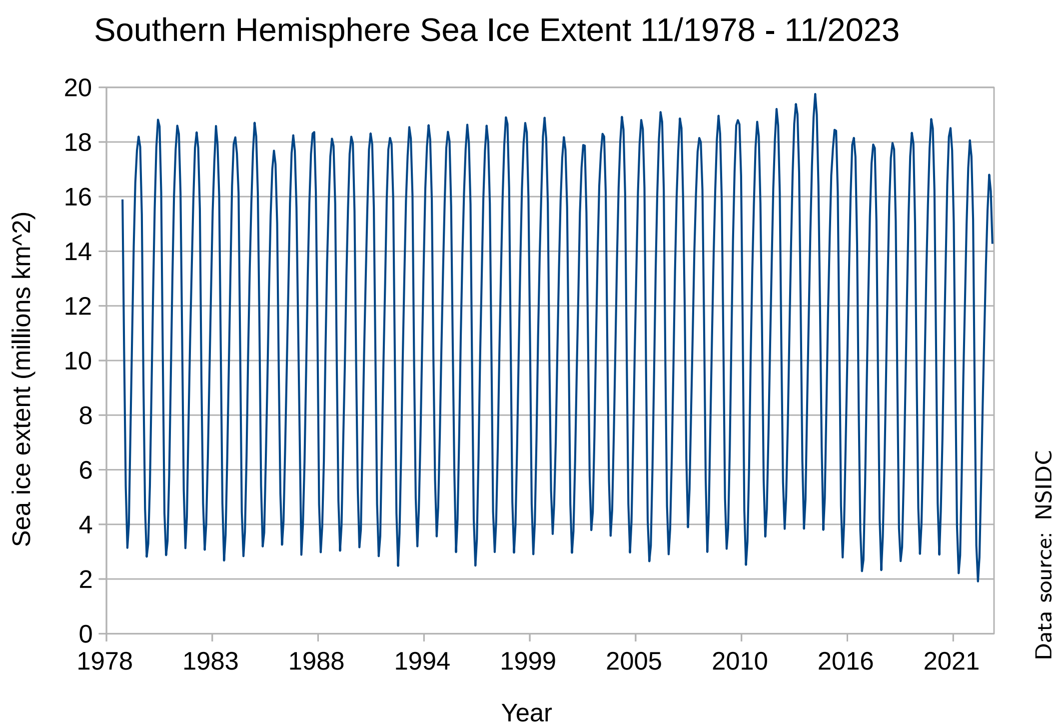


Source: https://nsidc.org/arcticseaicenews

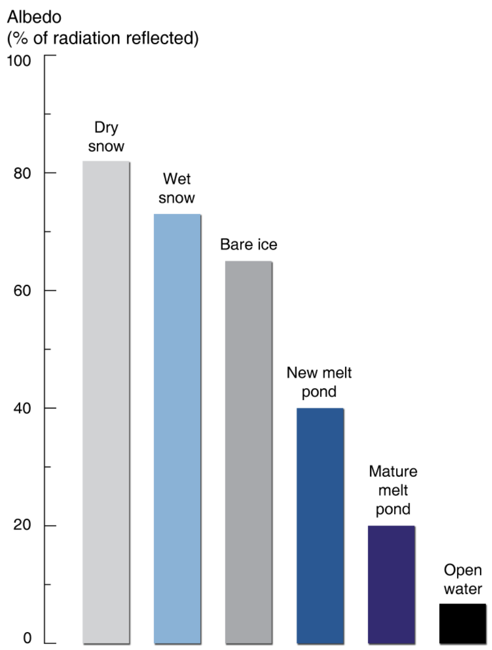
Arctic Sea Ice: Age Distribution



Antarctic Sea Ice: Evolution of the Extent



Sea Ice: Ice-Albedo Feedback

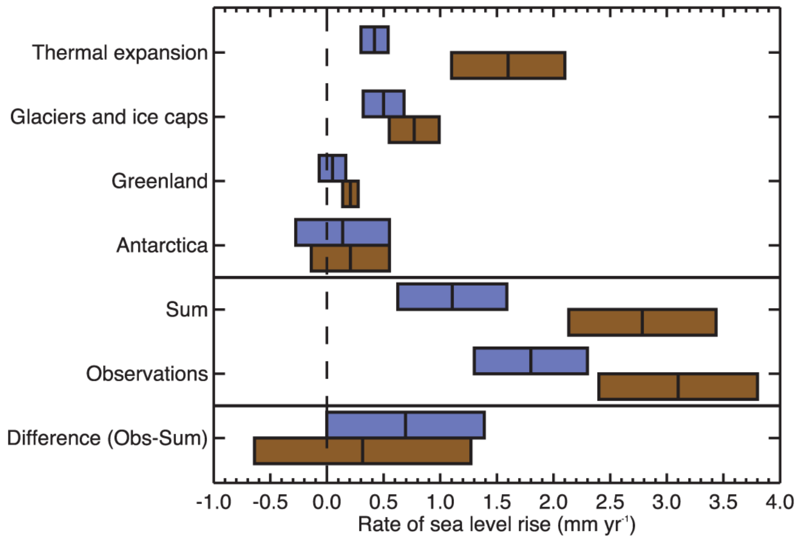


Source: UNEP (2007)

Sea Ice Decrease: Impact in the Arctic

Source: UNEP (2007)

Sea Level Rise: Analysis of the Contributions



Blue: 1961–2003
Brown: 1993–2003

Source: IPCC-WG1 (2007)

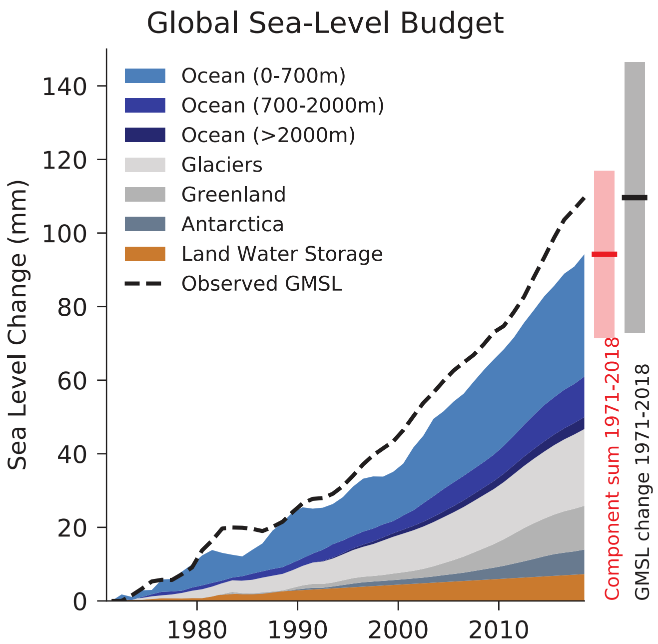
Sea Level Rise: AR5 Analysis of the Contributions

Source	1901–1990	1971–2010	1993–2010
Observed contributions to			
Thermal expansion	–	0.8 [0.5 to 1.1]	1.1 [0.8 to 1.4]
Glaciers except in Greenland and Antarctica[a]	0.54 [0.47 to 0.61]	0.62 [0.25 to 0.99]	0.76 [0.39 to 1.13]
