what is the cryosphere...?

DEFINITION: the components of the earth system that contain a substantial fraction of water in a frozen state

COMPONENTS: in this report → SIX components

1. sea ice
2. glaciers
3. ice sheets
4. snow
5. lake/river ice
6. frozen ground

some clarifications...

- glaciers vs ice sheets vs ice shelves
- frozen ground, permafrost, active layer

Sea ice: Ice found at the sea surface that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice concentration is the fraction of the ocean covered by ice.

Glacier: A perennial mass of land ice that originates from compressed snow, shows evidence of past or present flow (through internal deformation and/or sliding at the base) and is constrained by internal stress and friction at the base and sides. A glacier is maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes and/or discharge into the sea. An ice mass of the same origin as glaciers, but of continental size, is called an ice sheet. For the purpose of simplicity in this Assessment Report, all ice masses other than ice sheets are referred to as glaciers.

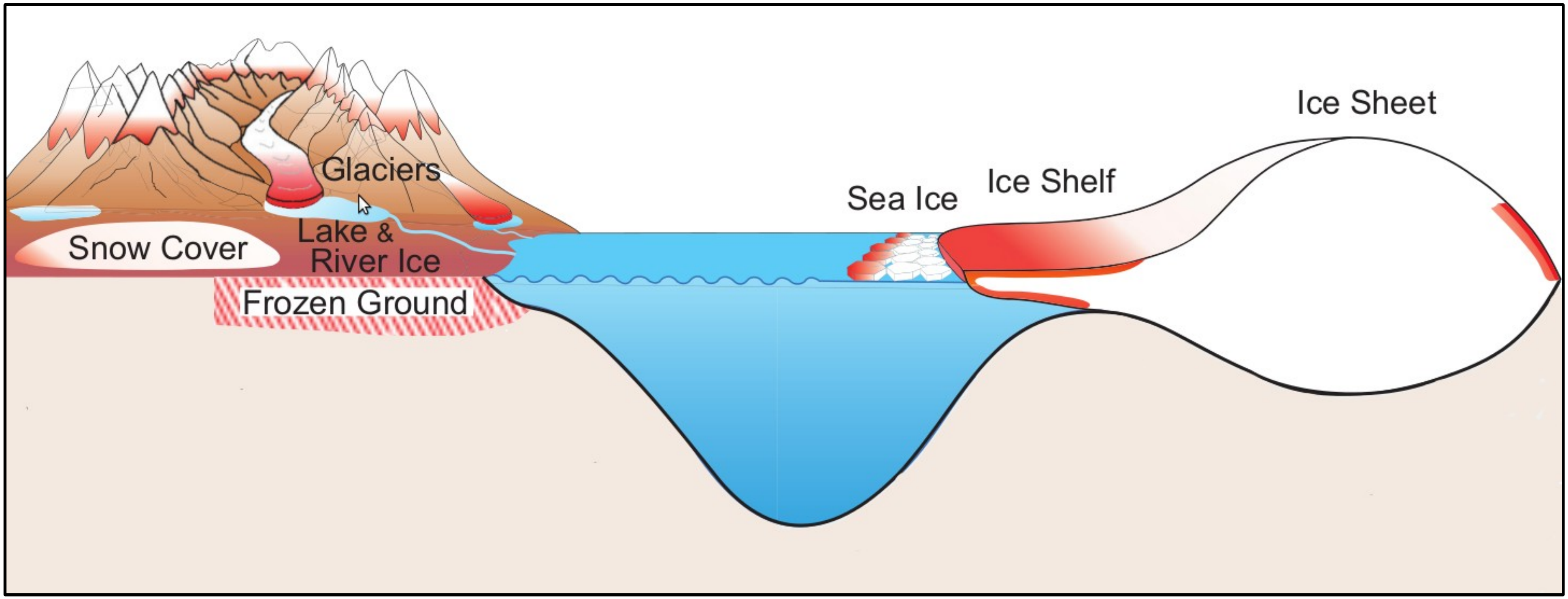
ice sheets

Ice sheet: A mass of land ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are only two ice sheets in the modern world, one on Greenland and one on Antarctica. During glacial periods there were others.

ice shelves vs. ice sheets

Ice shelf: A floating slab of ice of considerable thickness extending from the coast (usually of great horizontal extent with a very gently sloping surface), often filling embayments in the coastline of an ice sheet. Nearly all ice shelves are in Antarctica, where most of the ice discharged into the ocean flows via ice shelves.

summary sketch



THE CRYOSPHERE

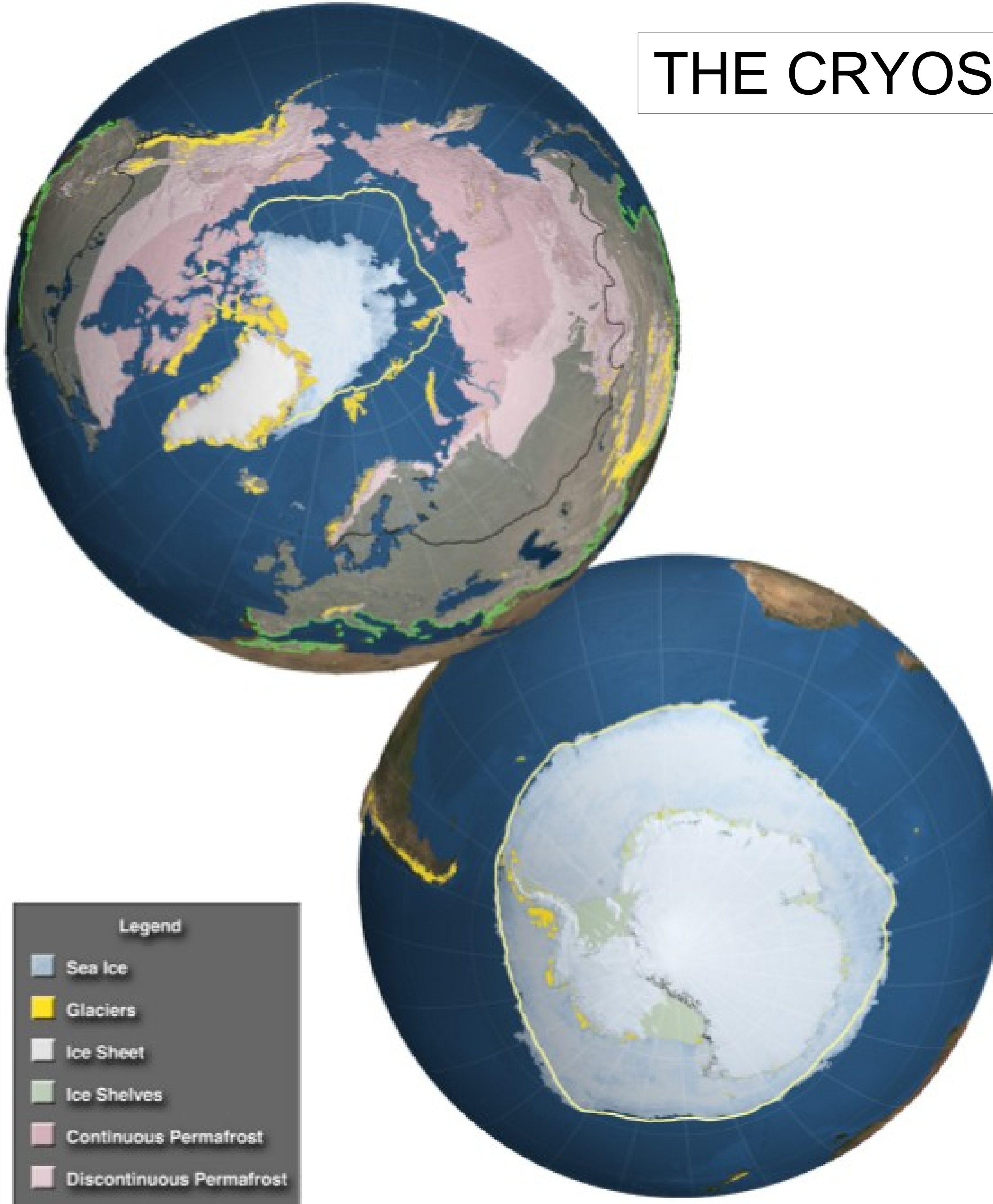


Figure 4.1

caption to Fig. 4.1

Figure 4.1 | The cryosphere in the Northern and Southern Hemispheres in polar projection. The map of the Northern Hemisphere shows the sea ice cover during minimum summer extent (13 September 2012). The yellow line is the average location of the ice edge (15% ice concentration) for the yearly minima from 1979 to 2012. Areas of continuous permafrost (see Glossary) are shown in dark pink, discontinuous permafrost in light pink. The green line along the southern border of the map shows the maximum snow extent while the black line across North America, Europe and Asia shows the 50% contour for frequency of snow occurrence. The Greenland ice sheet (blue/grey) and locations of glaciers (small gold circles) are also shown. The map of the Southern Hemisphere shows approximately the maximum sea ice cover during an austral winter (13 September 2012). The yellow line shows the average ice edge (15% ice concentration) during maximum extent of the sea ice cover from 1979 to 2012. Some of the elements (e.g., some glaciers and snow) located at low latitudes are not visible in this projection (see Figure 4.8). The source of the data for sea ice, permafrost, snow and ice sheet are data sets held at the National Snow and Ice Data Center (NSIDC), University of Colorado, on behalf of the North American Atlas, Instituto Nacional de Estadística, Geografía e Informática (Mexico), Natural Resources Canada, U.S. Geological Survey, Government of Canada, Canada Centre for Remote Sensing and The Atlas of Canada. Glacier locations were derived from the multiple data sets compiled in the Randolph Glacier Inventory (Arendt et al., 2012).

where is the frozen stuff...?

Table 4.1 | Representative statistics for cryospheric components indicating their general significance.

Ice on Land	Percent of Global Land Surface[a]	Sea Level Equivalent[b] (metres)
Antarctic ice sheet[c]	8.3	58.3
Greenland ice sheet[d]	1.2	7.36
Glaciers[e]	0.5	0.41
Terrestrial permafrost[f]	9–12	0.02–0.10[g]
Seasonally frozen ground[h]	33	Not applicable
Seasonal snow cover (seasonally variable)[i]	1.3–30.6	0.001–0.01
Northern Hemisphere freshwater (lake and river) ice[j]	1.1	Not applicable
Total[k]	**52.0–55.0%**	**~66.1**
Ice in the Ocean	**Percent of Global Ocean Area[a]**	**Volume[l] (10^3 km^3)**
Antarctic ice shelves	0.45[m]	~380
Antarctic sea ice, austral summer (spring)[n]	0.8 (5.2)	3.4 (11.1)
Arctic sea ice, boreal autumn (winter/spring)[n]	1.7 (3.9)	13.0 (16.5)
Sub-sea permafrost[o]	~0.8	Not available
Total[p]	**5.3–7.3**	

Table 4.1

an interesting point...

Changes in the longer-lived components of the cryosphere (e.g., glaciers) are the result of an integrated response to climate, and the cryosphere is often referred to as a ‘natural thermometer’...

...The cryosphere is, however, NOT simply a passive indicator of climate change; changes in each component of the cryosphere have a significant and lasting impact on physical, biological and social systems.

item 1 → sea ice: why do we care about it?

because sea ice cover on the ocean...

+ changes surface albedo

+ insulates the ocean from heat loss

+ provides a barrier to exchange ($CO2$, $H20$, etc)

also, salt ejected during sea ice formation alters the density of sea water and modifies the ocean circulation

Arctic sea ice extent 1979-2012

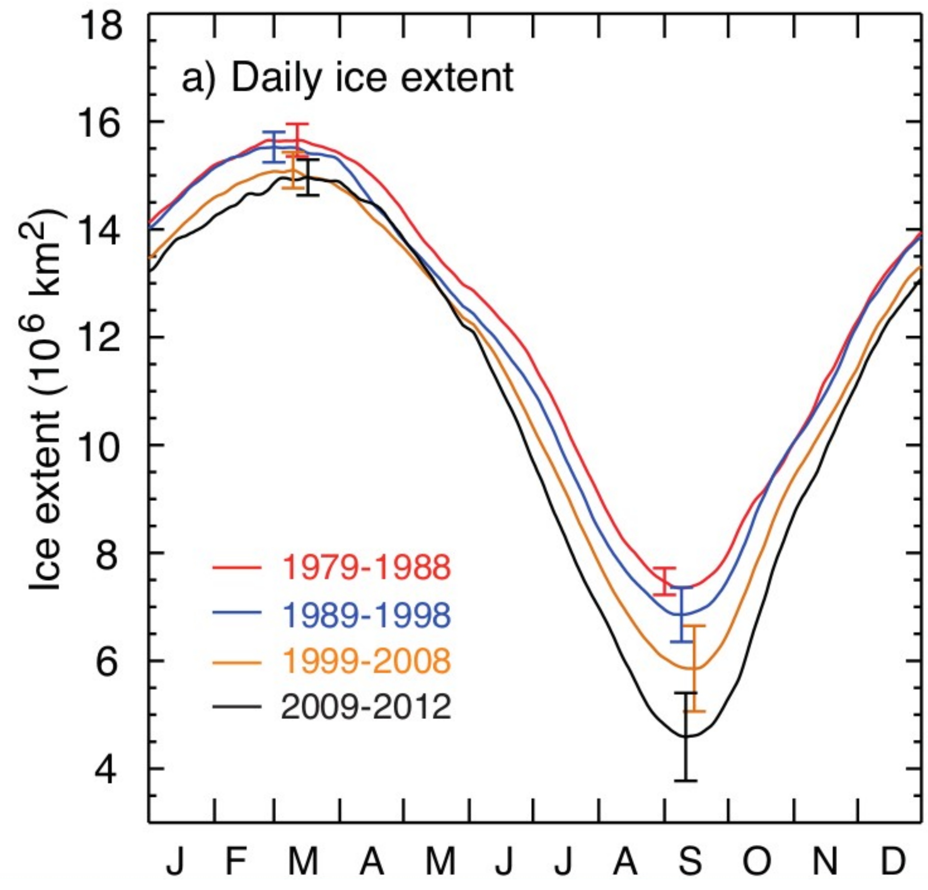


Figure 4.2a

Figure 4.2 | (a) Plots of decadal averages of daily sea ice extent in the Arctic (1979 to 1988 in red, 1989 to 1998 in blue, 1999 to 2008 in gold) and a 4-year average daily ice extent from 2009 to 2012 in black. Maps indicate ice concentration trends (1979–2012) in (b) winter, (c) spring, (d) summer and (e) autumn (updated from Comiso, 2010).

some more definitions...

