Sea ice

1. Formation

1.1 Factors influencing sea ice formation

Several parameters influence sea ice formation. The air plays its role like an energy absorbant because of the difference between its temperature and the temperature of the water. The state of the water, calm or rough, gives two different types of ice. In this paper the rough water model will be discussed. As shown on in figure 1, the latitude influences also the sea-ice formation because the phenomenon of pycnocline vs deepwater is not the same and it changes the convection circulation in the water temperature cold down step.

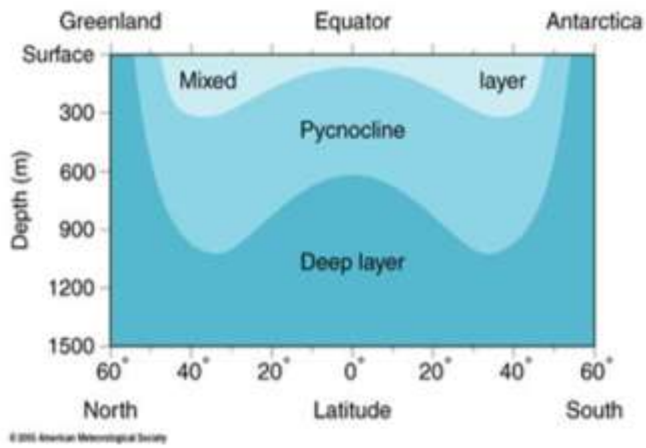

Figure 1 - Latitude and sea layers

1.2 Influence of the salinity

The salinity of the water has an impact in the sea ice formation. Like mentioned above, it influences the water cold down process. In fresh water the energy of the water is transferred to the air and cause the convection circulation. The cold water, until 4°C, drops into the deepest zone and the warm water reach the surface. At a certain moment, the entire surface layer for deep water systems or all the water for shallow systems reaches 4°C. At this starting point the water colder than 4°C is less dense than at 4°C, so it stays on the surface and starts to freeze up when the water reach the freezing point. As shown on the figure 2, the special characteristic of the water density with the denser point at 4°C is modified when salt is present in the water. The freezing point reaches -1,9°C for the salinity of the arctic water(30 – 35 psu). In this way of mind, it is easy to understand that the

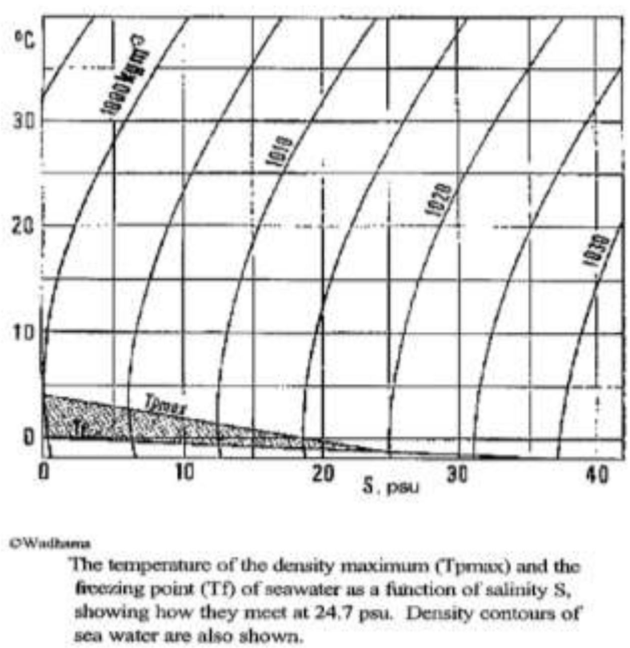

Figure 2 - Influence of salinity and temperature on the water density

convection phenomenon is true for all temperature of the water. In the literature there is some different thinking about the convection zone. Some of the authors talk about the absence of pycnocline in high latitude water and some others discuss about a convection depth of 100 to 150 meters.

1.3 Where the sea ice forms first

If a same air temperature model is taken as an assumption, the sea ice forms first in the bays, near the coast, in calm waters, in shallow waters and where the salinity is low (or in fresh water). As mentioned above, the water cold down is a critical step into sea ice formation. This is why the ice appears first in shallow water. The influence of salinity was discussed in the last paragraph.

