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Guide to the Science of Climate Change in the 21st Century

Chapter 6
Hydrological Cycle

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6.1 Introduction

The hydrological cycle describes how water, H_2O, is stored and transported from surface water storage to the atmosphere, returns to the surface and subsurface of the Earth where it might remain in temporary storage and ultimately returns to the atmosphere and back to surface water storage.

6.2 Basic elements of the hydrological cycle

Figure 6.1 illustrates the various elements and processes in the hydrological cycle.
Water leaves the ocean and other water bodies (liquid form) to the atmosphere (vapour form) by a process known as evaporation. Water will also enter the atmosphere as a result of plant transpiration and direct evaporation from the soil by a process known as evapotranspiration which lumps both plant transpiration and evaporation from the soil together since it is very difficult to separate the two processes over land surfaces. Evaporation and evapotranspiration require energy to turn the liquid water into vapour. This energy now exists in the water vapour and is known as the latent heat of evaporation. So, evaporation and evapotranspiration actually transfer energy from the Earth into the atmosphere. Water will also move directly into the atmosphere from frozen bodies of water through a process known as sublimation. The water vapour in this case carries the energy required to melt the ice and the energy required to turn the liquid into vapour. Atmospheric circulation will carry the moisture laden air to where it will leave the atmosphere in a process called precipitation after it becomes liquid or ice and ultimately return to the ocean.

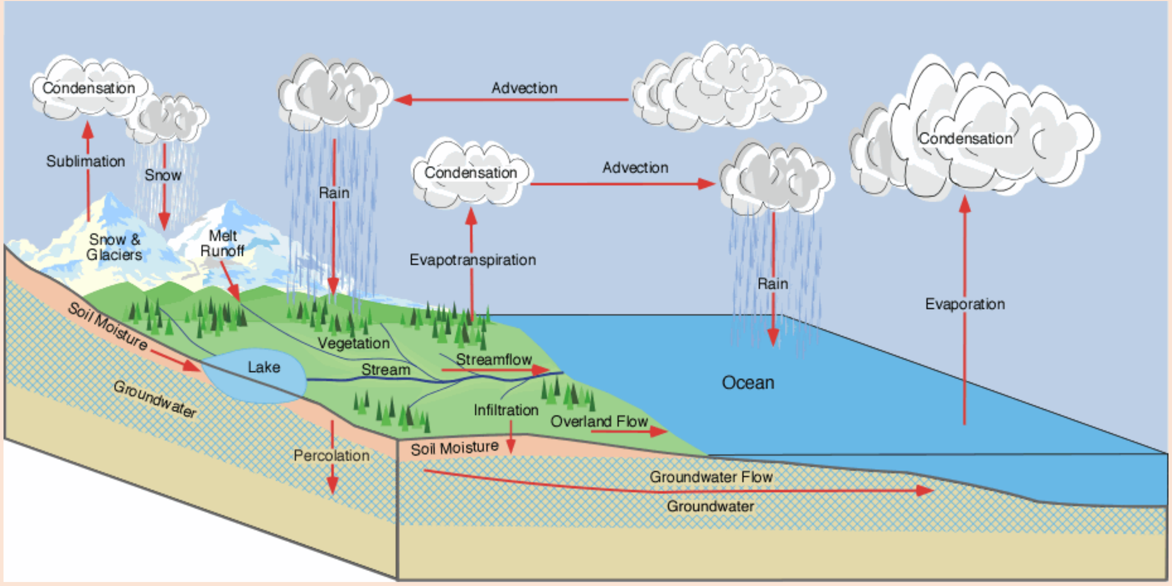

Figure 6.1 Hydrological cycle. http://www.physicalgeography.net/fundamentals/5c_1.html

6.3 Evaporation and evapotranspiration

The rate at which water will move into the atmosphere will depend on the temperature of water source (surface of the ocean and other water bodies and the land and biomass), the amount of energy being received by the contributing water sources, the temperature of the air and the amount of water already in the air above the contributing water sources. Winds can enhance the evaporation and evapotranspiration processes by physically transporting air with high concentration of water vapour away from the contributing sources allowing air with low concentration of water to move next to contributing sources (advection and convection).