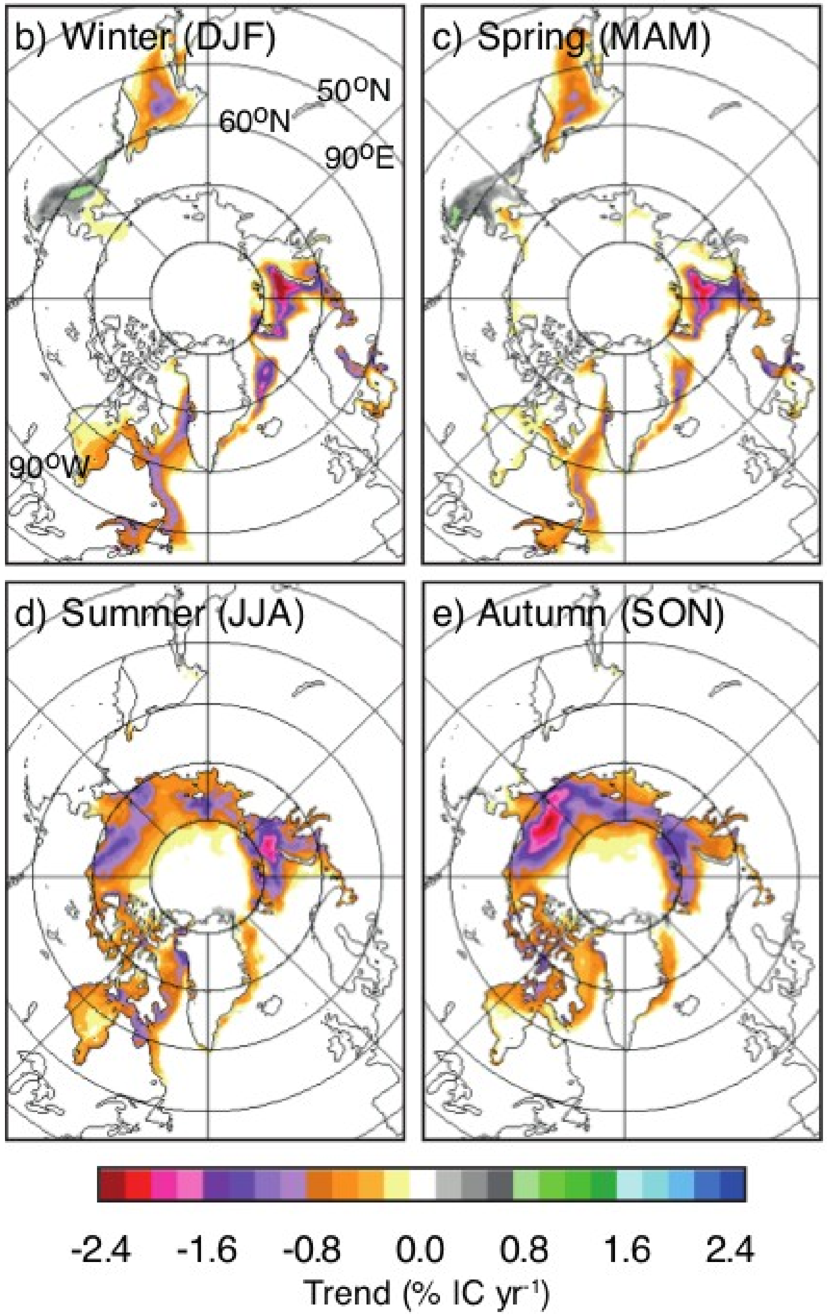
Sea ice concentration is the fraction of the ocean covered by ice in each data element (some lat/lon box, or pixel, or whatever).

Sea ice extent is defined as the sum of ice covered areas with concentrations of at least 15%.

Sea ice area is the product of the ice concentration and area of each data element within the ice extent.

sea ice concentration trends 1979-2012

Figure 4.2b



"This large spatial variability is associated with the complexity of the atmospheric and oceanic circulation system as manifested in the Arctic Oscillation (Thompson and Wallace, 1998)."

what does that mean...?!?!?

Arctic sea ice extent trends 1979-2012

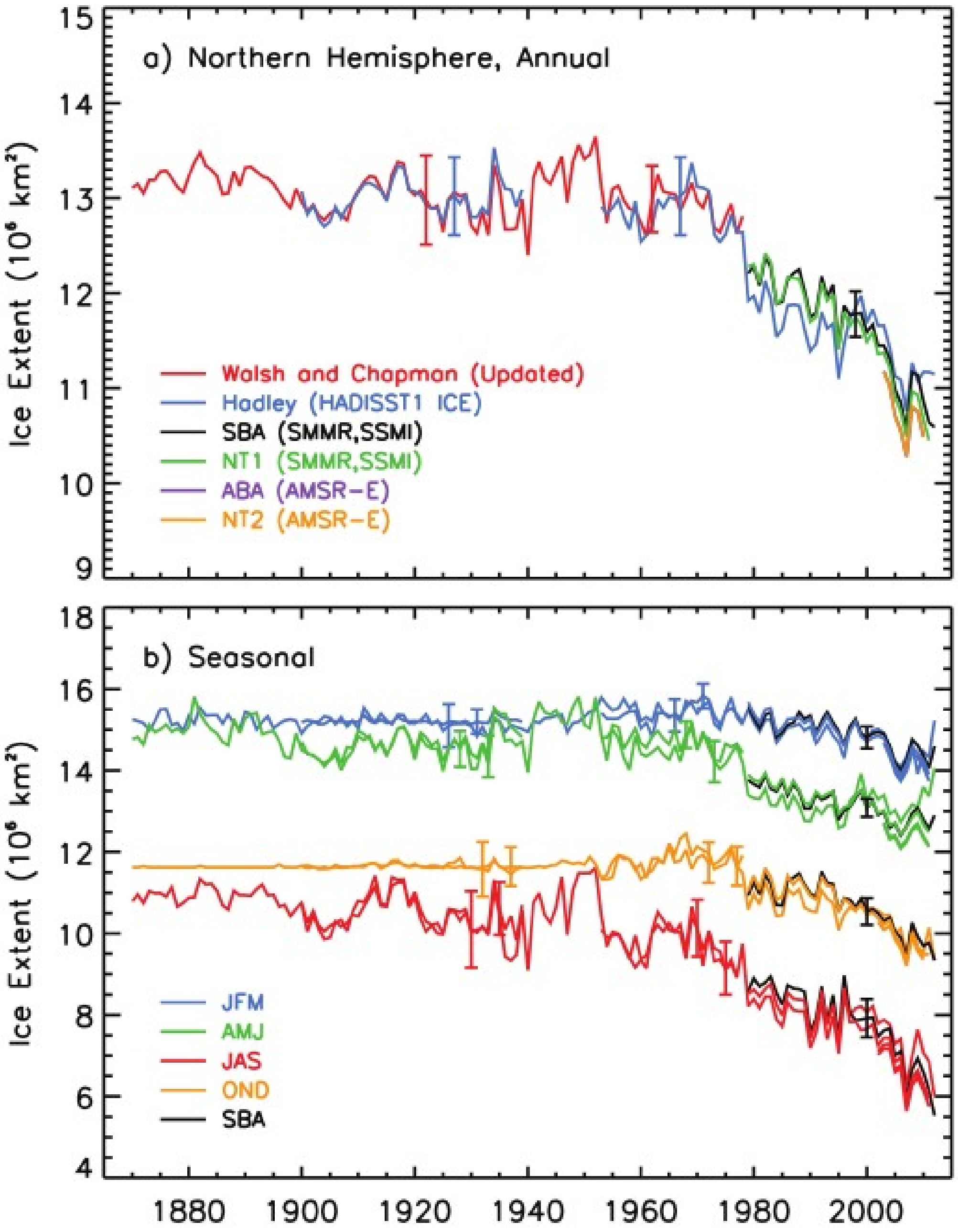


Figure 4.3

Figure 4.3 | Ice extent in the Arctic from 1870 to 2011. (a) Annual ice extent and (b) seasonal ice extent using averages of mid-month values derived from *in situ* and other sources including observations from the Danish meteorological stations from 1870 to 1978 (updated from, Walsh and Chapman, 2001). Ice extent from a joint Hadley and National Oceanic and Atmospheric Administration (NOAA) project (called HADISST1_Ice) from 1900 to 2011 is also shown. The yearly and seasonal averages for the period from 1979 to 2011 are shown as derived from Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) passive microwave data using the Bootstrap Algorithm (SBA) and National Aeronautics and Space Administration (NASA) Team Algorithm, Version 1 (NT1), using procedures described in Comiso and Nishio (2008), and Cavalieri et al. (1984), respectively; and from Advanced Microwave Scanning Radiometer, Version 2 (AMSR2) using algorithms called AMSR Bootstrap Algorithm (ABA) and NASA Team Algorithm, Version 2 (NT2), described in Comiso and Nishio (2008) and Markus and Cavalieri (2000). In (b), data from the different seasons are shown in different colours to illustrate variation between seasons, with SBA data from the procedure in Comiso and Nishio (2008) shown in black.

central Arctic sea ice trends 1979-2012

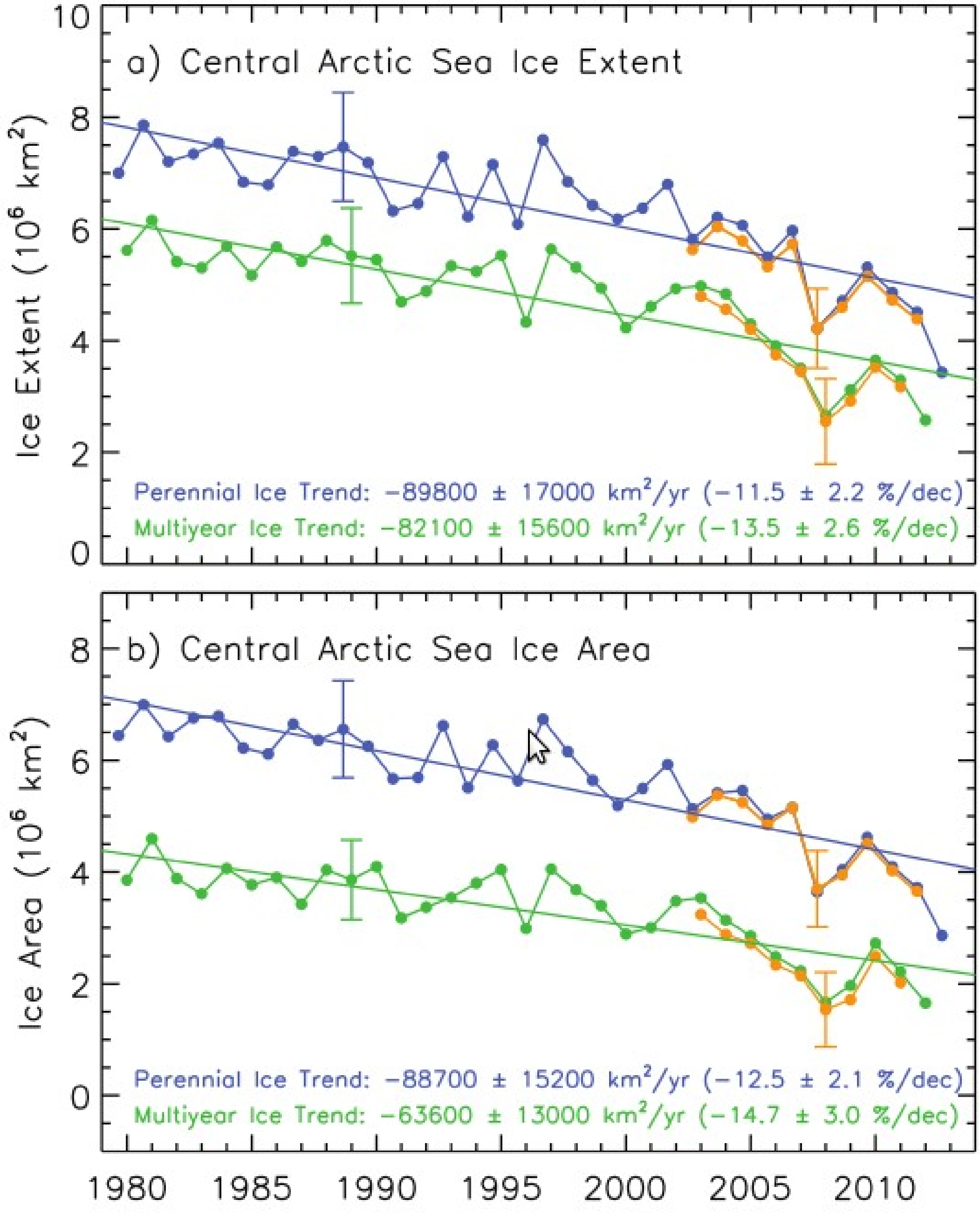


Figure 4.4

Figure 4.4 | Annual perennial (blue) and multi-year (green) sea ice extent (a) and sea ice area (b) in the Central Arctic from 1979 to 2012 as derived from satellite passive microwave data (updated from Comiso, 2012). Perennial ice values are derived from summer minimum ice extent, while the multi-year ice values are averages of those from December, January and February. The gold lines (after 2002) are from AMSR-E data. Uncertainties in the observations (*very likely* range) are indicated by representative error bars, and uncertainties in the trends are given (*very likely* range).