1.4 Formation steps

<u>Terminology:</u>

Frazil: fines needles or platelets of ice suspended in water.

Slush or grease ice: accumulation of white and spongy ice pieces.

Nilas: thin and dark ice; plastic ice layer wavelike with the waves and swell of the sea.

Pancakes ice: circular pieces of ice of 30cm to 5m of diameter and 10 to 70 cm thick; the edges are lift up due to friction with other pieces of ice.

Floes: any 20m horizontal extension fragment of ice relatively flat, formed by the fractionation or fracture of an ice layer.

Pack ice: form of ice composed of overlying ice floes, deformed sea ice

Brine: Water saturated by salt or almost saturated

<u>Waters' cooling down:</u>

Explained previously.

<u>First signs of freezing:</u>

Apparition of tiny discs at the surface, but these discs are rapidly broken due to the water movement, and then the grease ice suspension is called frazil. At this moment, snow fall can help slush's (frazil) formation. In figure 3, the grease-ice is shown while waves can still be seen. Suddenly, the grease ice hits each other because of the water movement and forms small pancake. Good to know that the process of heat transfer is still in action and will be in action as long as the air temperature will be lower than the water temperature.

Figure 3 - Grease-ice and small pancake ice

The pancakes' growth:

The Pancakes growth by the pumping keeps that is still going on at its surrounding edge. At the ice edge, the pancakes are only a few cm in diameter. They gradually grow in diameter and thickness as they are further from the coast. They can reach 3 to 5 m in diameter and 0,5 to 0,7 m thick. The surrounding frazil continues to grow and bring ice to the edge of the growing pancakes.

Merge of the pancakes:

Where the waves have less energy, far from the ice edge, the pancakes start to freeze (glued) together and form pack ice soon. It will occur until the moment where the pancakes (floes) will be transformed in floes in a continuous sheet called consolidated pancake ice (pack ice). The last description is on a theoretical model. In real sea the waves are strong and the wind blows hard, so the pancakes are glued in several positions and it results in a hard surface at the bottom as well as on the top. The top of the sea ice appears smooth but this is caused by the accumulation of snow. This snow accumulation will be discussed later in this paper.

You can follow theses first steps in the next figures.

Figure 4 - Small and medium pancake

Figure 5 - Medium and large pancake ice start to form pack ice

Figure 7 - Large pancake formed into pack ice

Figure 6 - Consolidated pancake ice continuous sheet (pack ice)

1.5 Thickness growth

Figure 8 - Cross section of ice with its different layers

Once the pack ice is formed the thickness' growth continues. The ice gets thicker and thicker by the bottom by freezing water and the heat is transferred across the ice sheet to reach the cold air. The growth is proportional to the difference of temperature between the air and the water. The ice thickness and the snow cover influence the heat transfer because they act as insulatiors. To have an idea of the growing rate's scale, at first, perhaps 8 to 10 centimeters can be accumulated in the first 24 hours and than the rate of growth gradually decreases as the ice thickens. During one season the ice can reaches 1 to 1,5 m thick. In the Arctic sea at the North Pole the perennial ice is 3 to 5 m thick.

1.6 Salinity displacement

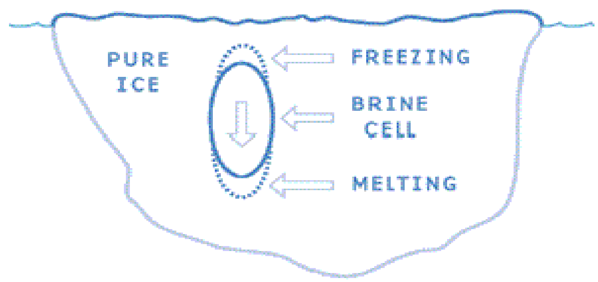

Figure 9 - Brine displacement

Once the slush is formed, the salt migrates to the water and the water become saltier. The ice crystal does not content salt, it forms as pure ice. The saltier water becomes denser and sinks under slush layer or in the bottom of the slush layer. The amount of crystals become higher and they freeze together as a pancake and brine cells or pockets are been trapped in the ice. The two-phase zone exists now. Sea ice contains the liquid phase even at very low temperatures. The ice is completely transformed into a one-phase solid system at temperatures that virtually never occur in situ.