6.4 Convection and cloud formation

Convection processes will carry the air containing the moisture vertically until it has a similar density to the surrounding atmosphere. Moisture laden air may be forced upwards by mountains (orographic effect) or when moving warm air is forced to rise when it collides with cold air.

Water vapour will cool as it is carried upwards and it will eventually condense to form liquid or solid water particles around nuclei such as dust, ash or smoke particles so releasing the energy it needed to change it into a vapour form in the first place (latent heat). The particles are seen as clouds. The latent heat added to the air warms it and continues to rise upward if possible. This process can result in very large convective storms that reach the troposphere.

Water is a very effective absorber of heat energy (infrared radiation). In this sense water vapour is considered a greenhouse gas. Infrared radiation from the Sun and from the Earth surface will be absorbed and warm the atmosphere and this heat energy will be radiated in all directions – outer space and back to the Earth's surface.

Clouds formed as part of the hydrological cycle will reflect incoming solar radiation back into space. A satellite image of Earth shown in Figure 6.2 shows the extent of reflecting cloud and ice cover. The manner with which clouds can affect global temperature is explained in a guest brief in the newsletter, 'Carbon Brief', https://www.carbonbrief.org/guest-post-why-clouds-hold-key-better-climate-models.

Research reporting cloud formation and their affect on the energy budget is reported in the journal 'Nature Climate Change' , https://www.nature.com/articles/s41558-021-01038-1 and summarized by one of the authors in 'Carbon Brief', https://www.carbonbrief.org/cooling-effect-of-clouds-underestimated-by-climate-models-says-new-study?utm_campaign=Feed%3A%20carbonbrief%20%28The%20Carbon%20Brief%29&utm_content=20210604&utm_medium=feed&utm_source=feedburner . The authors discuss the formation of clouds and production of rainfall stressing that climate models have underestimated the cooling effect from clouds and that existing climate models need to be modified.

