1) Introduction Arctic and Periglacial environments

December-12-14
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What is Arctic, why is it important?

- There is no single definition of "Arctic"
  - Derived from Greek arctos, in reference to the northern bear constellation
- The location of the Arctic, north, and polar regions varies and depends on perspective
- We may think of it in terms of climate, some measure of mean annual temperatureI
- The presence or absence of permafrost
- Distinctive sea ice or vegetation communities

The Arctic represents diverse and distinctive physical and ecosystem environments

- A crucial feature of the Arctic environment is the near-constant influence of water in all three states
  - Climate drives overall availability of energy
  - Ice, snow and water present to some degree year-round
- A key Earth System: the cryosphere, pertaining to processes and phenomena associated with ice, snow and frozen conditions
  - Sea ice, glaciers, snowpack, permafrost, etc.

Sensitivity of the cryosphere to environmental change

- Feedbacks between weather (short term), climate (long term)
- Surface radiation budget
- Snow, ice cover
- Heat storage and release
- These processes are substantially more sensitive to change than those found in more temperate environments
- Manifests as extreme weather
- Heightened response to longer term climate change
- Threshold responses as components of the cyrosphere change
  - For example: the presence of sea ice is critical for winter climate
  - Removal of winter sea ice results in heat loss from warmer water to the overlying atmosphere
  - Significant winter warming and evaporation
  - Increased snowfall

Arctic Context:

- The goal of this course is to provide a context for the Arctic
  - We will investigate the key Arctic environmental systems
  - Consider processes that occur, and feedback mechanisms
  - Consider the impact of changes to these systems on human and natural ecosystems
- Keeping in mind the implications for communities, regional development, and the larger global ecosystem and economy

Human history: what lessons can we draw from Inuit and European in the Arctic?

- Both cultures have struggled to survive in the Arctic
- Inuit are a circumpolar indigenous people, with a complex history based on oral traditions and an emerging archaeological context
- European explorers and settlers brought concepts and practices from a temperate, highly structured setting
- Both have suffered through depravation to live and travel through the Arctic

Arctic pre-history

- Peopling of the Americas likely occurred recently, during or following the last glaciation
- Early human remains point to Asia as the origin for the first migrants
- Crossing to the Americas was facilitated by the Bering land bridge between Siberia and Alaska
    - Caused by eustatic sea level lowering during the last glaciation
- Alaska and adjacent Yukon was largely unglaciated

Peopling of the Arctic:

- The first evidence for pre-Inuit dates to c. 4500 years BP
    - Associated with small tools made of stone and bone
- Hunted marine mammals and travelled inland to hunt caribou
- There were two primary streams to this migration:
    - Independence culture that followed the Muskoxen northeast
    - Pre-Dorset culture that moved eastward in the
    - central Arctic to Baffin Island
- Both cultures used harpoons and other sophisticated technologies to hunt and adapt to the Arctic environment

Dorset Thule cultures:

- By 2800 BP, The Pre-Dorset culture had expanded to most of the central and eastern Arctic, and developed technologies that allowed hunting of all marine mammals except the Bowhead whale
- This Dorset culture was successful until AD 1400, when they were rapidly supplanted by a migration of advanced hunters from Asia to establish the Thule culture
    - The Thule people rapidly replaced Dorset (about a century) and brought sophisticated boating, sledding and hunting technology
    - They hunted bowhead whale, used dogs, and adapted to the cooling climate of the past c. 400 years
- Today's Inuit are descendants of the Thule culture
    - Note: Inuit or "the people" is plural, Inuk is singular
- While Inuit language is relatively uniform across much of the north (Inuktitut), there are a number of local variations (for example Inuinnaqtun in the western Kitikmeot region)
- Similarly, there are a number of cultural groups in Canada:
    - Inuvialuit (Mackenzie Delta)
    - Netsilik (Kitikmeot region)
    - Innu (Labrador)

- Traditional Inuit culture was superbly adapted to the Arctic environment through a cooperative, nomadic hunting tradition
- Success was based on intimate knowledge of the land, sea ice and water, and recognizing signs of animals and risks

European exploration:

- There were three major phases of European exploration of the Canadian Arctic
    - In 981 AD, Eric the Red sailed from Iceland and discovered Greenland.
    - Colonies were established in East Greenland and West Greenland
    - Artifacts found on Ellesmere and Devon Islands indicate that the Norse travelled around Baffin Bay and traded with Thule Inuit
    - The Norse colonized Newfoundland, but there is no evidence that they colonized further north

British exploration: 1576-1630

- Based on mapping available from the Norse era, British and French exploration of northern North America proceeded
- In 1576-8 Frobisher carried out three expeditions to what is now Baffin Island, under the auspices of mining exploration and development
    - The rocks believed to be rich in gold turned out to be worthless and the efforts were abandoned
- In 1585-7, Davis explored southern Baffin Island and identified Hudson Strait, which was believed to be a possible route to Asia- the Northwest Passage
- War delayed further exploration, but by 1610, Hudson led an expedition to Hudson Bay, and determined that this was a dead end
    - Subsequent trips by Bylot, Baffin, Munk and Fox delineated Hudson Bay and much of Baffin Bay
- From this effort, it appeared that a route to Asia did not exist
- For much of the 17th and 18th centuries, there was little exploration
- Key developments in navigation technology
    - Accurate chronometers and sextants for longitude measurement
- Also, it was recognized that scurvy could be prevented by the use of lemon or lime juice, which decreased the health risks of long voyages

European exploration: 1770-1900

- The epic explorations of the interior Arctic and northwest coast of Alaska by Hearne, Mackenzie and Cook, demonstrated that there was a contiguous northern coast to North America
- By 1789, when Mackenzie reached the mouth of the Mackenzie River, new interest was emerging for the Northwest Passage
- At the same time, the British Empire was waxing and the Royal Navy dominated the seas

- In 1818, John Ross led an expedition to northern Baffin Bay.
- His ships entered Lancaster Sound, but weather and nerves failed Ross and they retreated
- In 1819, William Parry on the ships Hecla and Griper entered Lancaster Sound and followed it to Melville Island, nearly across the archipelago

  - They wintered at Winter Harbour and explored the region on sledge before returning to England
- Also in 1819, John Franklin, along with Richardson, Hood and Back, travelled from Hudson Bay overland and down the Coppermine River to the coast.
- In 1821-3, Parry tried again, this time through Foxe Basin and he attempted to pass Fury and Hecla Strait between Baffin and the mainland without success
- In 1824, Parry sought the passage south of Lancaster Sound, but the Fury was wrecked and little new mapping was accomplished
- In 1825, Franklin journeyed overland again, down the Mackenzie River, and his teams explored the north coast in both directions
- In 1829, John Ross obtained private funding and sought a passage south through Prince Regent Sound. The Victory was wintered over two years, abandoned in ice and the members overwintered an additional year before rescue

- In 1845, the most famous expedition, John Franklin's third, set out in search of the Northwest Passage.
- His ships, the Erebus and Terror left the west coast of Greenland and were never seen again
- After several years, it was clear that a rescue for Franklin needed to be sent
- In 1850-1, M'Clure travelled from the west, and reached Mercy Bay on Banks Island where the ship was locked in ice
  - They travelled by sledge to Winter Harbour, proving the existence of the Northwest Passage
- An expedition under Admiral Belcher was mounted to search for Franklin and M'Clure
- Two ships, the Resolute and Intrepid were captained by Kellett and McClintock
- They wintered at Dealey Island near Winter Harbour and travelled to the latter on sledge
  - They discovered a recent visit by M'Clure's team from Mercy Bay
  - Kellett rescued M'Clure's crew and returned them to Dealey Island
- Belcher, for debated reasons, ordered all of the ships abandoned and the crews met at Beechey Island where they were rescued by other ships and returned to England

Victory Point: *The end of the Franklin Expedition?*

- A cairn and message was found by McClintock in 1859 describing the fate of some members of the expedition.
- In 2014, after years of searching, the Erebus was located south of Victory Point

Cape Bounty and the echoes of Arctic Exploration

- Located at nearly 110°W, Cape Bounty is in walking distance to Winter Harbour and Dealey Island
- The name derives from the optimism and adventure of the 19th century explorations that drove men to fame and infamy
- Parry's crew, on taking a longitude position off of Cape Bounty, recognized that they had earned Queen Victoria's "bounty" of 10 000£