Sea ice: Ice found at the sea surface that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice concentration is the fraction of the ocean covered by ice. Sea ice less than one year old is called first-year ice. Perennial ice is sea ice that survives at least one summer. It may be subdivided into second-year ice and multi-year ice, where multiyear ice has survived at least two summers.

Arctic sea ice thickness and 2004-08 trends

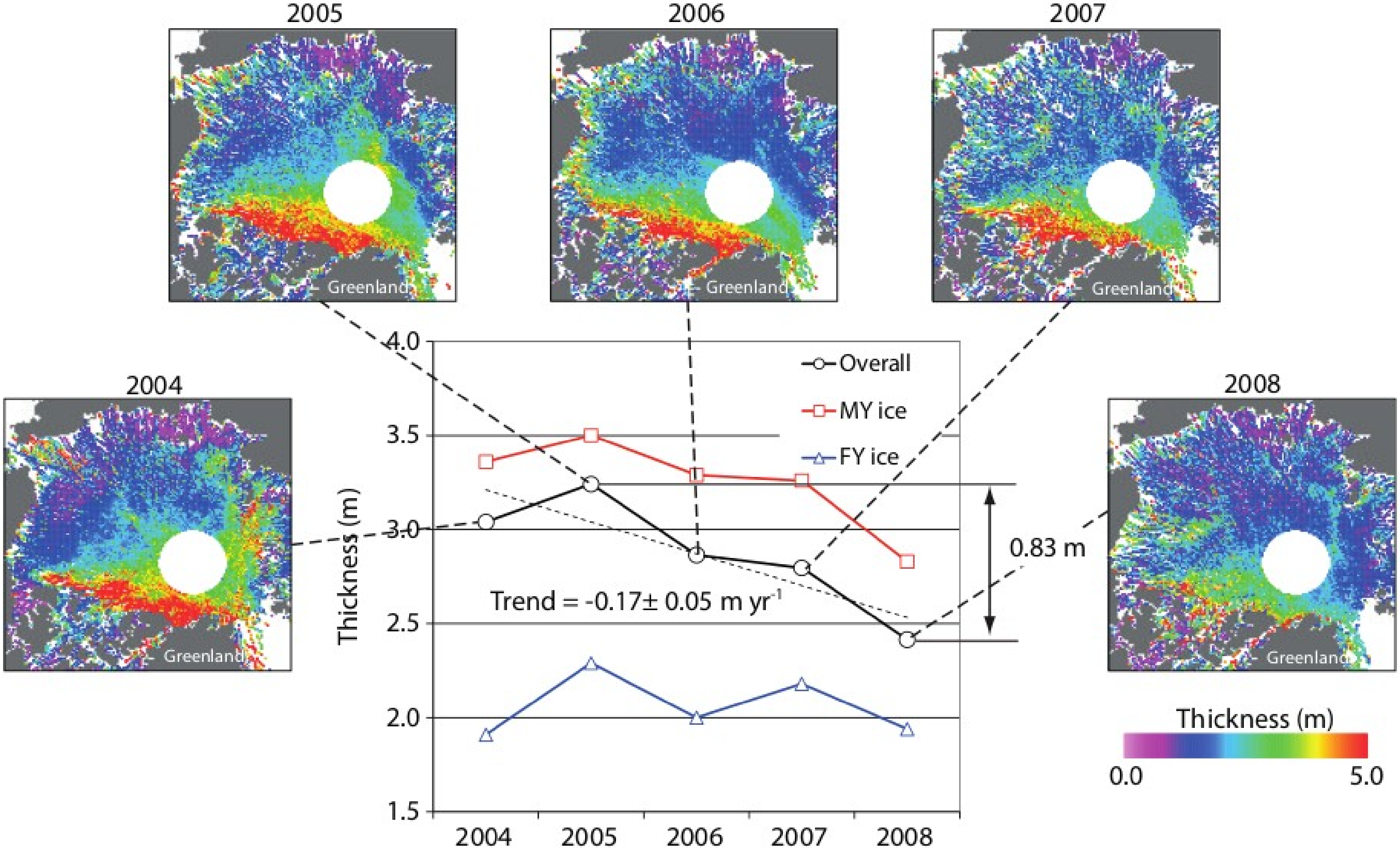
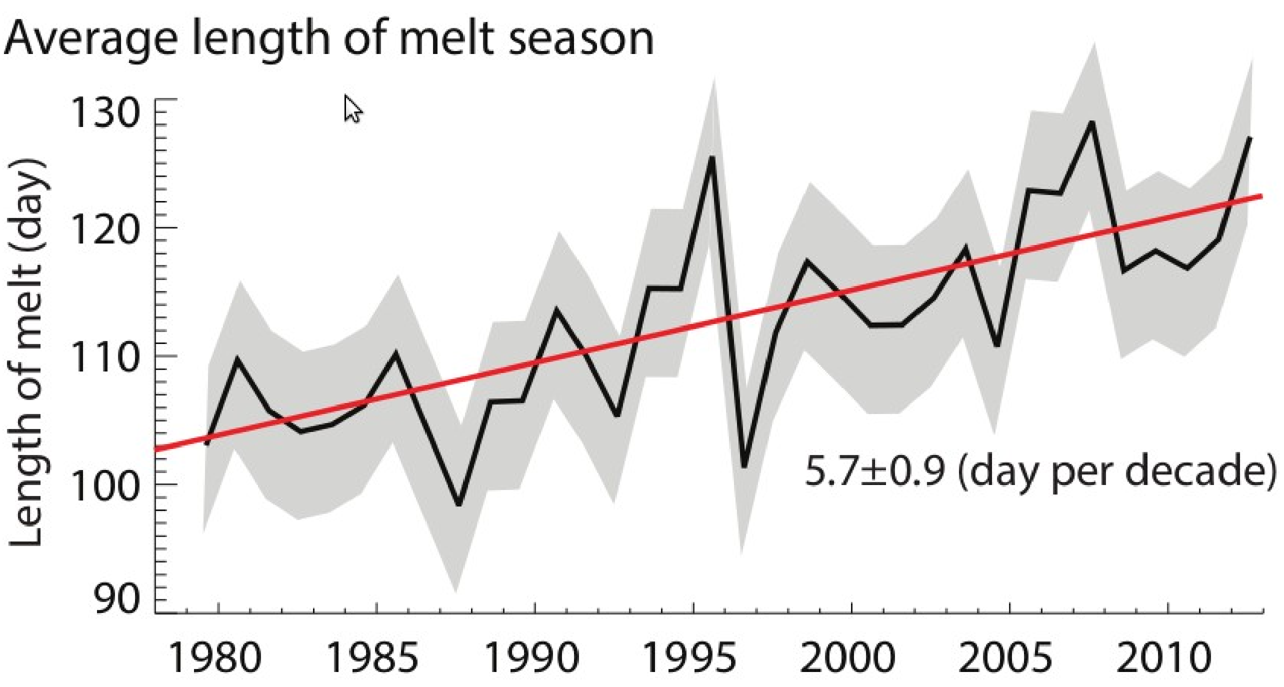


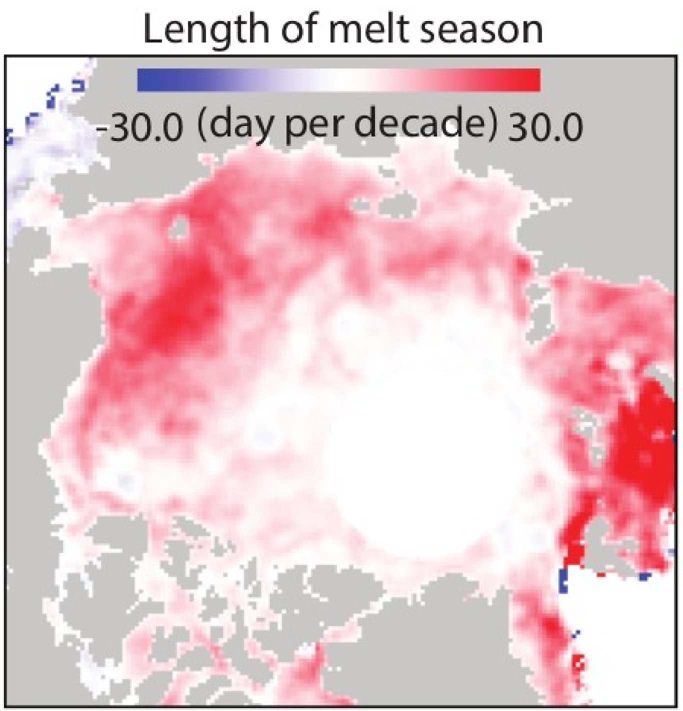
Figure 4.5 | The distribution of winter sea ice thickness in the Arctic and the trends in average, first-year (FY and multi-year (MY) ice thickness derived from ICESat data between 2004 and 2008 (Kwok, 2009).

Figure 4.5

trends in length of Arctic melt season

Figure 4.6e





AA vs A sea ice

Antarctic sea ice is

– mostly first year ice

– largely seasonal: SIE varies from 3 in Feb
to 18 in Sep (x10e6 km^2)

