Sea ice

Global Warming Science, EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/
Arctic sea ice record over past decades

![Graph showing the decrease in sea ice area over decades](image)
Arctic sea ice minimum over past decades

Arctic sea ice minimum over past decades


NASA
Arctic sea ice seasonal cycle over past decades

[Graph showing Arctic Sea Ice Extent from 1979 to 2021, with data from various years highlighted.](http://nsidc.org/arcticseaicenews/charctic-interactive-sea-ice-graph/)
And now it's global COOLING! Return of Arctic ice cap as it grows by 29% in a year

- 533,000 more square miles of ocean covered with ice than in 2012
- BBC reported in 2007 global warming would leave Arctic ice-free in summer by 2013
- Publication of UN climate change report suggesting global warming caused by humans pushed back to later this month

By DAVID ROSE FOR THE MAIL ON SUNDAY
PUBLISHED: 00:37 GMT, 8 September 2013 | UPDATED: 15:58 GMT, 11 October 2014

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The adventures of Kevin: bad day on the sea ice

https://www.youtube.com/watch?v=K16lZU0agbg
The adventures of Kevin: bad day on the sea ice

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Notes: section 1
quantifying the state of sea ice: area, concentration, extent, age, thickness

workshop #1: characterizing observed changes in Arctic sea ice
Arctic vs Antarctic sea ice trends

Figure 9.1: Time series of Arctic sea-ice area (a) and extent (b), and for Antarctic sea-ice area (c) and extent (d).

Where sea-ice concentration is at least 15%. Sea-ice extent therefore contains areas of both sea ice and open ocean, and is by definition larger than or equal to the sea-ice area. The extent measure also shows strong decline...
Sea Ice Age 1985-2019

- Processes and feedbacks
  - Older sea ice, which has been subject to the process over several years, is characterized by a rougher surface. Melt ponds that form over such older ice during the summer therefore tend to be deeper and smaller and the ice effective albedo larger.
  - As a result of this process, when ice age declines, its surface becomes less rough. This results in shallower and larger-area melt ponds and therefore in a smaller effective albedo. This leads to further melting and therefore to an even smaller ice area, amplifying ice retreat via this positive feedback.

- Ice thickness and insulation feedback.
  - The winter atmosphere above sea ice is typically much colder than the ocean water underneath the ice, which is at its freezing temperature of $T_f = 1.8 \, ^\circ C$. As a result, heat diffuses through the ice from the relatively warm ocean toward the cold upper sea-ice surface.
  - Ice is a good heat insulator, leading to slower diffusion of heat and therefore weaker heat flux away from the ocean below the ice and toward the cold atmosphere. This weaker heat flux away from the ocean under thick ice implies a slower freezing for thicker ice.

- Upward diffusive heat flux $F$ from the relatively warm ocean to the colder atmosphere is proportional to the vertical temperature gradient in the ice, with the proportionality constant being heat conductivity in ice ($k$, in Chapter 9. Arctic Sea Ice).

- How sea ice grows & how it melts.
  - Sea ice starts growing as small (3–4 mm) crystals suspended in the upper few cm of the ocean, known as “frazil ice.” In a calm ocean, these later coagulate into “grease ice,” and then freeze into a smooth-bottom sea-ice sheet.
  - In a rough ocean, the frazil ice crystals accumulate into “pancake ice,” composed of roughly circular floes from 30 cm to 3 m, shaped by collisions between individual floes.
  - Once covered by a first snow or exposed to cooling, the pancakes merge into a thin layer of rough-bottomed ice which then grows in thickness leading to older and thicker ice via freezing from below and snow accumulation from above.
  - Melting can occur via melt pond formation from above, or via heating and melting by the ocean below.

- Sea-ice area and the albedo feedback.
  - Sea-ice albedo (reflectivity of shortwave radiation) ranges from 0.5–0.8. Its large-scale value is affected by the sea-ice concentration and extent, and by the existence of snow cover which increases the reflectivity relative to that of exposed ice, among other factors.
  - A smaller sea-ice area leads to more SW absorption by the ocean near sea-ice floes, which leads to further melting, creating a positive feedback.

- Ice age, roughness and albedo feedback.
  - The uneven surface height of sea ice, especially of older sea ice, implies that during the melt season, melt ponds would accumulate in the depressions in the sea-ice surface. Melt ponds have lower albedo than the ice itself, leading to further melting via this feedback.
Arctic sea ice record over past decades

![Sea Ice thickness, 1979 vs 2018](image)

### Chapter 9. Arctic Sea Ice

The thickness of sea ice over the past decades has been recorded. Data from [nsidc.org](http://nsidc.org/)

### Equations:

\[ F = k \left( \frac{\partial T}{\partial z} \right) = k T_f T_{surface} h \]

This equation represents the heat flux away from the ocean, and therefore thickness growth during winter, which is inversely proportional to the ice thickness.