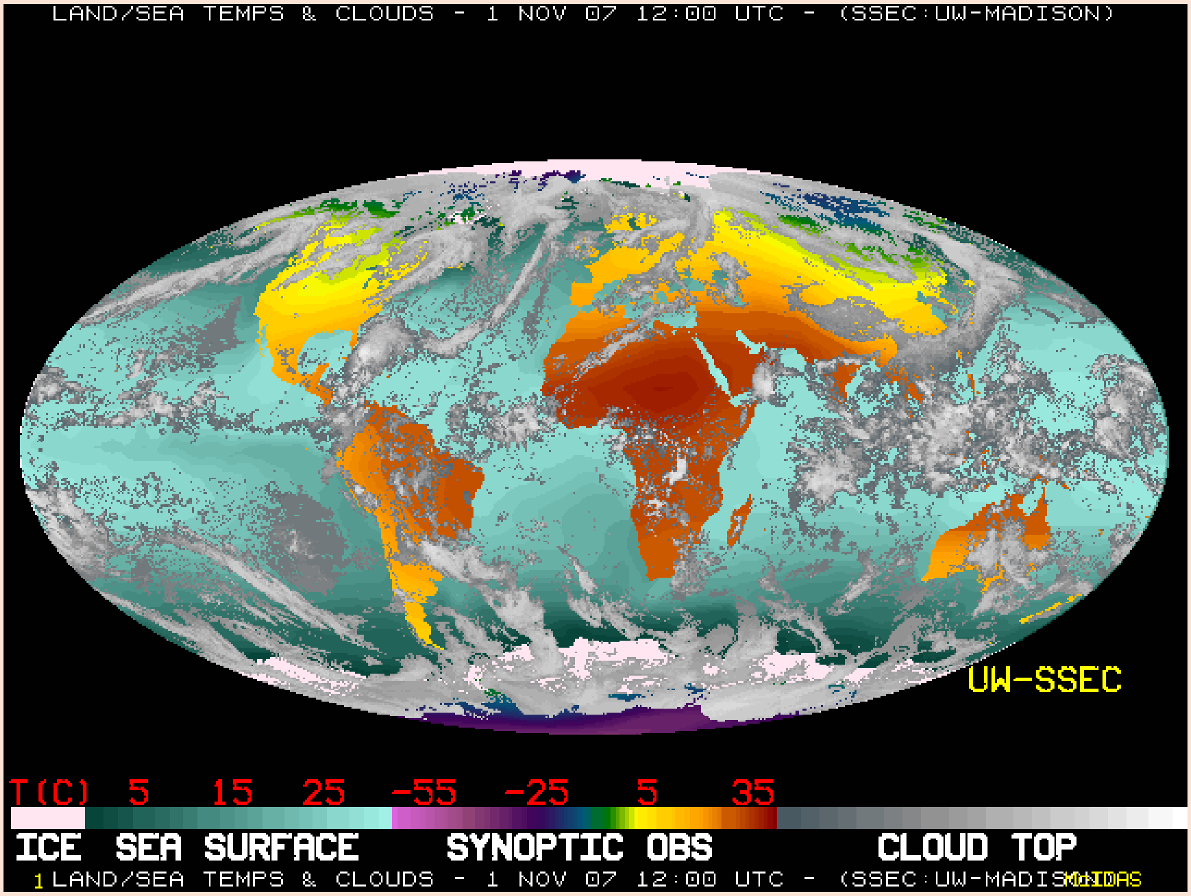

Figure 6.2 A satellite image of Earth showing the extent of reflecting cloud and ice cover.

6.5 Precipitation

These particles will grow in size to the point where they fall to the Earth surface (precipitate) as rain or snow (there are several other types of precipitation but they are minor in comparison to rain or snow). While in the atmosphere the moisture laden air and clouds are being transported by both the horizontal and vertical movement of air (atmospheric circulation) and the precipitation process may occur a very long distance from where the moisture originally entered the atmosphere. Water that is evaporated must also be precipitated. ‘What goes up must come down.’

6.7 Runoff

All precipitation will eventually return to the ocean. If it occurs over land surfaces it may drain over the surface (overland flow) or infiltrate into the soil and percolate into the groundwater where it will then drain into the oceans (groundwater flow). Snow may be stored for short periods of time, melt and then drain (seasonal accumulations); or, portions may accumulate to form ice sheets, ice caps or ice fields on the surface of land. The ice accumulations will also

exhibit seasonal melt and flow directly into the ocean or drain into the ocean as part of seasonal overland flow. Very large amounts of frozen water will flow directly into the oceans as part of ice streams and glaciers with marine termination that form ice bergs.
Water may evaporate or transpire (return to the atmosphere) and precipitate many times through local and regional hydrological cycles but all water will eventually return to the ocean. Local and regional hydrological cycles can be very important to local and regional environments. Snow accumulations will melt when the temperature of the air above the snow surface reaches or exceeds the melting temperature of ice, 0° C. The melting process may be accelerated with precipitation of warmer rain. Snow accumulations on plains regions, which are more-or-less at the same elevation, will melt at the same time and drain at the same time. Snow accumulations in mountainous regions will melt as the temperature at the different elevations reaches the melting point. The rate of melting and drainage will reach a maximum when the greatest snow-covered area is at or above the melting temperature and then gradually decrease.

A typical graph of overland flow in drainages that include both plains and mountainous regions is illustrated in Figure 6.2. As illustrated overland flow resulting from melting snow over plains regions will reach a maximum relatively quickly and will reduce to pre-melt conditions equally quickly. Overland flow resulting from melting snow over mountainous regions will reach a maximum more slowly and reduce to pre-melt conditions more slowly. Because snow accumulations over mountainous regions may be much greater than that on plains regions the volume of overland flow produced from the melting of snow accumulations from mountainous regions may be much greater than that of plains regions.