– thinner, warmer, saltier that Arctic ice

– not enclosed by land

A and AA sea ice extent 1979-2012

ARCTIC

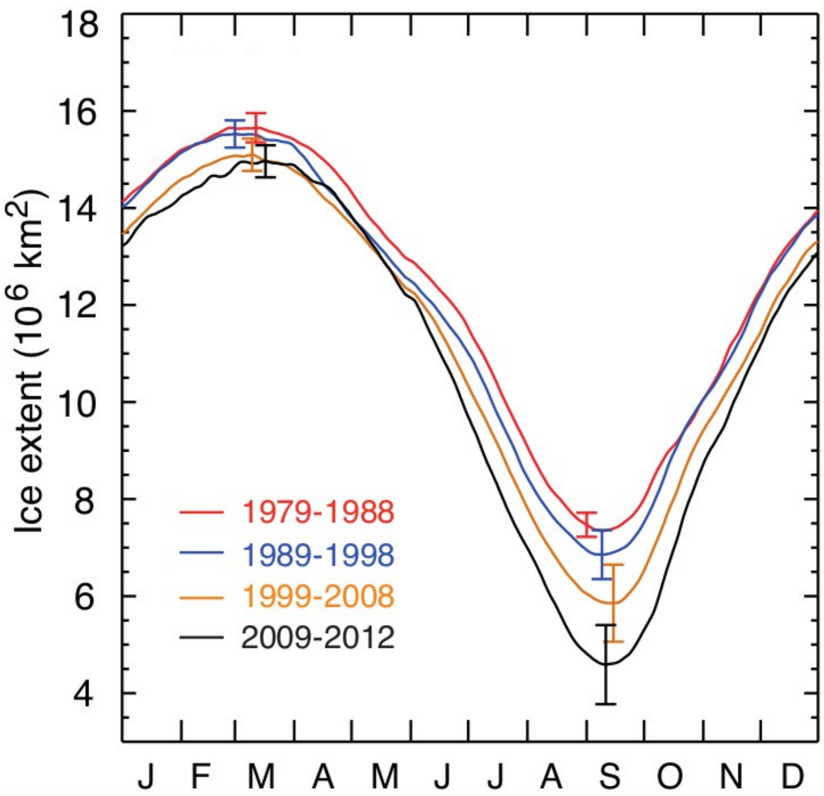


Figure 4.2a

ANTARCTIC

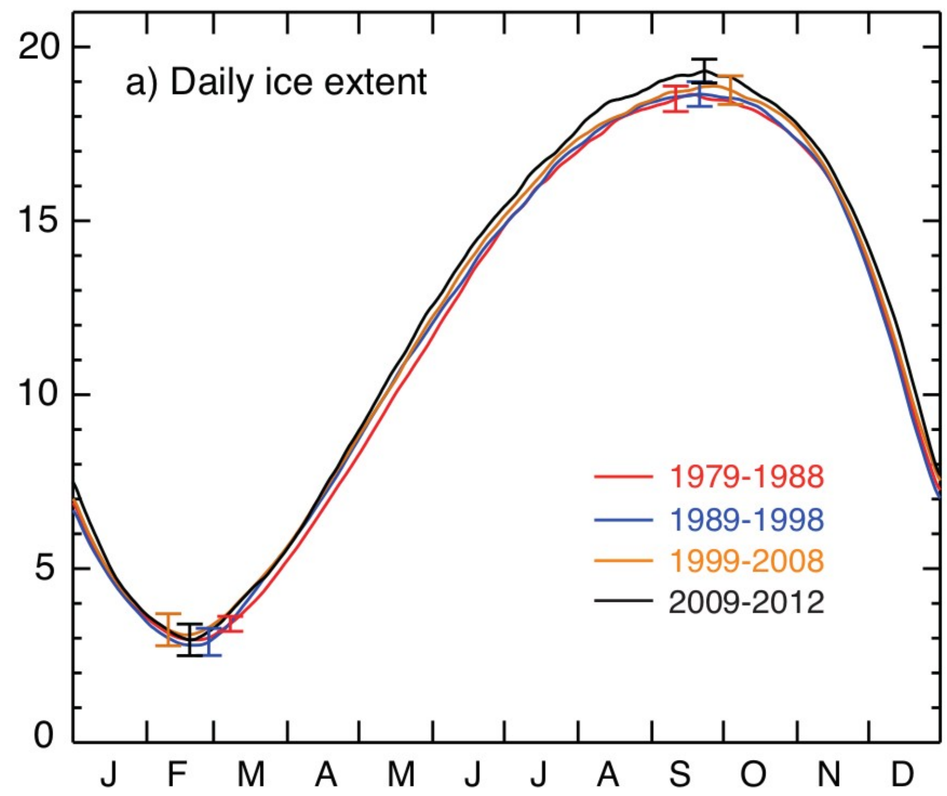


Figure 4.7a

AA sea ice concentration trends 1979-2012

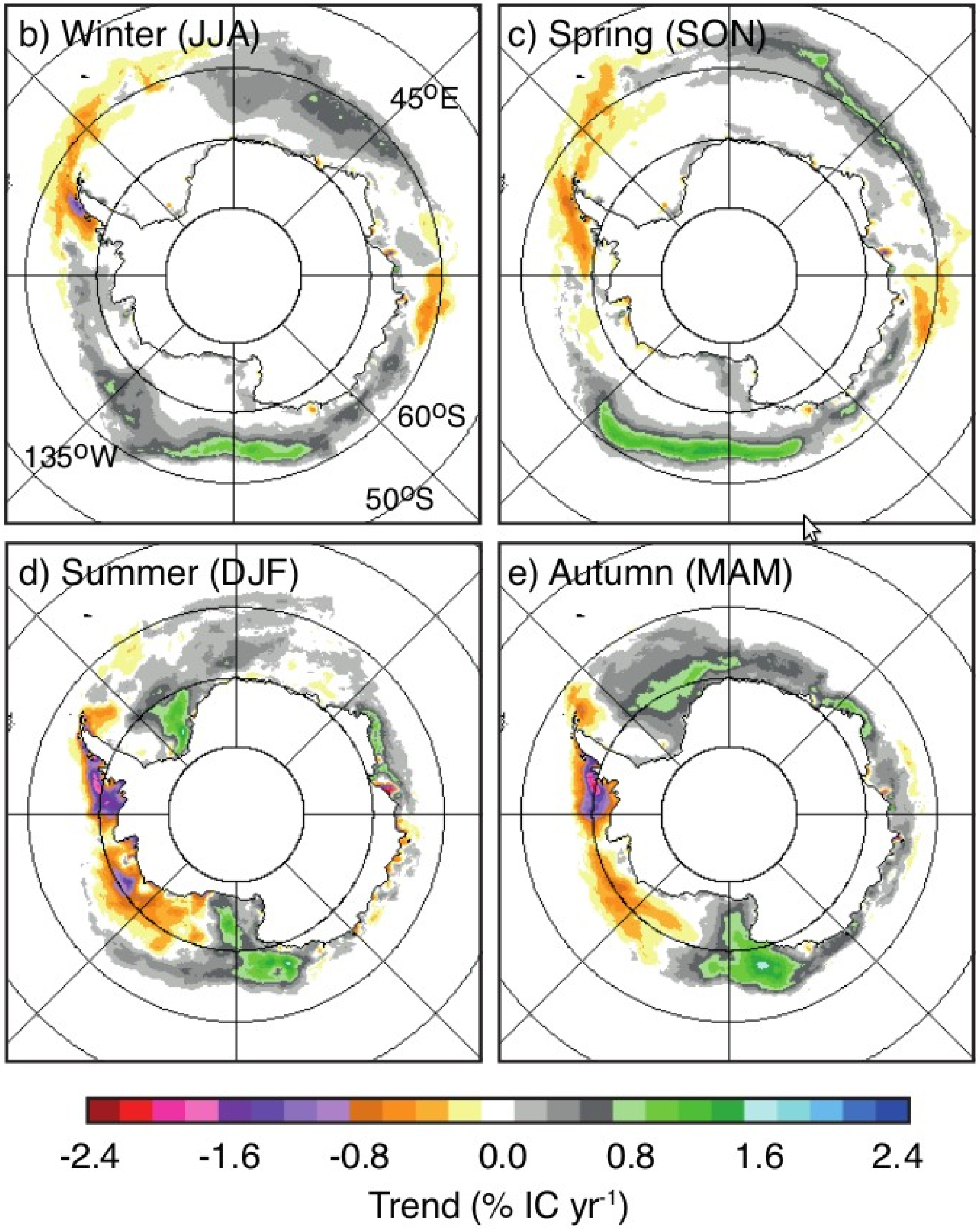
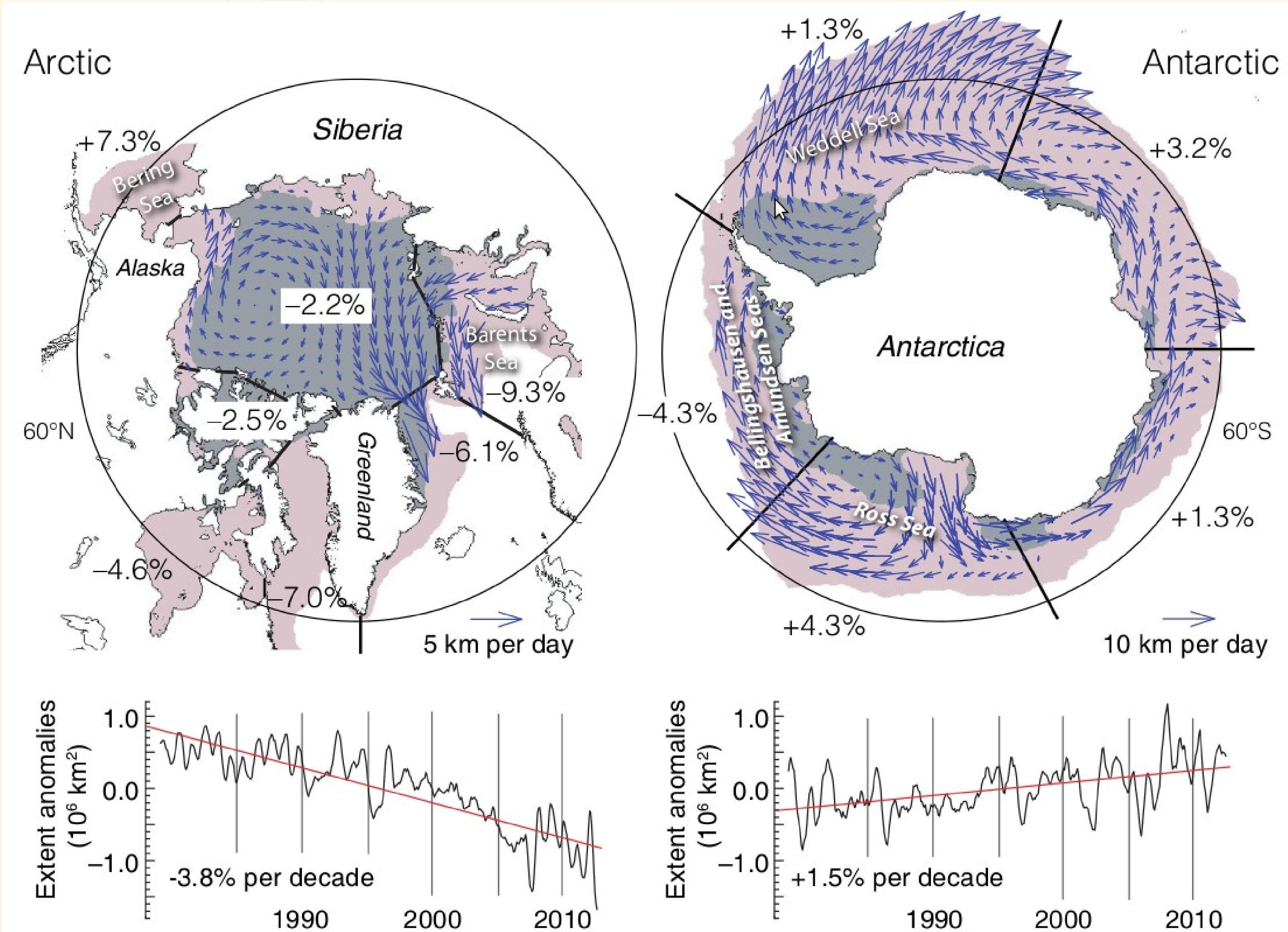


Figure 4.7b

Figure 4.7 | (a) Plots of decadal averages of daily sea ice extent in the Antarctic (1979–1988 in red, 1989–1998 in blue, 1999– 2008 in gold) and a 4-year average daily ice extent from 2009 to 2012 in black. Maps indicate ice concentration trends (1979–2012) in (b) winter, (c) spring, (d) summer and (e) autumn (updated from Comiso, 2010).



FAQ 4.1, Figure 1 | The mean circulation pattern of sea ice and the decadal trends (%) in annual anomalies in ice extent (i.e., after removal of the seasonal cycle), in different sectors of the Arctic and Antarctic. Arrows show the average direction and magnitude of ice drift. The average sea ice cover for the period 1979 through 2012, from satellite observations, at maximum (minimum) extent is shown as orange (grey) shading.

item 2 – GLACIERS

– perennial surface land ice masses
(except Greenland and Antarctic ice sheets)

– sum of *accumulation* and *ablation* → *mass balance*
– *accumulation:* mostly precip
– *ablation:* mostly surface melting and runoff

– new "inventory" of glaciers compiled for AR5
– a set of 19 distinct regions

Table 4.2 | The 19 regions used throughout this chapter and their respective glacier numbers and area (absolute and in percent) are derived from the RGI 2.0 (Arendt et al., 2012); the tidewater fraction is from Gardner et al. (2013). The minimum and maximum values of glacier mass are the minimum and maximum of the estimates given in four studies: Grinsted (2013), Huss and Farinotti (2012), Marzeion et al. (2012) and Radić et al. (2013). The mean sea level equivalent (SLE) of the mean glacier mass is the mean of estimates from the same four studies, using an ocean area of 362.5×10^6 km^2 for conversion. All values were derived with globally consistent methods; deviations from more precise national data sets are thus possible. Ongoing improvements may lead to revisions of these (RGI 2.0) numbers in future releases of the RGI.

Region	Region Name	Number of Glaciers	Area (km^2)	Percent of total area	Tidewater fraction (%)	Mass (minimum) (Gt)	Mass (maximum) (Gt)	Mean SLE (mm)
1	Alaska	23,112	89,267	12.3	13.7	16,168	28,021	54.7
2	Western Canada and USA	15,073	14,503.5	2.0	0	906	1148	2.8
3	Arctic Canada North	3318	103,990.2	14.3	46.5	22,366	37,555	84.2
4	Arctic Canada South	7342	40,600.7	5.6	7.3	5510	8845	19.4
5	Greenland	13,880	87,125.9	12.0	34.9	10,005	17,146	38.9
6	Iceland	290	10,988.6	1.5	0	2390	4640	9.8
7	Svalbard	1615	33,672.9	4.6	43.8	4821	8700	19.1
8	Scandinavia	1799	2833.7	0.4	0	182	290	0.6
9	Russian Arctic	331	51,160.5	7.0	64.7	11,016	21,315	41.2
10	North Asia[a]	4403	3425.6	0.4	0	109	247	0.5
11	Central Europe	3920	2058.1	0.3	0	109	125	0.3
12	Caucasus	1339	1125.6	0.2	0	61	72	0.2
13	Central Asia	30,200	64,497	8.9	0	4531	8591	16.7
14	South Asia (West)	22,822	33,862	4.7	0	2900	3444	9.1
15	South Asia (East)	14,006	21,803.2	3.0	0	1196	1623	3.9
16	Low Latitudes[a]	2601	2554.7	0.6	0	109	218	0.5
17	Southern Andes[a]	15,994	29,361.2	4.5	23.8	4241	6018	13.5
18	New Zealand	3012	1160.5	0.2	0	71	109	0.2
19	Antarctic and Sub-Antarctic	3274	13,2267.4	18.2	97.8	27,224	43,772	96.3
	Total	168,331	726,258.3		38.5	113,915	191,879	412.0