Glaciers in Greenland[a]	0.15 [0.10 to 0.19]	0.06 [0.03 to 0.09]	0.10 [0.07 to 0.13][b]
Greenland ice sheet	–	–	0.33 [0.25 to 0.41]
Antarctic ice sheet	–	–	0.27 [0.16 to 0.38]
Land water storage	−0.11 [−0.16 to −0.06]	0.12 [0.03 to 0.22]	0.38 [0.26 to 0.49]
Total of contributions	–	–	**2.8 [2.3 to 3.4]**
Observed GMSL rise	**1.5 [1.3 to 1.7]**	**2.0 [1.7 to 2.3]**	**3.2 [2.8 to 3.6]**
Modelled contributions to GMSL rise			
Thermal expansion	0.37 [0.06 to 0.67]	0.96 [0.51 to 1.41]	1.49 [0.97 to 2.02]
Glaciers except in Greenland and Antarctica	0.63 [0.37 to 0.89]	0.62 [0.41 to 0.84]	0.78 [0.43 to 1.13]
Glaciers in Greenland	0.07 [−0.02 to 0.16]	0.10 [0.05 to 0.15]	0.14 [0.06 to 0.23]
Total including land water storage	**1.0 [0.5 to 1.4]**	**1.8 [1.3 to 2.3]**	**2.8 [2.1 to 3.5]**
Residual[c]	**0.5 [0.1 to 1.0]**	**0.2 [−0.4 to 0.8]**	**0.4 [−0.4 to 1.2]**