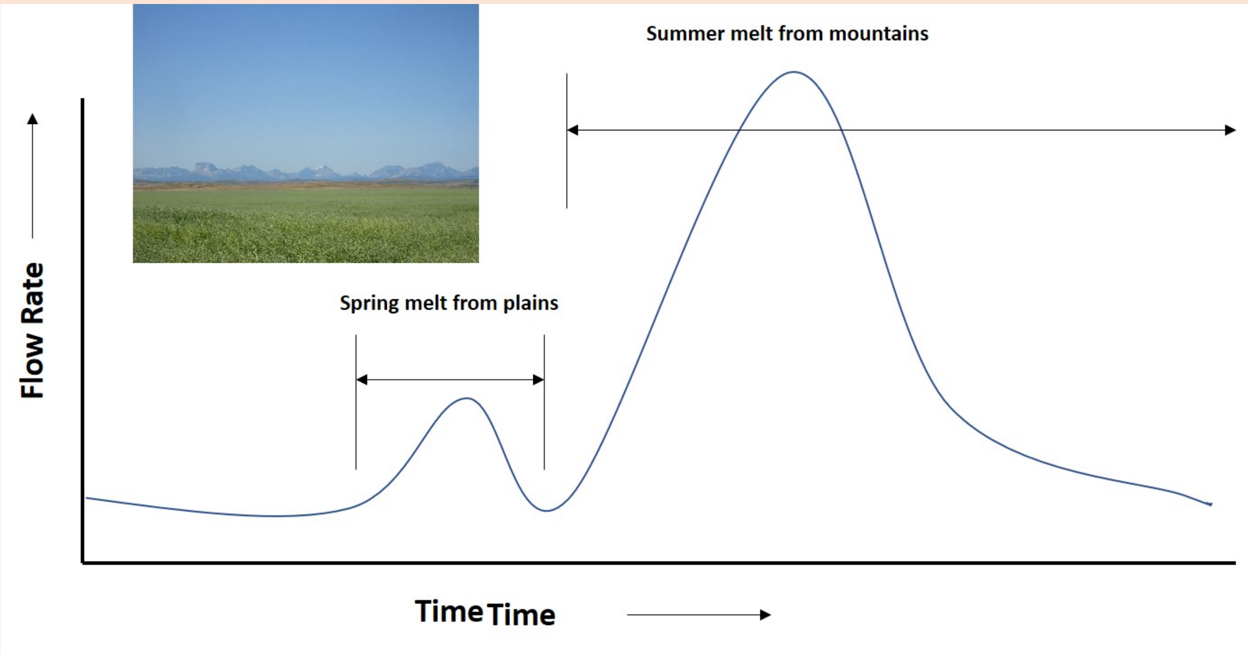

Figure 6.2 Graph showing surface runoff from melting snow from plains and mountainous regions.

The volume of snow melt and the manner with which it occurs has been predictable – particularly from mountainous regions. For this reason, humans have developed a dependency on the mountain melt for domestic and agricultural use. In some regions of the world mountain snow melt is captured using dams and reservoirs so that it can be gradually used for irrigation purposes or when the melt would be insufficient for domestic, municipal and industrial use. Melt water is often stored for generation of electricity.

6.8 Distribution of water on Earth

The distribution of water on Earth is shown in Figure 6.3. Note that 97% of the water is in the oceans (includes all forms of floating ice). The remaining 3% is divided between groundwater, 22%, and ice sheets, ice caps, ice streams, glaciers and inland seas, 77%. Very little is stored in rivers, lakes and the atmosphere. There is little opportunity for groundwater storage to change; but there is significant opportunity for water stored in ice sheets, ice caps, ice fields and glaciers to melt and become part of the oceans.