- In 1819, reaching Winter Harbour, the expedition penetrated a region that has only recently become navigable due to sea ice loss
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- It was also Winter Harbour, on July 1, 1909, that Captain Joseph-Elzéar Bernier, as part of the Canadian Coast Guard travels in the Northwest Passage on board the Arctic, formalized the Canadian claim to the Arctic Archipelago and in a ceremony, mounted a plaque to Parry's Rock, overlooking Winter Harbour
- **Other ghosts:** *Whalers of Kekerten Island 1840-1882*

Intro notes
February-08-15
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    - We may think of it in terms of climate, some measure of mean annual temperature
    - The presence or absence of permafrost
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2. what lessons can we draw from Inuit and European in the Arctic?
    - Both cultures have struggled to survive in the Arctic
    - Inuit are a circumpolar indigenous people, with a complex history based on oral traditions and an emerging archaeological context
    - European explorers and settlers brought concepts and practices from a temperate, highly structured setting
    - Both have suffered through depravation to live and travel through the Arctic
3. Two ships, the Resolute and Intrepid were captained by Kellett and McClintock
4. Belcher ordered all of the ships abandoned and the crews met at Beechey Island where they were rescued by other ships and returned to England
5. HMS Investigator - mc'clure capitain, abandoned in mercy bay. First crew to complete the loop
6. Victory Point: *The end of the Franklin Expedition?*
    - A cairn and message was found by McClintock in 1859 describing the fate of some members of the expedition.
    - In 2014, after years of searching, the Erebus was located south of Victory Point

    Origin of president's desk?
    - HMS resolute, abndoned, recovered, repaired, regifted, returned

2) Climate
February-08-15
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1. **Arctic climate** is characterized by a wide diversity of conditions, both **_______** and **__________.**
    - ***spatially , seasonally***
2. **Key characteristics that distinguish climate from lower latitudes:**
    - Season distribution of solar radiation and resultant energy balance
    - Important role of sea ice and snow-cover in energy balance
    - Important feedbacks between surface characteristics and energy balance
    - High inter-annual variability in climate
3. On June 22 (summer solstice) and December 22 (winter solstice), areas at and north of the Arctic Circle have 24 hours of daylight and darkness (respectively)
    - Conversely, on March 22 (***vernal equinox***) and September 22 (***autumnal equinox***), all latitudes have 12 hours of daylight
    - Further, these effects are altered by refraction of sun light in the atmosphere, so in practice, the sun does appear in the sky longer in the winter than predicted
4. Energy Balance:
    - Seasonal changes of incoming radiation mean that the energy balance depends on other factors:
    - Surface albedo- reflectance of surface material with respect to insolation (shortwave)
    - Materials with high albedo (>50%) like snow and ice, result in less incoming radiation in the system
    - Reflectivity also depends on angle of sun relative to a point on the Earth's surface
        - Conversely, all surface materials emit infrared radiation (longwave).
        - In absence of substantial shortwave inputs, longwave emissions can result in a net energy loss to the climate
        - Advected energy, often as latent heat contained in atmospheric water vapour, may be a significant source of energy to Arctic systems, particularly in winter
5. Albedo

    the proportion of the incident light or radiation that is reflected by a surface

6. Characteristic air masses develop due to persistent energy balance conditions
    - In the winter, the descending cold air over the Arctic Ocean basin generates a broad zone of surface high pressure, while strong surface low pressure systems develop over the Gulf of Alaska and Iceland
    - The strong westerly circulation around the polar low pressure is evident as a high elevation jet stream
    - The boundary between the polar air and temperate air masses is termed the polar front
    - The polar front has a long term persistent location but will vary over the short term substantially

7. **The North Atlantic Oscillation (NAO)**
   - a measure of the north-south gradient measured by the strength of the *Icelandic Low* and *Azores High*
8. **Continental locations:**
   - ○ Strong positive (summer) and negative (winter) energy balances
     - cold winters and warm summers
     - E.g., Siberia, NWT, central Alaska

   Maritime locations:
   - ○ Moderating effect of ocean and duration of ice-free conditions
     - E.g., Iceland, Norway, southern Alaska

   Recent trends in Arctic temperature
   - ○ 2005-2010: five warmest consecutive years since instrumental records began in late 19th century
   - ○ Arctic summer temperatures have been higher in the past few decades than at any time in the past 2000 years

3) Cryosphere

January-20-15

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Cryosphere:
- Represents the combination of snow, lake, river and land ice and sea ice
  - ○ Permafrost and ground ice are also typically considered part of the cryosphere
- Varies considerably in temporal persistence- seasonal to perennial
  - ○ A key component for climate system feedbacks in the Arctic
- Cryosphere is a key component in the broader earth system
  - ○ A major global heat sink
  - ○ Controls broad climate patterns in mid-latitudes
- Vital for northern communities
  - ○ Inuit continue to make use of sea ice as a primary hunting and travel region
- Crucial for current and future resource development and marine navigation

Snow
- The most widespread and sensitive cryosphere component
- Seasonal snow cover is present across essentially all of the Arctic, and may last as long as 9 months
- Snowfall occurs as precipitation that remains frozen as it falls and accumulates on the surface.
- Can happen any time when the freezing level of the atmosphere is at or near the surface
  - ○ Ranges from winter months to potentially all year in colder environments, typically at high latitude or elevation

- Generally, the proportion of annual precipitation that comes from snowfall increases with elevation and latitude
  - In the High Arctic and high mountains, potentially all of precipitation falls as snow

Snow accumulation and distribution:

- Unlike rainfall, snowfall can be reworked and the distribution on the landscape may change during the year
- Snow structure and age, along with topography, vegetation cover, and prevailing winds are the primary controls over the accumulation of snow
- Snow structure:
  - Cohesion of the snow through metamorphism
  - Presence of one or more icing layers on or within the snow pack
  - Surface roughness of snowpack- irregularities can cause turbulence that results in snow scour and deposition
- Snow age:
  - Gradual alteration of snow grains to form more cohesive pack resistant to wind erosion
  - Snow typically becomes denser and more compact as it ages
- Topography:
  - Slope and aspect of the land surface alters effective wind fetch
- Generally, combined with persistent wind directions, some aspects are subject to frequent high wind stress and scour
- Windward slopes and open areas with long wind fetch are typical scour zones
  - Flow accelerates as it rises up slopes
- Lee slopes and concavities in slopes are areas of low wind stress or turbulent back eddies that result in snow deposition and accumulation
  - Thick accumulations can occur in lee slopes and incised channels

Vegetation

- Low vegetation increases surface roughness
- The result is increased accumulation in the vegetation
  - In low tundra shrub, snow may accumulate to the height of the plants
- In forest cover, snow accumulates and is protected by the forest canopy from subsequent movement

Snow cover depth patterns and measurement:

- Snow cover depth patterns may vary substantially on an interannual basis, primarily due to wind conditions
- Despite these differences, research suggests that relatively persistent patterns in snow accumulation patterns may be similar and relatively consistent in different landscape types
  - Concavities like stream channels typically have enhanced snow accumulation, while windward slopes and level surfaces have moderate or lower accumulation
- Representative measurement of snow cover is difficult due to these variations

    - Typically, point measurements are less representative than transects that are composed of many points
- For hydrological purposes, snow cover needs to be converted into snow water equivalence where (SWE)= snow depth * density

Snow cover effects:

- The low density of snow, together with low thermal conductivity, make it an effective thermal insulator
- Hence, snowpack represents an important modifier of many surface systems
- Deep snow is a suitable habitat for several animal species (lemmings, fox, bear) for overwintering
- The thermal insulation of snow also affects soil temperatures- timing is important
    - Early snowpack formation results in maximum thermal insulation, maintains soils as higher temperatures over winter
    - Late snowpack formation allows soil to cool quickly. Subsequent snow thermal insulation may delay warming of soil in spring
- The insulation provided by snow may extend the biologically active period in soil
    - -10°C and warmer is generally suitable for microbial activity
- Deeper snow typically takes longer to melt in the spring, delaying soil thaw
- Snow distribution and duration of cover
    - Because snow can have such substantially different cover characteristics residual snow can play an important role after the primary melt period in spring
        - Snow may isolate stream and river flow from the channel bed, affect erosion
        - Soil and plants may have a substantially shorter growing season
        - Residual or perennial snow banks provide ongoing water supply
    - Similarly, thin snow cover can melt early
        - Early warming of soil and exposure of plants
        - Thaw of soil may increase soil water storage compared to typical runoff