Units: mm/yr

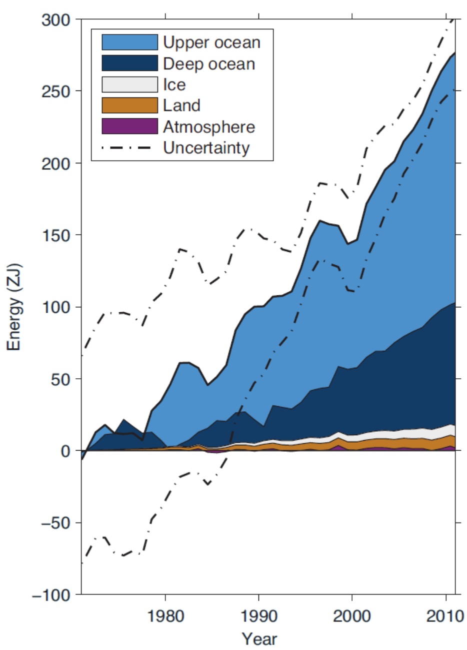
Source: IPCC-WG1 (2013, Tab. 13.1)

Global Sea-Level Budget: AR6 Analysis 1971–2018

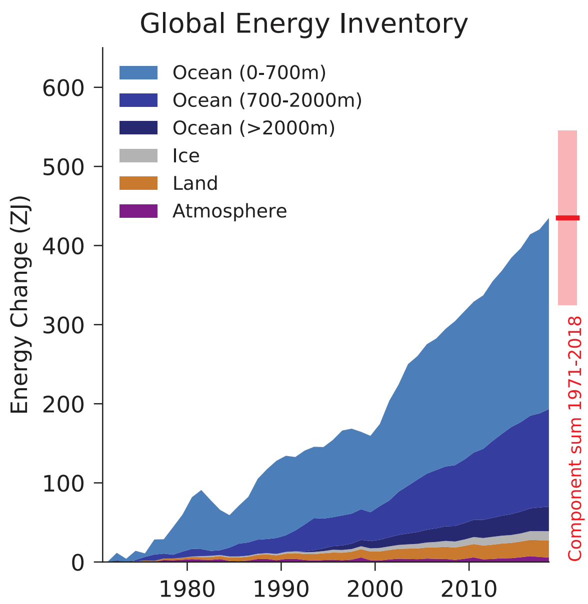


Source: IPCC-WG1 (2021, Box. 9.1, Fig. 1b)

Heat Content in the Climate System

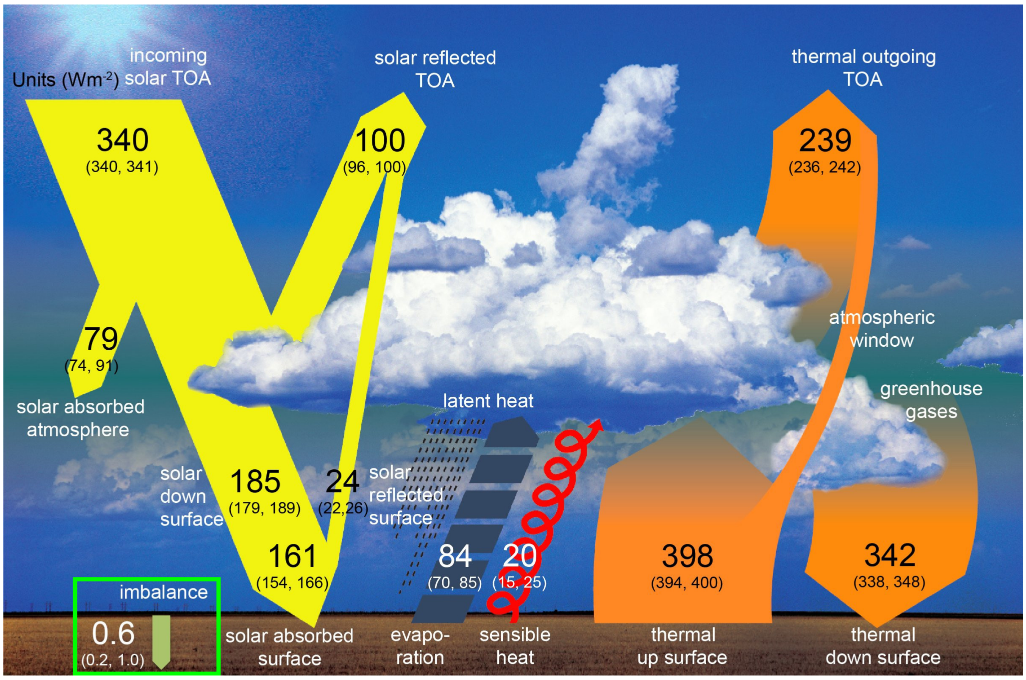


Source: IPCC-WG1 (2013, Box. 3.1, Fig. 1)