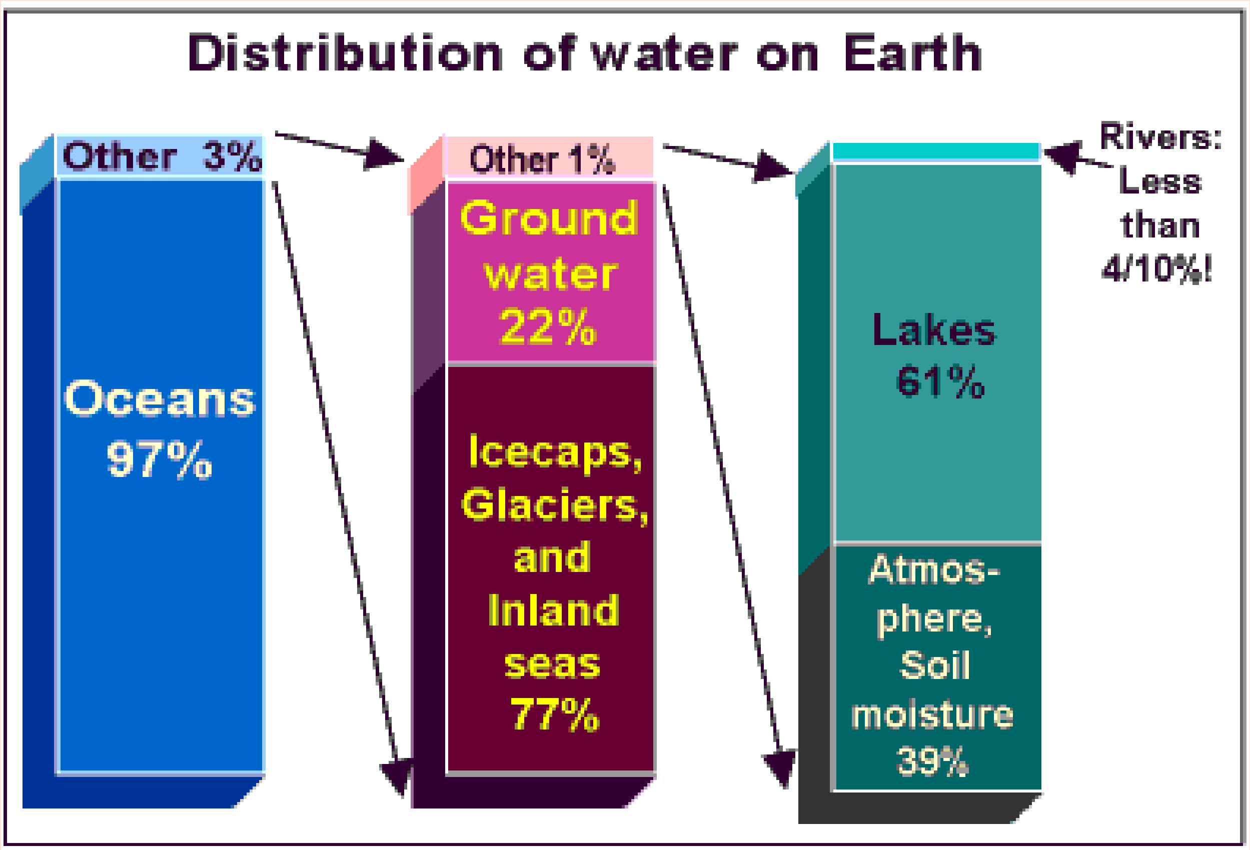

Figure 6.3 Distribution of water on Earth.

6.9 Ice caps, glaciers, ice streams, ice field, ice sheets, ice shelfs, sea ice

Ice caps are glaciers that cover an area of less than 50,000 square kilometres. See Figures 6.4 (a), (b) and (c). Ice caps that interconnected form an ice field. A glacier that is surrounded by mountain terrain is called a mountain glacier or alpine glacier. Glaciers that terminate in water may disintegrate to form ice bergs. Melt water from glaciers may form the headwater for streams and rivers which ultimately return the water to the ocean. Frequently the melt water will form a glacial lake which will overflow as it fills https://nsidc.org/cryosphere/icelights/2013/05/ebb-and-flow-glacial-lakes . The outflow capacity from a glacial lake must match the inflow rate. If it doesn't there is a danger of a glacial lake outburst which has the potential of damaging human activities downstream. The damage could include structures such as hydro-electric dams and their catastrophic failure. See video, https://www.youtube.com/watch?v=ZN8a-pP60wk .

Glaciers that flow directly into the ocean gradually break off in a process called calving. This is best explained by watching the video produced by NASA, https://www.youtube.com/watch?v=0QVVzFPChAU&feature=emb_logo.

Ice sheets have a surface area greater than 50,000 square kilometres. See Figure 6.5 and Figure 6.6. The most important examples are the Antarctic and Greenland ice sheets. They are also known as continental glaciers. The portion of the ice sheet that extends over water is known as an ice shelf.

Ice streams are a type of glacier flowing from an ice sheet (not to be confused with water flowing under or over the ice). Ice streams may flow into marine terminating glaciers or directly into the ocean itself. The flow of the ice stream may be slowed by a blocking ice shelf.
Ice shelves and ice streams disintegrate to form ice bergs.