Glaciers and ice caps

- Represent the major store of fresh water on Earth- 78%
- Found throughout the Arctic, especially in high elevation locations
- Glaciers are essentially a net positive accumulation of snow over long time scales
    - Accumulation exceeds ablation
- As the snow accumulates, it is compressed first to firm and then to ice, both of which have higher densities.
    - Ice can attain a density of c. 900-910 kg/m3
- Under increasing mass, the ice will begin to deform internally and flow downslope
- Accumulation:
    - Snowfall is most important
    - Aeolian and avalanching
    - Sublimation may be important in maritime locations
- Ablation:
    - Melt of ice and snow most important

    - With glaciers that terminate in lakes and the ocean, calving may be an important mechanism for ablation
    - Sublimation may be important in some cold, dry settings
- Mass Balance:
    - Arithmetic sum of accumulation and ablation
    - Positive with net accumulation
    - Mass balance varies across an ice mass
    - The Equilibrium Line separates the positive and negative mass balance zones
        - ELA= Equilibrium line altitude
    - The zone separating the positive and negative mass balance areas
- Mass balance may vary substantially from year to year and also exhibit long term positive and negative trends

- Mass balance may vary substantially by the climatic regime
- Most glaciers depend on winter accumulation and summer ablation
- Some depend on accumulation and ablation primarily in summer where seasonally high precipitation occurs (mostly the tropics)
- Others have year-round ablation and accumulation, again mostly in the tropics

- As ELA is effectively controlled by climate, changes can affect glaciers in different ways
- Depending on the geometry of a glacier, a change in ELA may result in a substantial increase in accumulation or ablation

Glacier flow:

- Snow crystals begin to change rapidly with burial and time
- The tips of snowflakes are melted or sublimated due to the higher pressure at these points
- Crystals begin to grow and bond together through sintering
    - Crystals realign and grow and they begin to creep downward
    - Aided by summer melting and growing pressure of the overlying snow
- Firn is produced at depths of 10-50 m, depending on the thermal regime
- Continued firnification increases density and seals off air spaces forming ice
- Molecules in the ice structure form honeycomb pattern sheets
- Ice flow can occur as slippage along the sheet structures, which are weakly joined together
- They also become increasingly oriented in the direction of flow
- Ice behaves both as a viscous fluid and a plastic
    - Deformation will not occur until a small stress builds up (due to gravity)
    - At higher stress levels, deformation increases and the ice behaves nearly as a plastic material
- Stress and strain in ice is highly dependent on temperature and decreases considerably with lower temperatures
- Thermal conditions also affect the behaviour of the glacier at its bed
- Glaciers can be either cold or warm based

- Ice in cold glaciers is below pressure melting point
    - Absence of liquid water and ice is frozen to bed
    - Movement is only by internal deformation
- In warm based glaciers, a film of basal meltwater allows basal slip to occur, in addition to internal deformation

- Glacier flow rates vary from several metres per year in High Arctic settings, to hundreds of metres per year in some dynamic settings
- Some glaciers undergo periods of accelerated flow referred to as surges
- Ice builds up in the lower reaches of the accumulation area•When the excess is released, velocities may exceed 50 m/day
    - The thermal regime of a glacier determines how it flows and interacts with the landscape
    - Controlled by the thickness, climatic regime, heat generated by friction within and at the base of the ice, and the geothermal heat flux
- In the case of thick ice (Greenland), the basal temperature is much warmer than the air temperatures (-10°C at the base, about -30°C air)

Glacier-landscape interaction:

- The flow if ice is a powerful force for modifying landscapes
- Erosion at the base of ice occurs by:
    - Pressure exerted on obstacles on the bed
    - Abrasion by stones carried in the ice
    - Freeze-thaw action at the bed of warm-based ice
- These processes are typically more effective with warm-based ice
- In addition to basal sliding, the internal deformation tends to bring sediment in contact with the bed as ice at the bed melts
- Arctic glaciers are often quite thin, but in valleys, the ice thickness can generate warm-based conditions
- Enhances erosion in valleys
- Generates characteristic U-shaped valleys in a process referred to as selective linear erosion
- Water at the base of ice can be an important erosional agent as well
- It can flow at high velocity, often under pressure
- Result in glacio-fluvial transport of sediment, sculpting of bedrock and deposition of subglacial material in forms such as eskers

Sea ice:

- Sea ice is important both as a key component in the Earth system, and as a component of the cryosphere
- It is one of the most visible and sensitive changes to climate change in the Arctic
- Sea ice, and winter snow cover, have much higher albedo than open water
- Minimizes wind and wave activity in coastal areas

- Sea ice reduces photosynthetic radiation in the upper water column, reduces primary productivity
- Critical for several marine mammals that are important to Inuit
-
- Physical characteristics of saline water:
    - The freezing point of salt water decreases to -1.65°C at S=30, to -1.92°C at S=35
    - Unlike freshwater, which reaches maximum density at 4°C
    - Salt water (S>24.7) reaches maximum density at freezing temperature
    - This means that as freshwater cools towards freezing, it is stable
    - Salt water is unstable as it cools towards freezing, mixing down and requiring much more heat loss than freshwater

- Generally, supercooling of the upper mixed layer by 0.2 to 0.4°C is necessary
- The first frazil crystals are very small and form near the surface
- These crystals grow and accumulate on the water surface to form a slush referred to as grease ice
- Waves will mix the frazil vigorously, forming larger balls and pans up to several metres in diameter
- Eventually, the pans freeze together and stable ice cover forms
- In stable ice, the crystals grow vertically downwards as separate plates

- The lattice of the ice does not include salts, so these are rejected and accumulate in tiny brine pockets where salinity may reach S=80 or higher
    - These pockets are dispersed in the ice, so the overall ice S=8-12
- The brine pockets give the new ice a soft and rubbery texture
- As the ice ages, the brine pockets migrate down under gravity along crystal boundaries
    - Brine drains along increasingly dendritic drainage
    - Salinity declines to S=4 to 6 in first year ice, and S=0 to 4 in multi-year ice (drinkable)
- The drainage of brine to the water below is a thermohaline circulation
- Important mechanism to mix the surface waters, carrying nutrients and oxygen to depth

Distribution of sea ice:

- Sea ice forms several zones in relation the shore
- Pack ice is found far enough from shore that it is almost always in motion due to ocean currents and the wind
- Shorefast ice is close enough to the shore that it is immobilized by the coast
    - Varies from zero to many kilometres, depending on the ice, winds, and currents
    - Also, tends to be wider in bays and narrower at capes and promontories
- The ice foot is a narrow zone of ice frozen to the shore that does not move with tidal cycles
- It is separated from the shorefast ice by a tidal crack
- Leads are long cracks of open water that are short lived and wax and wane with ice movement
    - New ice can form in leads, referred to as nilas

- Across the Arctic, the pattern of sea ice varies considerably from year to year
- Reaches a maximum usually in March, and a minimum in late September
- Warm currents preclude ice from most of northwestern Europe and the Alaska-BC coasts
- Ice is extensive on the Eurasian Shelf, Canadian Archipelago and the east coast of Greenland, extends rarely southward to Nova Scotia, Japan, Iceland
- Perennial ice remains in much of the Arctic Ocean basin,
- Canadian Archipelago and northern Greenland during the summer
- Areas of extensive multi-year ice
- Ice cover is rarely completely absent or full- there is typically some degree of ice and open water present
    - Ice cover can be considered a function of density, or proportion of cover

Sea ice melt:

- Sea ice melts differently than freshwater ice
- In spring, small depressions in the snow cover (due to wind scour) enhance melt through lower albedo
- Meltwater ponds in depressions, which accelerate snow and underlying ice melt
- Drainage connects ponds as individual ponds melt through the ice and begin to drain vertically
- Ongoing drainage channel melt isolates pans of residual ice
- Pans are relatively strong and unaltered, and hence, move with the current and winds and remain a navigation hazard
- The freshwater from sea ice melt largely remains at the surface
- Maintains some degree of isolation of the underlying marine water until waves and wind mix the layer away

Polynyas:

- Polynyas represent persistent areas of open water surrounded by ice cover
- Remain unfrozen in winter despite below freezing temperatures
- They are maintained by two key processes:
    - Persistent winds or currents that remove newly-formed ice
    - Often found where currents converge due to narrowing of channels
    - Ice flow blockage may also assist with maintaining open water (e.g., North Water)
- Polynyas are critical habitat for a wide variety of marine and avian wildlife
    - Amongst the most productive Arctic ecosystems

Icebergs:

- Produced by calving of glaciers
- Produced dominantly on West Greenland, but also Svalbard and the eastern Canadian Arctic
- Bergs draft approximately 90% of their overall depth, which may reach as much as 500 m
- Hence, they are driven by currents over their entire depth range
- They move throughout the year, often substantially faster than the surface sea ice

- As they move southward, they progressively melt and ultimately disappear
- Rare south of Newfoundland, but relatively common on shipping lanes in North Atlantic Ocean

- The great depth of icebergs results in substantial mixing of waters as they move
- They raft a substantial amount of sediment from the glaciers they were sourced from
- Bergs also effectively scour the sea floor on continental shelves
  - Scour trenches may be hundreds of metres wide, tens of kilometres long
  - Common on the coast of Beaufort Sea, Labrador,
  - Barents Sea, etc.
- Important hazard for off-shore petroleum development
  - Even in cases where rigs can be moved, wells are at risk of berg disruption

Ice shelves:

- While largely extinct in the Arctic, a few residual ice shelves remain on northern Ellesmere Island and Greenland
- These multi-year sea ice masses combine growth of sea ice with the accumulation of snow and ice from precipitation
- May form over thousands of years and reach thicknesses of 100+ m
- They generate unique marine environments
  - Trap fresh meltwater from land and can form freshwater epishelf lakes in fiords
  - Fracture and form large, stable ice islands that can move in the Arctic Ocean for decades
- Recent observations show that the few remaining ice shelves are fracturing and disintegrating rapidly
- Recent fracturing of the ice shelves has continued, the most recent is the Ayles Ice Shelf, which was recorded in break up via satellite images

Lake ice:

- Lakes cover a large proportion of Arctic land areas due to recent glaciation and permafrost processes
- Unlike many temperate lakes, ice cover in the Arctic is typically long lived and in some rare cases, perennial
- Like sea ice, important for lake water column conditions
- Important control over aquatic ecosystem
- Lake ice can be a hazard to navigation and shores through ice push

Freshwater ice formation:

- Freshwater freezes at 0°C but the maximum density occurs at 4°C
- As a lake begins to cool in the autumn, the surface water reaches maximum density and begins to sink
- In conjunction with wind mixing, the entire water column can cool to 4°C (isopycnal)
- Further cooling results in less dense, cooler water at the surface- stable water column
- When surface reaches 0°C, initial ice can form

- This may occur as a thin skim of ice, typically around the shore areas, but may occur across the lake
- Wind may break up initial ice into frazil fragments or ice may remain intact and thicken
- The timing of lake freeze-up varies according to weather conditions, wind fetch and lake volume
- Larger lakes tend to freeze later, often when the overall water temperature is about 1°C
- Smaller lakes freeze earlier, often when the overall temperature is 2-3°C

- After an initial ice layer is formed, ice growth is in the form of vertical crystals that growth down into the water column
- Referred to as congelation ice
- The vertical crystals freeze together to make a solid ice mass, but they have greatest strength internally

- Ice growth continues during the winter under snow cover
- The rate of ice growth is dependent on the loss of heat from the lake to the atmosphere
- Colder conditions accelerate ice cover
- Wind acts to pump heat from ice
- Snow accumulation acts as insulation from radiative heat loss and wind pumping
- Due to the low roughness of the ice surface, wind may effectively scour the ice free of snow between drifts and over larger areas
- Differential snow cover may result in substantially different ice thickness
- Ice may reach 2.5 m thickness in the coldest conditions, 1-1.5 m more typical of Arctic regions
- As ice thickens it is subject to thermal pressure, wind drag and water level changes
- Fractures can be formed by thermal contraction of the ice
- Wind can impose pressure on the ice cover, causing a seiche, a standing wave oscillation in the water column
- Induces "sloshing" of the lake and typically causes fractures parallel to the shore

- Loading of the ice by snow will result water from a fracture to flood the ice surface
    - Re-freezes as snow ice which is typically bubbly and distinctive from "black" congelation ice
    - Also referred to as overflows, icings and naleds

Lake ice break up:

- Lake ice melt occurs from both the surface and base once the ice was isothermal at 0°C
- Melting at the surface depends on the albedo of the ice, which varies depending on snow and debris cover
- Once surface snow melts, exposure of relatively dark congelation ice and high albedo snow ice will melt differentially
- Melting occurs along the congelation ice crystal boundaries, resulting in candled ice
- Continued melt thins the ice and the candling becomes increasing distinctive

- During the melt process, ice on the shore is subject to enhanced melt
- Shore ice is also thinner, and usually disintegrates early
- Results in the formation of a moat around the perimeter of the lake
- The open water of the moat is of tremendous biological significance and supports a variety of aquatic organisms
- Ongoing ice decay is a combination of both melt and fragmentation of candled masses that rapidly melt
- Ultimately, the ice becomes thin enough and the candle structure weakened to the point where wind can break up the ice into small fragments
- In rare cases, residual ice may survive the melt season
- Typically only large lakes found in cold climates of High Arctic and higher elevation sites

- The residual ice may be driven by wind and move over the lake
- Where it reaches the shore, it can plough up shoreline material

- The presence of ice cover during the melt season alters the warming of the water column and reduces or eliminates the physical mixing by wind
- The persistence of ice is thus a function of the relative melt conditions (melt energy, wind for mechanical break up)
- Alters the radiation regime of the water column and reduces primary productivity under the ice
  - Most productivity occurs in the moat area

4) The Periglacial Environment:

March-24-15
6:44 PM

- The term *periglacial* implies environments near or around glaciers
- A more suitable definition would be associated with environments where processes are dominated by the action of freezing and ice formation
  - Typically most frequently used in the context of ***periglacial geomorphology***: landforms that are created or affected by these processes
- Hence, the periglacial environment is one of cold conditions, but not necessarily year round or just in the Arctic
  - Occurs in temperate regions on a seasonal basis

Permafrost:

- By definition, *permafrost* is permanently frozen ground
- In practice, “permanent” refers to a period of two years or more
  - However, this is too short of a period to affect landform characteristics associated with periglacial environments
    - or the opposite in the case of thaw
- Similarly, “frozen” is not self-consistent in terms of the effects it has on processes

- Frozen, dry sand, behaves essentially the same as warm, dry sand
- Saline waters in soils may remain liquid below 0°C
- At depth in the ground, high pressure decreases the freezing point of water
    - Solid rock does not necessarily change physical properties when frozen or thawed
- Hence, much of what we consider to be associated with permafrost is actually *ice-bonded permafrost*
    - Soil pores are ice filled to some extent

Extent of permafrost:

- Permafrost varies significantly in terms of thickness and areal extent
    - Mapping is an over generalization
- In colder regions, permafrost underlies most (although not all) of the land, and is *continuous*
- In climatically favourable areas (south facing slopes, etc.), the permafrost will be characterized as *discontinuous*
- Similarly, further south, the overall climate warms and results in discontinuous permafrost
- At the southern margin of permafrost, it is highly localized and is termed *sporadic*
- Permafrost occurs at higher elevation sites as well, and is considered *alpine*
    - Permafrost also occurs under the ocean in some cases, such as the continental shelf of northern Canada and Russia
    - This *subsea* permafrost is a remnant of past conditions where sea level was lower and exposed the shelf.
- Cold overlying ocean water helps to preserve this relic permafrost

Factors controlling the occurrence of permafrost:

- Principle factors:
    1. Ground temperature
    2. Nature of ground cover
    3. Thermal properties of the ground
    4. Geothermal heat from the interior of the earth that must be transferred to the surface
- Important in the one-dimensional sense
- The thermal characteristics of materials in and on the ground vary widely:
    - Thermal conductivity (W/m·°C)

Cast iron	(47.0)
Rock	(2.0-2.7)
Dry sand	(0.26)
Wet soil	(1.2-3.3)
New snow	(0.12)
Water	(0.55)

Dry moss	(0.04)
Air	(0.023)
Goose down	(0.038)

