How to define it?
- mean
- mode
- maximum
- average?

How to measure it?

Data from CREL, from the SHEBA experiment, western Arctic
Minimum (Sept) Sea-ice extent

1979 1985 1990 1995

2002 2005 2007

1 in 50

1 in 1000

1 in 1000

1 in 50

Stern, UW, Data NASA

1/3 total USA
Changes in Sea Ice Extent

Comiso et al, GRL, 2008

Figure 1. Daily ice extents and ice areas for 2005, 2006, 2007, and averaged over the 5-year periods 1980–1984 through 2000–2004. Values are derived from satellite passive-microwave data from NASA’s Scanning Multichannel Microwave Radiometer (SMMR) and the Department of Defense’s Special Sensor Microwave Imager (SSMI).

Figure 2. Daily Arctic ice concentrations from AMSR-E for 14 September 2007, when the ice cover reached its minimum extent. The gold contour represents the ice edge inferred from the average of the ice concentration maps during ice minimum extent over the period 1979–2006, while the red contour represents the ice edge during ice minimum in 2005, which was the previous record low.

Figure 4. Monthly ice extent and ice area anomalies from November 1978 to September 2007 (green and blue), with the 12-month running average (red) and linear trend lines for the full record (black) and for 1978–1996 (green) and 1996–2007 (blue).
Thinning of the Arctic Sea-Ice Cover
D.A. Rothrock, Y. Yu, and G.A. Maykut
University of Washington, Seattle, Washington

GRL, 1999

Figure 4. Changes in mean draft from the early period to
the 1990s. The change at each crossing is shown numerically.
The crossings within each regional group (Figure 3) are given the
same shading equivalent to their group mean. Each square covers
about 150 km, the typical sample size.

Figure 2. Modeled seasonal cycle of ice thickness and draft
used to correct observations to 15 September. Draft is computed
as modeled thickness divided by 1.12. The observations all lie be-
tween late July and late October, as shown by the dotted vertical
lines.

Arctic
Sea-ice
Change
- Thickness

BUT – seasonal cycle
- aliasing due to submarine tracks
The decline in arctic sea-ice thickness: Separating the spatial, annual, and interannual variability in a quarter century of submarine data

D. A. Rothrock, D. B. Percival, and M. Wensnahan

Seasonal variability comparable with interannual trend

NEED TO DO STATS CAREFULLY
Variations in the age of Arctic sea-ice and summer sea-ice extent

Ignatius G. Rigor\textsuperscript{1,2} and John M. Wallace\textsuperscript{3}  

Received 14 January 2004; revised 17 March 2004; accepted 26 March 2004; published 8 May 2004.

Changing AGE of Sea Ice

\textbf{Figure 2.} Age of oldest sea-ice in September 1981, and September 2002 based on the simulation. Open water (OW) is shown as dark blue, and the oldest ice is shown as white. The drift of buoys that reported for at least 8 months of the prior 12 months are also shown (magenta lines with black dots), with a large red dot marking the current position. Tracks without large red dots mark buoys that have ceased reporting. The thick yellow lines mark 90\% ice concentration, while the thinner yellow lines mark ice concentrations of 50, 60, 70, and 80\% for those months. Figure a) also shows the drift of the Russian manned drifting station, NP-22, from 1973 to 1982 (black trajectory), with dots marking monthly positions, and circles noting the position of the station during September of each year; and areas of open water, first (FY), second (2Y), and third year (3Y) ice are noted in red. The Beaufort Gyre and Transpolar Drift Stream are also shown (black arrows).

Age of sea ice movie
Ice age to ice thickness

A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss  
GRL, 2007

J. A. Maslanik,¹ C. Fowler,¹ J. Stroeve,² S. Drobot,¹ J. Zwally,³ D. Yi,³ and W. Emery¹

Age from ice tracking/ buoy data
Thickness from ICESat (2003-2006)

.. then use this relationship to INFER thickness from age (for years before ICESat)

Figure 2. Mean 2003–2006 spring ice thicknesses as a function of age. The ranges of mean thick 4 years are indicated.

Eos, Vol. 89, No. 2, 8 January 2008

Stroeve et al, 2008, EOS

Fig. 2. March sea ice thickness for 1987 and 2007 from Maslanik et al. [2007b] ice-tracking algorithm, and for March 2007 from ICESat (data provided by D.Yi and J.Zwally, NASA).
Loss of MultiYear ice

Ngheim et al, GRL, 2007
- QuickSCAT backscatter distinguishes multiyear ice
- compare to IABP drift age model

Kwok, GRL, 2007
- summer 2005, no replenishment of MY ice
- Fram Strait export 40% of MY ice loss
(rest = melting)
But not so dramatic in volume

Using ice-ocean model, forced by NCEP winds

Ice extent good (as you’d expect!)