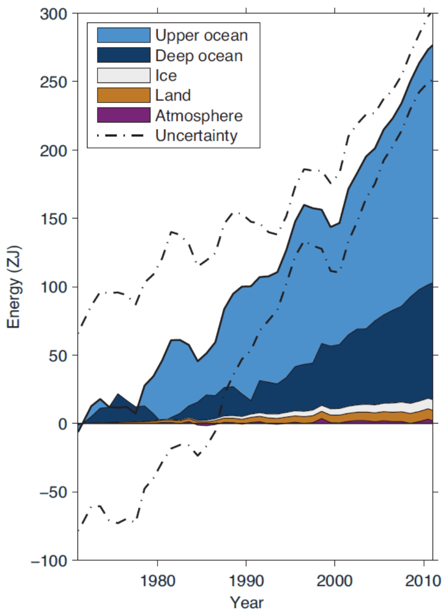
Source: IPCC-WG1 (2021, Box. 9.1, Fig. 1b)

While we are Here: a Short Flashback . . .



Source: IPCC-WG1 (2013, Fig. 2.11)

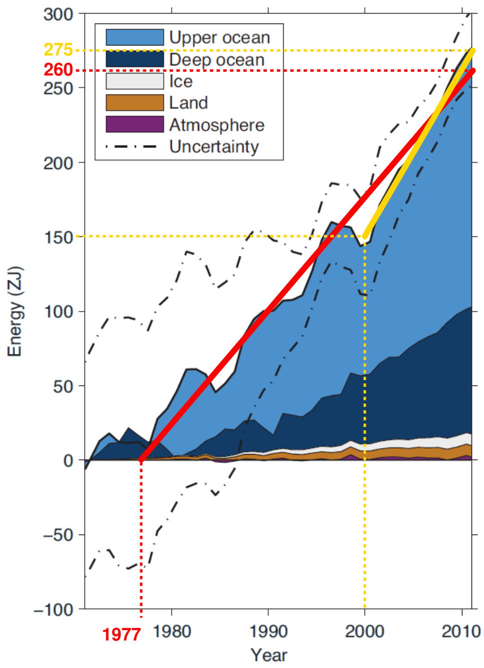
Heat Accumulation in the Climate System



- $1\,\mathrm{ZJ} = 10^{21}\,\mathrm{J}$
- $A_{\mathrm{Earth}} = 510.1 \times 10^6\,\mathrm{km}^2$
- ΔQ_1: energy change per m^2 per yr for 1 ZJ

$$\Delta Q_1 = \frac{10^{21}\,\mathrm{J}}{A_{\mathrm{Earth}} \times 1\,\mathrm{yr}} = \frac{10^{21}\,\mathrm{J}}{5.101 \times 10^{14}\,\mathrm{m}^2\ 3.15576 \times 10^7\,\mathrm{s}} = 0.0621213\,\mathrm{W m}^{-2}$$