- In practice, the factors that control the presence of permafrost reflect heat flow that is three-dimensional and transient (seasonal, longer term)
- In the case of the seasonal cycle, the ground near the surface warms significantly above freezing
- The thawed *active layer* develops during the melt season, and refreezes in the winter
    - As the active layer refreezes, a zone of unfrozen ground may persist temporarily in the soil and is referred to as *talik*
    - Talik is important for soil water movement in the autumn to early winter
- The depth of the active layer will vary annually, depending on available melt energy
- With increasing depth the frequency of active layer thaw diminishes
    - The Russian permafrost literature has emphasized this *transition layer*, at the base of the active layer that is subject to less frequent thaw
    - This layer is important in ice-rich permafrost zones, as water tends to drain down and accumulate
- This provides substantial thermal buffering of the underlying permafrost due to the latent heat required to melt the ice in the transient layer
- The depth of permafrost is determined by the propagation of temperature variations from the surface to depth
- The variation in soil temperature declines sharply with depth, and by depths of 2-5 m, the variation in annual temperature is essentially zero
- During the refreezing process, the release of the latent heat of fusion (333 kJ/kg) caused by freezing will warm the soil, resulting in a delay of cooling in the soil
    - This *zero curtain* effect is most prominent with saturated soils, where the zero curtain can delay cooling below freezing for several months

Conditions at surface and the presence of permafrost

- Two key factors affect the freezing of the ground surface: the presence of water and snow cover
- Snow has a high albedo and high emissivity of long wave radiation. Hence, it minimizes heat absorption from the sun, and effectively radiates heat stored
    - Despite these properties, snow tends to keep the ground warm due to the low thermal conductivity of the air it contains within
- The result is that areas with thick snow cover tend to have warmer soil temperatures, and lack permafrost in discontinuous regions
    - Vegetation and other snow trapping controls are important predictors of localized permafrost
- Water in soil pores influences the thermal regime through the zero curtain effect
- Standing water has an even greater effect

  - Given that ice cover rarely exceeds about 2 m, water bodies deeper than this typically do not have permafrost
  - If the water body is small, less than c. 200 m diameter, lateral heat flow will allow the formation of permafrost
- Unfrozen *windows* under lakes and rivers may occur in even continuous permafrost
- Important conduits for water, solutes and contaminants

Changes in permafrost:

- Temperature profiles in permafrost areas typically show an inverse gradient near the surface
  - Demonstrates some degree of non-equilibrium condition where heat is flowing towards the coldest depths
  - Ultimately, an equilibrium may form, but these profiles are indicative of surface warming
- As the profile adjusts, which may take thousands of years, the base of the permafrost will change.
  - In the case of warming, the permafrost base will become shallower
  - Additionally, the active layer will thicken seasonally with surface warming

Periglacial processes:

- The key control over most important periglacial processes is the freezing of water
- This causes changes in density/volume of water which either generate localized pressure in materials
  - Or, the proximity of freezing conditions results in movement of water in the material and displacement in compensation
- A key concept is the *freezing plane*, the theoretical boundary between frozen and unfrozen material that can be considered the 0°C isotherm
  - A *freeze-thaw cycle* is the climatically-induced movement of the freezing plane through a material
- As the freezing plane advances downward, pore water can do one of two things:
  - Freeze *in situ* as *pore ice*
  - Move towards the freezing plane and freeze, forming *segregated ice*
- Ice segregation is favoured in fine grained sediment, typically finer than 0.01 mm diameter (fine silt and clay)
- Water movement is controlled by *cryosuction*, a measure of the soil water tension in proximity to the freezing plane
  - Cryosuction is 1.2 MPa per °C below freezing temperature
- Fine grained sediment is able to maintain high cryosuction and favours segregated ice formation
  - Referred to as *frost susceptible* material
- By contrast, sand and gravel tend to have low cryosuction and form pore ice
- The release of latent heat during freezing of water in the soil can result in what is referred to as a *zero curtain effect*

    - During the freezing, latent heat release results in warming, causing the temperature to stabilize temporarily at freezing
- Essentially, the freezing process, together with capillary forces in the soil, draw water towards the freezing plane
- As long as latent heat released by freezing is removed by conduction through the overlying soil, the freezing plane will be stationary and the segregated ice mass will continue to grow
    - As water is converted into ice, additional water must be drawn from further away
    - Requires increasing cryosuction
- Eventually, water supply may be exhausted and segregated ice no longer forms
- The freezing plane may advance downwards and a new segregated ice mass may begin to form
    - This sequence can lead to the formation of multiple *ice lenses* in a soil profile, horizontally elongated structures of segregated ice
- As segregated ice forms, it heaves the overlying material
- In part this is due to the 10% increase in volume associated with the phase change from liquid to solid
    - Part is due to movement of water to the freezing plane and ice growth through mass accumulation
- **Heave** occurs primarily during the autumn freeze period
- Some secondary heave may occur in the frozen material later, due to subsequent moisture movement through the frozen soil
    - **Heave** may range from 3% on dry slopes to as much as 60% in wet susceptible soils
- **Heave** affects different particle sizes differently
    - When a stone is heaved upwards by ice formation, a cavity forms below the stone
    - Fills with ice and sediment
- When the ground thaws, the ground returns to the pre-frozen level, but the fill of material below the stone displaces it upwards
- Stones move upwards via heave mm- cm per year, often reaching the surface in a vertical *monument stone*

Intrusive and extrusive ice:

- Where there is substantial groundwater flow, either in taliks or through groundwater aquifers, this lateral movement of water towards the freezing plane can result in ice growth
    - Extrusive ice occurs when water reaches the surface, spreads and forms an *icing*
    - Icings can cover hectares
        - Also common on rivers
- Where the water reaches the freezing plane below the surface, *intrusive* ice forms and can accumulate to great thicknesses

Pingos:

- In the most remarkable form, intrusive ice can form *pingos*, ice cored hills up to 60 m high

- ***Closed system* pingos** form in **drained lake beds** where water flow is directed towards the depression
    - As permafrost aggrades below the former lake, a large amount of water is subject to freezing and a massive segregated ice mass can form
        - As the ice grows, the overlying soil is eventually cracked, exposing the ice core
    - Results in melting of the pingo
    - Residual scar is prominent on the landscape, and represents centuries to millennia of development and decay
- ***Open system* pingos** form on slopes, where groundwater flow is locally directed towards the freezing plane
    - Open system pingos are common in hilly terrain in discontinuous permafrost

Ice veins and wedges:

- During intense cooling, particularly when snow cover is minimal, the ground can crack
- Forms up to 2 cm wide cracks, typically 5-20 m apart and in a polygonal pattern
- Snow, meltwater and soil will fill the crack and refreeze as ice
    - Can crack again and grow progressively by infill, refreezing and recracking
- May reach widths of several metres and push aside soil on either side as it has grown
- **Ice wedges** are expressed at the ground surface as ***patterned ground***
- Result in ***ice wedge polygons***, a common landform in periglacial regions
    - ***High-centred* polygons** have soil forced by wedge development into mounds in the middle of the polygon
    - ***Low-centred* polygons** have a depression in the middle with ridges of soil adjacent to the wedges
- Ice wedge polygons are important features that can disrupt vegetation, drainage and make surface travel difficult

Patterned ground:

- One of the most interesting and unique features of the periglacial environment
- Broadly, these features fall into several broad categories:
    - Ice wedge polygons
    - Soil polygons
    - Earth circles
    - Earth hummocks
- These features can be further divided into sorted and non-sorted forms if the material they are formed in has a range of grain sizes
- All of these features are associated with *cryoturbation*, the vigorous mixing of the active layer by frost action
    - Unlike frost wedge polygons, most of these forms do not require the formation of massive ice

Frost sorting:

- The seasonal freezing and ice formation in the active layer is the likely mechanism to induce circulation of soil materials

