Life Cycle of Sea-Ice

Sea-water
~ 35 psu

Frazil, or grease ice
- small crystals

Rough Conditions
Pancake Ice

Calm Conditions
Nilas

Ice Floes

Sea-ice

First-year ice
~ 4-10 psu
Flat and ridged
1-2 m thick unridged

MULTI-YEAR ICE
~ 1-4 psu
Thermodynamic equilibrium
thickness ~ 3m
Ridges ~ 10-25m, keels maybe 50m!

Thickens

Ice Melt
~ 4 psu

Distillation effect

Rotten Ice
- surface melt ponds

Melts

FIRST-YEAR ICE
~ 4-10 psu
Thermodynamic equilibrium
thickness ~ 3m
Ridges ~ 10-25m, keels maybe 50m!
Internal Structure of Sea Ice

away from surface,
long crystals as congelation ice
(frozen on from below)

Brine Channels within the ice
(\textasciitilde width of human hair)
Brine rejected from ice (4-10psu),
but concentrates in brine channels
(small volume but VERY HIGH SALINITIES)
-6 deg C  -10 deg C  -21 deg C
100psu  145psu  216psu

Pictures from AWI
Brine Volume and Salinity

Fig. 2. Gradients of temperature, salinity, and brine volume are established across an ice floe. The underside is always at the freezing point of seawater –1.8°C and the top of the ice close to air temperature, although this is largely dependent on snow cover. The illustration shows how snow cover can significantly reduce the amount of incident irradiance (I0). [Adapted from (3), with permission from Springer-Verlag]

From Thomas and Dieckmann 2002, Science .... adapted from papers by Hajo Eichen

???? nutrients??
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Thickens

Thickens

Distillation effect

Thickening:
- thermodynamic = congelation ice
- mechanical = finger rafting
- ridging

FIRST-YEAR ICE
~ 4-10 psu
Impacts of Sea-ice on the Ocean

**ICE FORMATION and PRESENCE**
- brine rejection
- Ocean-Atmos momentum barrier
- Ocean-Atmos heat barrier
- ice edge processes (e.g. upwelling)
- keel stirring (i.e. mixing, but < wind)

**MELTING ICE**
- stratification (fresher water)
  (cf. distillation as ice moves from formation region)
- transport of sediment, etc

**FREEZE**
- how deep does this mix?
- S increases

**MELT**
- Fresh
- Saltier

**START**
- 35psu
- 4-10psu

Wind

Ocean
How big a change in salinity?

25m of water with salinity 35 psu
grow 1m of ice at 4 psu
- what is the new salinity of the water?

Conserve Mass         (1)  \[ \rho_w A_w H_w = \rho_i A_i H_i + \rho_f A_f H_f \]
Conserve Salt           (2)  \[ \rho_w A_w H_w S_w = \rho_i A_i H_i S_i + \rho_f A_f H_f S_f \]

A is all the same, \( \rho \) are all known, \( H_w \) and \( H_i \) are given.
\( H_f \) and \( S_f \) are unknown, want \( S_f \).
So, cancel A, remove \( H_f \), to get:
Rearrange (1)  \[ \rho_f H_f = (\rho_w H_w - \rho_i H_i) \]
Substitute into (2)  \[ S_f = (\rho_w H_w S_w - \rho_i H_i S_i)/\rho_f H_f \]
\[ S_f = (\rho_w H_w S_w - \rho_i H_i S_i)/ (\rho_w H_w - \rho_i H_i) \]
\[ = (1023 \times 25 \times 35 - 920 \times 1 \times 4)/(1023 \times 25 - 920 \times 1) \]
\[ = 36.16 \text{ psu} \]

DOES THIS SEEM ABOUT RIGHT??
- about the same as removing 1m of fresh water
- so volume changes ~ 4% .. so we might expect salinity to change about 4% ... 4% of 35 is ... oh around 1 ...
i.e., ~ 1 psu change
Impacts of Sea-ice on the Atmosphere

ICE PRESENCE
- albedo change
- Ocean-Atmos momentum barrier
- Ocean-Atmos heat barrier

Water Sky

Sea Smoke
Heat balance

From N. Untersteiner

S = Shortwave radiation from sun (reflects off clouds and surface)

albedo = how much radiation reflects from surface
albedo of ice ~ 0.8
albedo of water ~ 0.04 (if sun overhead)