The upper layers (low percentage of salt) have the lowest temperature, so the liquid phase in them is almost 100% frozen. The temperature of the lower layers is near to the freezing point of seawater, and they are more saturated with brine. With the growth of ice thickness, the thickness of the lower layers saturated with water also increases. And then, as shown on figure 9, the migration of brine in the direction of lower level starts and takes place in the secondary growth phase of the sea ice.

1.7 Sea ice component

The sea ice is nothing more than pure crystal ice, brine pocket and air bubble forming way for the movement or the migration of the brine in downward direction. Some micro life found place in sea ice also, like several kind of plankton.

2. Growth and decay of sea ice

2.1 Dynamic processes

Dynamics processes acting on sea ice can be best described by this formula:

$m\delta u/\delta t = - mfk \times u + T a + Tw + F - mgH$,

where the momentum balance is equal to sum of Coriolis effect ($mfk \times u$), air stress (T_a), water stress (T_w), internal stress (F) and the tilt of the ice (mgH).

- **Coriolis stress:** Ekman has showed that sea ice on water will be deflected of 20° to 40° on the right while drifting.

- **Air stress:** Geostrophic winds are modified as it gets closer to the surface because Coriolis effect is decrease. Thus, surface winds in polar areas will be the result of the topography, the friction behaving on geostrophic winds, and katabatic winds. Wind has a great influence (70% of ice drift) on the extent and the distribution of sea ice because it follows its general trend. The result will be an ice drift deflected 5° to 15° to the right in the Northern Hemisphere.

- **Water stress:** Many sources influence water movement including tides, bathymetry and wind. Water is less strong than wind but because it is constant, it will have an impact on ice drift.
  How fast will sea ice go under wind and current? It will depend on the wind's speed, the friction of air layers, the friction between ice and air and water friction (also depending on the texture of the ice under the water).
  Finally, ice drift can be piled up against coast or drifting quickly in the ocean by the wind and the current. A wide range of responses between those two possibilities exists too. It will have an impact on the ice internal stress.

- **Internal stress:** It is a function of ice thickness and the conditions of the surrounding environment. If the wind is strong enough and last long enough, increasing the internal stress, the latter gets higher than ice's strength producing leads, fractures, ridging, rafting, etc. Ice strength depends on its thickness and its concentration. Thus, hardening of ice will occur quickly as weak ice (thin ice, low concentration) will be quickly incorporated in ridges. Ice will get harder and harder with the many stresses acting on it.

- **Tilt:** The last parameter to be considered in the ice dynamic formula is the sea level tilt. It can be caused by two external agents: wind and variability in sea level pressure.