Heat Accumulation in the Climate System



1977–2011

260 ZJ in 34 yr → 7.65 ZJ/yr

$$\Delta Q = 7.65 \times \Delta Q_1 = 0.48\,\mathrm{Wm}^{-2}$$

2000–2011

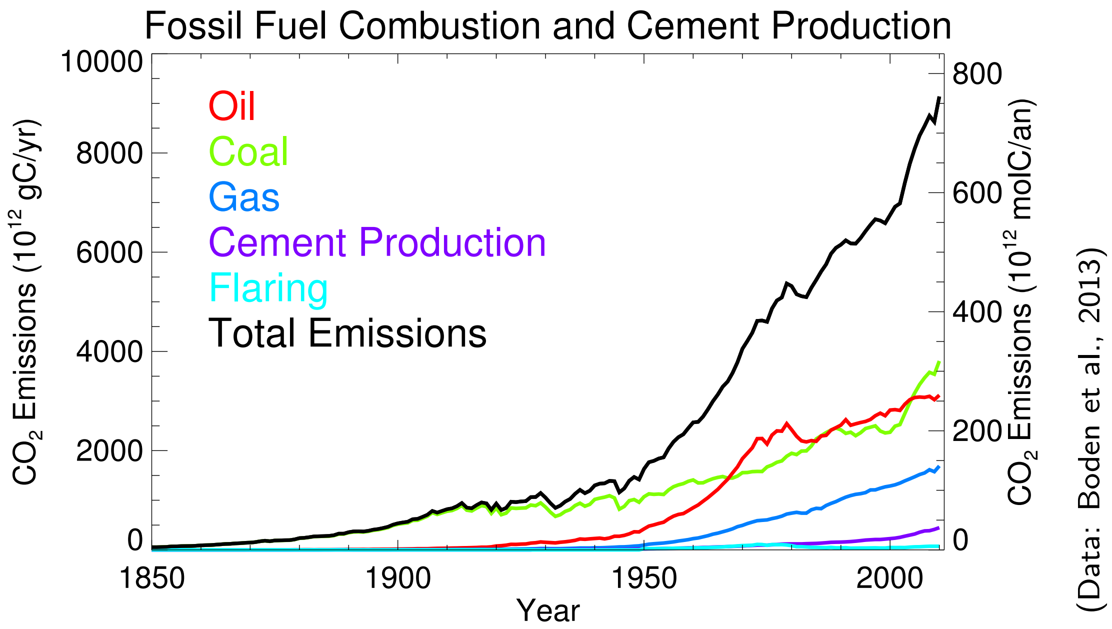
125 ZJ in 11 yr → 11.36 ZJ/yr

$$\Delta Q = 11.36 \times \Delta Q_1 = 0.71\,\mathrm{Wm}^{-2}$$

Ocean Warming: Impacts on Coral Reefs

- Coral reefs can cope with rates of sea-level rise of up to 10 mm/yr
- Warming represents greater threat
- Bleaching if summer sea-surface temperature exceeds average maximum by 1 to 2 °C one year
- In case of repeated exceeding: death
- Other threats: pollution, ocean acidification

CO_2 Emissions by Human Activity



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Cumulated Budget For CO_2 Emissions From 1800 to 1994

Sources end Sinks	1800 – 1994	1980 – 1999
Fossil fuels and cement production	240 ± 20	117 ± 5
Storage in the atmosphere	-165 ± 4	-65 ± 1
Ocean uptake	-118 ± 19	-37 ± 8
Net continent	39 ± 28	-15 ± 9
Emissions due to land-use change	100 – 180	24 ± 12
Net sequestration by terrestrial biosphere	-61 to -141	-39 ± 18

Units: 10^{15} g C (Sabine et al., 2004)

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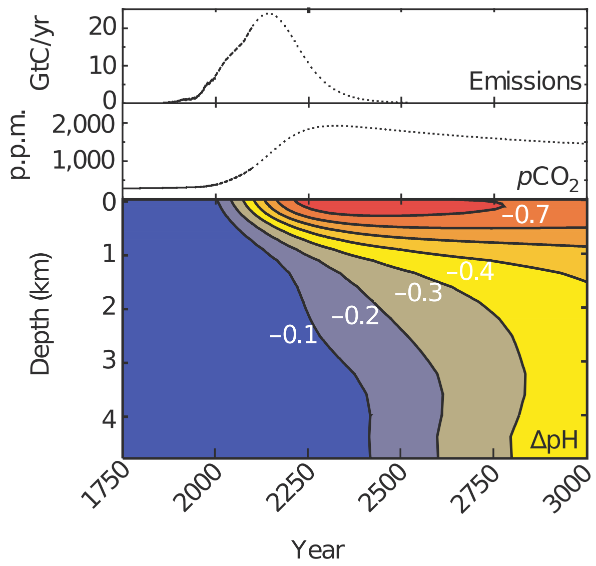
Surface Ocean Acidification



Source: Caldeira and Wickett (2003)