Ice sheets and glaciers will gain or lose mass as a function of snow accumulation versus melting processes and iceberg calving.

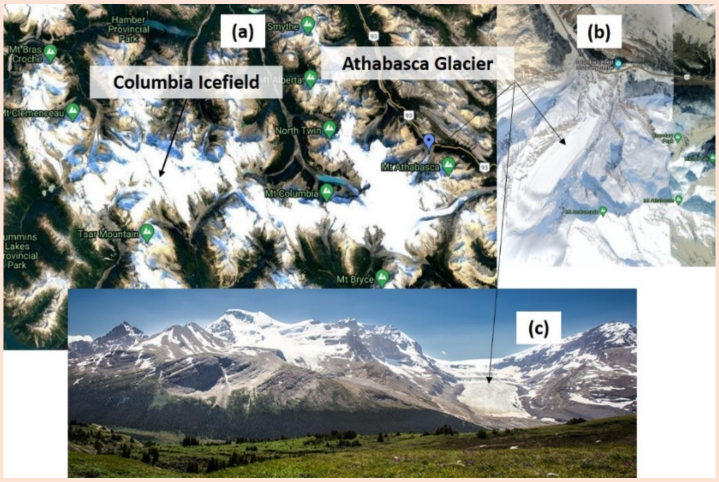

Figure 6.4 Columbia icefield, Canada and the Athabasca Glacier flowing from it.

Figure 6.5 Greenland ice sheet.

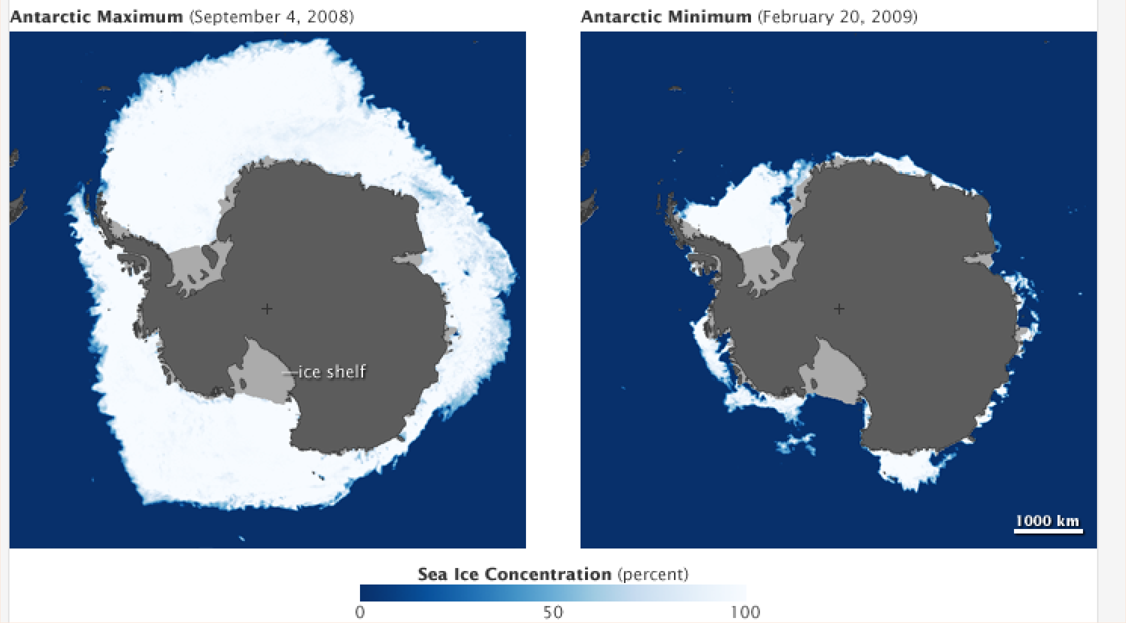

Figure 6.6 Antarctica ice sheet, sea ice and shelf.

Most floating sea ice is found in the Arctic. See Figure 6.7. The ice cover is divided into seasonal and permanent. Seasonal ice is formed during the winter months and melts during the summer. The permanent ice is replenished during the winter months and also melts during the summer. The area of permanent ice will increase or decrease with temperature of the atmosphere and ocean. Sea level is not affected by formation or melting of floating sea ice.