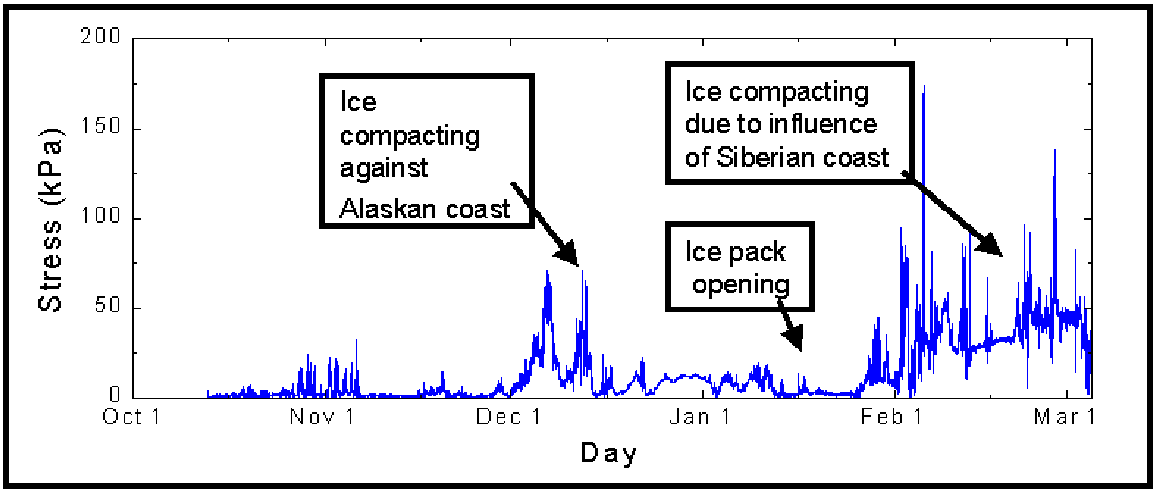

Figure 10: Evolution of internal stress against day

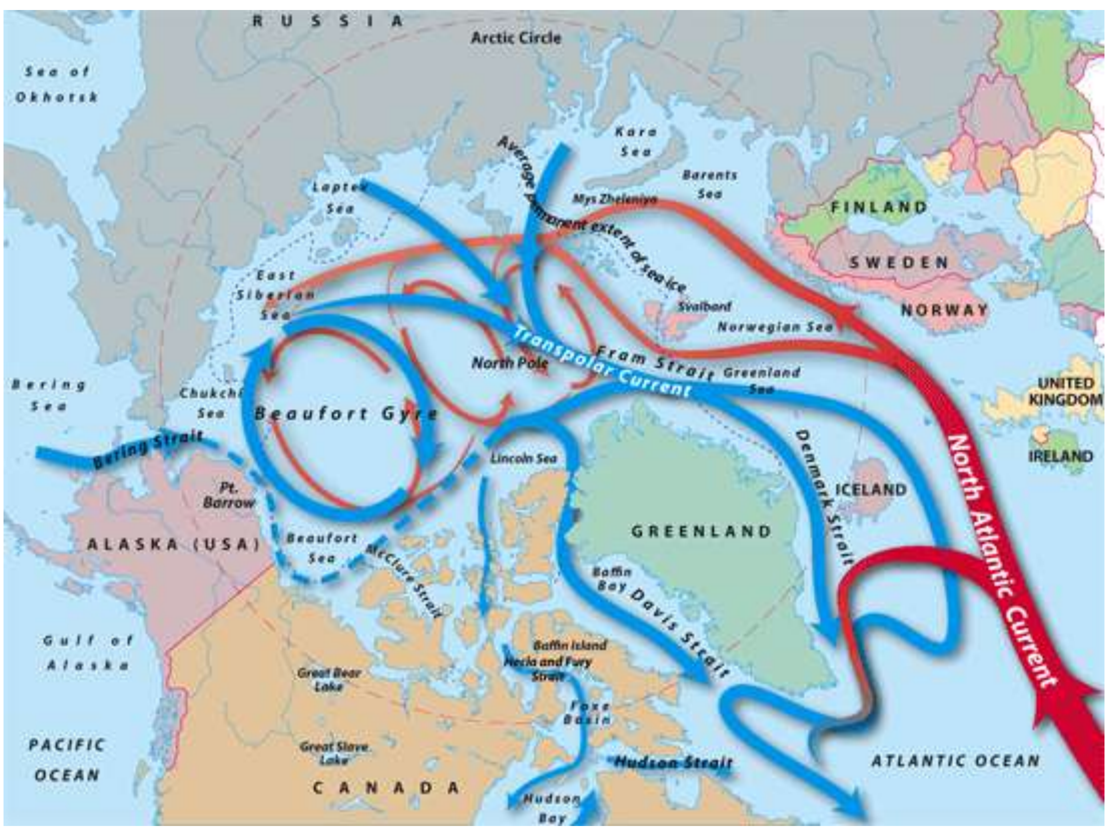

Figure 11: Circulation pattern in the Arctic Ocean mainly as a result of dynamic processes.

2.2 Thermodynamics processes

Solar radiations constitute the major source of energy for the pack ice during the melting season and, are the fundamentally explanation responsible for the breakup and decay of ice.

The initial stages of breakup and decay are the melt of snow cover and the deformation of melt ponds (occurring in parallel). This is due to sensible and latent heat fluxes.

A very rapid melting of the snow cover takes place when the air temperature reaches 0°C. The melt water of the snow gathers and forms a pools network on the surface of the ice. The shallows pools at the end of winter are becoming deeper and wider. The melt water just accumulates in little depressions or can be retained by slush. The water contained in those pools reduces the albedo (reflects 15%-40% of radiation compared to 40%-70% for bare-ice) and increases the rate of ice melt. Then, as the summer progresses, the pools get fix and became deeper and wider.