Sea Level
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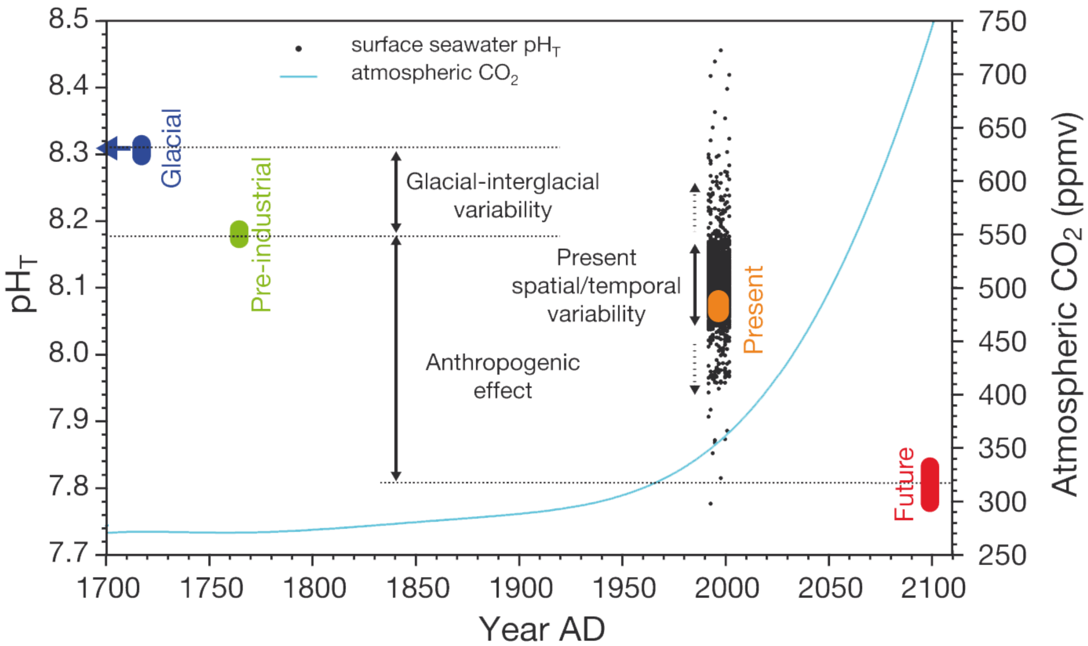
Surface Ocean Acidification



Source: IMBER (2005, `http://www.imber.info`)

Acidification, Saturation: a Carbonate System Primer

Dissolution of CO_2 in water: release of acidity (H^+ ions):

$$\begin{aligned} CO_{2(g)} &\rightleftharpoons CO^*_{2(aq)} \\ CO^*_{2(aq)} + H_2O &\rightleftharpoons HCO_3^- + H^+ \\ HCO_3^- &\rightleftharpoons CO_3^{2-} + H^+ \end{aligned}$$

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Acidification, Saturation: a Carbonate System Primer

Degree of saturation with respect to a carbonate mineral

$$\Omega_{\mathrm{carb}} = \frac{[Ca^{2+}]\,[CO_3^{2+}]}{K_{\mathrm{sp\,carb}}}$$

where

- $[Ca^{2+}]$ and $[CO_3^{2+}]$ are the concentrations of Ca and CO_3^{2-}
- $K_{\mathrm{sp\,carb}}$ is the solubility product of the carbonate mineral ($= f(S,T,P)$, different for each mineral)

If $[Ca^{2+}]$ and $[CO_3^{2+}]$ such that

- $\Omega_{\mathrm{carb}} > 1$: super-saturation, precipitation of 'carb' possible
- $\Omega_{\mathrm{carb}} = 1$: saturation
- $\Omega_{\mathrm{carb}} < 1$: under-saturation, dissolution of 'carb'

Acidification, Saturation: a Carbonate System Primer

Dissolution of CO_2 in water: effect on CO_3^{2-}

$$CO^*_{2(aq)} + CO_3^{2-} + H_2O \rightleftharpoons 2HCO_3^-$$

Accordingly

$$[CO^*_{2(aq)}] \nearrow \quad \Rightarrow \quad [CO_3^{2-}] \searrow$$

$$\Rightarrow \quad \Omega_{carb} = \frac{[Ca^{2+}]\,[CO_3^{2+}]}{K_{sp\,carb}} \searrow$$