global distribution of glaciers

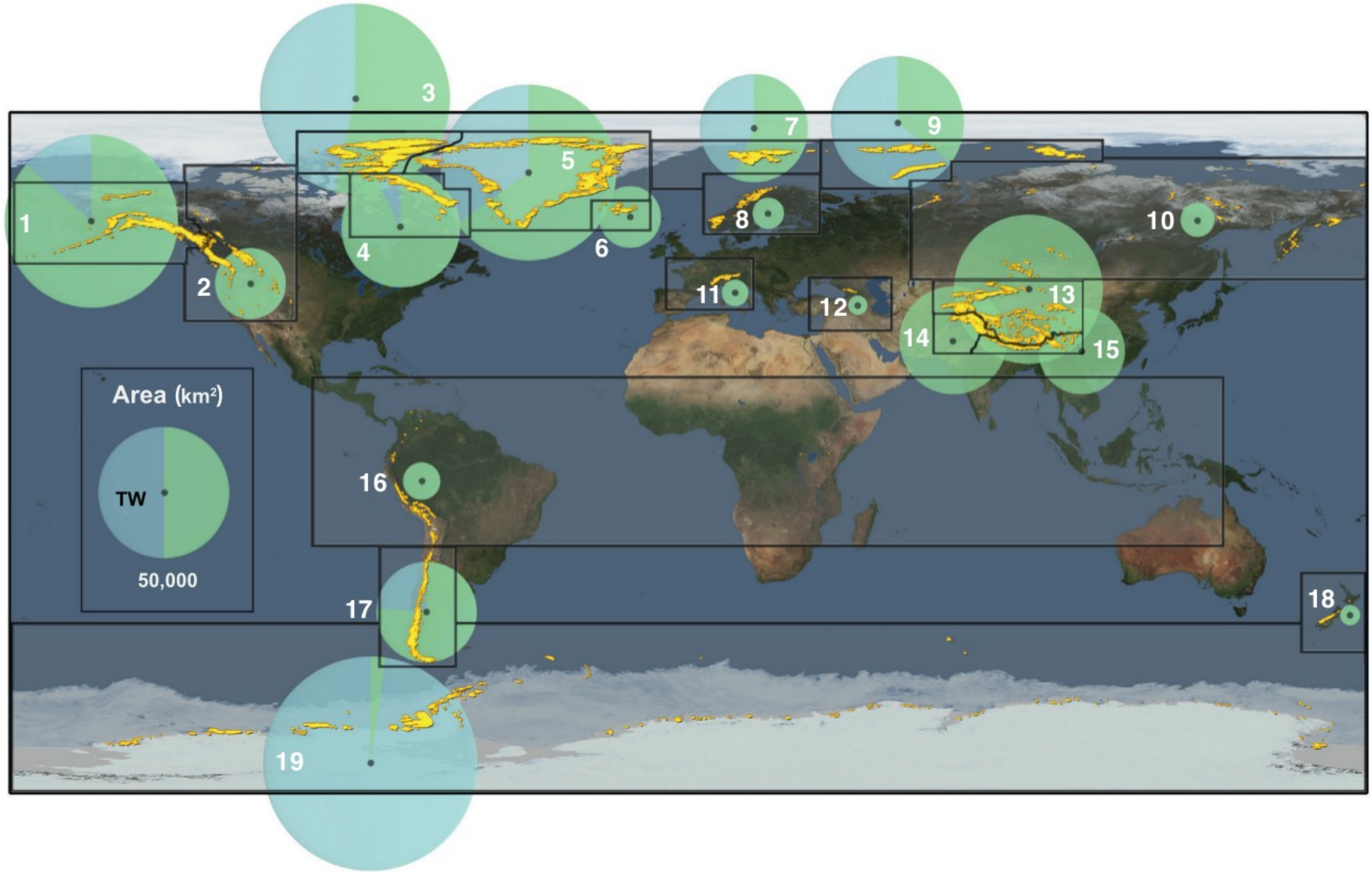


Figure 4.8 | Global distribution of glaciers (yellow, area increased for visibility) and area covered (diameter of the circle), sub-divided into the 19 RGI regions (white number) referenced in Table 4.2. The area percentage covered by tidewater (TW) glaciers in each region is shown in blue. Data from Arendt et al. (2012) and Gardner et al. (2013).

large uncertainties...

of detail and quality (Arendt et al., 2012). Regional glacier-covered areas for 19 regions were extracted from the RGI and supplemented with the percentage of the area covered by glaciers terminating in tide-water (Figure 4.8 and Table 4.2). The areas covered by glaciers that are in contact with freshwater lakes are only locally available. The separation of so-called peripheral glaciers from the ice sheets in Greenland and Antarctica is not easy. A new detailed inventory of the glaciers in Greenland (Rastner et al., 2012) allows for estimation of their area, volume, and mass balance separately from those of the ice sheet. This separation is still incomplete for Antarctica, and values discussed here (Figures 4.1, 4.8 to 4.11, Tables 4.2 and 4.4) refer to the glaciers on the islands in the Antarctic and Sub-Antarctic (Bliss et al., 2013) but exclude glaciers on the mainland of Antarctica that are separate from the ice sheet. Regionally variable accuracy of the glacier outlines leads to poorly quantified uncertainties. These uncertainties, along with the regional variation in the minimum size of glaciers included in the inventory, and the subdivision of contiguous ice masses, also makes the total number of glaciers uncertain; the current best estimate is around 170,000 covering a total area of about 730,000 km^2. When

quantification of glacier changes

– length: coordinated obs start in 1894!

– area: recently measured via satellites,
earlier via photography, old maps, etc

– volume/mass: measured via...
  – snow/ice stake readings on individual glaciers
  – surface elevation changes
  – gravity changes from satellites
  – "models" that convert length/height to mass/volume
  – residuals of water balance for hydrological basins

quantification of glacier changes

– length: coordinated obs start in 1894!

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earlier via photography, old maps, etc

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  – snow/ice stake readings on individual glaciers
  – surface elevation changes
  – gravity changes from satellites
  – “models” that convert length/height to mass/volume
  – residuals of water balance for hydrological basins

glacier length changes 1854-2012

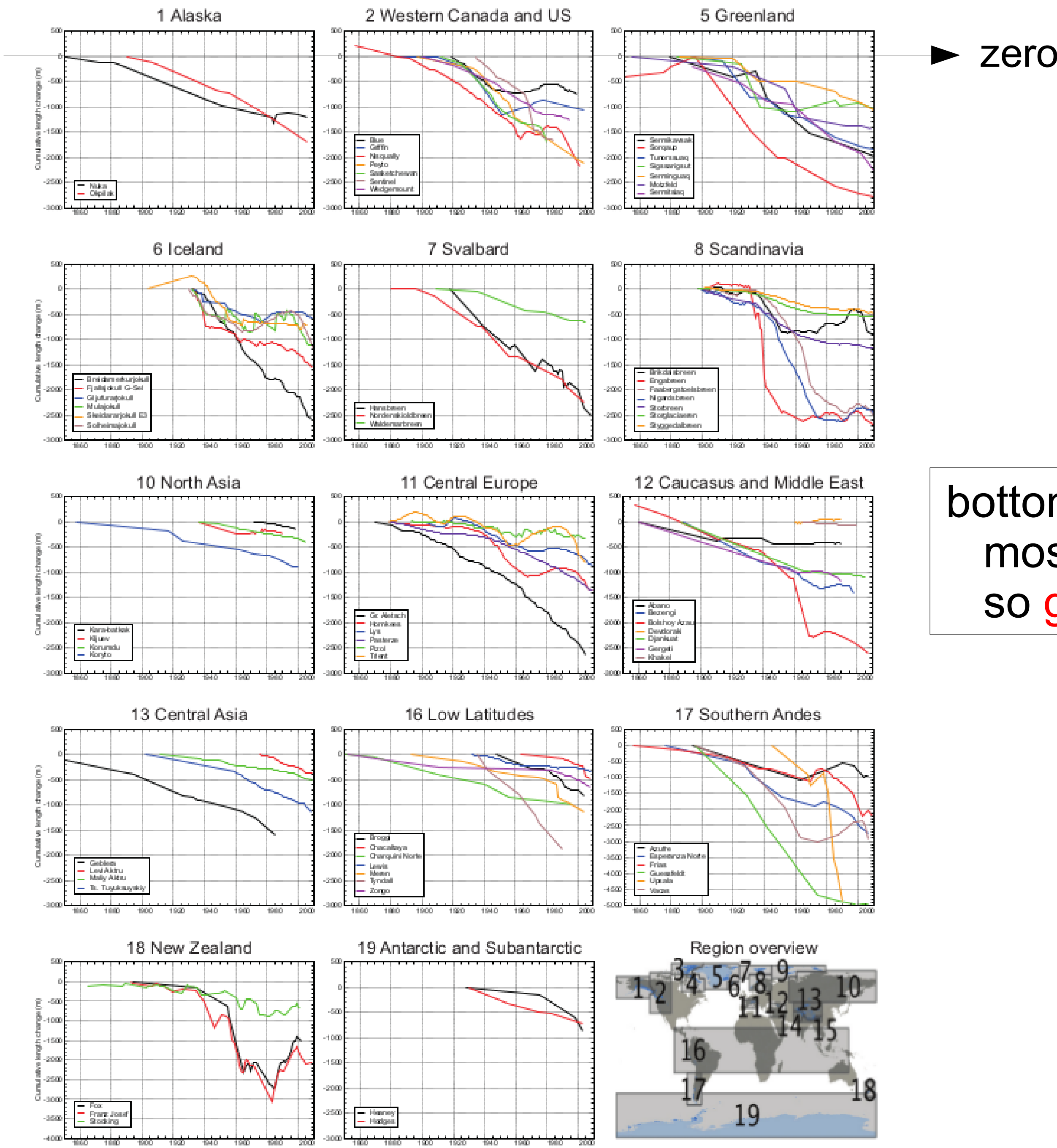


Figure 4.9

bottom line:
most of the curves trend DOWN
so glaciers are getting shorter!

glacier area changes 1950-2010

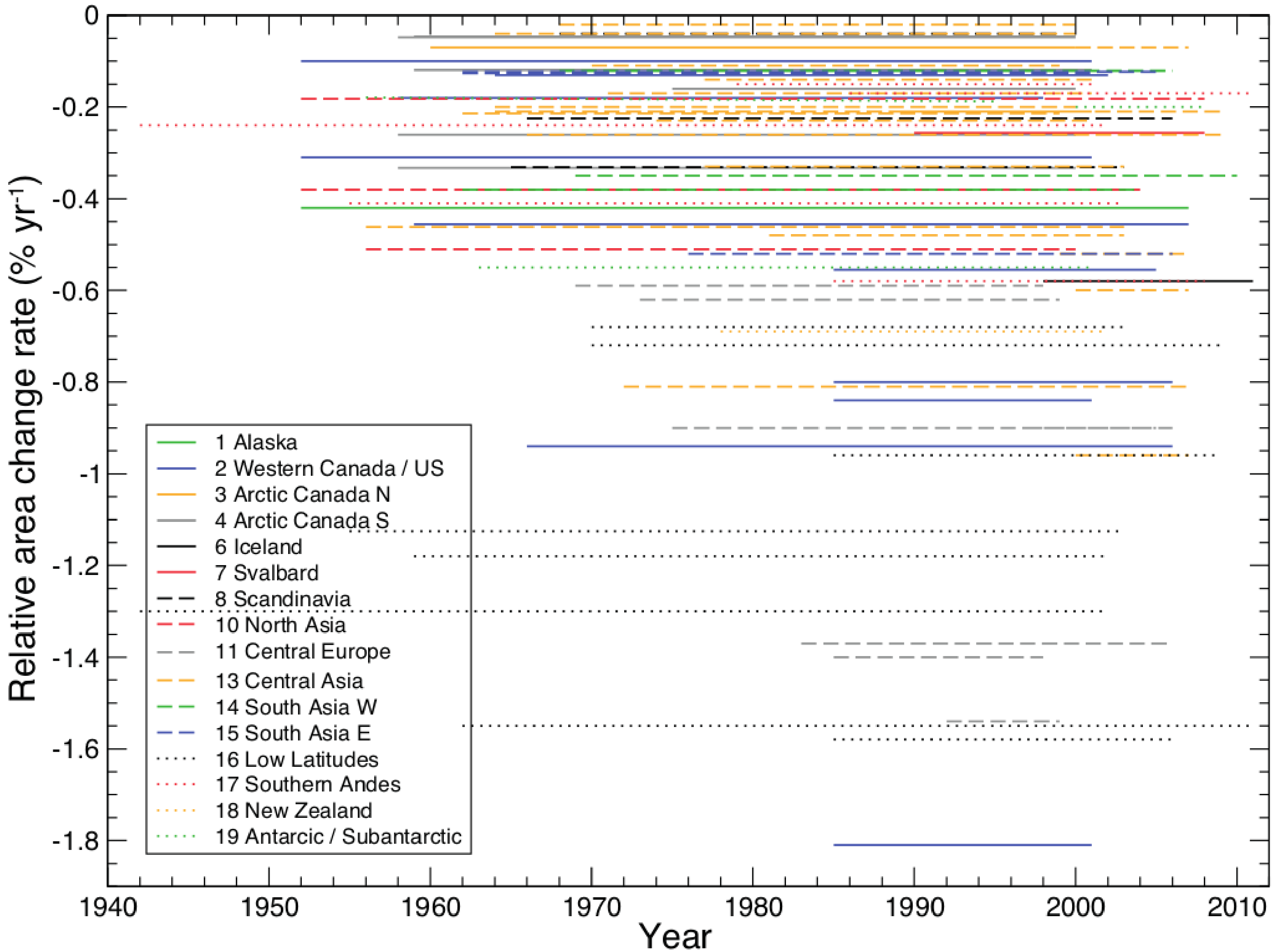


Figure 4.10 | Mean annual relative area loss rates for 16 out of the 19 RGI regions of Figure 4.8. Each line shows a measurement of the rate of percentage change in area over a mountain range from a specific publication (for sources see Table 4.SM.1), the length of the line shows the period used for averaging.

glacier mass change 2003-2009

Table 4.4 | Regional mass change rates in units of kg m^{-2} yr^{-1} and Gt yr^{-1} for the period 2003–2009 from Gardner et al. (2013). Central Asia (region 13), South Asia West (region14), and South Asia East (region 15) are merged into a single region. For the division of regions see Figure 4.8.