After a few weeks, the water will eventually go in the sea by canals, cracks or by vertical holes right through the ice (where the ice is at its thinnest point or at the deepest point of the pool). The sea-ice takes the typical appearance of a summer ice cover: melt ponds with smooth hummocks around. Thereafter, as the coming/outgoing long wave radiations of the earth system are balanced and as the sensible and latent heat is nonsignificant in summer, the remaining decay of ice cover is mainly due to short wave radiation incident on the ice surface.

If the solar radiations are not absorbed by the ice, they are then reflected (albedo). The most important thing determining the sea-ice albedo is the presence or absence of snow. For example, on young sea-ice without snow, sunlight is reflected at the surface and also scattered by the presence of air bubbles and brine pockets inside the ice. The albedo is controlled by size and number of air bubbles and by the thickness of the ice. Thus, the albedo is lower on young sea-ice than on thick ice covered by snow. The energy absorption is then more important on young sea-ice and the melting should be faster.

2.3. Deformation

The nature of sea-ice deformation depends on its scale. Small-scale (diameter of a floe) deformation are determined by internal forces and described in term of basic deformation processes.

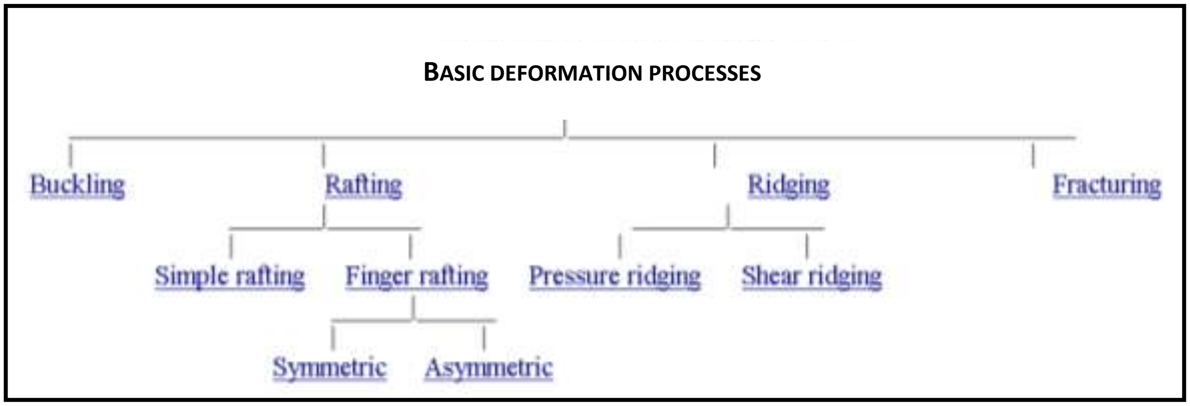

Figure 12 : Basic deformation processes

Some deformation features:

- Pressures ridges due to thermal expansion: more in recent ice (more salty, more fragile)
- Hummocks: mounds of broken ice lifted by pressure coming from the meet of several ice patches, eroded under the action of blowing, melt and solar radiation

*Hummocks are less salty and more solid than pressure ridges. These are the last types of sea-ice to melt.

- Floes
- Rifting
- Cracks

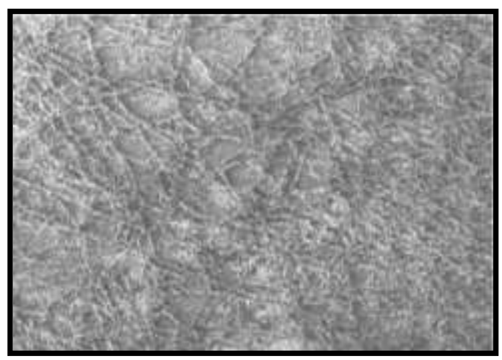

Figure 13 : Pressure ridges network

Ice expansion and thermal contraction are other types of deformation.

- When the temperature of the sea-ice goes down under freezing point, the ice takes expansion, quickly at the beginning and then slowly, until it reaches the temperature where it starts to contract slightly. Higher is the salinity, quicker is the expansion. Due to thermal expansion, there is formation of pressure ridge at the ice surface. Then:
  - If the temperature is even lower, the ice starts to contract and crack. As the contraction is inferior to the expansion, the cracks are thin.
  - If a very cold ice heats, the expansion is slow (causing closure of cracks) and the contraction is gradual until the freezing point is reach. Then, after a warm period, large cracks travel around the ice.