### Feedbacks:

**Negative Feedback**

A thicker ice cover implies less upward heat flux from the ocean, meaning less growth of sea ice thickness. Clearly, this is a negative feedback on ice thickness growth as the thickness growth is slower for thick ice. This may be crudely represented by an ice thickness equation which assumes that the heat flux away from the ocean, and therefore thickness growth during winter, is proportional to the temperature difference between the surface and bottom of the ice, and inversely proportional to the ice thickness.

**Positive Feedback**

Sea ice has been thinning for a few decades (possibly since the 1960s), and once thin enough, it is prone to being broken by wind and ocean waves and being transported out of the Arctic by atmospheric storms. This leads to a mostly thin new ice the following year, again prone to being exported, presenting a positive feedback on ice thinning. The strong sea-ice minima of 2007 and 2012 were forced, among other factors, by unusual atmospheric weather patterns that led to strong Arctic sea-ice export.

**Processes and feedbacks**

- Sea ice starts growing as small (3–4 mm) crystals suspended in the upper few cm of the ocean, known as "frazil ice." In a calm ocean, these later coagulate into "grease ice," and then freeze into a smooth-bottom sea-ice sheet. In a rough ocean, the frazil ice crystals accumulate into "pancake ice," composed of roughly circular floes from 30 cm to 3 m, shaped by collisions between individual floes. Once covered by a first snow or exposed to cooling, the pancakes merge into a thin layer of rough-bottomed ice which then grows in thickness leading to older and thicker ice via freezing from below and snow accumulation from above. Melting can occur via melt pond formation from above, or via heating and melting by the ocean below.

**Sea-ice area and the albedo feedback.**

Sea-ice albedo (reflectivity of shortwave radiation) ranges from 0.5–0.8. Its large-scale value is affected by the sea-ice concentration and extent, and by the existence of snow cover which increases the reflectivity relative to that of exposed ice, among other factors. A smaller sea-ice area leads to more SW absorption by the ocean near sea-ice floes, which leads to further melting, creating a positive feedback.

**Ice age, roughness and albedo feedback.**

The uneven surface height of sea ice, especially of older sea ice, implies that during the melt season, melt ponds would accumulate in the depressions in the sea-ice surface. Melt ponds have lower albedo than the ice itself,
Sea ice formation: frazil to pancakes to new ice

Frazil ice, Grease ice, Pancake ice, First-year ice, Old ice, multi-year ice

Sea ice formation: frazil to pancakes to new ice

Frazil ice, Grease ice, Pancake ice, First-year ice, Old ice, multi-year ice


Frazil ice

pancake ice
Sea ice formation: frazil to pancakes to new ice

Frazil ice, Grease ice, Pancake ice, First-year ice, Old ice, multi-year ice

Maturing sea ice: rafting, ridging

1 m by 3 m rafted ice
Stephen F. Ackley, Peter Wagner, Hongjie Xie 2007
Maturing sea ice: rafting, ridging

ridging, https://earthobservatory.nasa.gov/features/SeaIce

1 m by 3 m rafted ice
Stephen F. Ackley, Peter Wagner, Hongjie Xie 2007
Figure SPM.3 | Multiple observed indicators of a changing global climate: (b) extent of Arctic July-August-September (summer) average sea ice; All time-series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading. See Technical Summary Supplementary Material for a listing of the datasets. {Figures 3.2, 3.13, 4.19, and 4.3; FAQ 2.1, Figure 2; Figure TS.1}
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FAQ 4.1 (continued) 
varies so much from year to year and from place to place around the continent. Results from a recent study suggest that these contrasting trends in ice coverage may be due to trends in regional wind speed and patterns. Without better ice thickness and ice volume estimates, it is difficult to characterize how Antarctic sea ice cover is responding to changing climate, or which climate parameters are most influential.

There are large differences in the physical environment and processes that affect the state of Arctic and Antarctic sea ice cover and contribute to their dissimilar responses to climate change. The long, and unbroken, record of satellite observations have provided a clear picture of the decline of the Arctic sea ice cover, but available evidence precludes us from making robust statements about overall changes in Antarctic sea ice and their causes.

FAQ 4.1, Figure 1 | The mean circulation pattern of sea ice and the decadal trends (%) in annual anomalies in ice extent (after removal of seasonal cycle), in different sectors of the Arctic & Antarctic. Arrows: the average direction and magnitude of ice drift. The average sea ice cover for the period 1979-2012, from satellite observations, at maximum (minimum) extent is shown as orange (grey) shading.
Notes: section 9.1
albedo feedback, thickness feedbacks (insulation and mobility feedbacks)
workshop 2: how much heat is needed to melt sea ice
Seasonal reduction of ice albedo due to melt ponds

- Surface consists of bare, white ice and melt ponds
- White ice surface shows stable albedo
- Areal fraction (and type) of melt pond determine large-scale ice albedo
Ice roughness and ponding

- Pond shrinkage and albedo increase with age: Is the Arctic darkening?
- Pond shrinkage and albedo increase with roughening through deformation: Is the Arctic whitening?