- A number of models for cryoturbation have been advanced
    - Some are supported by observations of soil movement and patterns of organic material included in the soil
- During freezing, the ice formation generates ***cryostatic pressure*** in frost susceptible material
    - This pressure results in differential heave in the soil during freezing, and subsidence during thaw
    - Coupled, in some cases, with thermal contraction cracking at a small scale
        - Results in the formation of mounds of soil material
- Repeated heave and contraction generates an effective circulation of the soil
- The result is that frost heave can produce a wide range of surface features that range from vegetated and bare mounds and hummocks, to sorted circles and polygons
- Sorting likely occurs due to differential heaving of coarser clasts to the surface and away from the high centre of the mound
    - Once the material is sorted, it remain so without further cryoturbation
- The resulting surface is important control over surface soil moisture, with lower margins of the mound generally wetter and with better snow retention
    - Typically enhances vegetative success and results in contrast in vegetation cover between higher, dryer mound and edges
- In some cases, again in frost susceptible material (fine grained), hydrostatic pressure can result from water confinement in the active layer
- Particularly when the soil surface is dry, this higher soil water pressure at depth can result in the ejection of mud to the surface to form a *mud boil*
- These features often occur after summer rainfall and are widespread features in the Arctic

Frost shattering:

- Water that seeps into joints and cracks in rock will freeze
- Exerts significant pressure on the rock that can split it further along lines of weakness
- Generally occurs only at surface
    - The rock must be susceptible to shattering
      Crystalline and well cemented rocks are less susceptible
- Sediment may fall into the cracks, wedging them open and making additional shattering possible
- Water is necessary, so more common in wet areas
- Most effective with increased numbers of freeze-thaw cycles
- Because the Arctic is generally so cold, the number of freeze-thaw cycles is relatively small, perhaps 10-20 per year
    - Further south (S. Ontario), they are more frequent (up to 60 per year)
- A variety of landforms occur from frost shattering
- Where a large area of rock is exposed and shattered, this is referred to as *felsenmeer*
- Frost shattering is very effective in mountainous areas, where mass movements remove the shattered rock to form *talus*
- When a large mass of a rock slope has been removed (e.g., glacier), it leaves a distinctive fracture pattern in the rock

- This rock is highly susceptible to shattering and results in a distinctive *exfoliation surface* characterized by large slabs of rock

Sorted and unsorted stripes:

- On slopes, the patterned ground can exhibit similar structures that are elongated down the slope direction
- These *stripes* are distinctive features, and may be either unsorted or sorted
    - Given that the slope generates some slope wash and overland flow, it is likely that these processes also contribute to the formation of stripes, although it has not been clearly demonstrated
- Non-sorted stripes tend to be composed of fine grained material with distinctive lines of vegetation that converge downslope

Slope processes and development:

- Slope environments are substantially altered by ongoing freeze-thaw
    - Slopes in periglacial environments have several distinctive morphologies that are attributed to typical processes in these settings
        - Free-face slope
        - Rectilinear debris-mantled
        - Convexo-concavo debris-mantled
        - Stepped or terraced
        - Pediment-like form
- Free-face slopes are similar to those found in other climatic regimes
    - Associated with steep faces where frost shattering and other mechanical weathering occur
    - Talus accumulates below the face
- In many cases, what appears to be a thick talus accumulation is a relatively thin cover over bedrock
- Rectilinear debris-mantled slopes typically develop in areas that have not been glaciated
    - They form in consolidated bedrock
    - Generally a uniform slope angle, close to the angle of repose (35-38°
- Debris is removed by slow mass creep and wind erosion
- Convexo-concavo debris-mantled slopes have a relatively smooth profile with no abrupt breaks of slope
    - Generally form in soft, poorly-consolidated bedrock and tend to form lowland terrain
    - The lower angled slope elements reflect solifluction and slope wash
    - Higher angled elements reflect gravitational movements
    - Resistant bedrock can outcrop and form *tors* or outliers in the overall slope form
- Pediment-like slopes are characterized by extensive, low angled slope elements, with a varying cover of debris
- Similar slopes are found in hot, arid regions, and in these settings, the morphology is associated with slope wash, gullying and related sediment removal
    - It is likely that these processes also play a role in periglacial settings

    - These types of slopes are associated with *cryoplanation* or *nivation*
    - The presence of snow in hollows results in sustained water supply and accelerated gelifluction

Solifluction/Gelifluction:

- ***Mass wasting*** is the downslope movement of debris under the influence of gravity
    - ***Solifluction*** refers to the downslope movement of soil under gravitational force, in presence of excess soil water
        - Solifluction is not a specific cold environment process, but a general slope movement
        - In periglacial environments, solifluction is comprised to three components:
    - ***Gelifluction*** refers to the movement of soil particles due to frost displacement and heave
    - ***Frost creep*** refers to the movement through downward reordering of the soil grains, enhanced by freeze-thaw
    - ***Sliding*** occurs at the base of the active layer, and results in en masse movement of the soil
- These processes occur during both diurnal and seasonal freeze-thaw cycles
- Diurnal freeze-thaw supports frost creep and small scale movements
    - Annual freeze-thaw is more associated with gelifluction and sliding and leads to larger slope movements
- **Solifluction** processes result in a wide range of lobate structures on slopes
    - Where frost creep and thin active layers occur, slope movement is dominated by solifluction sheets that have limited morphological evidence
    - Where thicker active layers occur, solifluction lobes form, particularly where moisture is present or where vegetation (trees) is minimal
        - Vegetation and soil can be "rolled over" or buried by the advancing solifluction lobe

Rapid mass movements:

- Localized rapid mass movements are common in areas underlain by permafrost, especially in ice-rich unconsolidated sediment
- ***Active layer detachments*** (**ALD**) are common on higher and middle slope areas
- Represent failure and movement of the active layer downslope, usually in a few hours to days
- Caused by the reduction of shear strength at the base of the active layer
    - Due to increasing soil water from precipitation or ice melt
    - The underlying permafrost acts as a lubricated failure plane for the movement
- **ALD** may move a few metres to hundreds of metres and usually have distinctive morphologies
- A head scarp is the location of detachment and is usually characterized by broken blocks of soil and vegetation that are displaced downslope
    - Longer ALD have translation zones where movement of soil is nearly complete, exposing underlying frozen material

- A lower accumulation area occurs where material stops moving and may stack or form extensive deformation zones
- In cases where ALD expose ground ice, ongoing melt of the ice will result in the collapse of soil and generate a ***retrogressive thaw slump***
  - Common along river and stream banks where active erosion removes protective sediment cover
- These will continue to recede up slope with ice melt, sustaining failure of slope material for up to years

Thermokarst:

- Karst refers to processes associated with the solution of soluble rocks like limestone, and the landscape that results from with irregular topography, sink holes, caves and other features
  - **Thermokarst** has nothing to do with real karst processes
- Refers to the melting of ground ice that results in the collapse of parts of the ground to form an landscape with irregular surface and drainage
  - Often associated with massive ground ice, although it can be associated with excess pore ice in the permafrost
- Many sedimentary deposits in permafrost regions contain a large amount of ground ice
- Up to 90% of the volume may be ice, particularly just below the active layer
- As long as the permafrost persists, the ice remains stable and the ground strength is maintained
- If the excess ice is located just below the active layer, any change in thaw will potentially affect the surface
  - For example, if summer thaw advances into ice-rich permafrost, the ice melts
    - If drainage conditions allow the melt water to be removed, the volume occupied by the former ice is left empty
    - This results in potential subsidence to fill the void
    - The new lower surface will result in a new depth of active layer development which will melt further ice and allow further, but diminishing subsidence
    - This process will continue until a new equilibrium is reached
- In practice, the extent of these processes is quite heterogeneous over space due to varying surface cover and active layer development
  - Results in irregular melt and surface subsidence

- A number of processes can cause the thickening or alteration of the active layer:
  - Warming climate
  - Altering the surface material through surface erosion
  - Altering the surface material by human activities
  - Increasing the thermal conductivity by compaction by vehicle passage
  - Forest or tundra fires that remove the insulating vegetation and blacken the surface (decrease albedo)