Ice thickness checked against subs

Volume loss about same trend as previous years – but manifests as large extent change as ice is thin

Note average ice thickness includes areas of open water

Area of Arctic used = 6.52 x 10^6 km^2; Thus 1m=6.5x10^3 km^3
Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum

Katharine A. Giles,^1 Seymour W. Laxon,^1 and Andy L. I

[1] September 2007 marked a record minimum in sea ice extent. While there have been many studies published recently describing the minimum and its causes, little is known about how the ice thickness has changed in the run up to, and following, the summer of 2007. Using satellite radar altimetry data, covering the Arctic Ocean up to 81.5° North, we show that the average winter sea ice thickness anomaly, after the melt season of 2007, was 0.26 m below the 2002/2003 to 2007/2008 average. More strikingly, the Western Arctic anomaly was 0.49 m below the six-year mean in the winter of 2007/2008. These results show no evidence of short-term preconditioning through ice thinning between 2002 and 2007 but show that, after the record minimum ice extent in 2007, the average ice thickness was reduced, particularly in the Western Arctic. Citation: Giles,
2007 Arctic Sea Ice
- decrease in extent
- thinner, and younger
- loss of MultiYear Ice

WHY????

Eos, Vol. 89, No. 2, 8 January 2008

Stroeve, et al

Fig. 2. March sea ice thickness for 1987 and 2007 from Maslanik et al. [2007b] ice-tracking algorithm, and for March 2007 from ICESat (data provided by D. Yi and J. Zwally, NASA).

Ngheim et al, 2007

Figure 3. Time-series of area of perennial sea ice extent in March of each year estimated by the Drift-Age Model (with a fifth-order regression) and observed by QuikSCAT satellite scatterometer within the model domain. In each year, the model result was an average over March, and the satellite observation was on the spring equinox (21 March).
What do we need to stay in the game?

Assume 1m thick ~ 2 x 10^{12} m^3 (extra volume lost) (i.e. 2 x 10^3 km^3)

Energy needed for melt ~ Mass x latent heat
~ 1000 x 2 x 10^{12} x 333,000
~ 6 x 10^{20} Joules

Which is equivalent to ~ 3 x 10^8 J/m^2 (or 300 MJ/m^2)
~ 10 W/m^2 (if all year)

(10 W/m^2 ~ 1m of ice melt in 1 year)
Ice Advection

Summer sea ice motion from the 18 GHz channel of AMSR-E and the exchange of sea ice between the Pacific and Atlantic sectors

Ron Kwok

Figure 3. Maps of the Arctic ice extent at the end of June (blue), July (green), August (red), and the summer minimum (yellow) for the five summers. Line plots show the ice area in the two sectors (Pacific, blue; Atlantic, green) and the contribution of ice advection (in red) across the flux gate (defined above) to the summer retreat of sea ice in the Pacific: (a) 2003, (b) 2004, (c) 2005, (d) 2006 and (e) 2007. The flux gate, the bounds of the Arctic Ocean, and the two sectors (P-Pacific, A-Atlantic) are identified in Figure 3a.

Fram Strait sea ice flux

2005 ~ 0.25 x 10^6 km^2
2006 ~ 0.16 x 10^6 km^2
2007 ~ 0.28 x 10^6 km^2

Extra area lost

~ 2 x 10^6 km^2

Ice export only

~ 15% of sea ice retreat
Summer retreat of Arctic sea ice: Role of summer winds

Masayo Ogi, Ignatius G. Rigor, Miles G. McPhee, and John M. Wallace

[1] The unprecedented retreat of first-year ice during summer 2007 was enhanced by strong poleward drift over the western Arctic induced by anomalously high sea-level pressure (SLP) over the Beaufort Sea that persisted throughout much of the summer. Comparison of the tracks of drifting buoys with monthly mean SLP charts shows a substantial Ekman drift. By means of linear regression analysis it is shown that Ekman drift during summer has played an important role in regulating annual minimum Arctic sea-ice extent in prior years as well. In combination, the preconditioning by events in prior years, as represented by an index of May multi-year ice, and current atmospheric conditions, as represented by an index of July–August–September SLP anomalies over the Arctic basin account for ~60% of the year-to-year variance of September sea-ice extent since 1979. Citation: Ogi, M., I. G.}

BUT ice advection of 15%
ice concentration only 10-37% of extent change
Role of the Pacific-North American (PNA) pattern in the 2007 Arctic sea ice decline

Michelle L. L’Heureux,¹ Arun Kumar,¹ Gerald D. Bell,¹ Michael S. Halpert,¹ and R. Wayne Higgins¹

[1] The extreme loss of sea ice over the western Arctic during the boreal summer of 2007 (July–August–September) was accompanied by a very unusual atmospheric circulation pattern. Here we show that the anomalous circulation was linked to a leading climate mode of the Northern Hemisphere, the Pacific-North American (PNA) pattern. The PNA index was three standard deviations above the 1950–2007 mean, and its primary signal in the atmospheric circulation is a strong anomalous anticyclone that was collocated with the location of the greatest Arctic sea ice decline. Therefore, the record-strength PNA along with recent climate trends in the Arctic help to explain the sudden and extreme sea ice melt during the summer of 2007. While the observed PNA was unique, the large decline in sea ice may be further evidence of increased vulnerability to natural atmospheric variability due to a changing climate system. Citation: L’Heureux, M.
Increasing Arctic Air Temperature (links to Sea ice?)