Hajo Eicken
workshop 3:
Sea ice age, roughness, melt ponds and albedo
Gauging societal interest

Citations (normalized) of “sea ice” in news media related to coverage of climate change, polar bears, access to the Arctic.
Impacts of sea ice changes

• Use of sea ice as platform by marine mammals (walrus, seals)
• Use of sea ice as a platform for hunting by Iñupiaq & Siberian Yupik hunters

Polar bear making its way across the Arctic sea ice floe © MARTIN JAKOBSSON
workshop 4: future projections
Figure SPM.7 | CMIP5 multi-model simulated time series from 1950 to 2100 for (a) change in global annual mean surface temperature relative to 1986–2005, (b) Northern Hemisphere September sea ice extent (5-year running mean), and (c) global mean ocean surface pH. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081−2100 are given for all RCP scenarios as colored vertical bars. The numbers of CMIP5 models used to calculate the multi-model mean is indicated. For sea ice extent (b), the projected mean and uncertainty (minimum-maximum range) of the subset of models that most closely reproduce the climatological mean state and 1979 to 2012 trend of the Arctic sea ice is given (number of models given in brackets). For completeness, the CMIP5 multi-model mean is also indicated with dotted lines. The dashed line represents nearly ice-free conditions (i.e., when sea ice extent is less than $10^6 \text{km}^2$ for at least five consecutive years). For further technical details see the Technical Summary Supplementary Material {Figures 6.28, 12.5, and 12.28–12.31; Figures TS.15, TS.17, and TS.20}

RCP projections to 2100

Northern Hemisphere September sea ice extent (5-year running mean)

IPCC, AR5 2013
RCP projections to 2100

IPCC, AR5 2013

Figure TS.17 | Northern Hemisphere (NH) sea ice extent in September over the late 20th century and the whole 21st century for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in the CMIP5 models, and corresponding maps of multi-model results in 2081–2100 of NH September sea ice extent. In the time series, the number of CMIP5 models to calculate the multi-model mean is indicated (subset in brackets). Time series are given as 5-year running means. The projected mean sea ice extent of a subset of models that most closely reproduce the climatological mean state and 1979–2012 trend of the Arctic sea ice is given (solid lines), with the minimum to maximum range of the subset indicated with shading. Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The CMIP5 multi-model mean is indicated with dashed lines. In the maps, the CMIP5 multi-model mean is given in white and the results for the subset in grey. Filled areas mark the averages over the 2081–2100 period, lines mark the sea ice extent averaged over the 1986–2005 period. The observed sea ice extent is given in pink as a time series and averaged over 1986–2005 as a pink line in the map. Further detail regarding the related Figures SPM.7b and SPM.8c is given in the TS Supplementary Material. {Figures 12.18, 12.29, 12.31}
The Arctic sea-ice cover: Model projections
The Arctic sea-ice cover: Model projections

Massonnet et al 2012
The Arctic sea-ice cover: Model projections

Arctic September Sea Ice Extent: Observations and Model Runs

Davy & Outten 2020
Notes: section 9.2, detection of climate change (use following two slides)
Climate change detection

Sea ice area time series from a "control" run of CESM showing 3 example four-year trends
Climate change detection

Sea ice area time series from a "control" run of CESM showing 3 example four-year trends
Climate change detection

Fig. 3. Estimated probabilities of observed or larger trend occurrence in NH sea ice extent for specified time intervals. Estimates are based on the GFDL climate model’s 5000-year control run. Circle corresponds to the observed 46-year (1953-98) trend of -0.19 X 10^6 km2 per 10 years (13). The probability for such a trend to occur by chance as the result of natural climate variability is <0.1%. Square corresponds to the observed 19.4-year (1978-98) trend of -0.37 X 10^6 km2 per 10 years (16). The probability of such a trend occurring by chance as the result of natural climate variability is <2%.

following Vinnikov et al 1999 Fig 3
workshop 5: detection of climate change
Processes leading to 2007 Arctic sea ice minimum

(1) Unusual weather pattern: persistent southerly winds brought warm air and moved ice towards North Pole in 2007
(2) Submarine data indicate 40% reduction in ice thickness between 1950s & 1990s → Long-term ice thinning in line with Arctic warming driven by impact of greenhouse gases on longwave radiation balance
(3) Thinner, more mobile ice cover more susceptible to extreme summer retreat
(4) Warming of water north of Alaska as a result of thinned & reduced ice cover melts back ice from below in summer (>2 m of summer bottom melt north of Alaska!); less clouds in 2007
(5) Warm inflow of water through Bering Strait(?)
workshop #6: animation...!
Sea ice summary

1. Significant melting of Arctic summer sea ice since ~1980; significant reduction in sea ice area, extent, age and thickness

2. No change in overall Antarctic summer sea ice, different trends in different sectors

3. Feedbacks:
   a) albedo...: positive feedback
   b) thickness slows bottom freezing: negative
   c) melt ponds become smaller with sea ice age: positive

4. Storms, waves fracturing, sea ice export

5. Climate change detection/attribution
The End