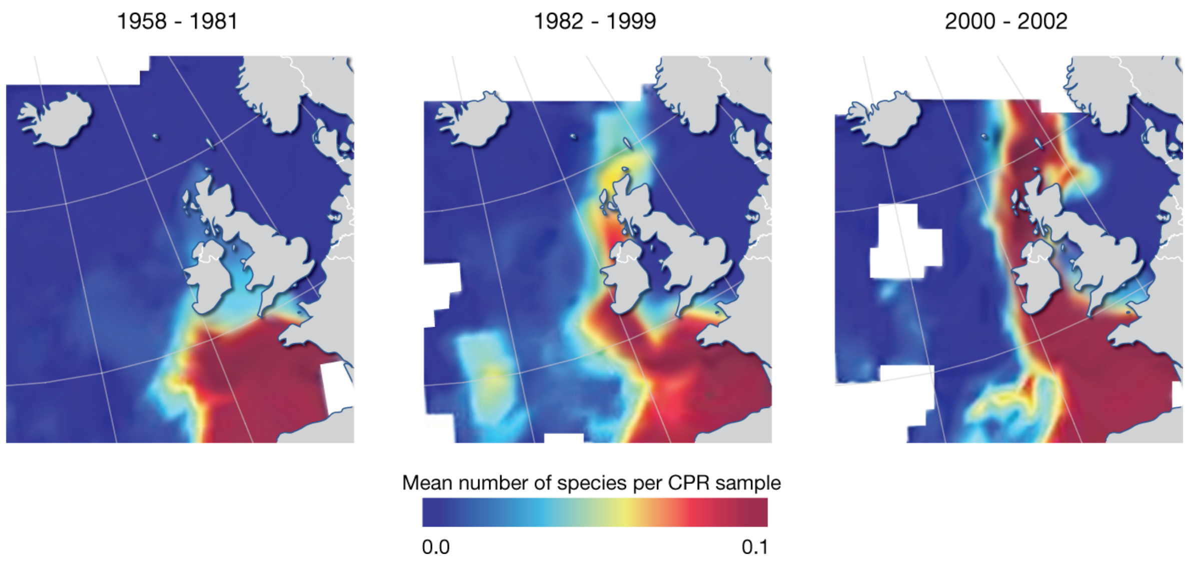
since $[Ca^{2+}]$ shows only little variation in general
and S, T and P not affected by CO_2 dissolution

Surface Ocean Acidification: Impacts

- Early 2000s: ΔpH de $-0.1 \Leftrightarrow \Delta[H^+]$ of $+26\%$
- IS92a scenario: 788 ppm of CO_2 in the atmosphere by 2100, leading to ΔpH of $-0.4 \Leftrightarrow [H^+] \times 2.6$
- Decrease of the degree of saturation with respect to common biogenic carbonate minerals in surface waters
- By 2100: under-saturation with respect to aragonite bbin the Southern Ocean and in the subarctic Pacific
- Doubling of atmospheric CO_2 (560 ppm): degree of saturation with respect to aragonite decreased to 2.1 (from 3.4 at pre-industrial time) $\Rightarrow$ calcification rate of corals and reef-building algae reduced by 10 to 50%
- Most calcareous organisms, neritic and pelagic, touched by this unfavourable evolution

References: Royal Society (2005), Kleypas et al. (2006)

Plankton shift



Source: Nellemann et al. (2008)

References

- IPCC Assessment Reports 2001, 2007 et 2013, WG1 et WG2.
- Caldeira and Wickett (2003) Nature 425, 365. DOI: 10.1038/425365a
- Dumas (2002) *Modélisation de l'évolution de l'Antarctique depuis le dernier cycle glaciaire-interglaciaire jusqu'au futur: importance relative des différents processus physiques et rôle des données d'entrée*. Doctoral thesis, Univ. J. Fourier, Grenoble.
- Kleypas et al. (2006) *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers* `http://www.isse.ucar.edu/florida`
- Lambeck et al. (2002) Nature 419, 199-206. DOI: 10.1038/nature01089
- Boden et al. (2013). Global, Regional, and National CO_2 Emissions. CDIAC, ORNL, US DOE, Oak Ridge, U.S.A. DOI: 10.3334/CDIAC/00001_V2013
- Nellemann et al., eds. (2008). *In Dead Water – Merging of climate change with pollution, over-harvest, and infestations in the world's fishing grounds.* UNEP, GRID-Arendal, Norway, `http://www.grida.no`.
- Oppenheimer (1998) Nature 393, 325-332. DOI: 10.1038/30661
- Royal Society (2005) *Ocean acidification due to increasing atmospheric carbon dioxide.* `http://royalsociety.org/document.asp?id=3249`.
- Sabine et al. (2004) Science 305, 367-371. DOI: 10.1126/science.1097403
- UNEP (2007) *Global Outlook for Ice and Snow*. Available online at `http://www.unep.org/geo/geo_ice`