No.	Region Name	(kg m^{-2} yr^{-1})	(Gt yr^{-1})
1	Alaska	–570 ± 200	–50 ± 17
2	Western Canada and USA	–930 ± 230	–14 ± 3
3	Arctic Canada North	–310 ± 40	–33 ± 4
4	Arctic Canada South	–660 ± 110	–27 ± 4
5	Greenland periphery	–420 ± 70	–38 ± 7
6	Iceland	–910 ± 150	–10 ± 2
7	Svalbard	–130 ± 60	–5 ± 2
8	Scandinavia	–610 ± 140	–2 ± 0
9	Russian Arctic	–210 ± 80	–11 ± 4
10	North Asia	–630 ± 310	–2 ± 1
11	Central Europe	–1060 ± 170	–2 ± 0
12	Caucasus and Middle East	–900 ± 160	–1 ± 0
13–15	High Mountain Asia	–220 ± 100	–26 ± 12
16	Low Latitudes	–1080 ± 360	–4 ± 1
17	Southern Andes	–990 ± 360	–29 ± 10
18	New Zealand	–320 ± 780	0 ± 1
19	Antarctic and Sub-Antarctic	–50 ± 70	–6 ± 10
	Total	**–350 ± 40**	**–259 ± 28**

bottom line:
all numbers are NEGATIVE
so glaciers are loosing mass!

item 3 – ice sheets

– only 2 at present: Greenland and Antarctica

– 3 methods to compute the ice sheet mass

  – mass budget method (regional models)
  – repeated altimetry (from satellites)
  – variations in the gravity field (GRACE)

– many uncertainties in each method...

Greenland ice sheet

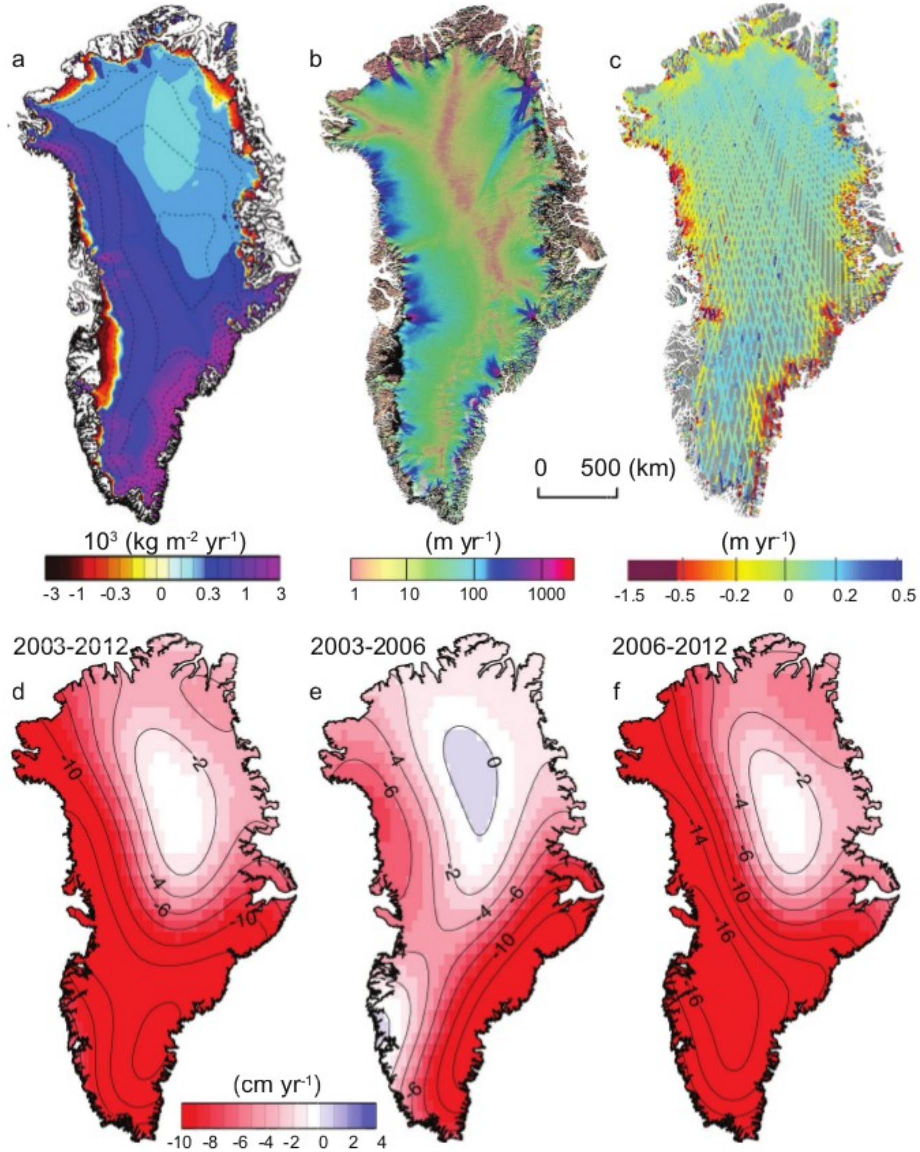


Figure 4.13 | Key variable related to the determination of the Greenland ice sheet mass changes. (a) Mean surface mass balance for 1989–2004 from regional atmospheric climate modelling (Ettema et al., 2009). (b) Ice sheet velocity for 2007–2009 determined from satellite data, showing fastest flow in red, fast flow in blue and slower flow in green and yellow (Rignot and Mouginot, 2012). (c) Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). (d, e) Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in centimetres of water per year for the periods (a) 2003–2012, (b) 2003–2006 and (c) 2006–2012, colour coded red (loss) to blue (gain) (Velicogna, 2009). Fields shown in (a) and (b) are used together with ice thickness (see Figure 4.18) in the mass budget method.

Antarctic ice sheet

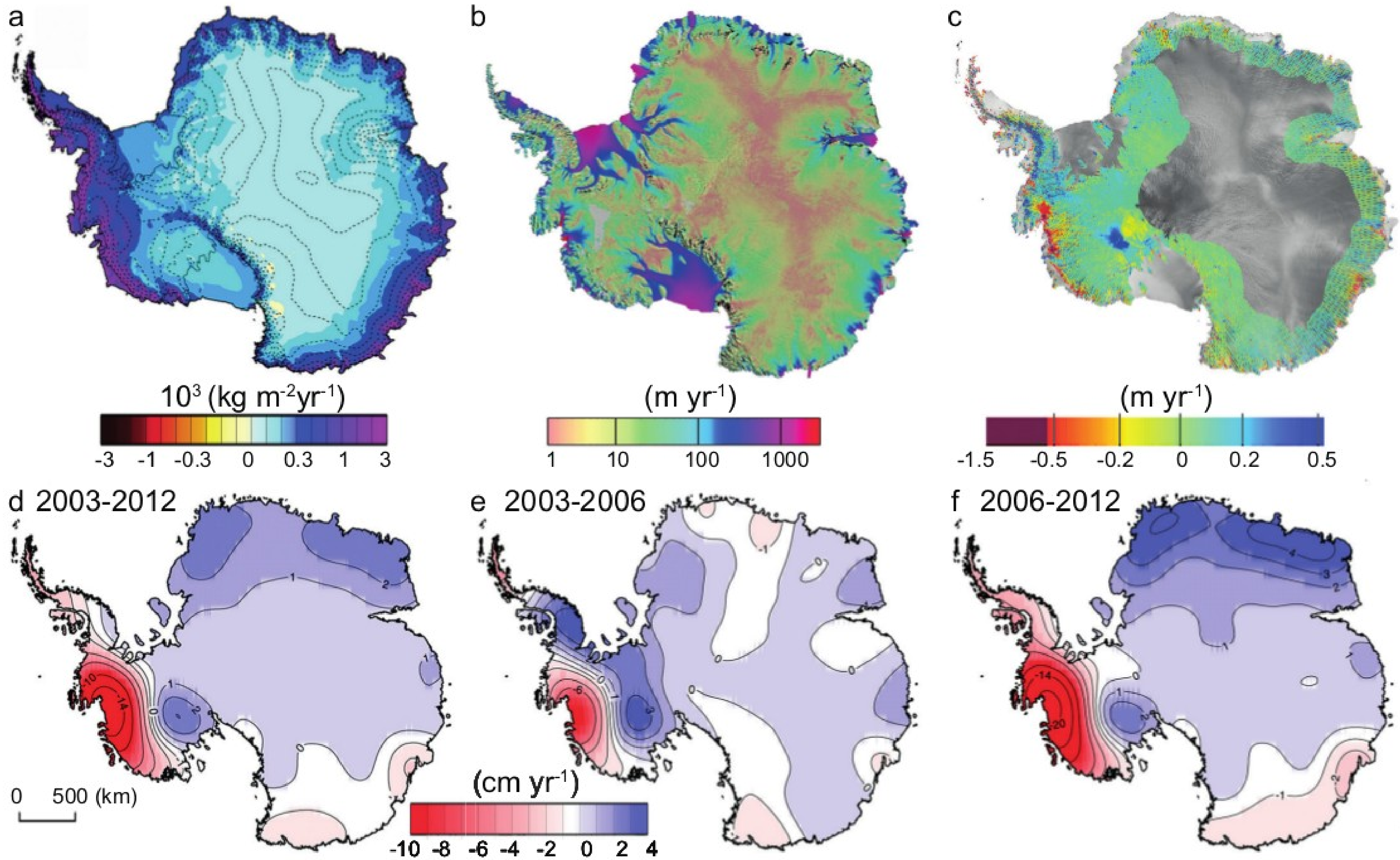


Figure 4.14 | Key fields relating to the determination of Antarctica ice sheet mass changes. (a) Mean surface mass balance for 1989–2004 from regional atmospheric climate modelling (van den Broeke et al., 2006). (b) Ice sheet velocity for 2007–2009 determined from satellite data, showing fastest flow in red, fast flow in blue, and slower flow in green and yellow (Rignot et al., 2011a). (c) Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). (d, e) Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in centimetres of water per year for the periods (a) 2003–2012, (b) 2003–2006 and (c) 2006–2012, colour coded red (loss) to blue (gain) (Velicogna, 2009). Fields shown in (a) and (b) are used together with ice thickness (see Figure 4.18) in the mass budget method.

ice sheet mass loss 1990-2012

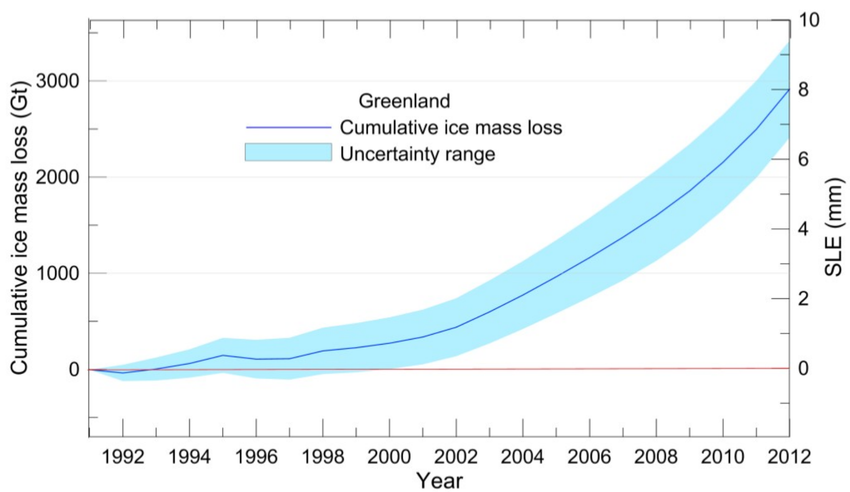


Figure 4.15 | Cumulative ice mass loss (and sea level equivalent, SLE) from Greenland derived as annual averages from 18 recent studies (see main text and Appendix 4.A for details).

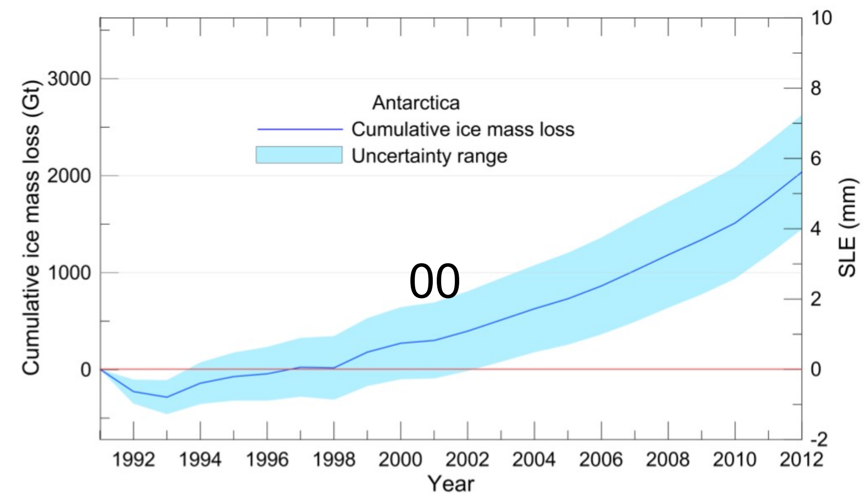


Figure 4.16 | Cumulative ice mass loss (and sea level equivalent, SLE) from Antarctica derived as annual averages from 10 recent studies (see main text and Appendix 4.A for details).

the Greenland ice sheet

+ has LOST mass in the last two decades *(very high confidence)*

+ rate of ice loss has accelerated *(likely)*

+ ice loss is partitioned equally between surface melt and glacier discharge *(medium confidence)*