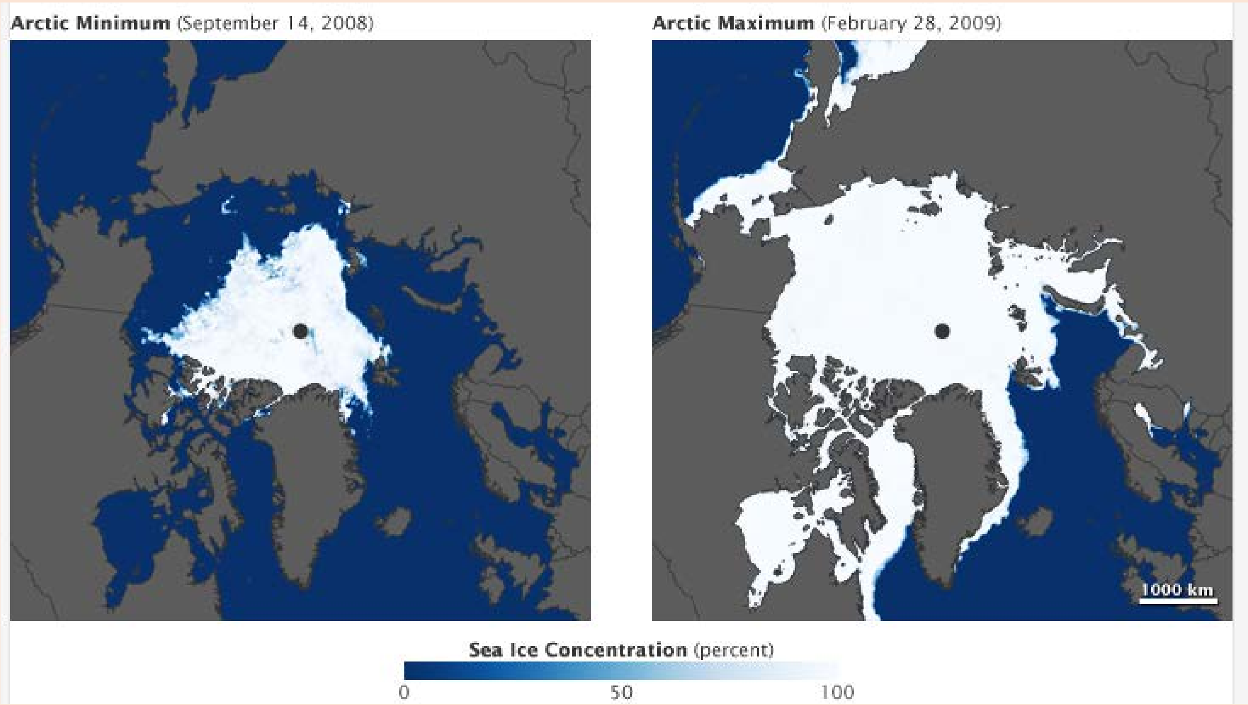

Figure 6.7 Floating sea ice in the Arctic.

While the volume of water entering the ocean is little when compared to the volume of water already stored in the oceans, should it melt or flow into the oceans, it is sufficient to raise the ocean surface level by over seventy metres. The volume of water stored in the Greenland ice sheet and Antarctic ice sheet are the most important. Sea levels would increase by at least six metres as result of the Greenland ice sheet melting and flowing into the ocean and an increase in the order of sixty metres as a result of the Antarctic ice sheet melting and flowing into the ocean.

6.10 Isotopes of oxygen, hydrogen, deuterium and water

Water will occur naturally with two molecular weights depending on whether the hydrogen atoms are combining with an oxygen atom containing eight neutrons known as oxygen 16 or ten neutrons known as oxygen 18 (isotopes of oxygen). These isotopes should not be confused with heavy water or deuterium oxide, D_2O, where the oxygen atom combines with two hydrogen atoms that include a neutron as well as a proton forming an atom known as deuterium, D.