L = Longwave radiation (from surface and clouds)

F = Heat flux from Ocean

M = Melt (snow and ice)
P = Precipitation
T = Atmospheric Heat Transfer
q = Atmospheric moisture transfer

ice albedo feedback
Sea Ice Motion

**OLD RULE OF THUMB**
Ice (Northern Hemisphere) moves with
- speed about 2% of surface wind
- about 45deg to the right of the wind

**Surface**
WIND = 10 m/s

**ICE ~ 20 cm/s, ~45 deg to right**
quite a fast ice speed – see next plots

**THORNDIKE AND COLONY 1982**
- speed 1% of geostrophic wind
- 5 deg to right of wind

Geostrophic
WIND = 20 m/s

**ICE ~ 20cm/s, 5 deg to right**
(NB 50cm/s ~ 1 knot ~ 1 mph)
Infer Sea ice motion from Sea Level Pressure and Buoy tracks

Fig. 4. Analyzed fields of SIM for (a) 1979 and (b) 1994 (gray vectors). The monthly positions of the buoys are also shown. Trajectories for individual buoys are indicated by black lines.

Fig. 2. Analyzed fields of SLP and SIM for Dec 1993. Dots mark positions of IABP buoys, and arrows show buoy velocities. Contours are shown every 2 hPa.

Rigor et al, 2002, Response of Sea Ice to the Arctic Oscillation, J Climate
Sea-ice motion

The drift of sea ice across the isobars in these long-term means (Fig. 3) reflects the influence of the ocean currents upon SIM. On timescales longer than a year the contributions from the winds and ocean currents in driving SIM are roughly equal, but as shown in Fig. 2, the drift of sea ice on shorter timescales (≤1 yr) follows the wind (Thorndike and Colony 1989). On short timescales SIM can be approximated by the simple rule of thumb that the ice drifts with a speed of about 1% of and 5° to the right of the geostrophic winds (e.g., Thorndike and Colony 1982, Eden 1988).

Long term Ice Drift = Winds + Ocean

Thorndike and Colony, 1982, Sea Ice Motion in Response to Geostrophic Winds, JGR

Rigor et al, 2002, Response of Sea Ice to the Arctic Oscillation, J Climate
Shorthand atmospheric circulation – the Arctic Oscillation (AO)

\[
\text{SEA LEVEL PRESSURE} = \text{MEAN} + \text{VARIABILITY}
\]

**WHAT THE ARCTIC SEES**

<table>
<thead>
<tr>
<th>Hi AO</th>
<th>Lo AO</th>
</tr>
</thead>
<tbody>
<tr>
<td>small Beaufort gyre</td>
<td>large Beaufort gyre</td>
</tr>
<tr>
<td>more Atlantic influence</td>
<td>less Atlantic influence</td>
</tr>
</tbody>
</table>

Covariance of Sea Level Pressure with AO index (hPa/30 years)

From D. Thompson, based on Thompson and Wallace 1998
HIGH AO
Lower SLP ► more cyclonic atmosphere
Beaufort Gyre (AC) ► weaker, smaller
More ice swept out with TransPolar drift
(more Atlantic Influence)
(Warm Phase)

LOW AO
Higher SLP ► more anticyclonic atmosphere
Beaufort Gyre (AC) ► stronger, bigger
Less ice swept out with TransPolar drift
More stored in Beaufort Gyre
(less Atlantic Influence)
(Cold Phase)

Rigor et al, 2002, Response of Sea Ice to the Arctic Oscillation, J Climate
**HIGH AO**

Lower SLP ► more cyclonic atmosphere
Beaufort Gyre (AC) ► weaker, smaller
More ice swept out with TransPolar drift
  - less convergence of sea ice
    (i.e. less ridging, ice thinner)
  - longer transit from Chukchi

Years to exit through Fram Strait

**LOW AO**

Higher SLP ► more anticyclonic atmosphere
Beaufort Gyre (AC) ► stronger, bigger
Less ice swept out with TransPolar drift
  More stored in Beaufort Gyre
  - more convergence, more ridging

Rigor et al, 2002, Response of Sea Ice to the Arctic Oscillation, J Climate
Sea-ice thickness

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

How to measure it?

Data from CREL, from the SHEBA experiment, western Arctic