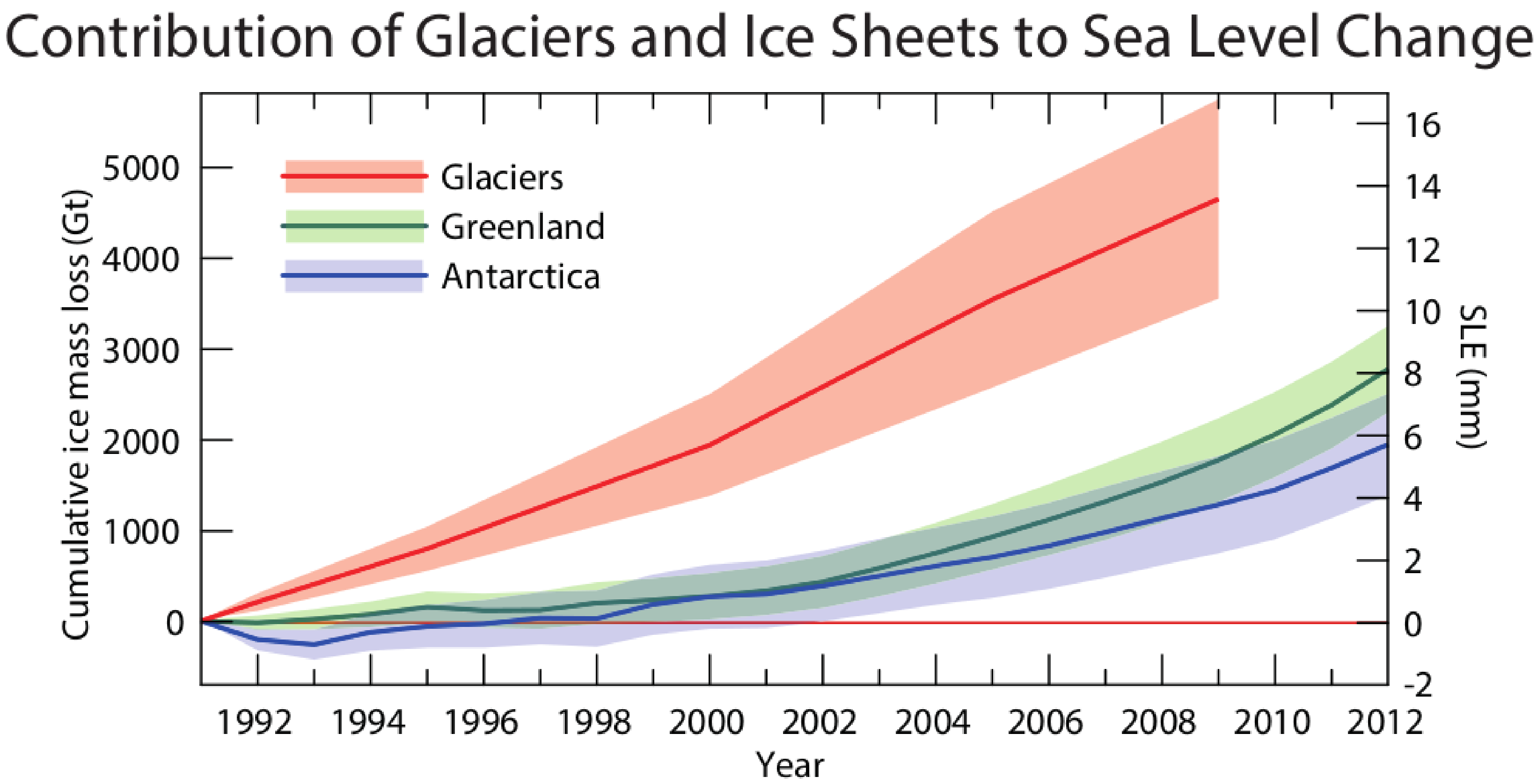
the Antarctic ice sheet

+ has been loosing mass in the last two decades *(high confidence)*

+ most looses in the Northern Peninsula and Amundsen sector of the WAIS *(very high confidence)*

+ *low confidence* that the rate of loss has accelerated recently

glaciers vs ice sheets



Cumulative ice mass loss from glacier and ice sheets (in sea level equivalent) is 1.0 to 1.4 mm yr^{-1} for 1993-2009 and 1.2 to 2.2 mm yr^{-1} for 2005-2009.

item 4 – seasonal snow

Snow cover extent has decreased in the Northern Hemisphere, especially in spring (*very high confidence*). Satellite records indicate that over the period 1967–2012, annual mean snow cover extent decreased with statistical significance; the largest change, –53% [*very likely*, –40% to –66%], occurred in June. No months had statistically significant increases. Over the longer period, 1922–2012, data are available only for March and April, but these show a 7% [*very likely*, 4.5% to 9.5%] decline and a strong negative [–0.76] correlation with March–April 40°N to 60°N land temperature. {4.5.2, 4.5.3}

item 4 – seasonal snow

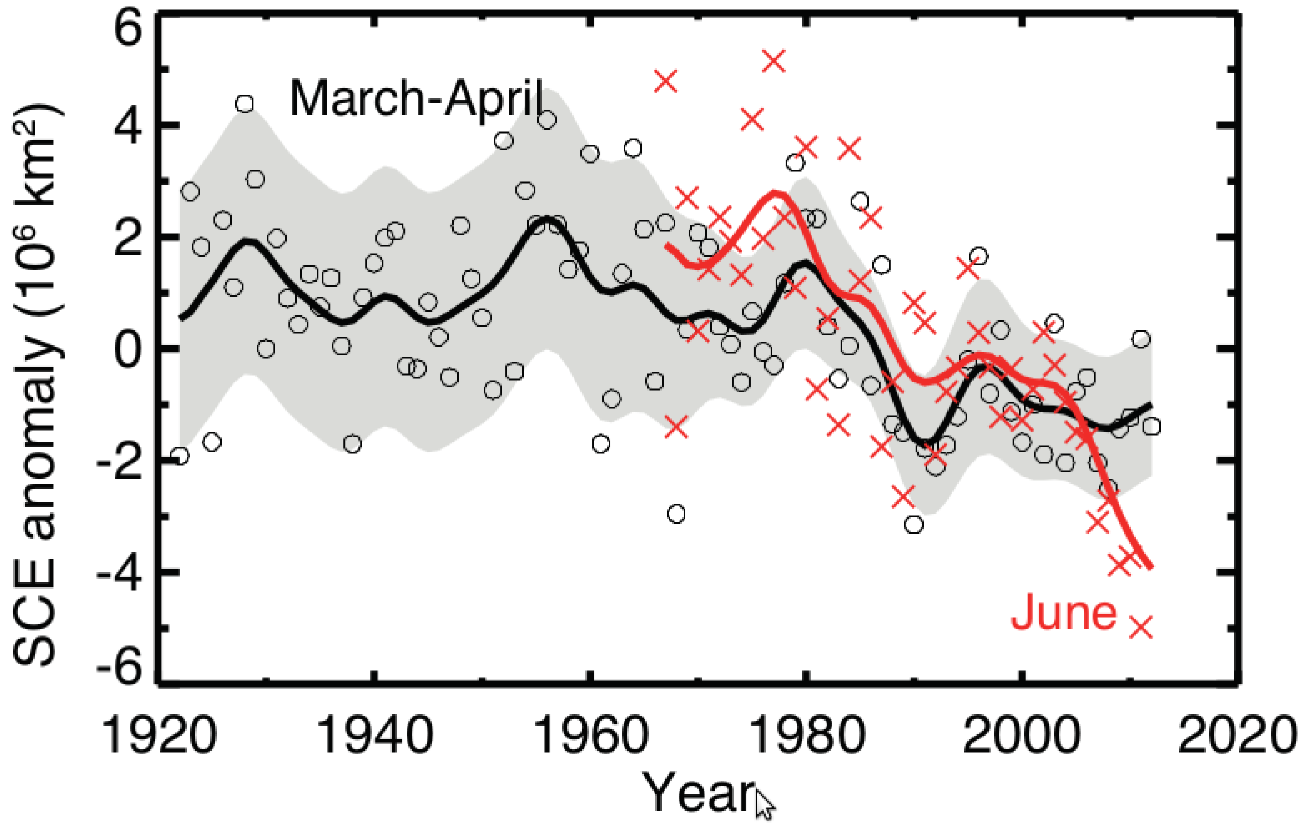


Figure 4.19 | March–April NH snow cover extent (SCE, circles) over the period of available data, filtered with a 13-term smoother and with shading indicating the 95% confidence interval; and June SCE (red crosses, from satellite data alone), also filtered with a 13-term smoother. The width of the smoothed 95% confidence interval is influenced by the interannual variability in SCE. Updated from Brown and Robinson (2011). For both time series the anomalies are calculated relative to the 1971–2000 mean.

item 5 – lake & river ice

The limited evidence available for freshwater (lake and river) ice indicates that ice duration is decreasing and average seasonal ice cover shrinking (*low confidence*). For 75 Northern Hemisphere lakes, for which trends were available for 150-, 100- and 30-year periods ending in 2005, the most rapid changes were in the most recent period (*medium confidence*), with freeze-up occurring later (1.6 days per decade) and breakup earlier (1.9 days per decade). In the North American Great Lakes, the average duration of ice cover declined 71% over the period 1973–2010. {4.6}

item 6 – frozen ground & permafrost

Frozen ground: Soil or rock in which part or all of the pore water is frozen. Frozen ground includes permafrost. Ground that freezes and thaws annually is called seasonally frozen ground.

Permafrost: Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years. See also *Near-surface permafrost*.

Near-surface permafrost: A term frequently used in climate model applications to refer to permafrost at depths close to the ground surface (typically down to 3.5 m)... The disappearance of near-surface permafrost in a location does not preclude the longer-term persistence of permafrost at greater depth.

Active layer: The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

ground temperatures at 10 to 20 m depth

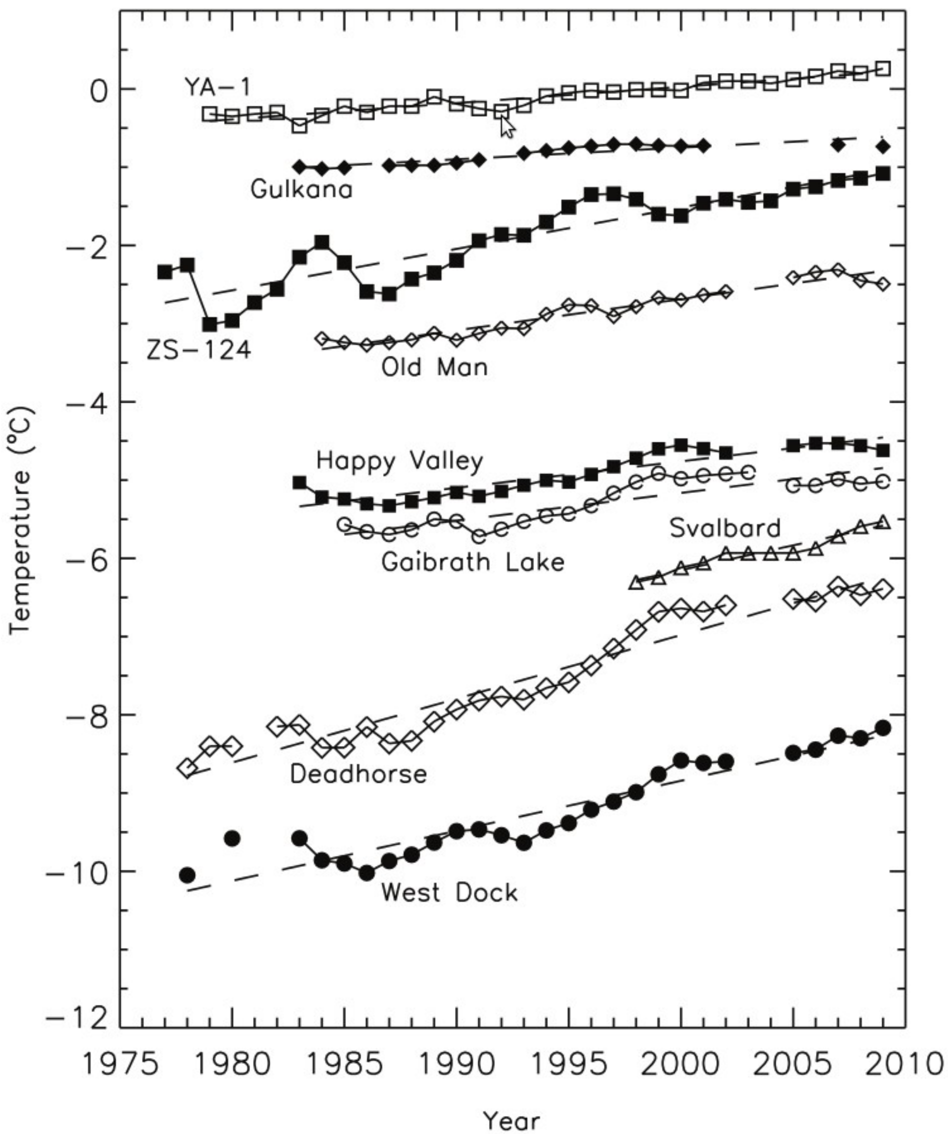


Figure 4.22 | Time series of mean annual ground temperatures at depths between 10 and 20 m for boreholes throughout the circumpolar northern permafrost regions (Romanovsky et al., 2010a). Data sources are from Romanovsky et al. (2010b) and Christiansen et al. (2010). Measurement depth is 10 m for Russian boreholes, 15 m for Gulkana and Oldman, and 20 m for all other boreholes. Borehole locations are: ZS-124, 67.48°N 063.48°E; 85-8A, 61.68°N 121.18°W; Gulkana, 62.28°N 145.58°W; YA-1, 67.58°N 648°E; Oldman, 66.48°N 150.68°W; Happy Valley, 69.18°N 148.88°W; Svalbard, 78.28°N 016.58°E; Deadhorse, 70.28°N 148.58°W and West Dock, 70.48°N 148.58°W. The rate of change (degrees Celsius per decade) in permafrost temperature over the period of each site record is: ZS-124: 0.53 ± 0.07; YA-1: 0.21 ± 0.02; West Dock: 0.64 ± 0.08; Deadhorse: 0.82 ± 0.07; Happy Valley: 0.34 ± 0.05; Gaibrath Lake: 0.35 ± 0.07; Gulkana: 0.15 ± 0.03; Old Man: 0.40 ± 0.04 and Svalvard: 0.63 ± 0.09. (The trends are *very likely* range, 90%.)