Deuterium oxide is also naturally occurring but in very small quantities. Heavy water plays a very important role in the nuclear industry.
Water molecules containing oxygen 18 are heavier and require more energy to evaporate and will release more energy when they condense. The ratio of the water containing oxygen 16 to oxygen 18 in the oceans is constant. The amount of water containing oxygen 18 evaporating from the ocean surface increases or decreases in response to the rising or falling temperature of the ocean surface and the air above it. Water containing oxygen 18 will be the first to condense.

6.11 Information support

Key web sites:

1. Hydrology and water resources. https://www.ipcc.ch/site/assets/uploads/2018/03/wg2TARchap4.pdf

2. Hydrologic cycle. http://www.physicalgeography.net/fundamentals/5c_1.html

3. Cloud physics and their role in climate models, Prof. Ellie Highwood, guest post in the newsletter, 'Carbon Brief', https://www.carbonbrief.org/guest-post-why-clouds-hold-key-better-climate-models.

4. Clouds, journal 'Nature Climate Change', https://www.nature.com/articles/s41558-021-01038-1 and newsletter, 'Carbon Brief', https://www.carbonbrief.org/cooling-effect-of-clouds-underestimated-by-climate-models-says-new-study?utm_campaign=Feed%3A%20carbonbrief%20%28The%20Carbon%20Brief%29&utm_content=20210604&utm_medium=feed&utm_source=feedburner

5. Glacial lakes. https://nsidc.org/cryosphere/icelights/2013/05/ebb-and-flow-glacial-lakes

6. Antarctic glaciers. http://www.antarcticglaciers.org/

7. Ice field. https://en.wikipedia.org/wiki/Ice_field#:~:text=An%20ice%20field%20%28also%20spelled%20icefield%29%20is%20a,there%20is%20sufficient%20precipitation%20for%20them%20to%20form

8. Global volume of land ice and how it is changing. http://www.antarcticglaciers.org/glaciers-and-climate/what-is-the-global-volume-of-land-ice-and-how-is-it-changing/

9. Columbia Icefield area and Athabasca Glacier. https://www.pc.gc.ca/en/pn-np/ab/jasper/activ/itineraires-itineraries/glacier-athabasca

10. Ice fields and ice caps. https://www.nps.gov/articles/icefieldsicecaps.htm

11. Glaciers and icecaps. https://www.usgs.gov/special-topic/water-science-school/science/glaciers-and-icecaps?qt-science_center_objects=0#qt-science_center_objects

12. Quick facts on ice sheets. https://nsidc.org/cryosphere/quickfacts/icesheets.html

13. Greenland ice sheet today. http://nsidc.org/greenland-today/

14. Antarctica. https://en.wikipedia.org/wiki/Antarctica

15. What is Antarctica? https://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-antarctica-k4.html

13. Ice shelves. https://nsidc.org/cryosphere/sotc/iceshelves.html

14. Sea level rise from ice sheets track worst-case climate change scenario. https://www.sciencedaily.com/releases/2020/08/200831112101.htm

15. Thwaites glacier. https://en.wikipedia.org/wiki/Thwaites_Glacier

16. Ice stream. https://en.wikipedia.org/wiki/Ice_stream#:~:text=A%20fast%2Dmoving%20ice%20or,are%20a%20type%20of%20glacier.&text=Most%20ice%20streams%20have%20some,base%2C%20which%20lubricates%20the%20flow.

17. Global ice viewer. https://climate.nasa.gov/interactives/global-ice-viewer/#/

18. Glacier. https://www.nationalgeographic.org/encyclopedia/glacier/

19. Glacier. https://en.wikipedia.org/wiki/Glacier

Video:

1. How a glacier melts and calves into the ocean, NASA. https://www.youtube.com/watch?v=0QVVzFPChAU&feature=emb_logo

2. The most dangerous lake in Nepal. https://www.youtube.com/watch?v=ZN8a-pP60wk

3. Imja Lake: A story of climate adaptation in Nepal. https://www.youtube.com/watch?v=z7GKW-u-Gg4

4. Glacial outburst incident in Garhwal on 7th February 2021., https://www.indiatoday.in/india/video/glacier-burst-leads-to-massive-flash-flood-in-uttarakhand-1766802-2021-02-07