3. Sea ice and the global warming

As mentioned by the Arctic Climate Change and Its Impacts 2001, 10 points can summarize the impacts of global warming in the Arctic. Six of them are directly linked with sea ice. Those are:

- Sea ice diminution, which is basically the origin of;
- An increasing absorption of sun's radiation;
- A reduction of habitat for a lot of species;
- A reduction in hunting area for indigenous people, as well as a lost of cultural elements for a lot of communities;
- An increasing erosion of coasts;
- An increasing maritime transport.

All these consequences of the reduction of sea ice covers are well known but often misunderstood. The focus here is on two major problems that are frequently mentioned and studied all around the Arctic Circle: coastal erosion and maritime transport.

3.1 Maritime traffic

Because of the sea ice reduction, northern countries, such as Canada, Denmark (on behalf of Greenland), Russia and United States claim as much of the Arctic seabed as possible, to gain as more underwater resources (methane, gas). Russia has already been able to use its northern sea route for up to 6 months, and Canada's International Policy Statement in 2005 did predict that "in addition to growing economic activity in the Arctic region, the effects of climate change are expected to open to Arctic waters to commercial traffic by as early as 2015." (Government of Canada)

Figure 104. Popular Northwest Passage routes. Popular Northwest Passage routes. Based on a NASA image (via UC Santa Barbara Department of Geography) at http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=16340

3.2 Impacts of sea ice in the coastal zone [1]

Sea ice plays an important role in the coastal dynamic. Its major effects are:

1. Protective role of fast ice and drift ice;
2. Evacuation of sedimentary materials from shallows;
3. Gouging of shores and bed ice;
4. Local erosion of the sea floor;
5. Processes of formation of fast ice and frozen ground in the near-shore zone.

However, with a reduction of sea ice covers, the Arctic sea coasts are less protected against hydrodynamic factors such as waves and tides. Furthermore, the fact that Arctic is surrounded by permafrost coastlines increases the erosion rate.

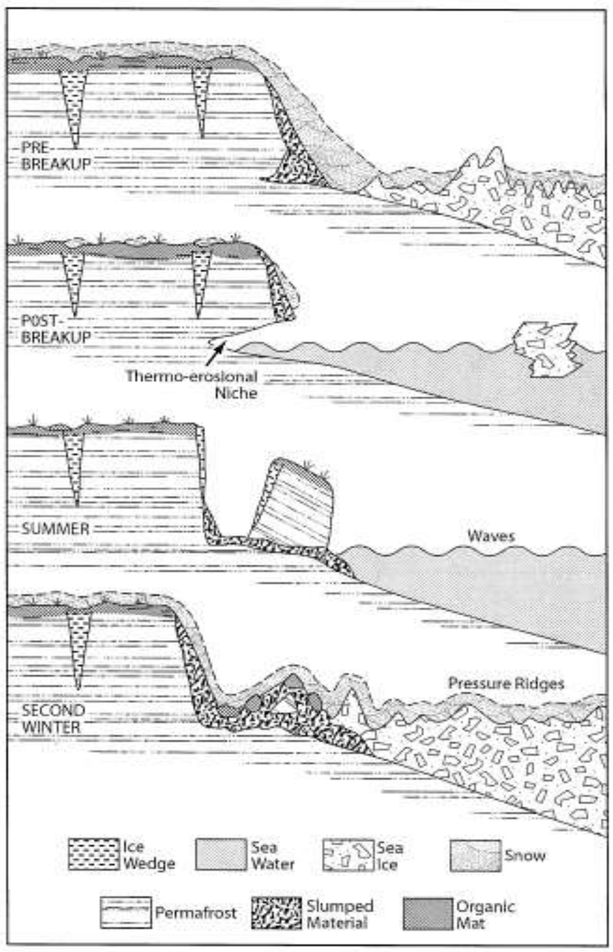

Figure 15: Block collapse and erosion along permafrost coastline.

[1] From Ogorodov (2003), in *The Role of Sea Ice in the Coastal Zone Dynamics of the Arctic Seas.*

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