active layer thickness

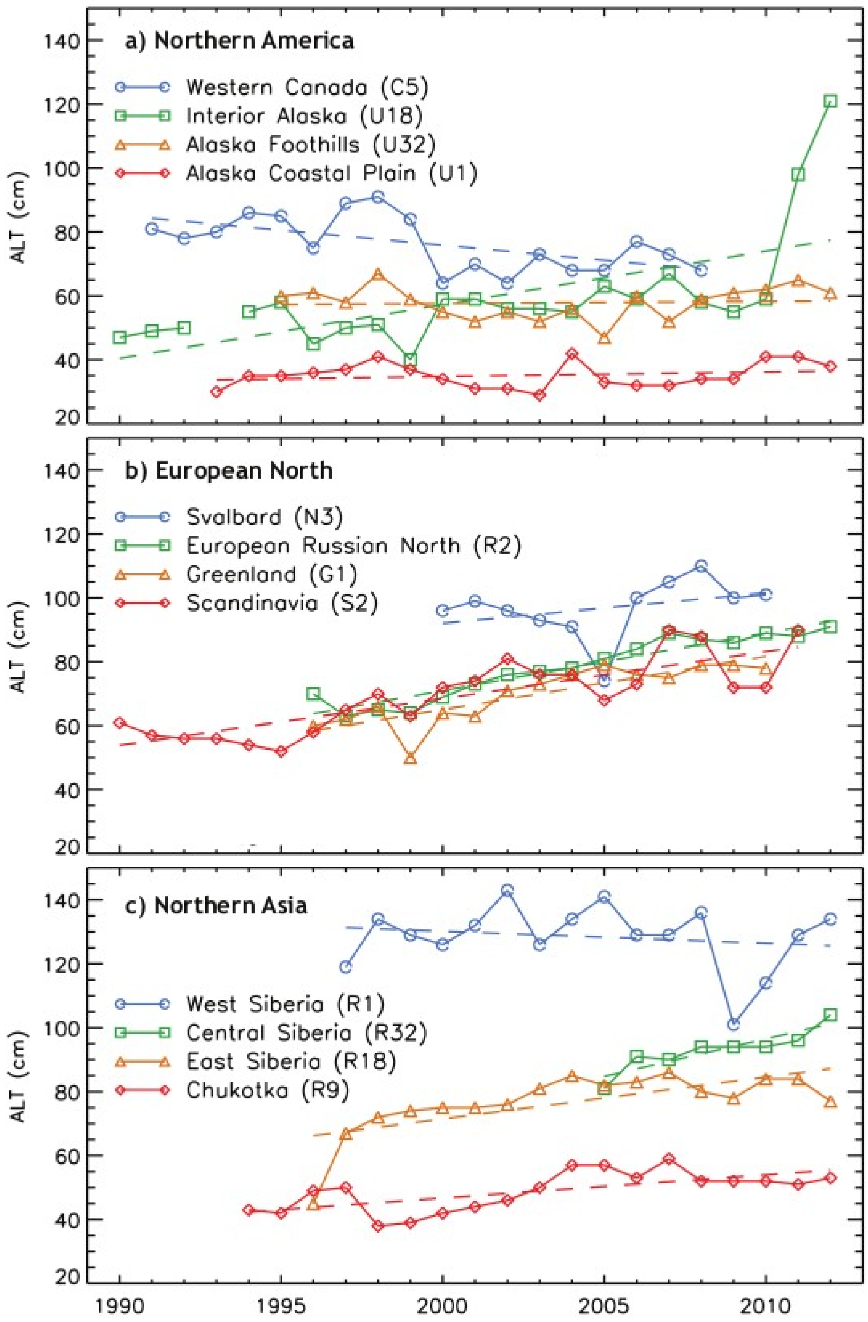


Figure 4.23 | Active layer thickness from different locations for slightly different periods between 1990 and 2012 in (a) Northern America, (b) Northern Europe, and (c) Northern Asia. The dashed lines represents linear fit to each set of data. ALT data for Northern America, Northern Asia and Northern Europe were obtained from the International Permafrost Association (IPA) CALM website (http://www.udel.edu/Geography/calm/about/permafrost.html). The number of Russian Hydrometeorological Stations (RHM) stations has expanded from 31 stations as reported from Frauenfeld et al. (2004) and Zhang et al. (2005) to 44 stations and the time series has extended from 1990 to 2008. (d) Departures from the mean of active layer thickness in Siberia from 1950 to 2008. The red asterisk represents the mean composite value, the shaded area indicates the standard deviation and the black line is the trend. Data for Siberia stations were obtained from the Russian Hydrometeorological Stations (RHM).

frozen ground summary

Permafrost temperatures have increased in most regions since the early 1980s (*high confidence*) although the rate of increase has varied regionally. The temperature increase for colder permafrost was generally greater than for warmer permafrost (*high confidence*). {4.7.2, Table 4.8, Figure 4.24}

Significant permafrost degradation has occurred in the Russian European North (*medium confidence*). There is *medium confidence* that, in this area, over the period 1975–2005, warm permafrost up to 15 m thick completely thawed, the southern limit of discontinuous permafrost moved north by up to 80 km and the boundary of continuous permafrost moved north by up to 50 km. {4.7.2}

***In situ* measurements and satellite data show that surface subsidence associated with degradation of ice-rich permafrost occurred at many locations over the past two to three decades (*medium confidence*).** {4.7.4}

thickness of the frozen ground

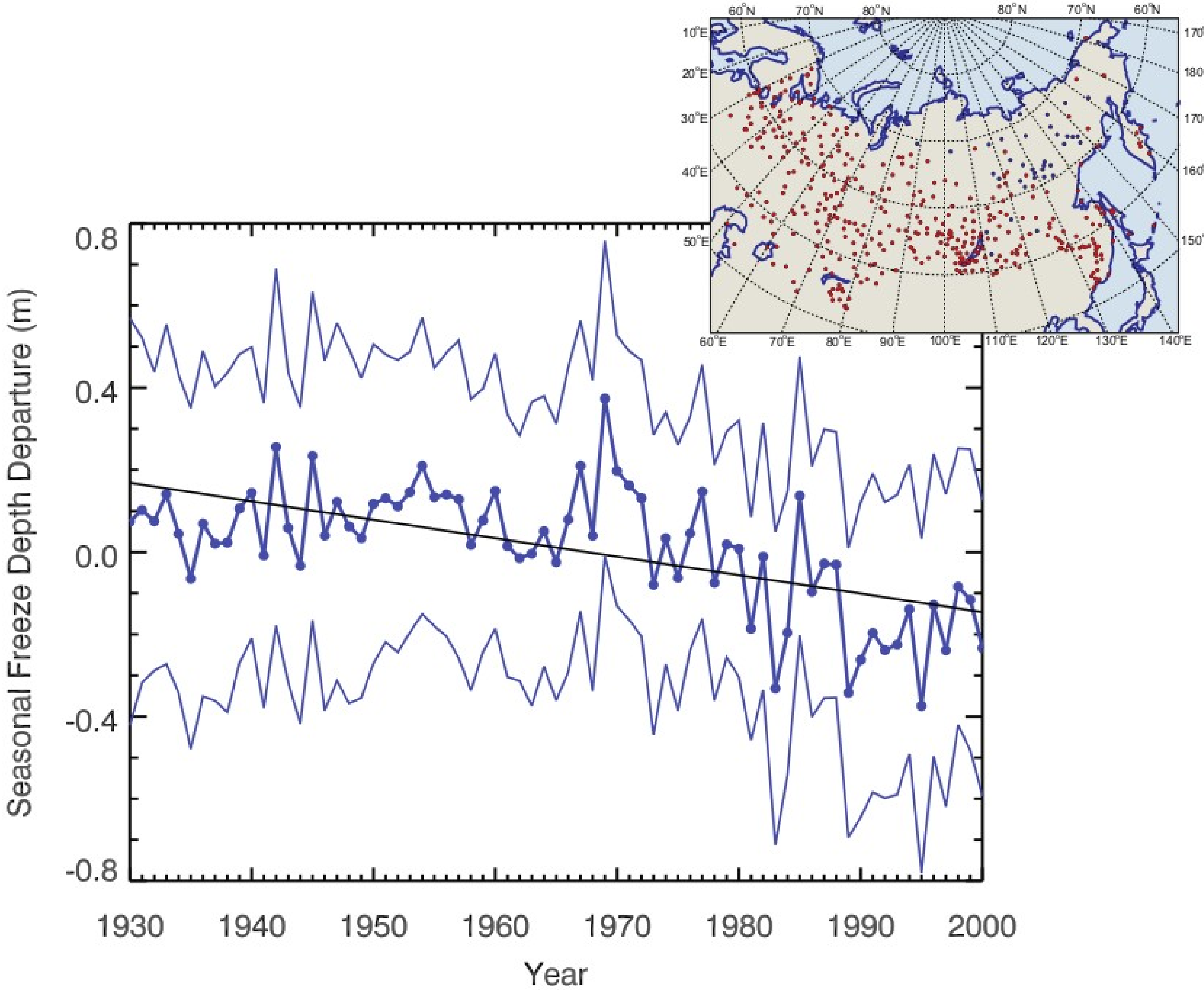
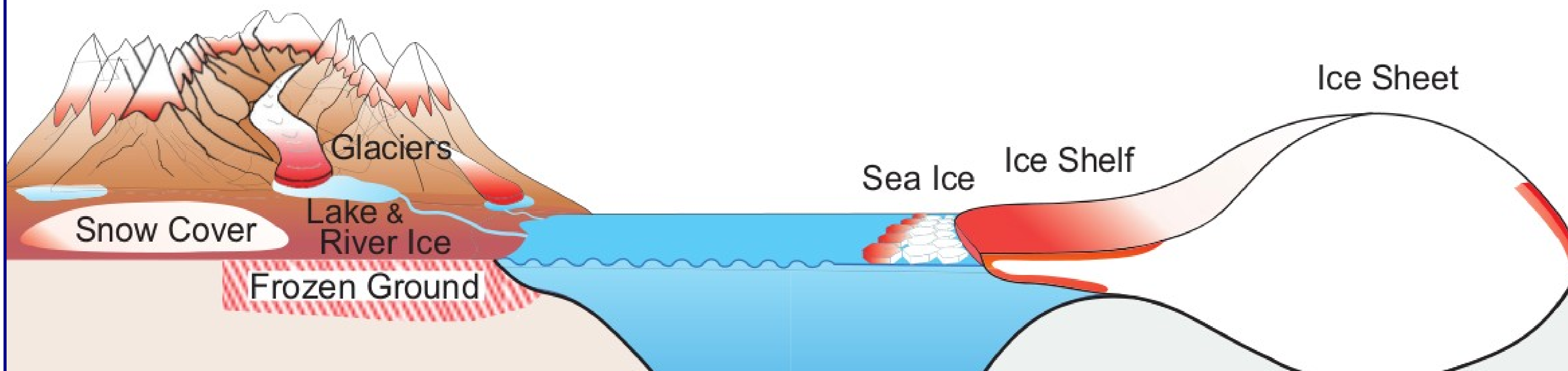


Figure 4.24 | Annual anomalies of the average thickness of seasonally frozen depth in Russia from 1930 to 2000. Each data point represents a composite from 320 stations as compiled at the Russian Hydrometeorological Stations (RHM) (upper right inset). The composite was produced by taking the sum of the thickness measurements from each station and dividing the result by the number of stations operating in that year. Although the total number of stations is 320, the number providing data may be different for each year but the minimum was 240. The yearly anomaly was calculated by subtracting the 1971–2000 mean from the composite for each year. The thin lines indicate the 1 standard deviation (1σ) (*likely*) uncertainty range. The line shows a negative trend of –4.5 cm per decade or a total decrease in the thickness of seasonally frozen ground of 31.9 cm from 1930 to 2000 (Frauenfeld and Zhang, 2011).

Changes in the Cryosphere



Frozen Ground: increasing permafrost temperatures by up to 2ºC and active layer thickness by up to 90 cm since early 1980s. In the NH, southern limit of permafrost moving north since mid 1970s, and decreasing thickness of seasonal frozen ground by 32 cm since 1930s.

Snow cover: between 1967 and 2012, satellite data show decreases through the year, with largest decreases (53%) in June. Most stations report decreases in now especially in spring.

Lake and river ice: contracting winter ice duration with delays in autumn freeze-up proceeding more slowly than advances in spring break-up, with evidence of recent acceleration in both across the NH.

Glaciers: are major contributors to sea level rise. Ice mass loss from glaciers has increased since the 1960s. Loss rates from glaciers outside Greenland and Antarctica were 0.76 mm yr^{-1} SLE during the 1993 to 2009 period and 0.83 mm yr^{-1} SLE over the 2005 to 2009 period.

Sea Ice: between 1979 and 2012, Arctic sea ice extent declined at a rate of 3.8% per decade with larger losses in summer and autumn. Over the same period, the extent of thick multiyear ice in the Arctic declined at a higher rate of 13.5% per decade. Mean sea ice thickness decreased by 1.3 - 2.3 m between 1980 and 2008.

what about GROWING AA sea ice...?!?

Ice Shelves and ice tongues: continuing retreat and collapse of ice shelves along the Antarctic Peninsula. Progressive thinning of some other ice shelves/ice tongues in Antarctica and Greenland.

Ice Sheets: both Greenland and Antarctic ice sheets lost mass and contributed to sea level change over the last 20 years. Rate of total loss and discharge from a number of major outlet glaciers in Antarctica and Greenland increased over this period.