Temperature Change 2003 - 1954

Alaska +2°C

Siberia +2°C

Greenland -1°C

Arctic Climate Impacts Assessment (ACIA) Report 2004

Courtesy of I. Rigor
The year 2007 was the warmest on record for the Arctic, continuing a general, Arctic-wide warming trend that began in the mid-1960s (Fig. A1).

From Overland et al, Arctic Report Card, 2008
http://www.arctic.noaa.gov/reportcard/
ArcticReportCard_full_report.pdf

Surface Air Temperature

Jan-Sept SAT over the Arctic Ocean from NCEP, reproduced from Zhang et al, 2008.
What drove the dramatic retreat of arctic sea ice during summer 2007?

Jinlun Zhang,¹ Ron Lindsay,¹ Mike Steele,¹ Axel Schweiger¹

Received 14 March 2008; revised 29 April 2008; accepted 8 May 2008; published 11 June 2008.

A model study has been conducted of the unprecedented retreat of arctic sea ice in the summer of 2007. It is found that preconditioning, anomalous winds, and ice-albedo feedback are mainly responsible for the retreat. Arctic sea ice in 2007 was preconditioned to radical changes after years of shrinking and thinning in a warm climate. During summer 2007 atmospheric changes strengthened the transpolar drift of sea ice, causing more ice to move out of the Pacific sector and the central Arctic Ocean where the reduction in ice thickness due to ice advection is up to 1.5 m more than usual. Some of the ice exited Fram Strait and some piled up in part of the Canada Basin and along the coast of northern Greenland, leaving behind an unusually large area of thin ice and open water. Thin ice and open water allow more surface solar heating because of a much reduced surface albedo, leading to amplified ice melting. The Arctic Ocean lost additional 10% of its total ice mass in which 70% is due directly to the amplified melting and 30% to the unusual ice advection, causing the unprecedented ice retreat. Arctic sea ice has entered a state of being particularly vulnerable to anomalous atmospheric forcing.
Solar

Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback

Donald K. Perovich, Bonnie Light, Hajo Eicken, Kathleen F. Jones, Kay Runciman, and Son V. Nghiem

TARGET

$\sim 6 \times 10^{20}$ Joules
$\sim 3 \times 10^8$ J/m$^2$ (or 300 MJ/m$^2$)
$\sim 10$ W/m$^2$ (if all year)

(10 W/m$^2$ $\sim$ 1m of ice melt in 1 year)

Figure 1. Map of mean total annual solar input averaged over 1979–2005 (units are in MJ m$^{-2}$).
Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007

Donald K. Perovich,1 Jacqueline A. Richter-Menge,1 Kathleen F. Jones,1 and Bonnie Light2

Figure 2. Time series from August 2006 to October 2007 from the Beaufort Sea ice mass balance buoy. (top) Air temperature. (middle) Internal ice temperature using color contours, with blue being cold and red warm. The gray shaded area represents snow, the black areas represent missing data, and the dark blue represents the ocean. (bottom) Upper ocean temperature near the bottom of the ice (black) and the bottom melt rate (red) in cm per day. Bottom melt rates were smoothed using a three-day running mean.

Figure 4. Results from the Beaufort Sea in 2007. The dashed line shows the time series of the heat required for the observed bottom melting, and the solid line shows the solar heat directly input to the ocean in the region defined by the average of the four points in Figure 3.
What’s the trigger?? .. and what’s left in the water??

Pacific Water Heat
- 2 to 5 x 10^{20} J/yr

Wind-driven polynyas?/ice retreat
Warm Air Advection?

TARGET
~ 6 x 10^{20} J per year

Atlantic Water Heat
- 2 to 13 x 10^{20} J/yr
Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean

Koji Shimada, Takashi Kamoshida, Motoyo Itoh, Shigeto Nishino, Eddy Carmack, Fiona McLaughlin, Sarah Zimmermann, and Andrey Proshutinsky

Sea Ice Outlook | Monthly Report

May Report: Outlook Based on May Data

Report Released 10 June 2008

SUMMARY

The May Sea Ice Outlook report for the September 2008 sea ice extent is based on outlooks from the international arctic science community. The outlook for September 2008 indicates a continuation of the recent trend of sea ice loss.
Possible suspects

PRECONDITIONING
Memory of ...
- Ice (age, thinning)
- Water
- Atmos (??)

MELT FROM ABOVE
- warmer air temperatures
- more clouds (thus more long wave)
- increased solar radiation??

ICE
- advected away by wind or water
  (Fram Strait, Barents Sea, ??)
  - ridged

(formed less in the first place??)

MELT FROM BELOW
- increased ocean heat input
  (Local heat, from albedo feedback)
  or
  Far field heat (advected in)