- Slope failure that strips off surficial material or exposes ground ice

- Lateral erosion by rivers the exposes ground ice
    - Both processes can initiate retrogressive thaw slumps, which represent a combination of thermokarst and slope failure processes
- Many permafrost areas are underlain by stable rock and are minimally susceptible to thermokarst
    - Large areas of central Siberia are subject to thermokarst
    - Subject to extensive ice formation during the last glaciation
        - Under current climate conditions, this ground ice is unstable and results in a well developed cycle of degradation
    - Covers up to 40% of the region
- In northwestern North America, thermokarst is most common in the form of extensive *thaw lakes*
- These form in flat lowlands underlain by fine grained, ice-rich sediment
    - They range from small ponds to large lakes, and often show coalescent forms that indicate they have grown by joining with adjacent lakes
    - The mechanisms of formation are poorly understood, but it is likely that they form either from initial perturbation of the active layer, potentially from poorly drained low centred frost wedge polygons that promote surface pooling and flow along wedges
- This combines to ultimately form the larger body of water
- Further shore erosion contributes to growth
- In addition to lakes, former lakes in the form of depressions are also common in these regions
    - Drainage occurs by the formation of an outlet and rapid drainage
    - Alternatively, the lake may fill with sediment gradually
    - ***Tapping***, or the establishment of drainage can occur by thermokarst activity in frost wedges or encroachment by adjacent lakes
- In many areas, thaw lakes exhibit a prominent orientation of features
- The orientation is often normal to prevailing winds
- Mechanisms for orientation are poorly understood, but may relate to wind-driven erosion and deposition
- Often attributed to paleo-wind patterns, but modern oriented thaw lakes continue to form

5) Hydrology:

March-22-15
2:20 PM

Arctic Hydrology:

- Hydrology pertains to the science of surface waters
- Concerned with both the **quantity** and **quality** of waters, as well as the **timing**, **spatial patterns**, and **extremes** of **surface flow**

- The highly seasonal melt period in the Arctic typically means that surface water flow is limited to less than half of the year
    - The exception is the largest **rivers**, which may flow year round due to groundwater and lake storage
- This results in what is referred to as a ***nival*** **hydrological regime**
    - **Rainfall** may also play a role, which represents a ***pluvial*** component
- Where present, **glaciers** contribute to additional surface water and a ***glacial*** **regime**

Snow melt dynamics:

- The presence of surface water depends on temperatures substantially above 0°C
- The seasonal rise in temperatures is accompanied by lengthening daylight which contributes additional solar insolation to snow melt
- Snow melt occurs in three key phases:
    1. **Warming**: The cold snow pack warms to the melting temperature
    2. **Ripening**: The snow is now isothermal at 0°C and begins to melt
        - **Meltwater is retained and refreezes in the snowpack, releasing latent heat**
    3. **Output-melt** The snowpack generates excess meltwater and this drains freely
- Because of the strong link between **solar insolation**, the **surface energy balance** and **snow melt processes**, meltwater production is characterized by a **strong diurnal pattern**
- However, due to **conductive delays** and relatively **slow percolation** of meltwater down through the snow pack, **meltwater output** lags **energy input** by several hours

Flow generation:

- Once snow melt is occurring, **meltwater** will begin to flow from slopes and accumulate in **channels** and **depressions**
- Due to the high variance in snow cover, some areas will become snow free rapidly while others continue to generate water
- Hence, the ***contributing area*** in a catchment varies considerably
    - As snow continues to be exhausted, the contributing area generally becomes smaller
    - Also moves to higher elevations, where snow melt may have been retarded by cooler temperatures
- The irregular distribution and often very thick accumulation of snow in channels usually results in extensive *ponding* of meltwater
- In larger rivers, **ponding** may accumulate a large amount of water and slow the onset of flow
- As potential ponding locations fill to *capacity*, they **overflow**
- Additionally, flow may develop through the snow in channels
- Continued melt will drive connection of ponds, flow in the snow and downstream movement of water
- At this stage, it is common for a ***slush flow*** to occur as a pond rapidly drains and a mix of water and slush moves rapidly downstream
    - Slush flows can clear the channel or may lose momentum and begin to deposit the slush as **levies** that confine flow temporarily

- Successive slush flows result in opening of the channel and the initiation of *open channel flow*
- Generally, **initial flow** is still confined to a **channel** formed in the snowpack
    - Low hydraulic resistance (rapid flow)
    - Minimal interaction with the bed (sediment)

- As snow melt continues and **open channel flow** is established, most **nival** systems rapidly increase water ***discharge***
- After a few days of flow, discharge may increase to a seasonal peak that lasts only a few days
    - Generally, the greater the **catchment SWE**, the longer the nival peak will persist
- During this time, discharge shows **strong diurnal patterns** that reflect snow melt inputs of water
- After the peak, discharge rapidly wanes as snow is exhausted from the catchment
- While residual snow may remain after spring, usually, most nival systems revert to a **summer *baseflow* period**, characterized by **low flows** and **minimal diurnal variation** in **discharge**

- In **smaller streams** and **rivers**, as the **melt season** ends, flow dissipates and may cease entirely
- In **discontinuous permafrost**, base flow may be maintained by **soil water drainage** and **groundwater** contributions
- **Lakes** and **wetlands** may also supply water to support **baseflow**
- Hence, discharge in **nival** systems is typified by **short**-**lived**, **high intensity** flow where the majority of **seasonal** (*and annual*) **discharge** occurs over **days** to **weeks**
- **Ground ice can contribute to baseflow:** *particularly in warm years when a deep active layer forms*
- In these cases, water from ground ice can accumulate from the **bottom up*,*** compared to snow and rain inputs that infiltrate from the **top down**
    - Results in **unusual patterns of surface wetting** on **slopes**, **ponding**
    - Subsurface water may emerge as **seeps** or **clay boils**
        - **Seep:** moist or wet place where water, usually groundwater, reaches the earth's surface from an underground water source.
        - **Clay boil:** google doesn't even know

Glacier Hydrology:

- **Glacial melt processes** are initially difficult to separate from **nival melt**
- Melt of **glacier ice** generally, or increasingly, becomes more important as snow wanes and energy available to melt reaches a maximum in **mid**-**summer**
- Hence, **glacial melt** shows **diurnal variations** and **increases** during the season
- Shows close correlation with available melt energy
- Melt occurs primarily on the surface and flows via ***supraglacial***, ***englacial*** or ***subglacial*** routes
    - **Supraglacial**:

        - may be pre-existing and form long term, efficient pathways for meltwater to flow
        - Like snow filled channels on land, they become more efficient for flow after snow is cleared
    - **Englacial**
        - may occur and require connections to the glacier surface to deliver meltwater
        - ***Englacial conduits*** are typically small and can close by ice deformation if they are not maintained through flow over longer time scales
        - Often, **englacial conduits** drain onto the **surface** or to **deeper flow paths**
    - **Subglacial conduits**:
        - Important for warm based glaciers
        - Meltwater from the surface and water released by basal melt support subglacial flows
        - Flow paths may be efficient conduits or linked cavity systems
- The latter delay drainage and may store a substantial amount of water
- **Ponding** on the glacier surface or **subglacially** may result in rapid or catastrophic release of water from glaciers
    - These releases, referred to as ***jökulhlaups*** and can exceed discharge several orders of magnitude until the storage is exhausted

Rainfall:

- In many Arctic environments, rainfall contributions to discharge may be important
- Even in areas like the *High Arctic* where intense rainfall is rare, pluvial discharge may be, in some years, the most important hydrological event of the year
- Generally, Arctic rainfall is of lower intensity that temperate systems
    - Associated with **frontal systems**
    - Few **convective storm systems**
- Intense rainfall on snow can result in exceptionally high discharge by increasing both water and energy supply to the system
- Rainfall events during the summer must overcome potential **soil water storage**
- Hence, **antecedent soil water conditions** are an important **control** over the catchment **response to rainfall**
- If soil water storage is exceeded, excess **rainfall** will generate **overland flow** and **downstream discharge**
    - *Multiple low intensity events* can '**prime**' the catchment by filling soil water storage
- Discharge responses are usually characterized by a rapid rise to **peak runoff**, followed by a multi-day **recession** to **baseflow conditions**

- The contribution of **nival**, **glacial** and **pluvial** water to **river discharge** varies considerably across the Arctic
    - Some areas are affected by all three (*Norway, Iceland, Alaska, Baffin Island*)
    - Others are dominantly nival
    - Pluvial dominance or influence is less predictable and sporadic

Arctic water quality:

- The wide range of discharge characteristics associated with surface waters in the Arctic have important effects on water quality measures
- **A key distinction between water quality measures:**
  - **Concentration:**
    - The instantaneous amount in the water (e.g., 10 mg/L)
  - **Flux**
    - The integrated, or total amount of transport during an interval
      - e.g. 2 Mg of sediment in a season
- Because discharge varies so widely during the Arctic runoff season, there may be a substantial bias in considering concentrations due to dilution or concentration effects

Hydrological fluxes:

- Water is effectively the medium for a wide range of material fluxes
  - **Dissolved**:
    - A variety of organic and inorganic solutes and compounds
  - **Suspended**:
    - Small particulate components, mostly mineral and organic, that travel in suspension
  - **Bedload**:
    - Larger particulate materials that saltate or roll down the channel
  - **Contaminants**:
    - Of special interest, although they are occur as one of the three categories listed above
- The relative contributions of different flux components varies substantially by river system, and depend on bedrock, soil, vegetation and climate
- Most river systems are dominated by dissolved components
  - Chemical weathering products •Organic particulates
  - Dissolved organic components
- Chemical weathering rates vary substantially, and can result in wide variations in solute loads
  - For example, in two catchments in Iceland showed substantial differences in solute fluxes based on bedrock type
- In **boreal** and **tundra** regions with extensive vegetation cover and **organic** soils, stream loads are dominated by dissolved and particulate organic components

- In High Arctic areas with less vegetation cover, or areas with widespread erodible sediment, suspended sediment and **bedload** may represent the dominant river fluxes
- In these environments, sediment transport dominates during most of the runoff season, and dissolved and organic components are secondary
- In **glacial** environments sediment and **bedload** typically dominate

- **Organic components** are minimal due to the limited vegetation and soil development

Sediment:

- Sediment erosion is a reflection of several catchment characteristics:
    - Availability of sediment for erosion (source)
    - Access of water to erodible sediment
    - Sufficient hydraulic energy to transport sediment
    - Sediment storage and release in the channel system
- Availability of sediment varies due to a number of key factors:
    - Exposure of erodible sediment to channel flow
    - Protection from erosion afforded by snow, frost, vegetation and sediment armouring
    - Hydrological *connectivity*- a path for water to transport the sediment downstream

- Sediment sources are associated with channel banks and bed
- Slope wash from exposed sediment
- Disturbances that locally increase exposed sediment
- In the channel, availability of sediment depends on the water level (or stage)
- Typically, higher flow is able to access more sediment due to increased wetted surface in the channel
- **Higher flow** also increases **stream *competence***, or **erosive power** and ability to transport sediment

- In *Arctic regions*, because much of the **discharge** occurs during snow melt, potential erosion occurs when the flows are constrained by channel snow and frozen soils
- Despite these limitations, sediment concentrations that reflect erosion and transport, are usually highest during peak nival flow
- Usually, a linear increase in discharge results in a non-linear increase in sediment load
    - Sediment concentration may lead discharge, as the rising flow accesses, erodes and exhausts available sediment
    - Results in characteristic *hysteresis* relationships between discharge and sediment concentration
    - Clockwise hysteresis indicates exhaustion of sediment supplies and is common during nival flow
    - Additional thaw or channel shifting on a daily basis make additional sediment available for erosion
- As a result, **suspended sediment concentrations** are typically high during the **nival peak period**
- Diminish with declining discharge afterwards, despite further thaw of channel snow and soils that could enhance potential erosion
- Hence, baseflow in streams is characterized by low sediment transport, but increasing catchment potential for erosion
- When intense rainfall events occur, erosion is widespread and sediment transport reaches levels substantially higher than during the snow melt period

- **Hence, the seasonal flux of sediment in nival catchments is dependent on:**
  - The availability of sediment in the catchment
  - The overall discharge, which in turn depends on catchment SWE
  - Specific catchment factors like the amount of snow in the channel, channel material, potential storage of sediment
  - The proportion of sediment erosion that occurs due to melt season rainfall
    - Particularly, the intensity of the rainfall runoff

- In glacial systems, sediment supply is highly variable and depends on the flow routing
  - In cold-based ice, supraglacial drainage dominates and sediment for erosion is typically quite limited
  - In warm-based ice, subglacial slide and abrasion produce large amounts of fine grained *rock flour* and water can also erode material from the bed
- The type of bedrock and it resistance to mechanical weathering is important
- Solid crystalline rock (e.g. granite) is less susceptible than softer sedimentary and other rocks (e.g., shale, siltstone, rhyolite)
  - As a result, subglacial runoff is associated with higher sediment transport, and is largely dependent on the production of sediment by glacial processes

Particulate organic material:

- **Particulate organic carbon** (**POC**) and **nitrogen** (**PON**) are important erosion products from soils and contribute to **aquatic** ecosystems
  - Generally, the amount transported is dependent on similar factors as mineral sediment
- Sources are typically soils where plant material accumulates
  - Like sediment the flux of POC/PON reflects discharge in the stream and the flux is greatest during snow melt, and during intense rainfall
- The proportion of these components in the overall all particulate load is typically <20%, and in the High Arctic, as low as ~1%

Dissolved organic material:

- **Dissolved Organic Carbon** (**DOC**) and **nitrogen** (**DON**) are vital for aquatic ecosystems and are leached from soils in the catchment
  - Few comprehensive Arctic studies have been carried out, but these suggest that DOC and DON levels are low compared to temperate catchments
- Contrary to common thinking, snow melt does not appear to dilute a limited amount of dissolved transport, but concentrations are generally high prior to and during the nival peak and in response to intense rainfall
- Hence, the flux of DOC and DON is also controlled by the timing and magnitude of discharge

- Unlike sediment, **DOC** and **DON** are sourced from soils, plants and other organic "*sites*" in the catchment

- Some of these are flushed by surface flow, but many require water to flow through the soil to acquire and transport as well
- The nature of the vegetation cover will affect the magnitude of **DOC** and **DON** concentrations substantially
- However, despite this factors, the high flushing rates during snow melt suggest much of the available **DOC**/**DON** is on the surface and available for transport

Dissolved solutes:

- Represent ions from salts, mineral weathering and other inorganic compounds
- A small amount may be deposited from aerosols in precipitation (Na, Cl, etc.)
- Generally, these components are associated with soils and underlying parent material
- Access to many solutes is limited by thaw depth and flow pathways
    - Moreover, as the potential solute loads may be limited by availability, solutes typically show dilution during snow melt, and increase in concentration during baseflow
- As the active layer develops, further solutes are accessed by deep water percolation
- May result in increasing solute loads later in the season, particularly with the lowest discharge levels

Questions: Hydrology and surface water quality

March-22-15
3:17 PM

Snow Melt Dynamics:

What are the three phases that snow melt occurs in? Describe them

- warming: The cold snow pack warms to the melting temperature
- Ripening: The snow is now isothermal at zero degrees celsius, and begins to melt. Meltwater is retained and refreezes in the snowpack, releasing latent heat.
- Output-melt: The snowpack generates excess meltwater and this drains freely

Why is meltwater production characterized by a strong diurnal pattern?

- The strong diurnal pattern is due to the strong link between solar insulation, surface energy balance, and snowmelt processes.

Why does meltwater output lag energy input by several hours?

- Meltwater output lags energy input by several hours because of conductive delays, and slow percolation of meltwater down through the snow pack

Flow Generation

Why does the contributing area in a catchment vary considerably?

The contributing area in a catchment varies considerably because as snow continues to be exhausted, the contributing becomes smaller, and moves to higher elevations, where snow melt was retarded by cooler temperatures.

Why does ponding occur?

Ponding occurs due to the irregular distribution, and thick accumulation of snow in channels

In larger rivers, how does ponding slow the onset of flow?

Ponding slows the onset of flows in large rivers because a large volume of water accumulates in ponds, and the ponds must fill to capacity for flow to continue.

What is slush flow, and why does it occur?

slush flow is when a mix of slush and water move rapidly downstream, they occur when a pond drains rapidly.

How does slush flow contribute to open channel flow?

- Slush flows contribute to open channel flow by potentially clearing the channel, or by depositing slush along the sides as levies to contain flow temporarily.

Why, in general, is initial flow confined to a channel formed in the snowpack?

- initial flow is confined to a channel formed in the snowpack because the snowpack has not yet had a chance to melt and expose the bed, and the water takes the path of least resistance.
    - Results in rapid flow, due to low hydraulic resistance
    - Allows for minimal interaction with the sediment.

What happens to most nival systems when open channel flow is established?

- Most nival systems rapidly increase water discharge in response to the establishment of open channel flow.

How long does a seasonal peak typically last?

- A seasonal peak typically lasts only a few days

Why does discharge rapidly wane after the seasonal peak?

Discharge rapidly wanes after the seasonal peak as snow is exhausted from the catchment.

What is the baseflow period, and how is it characterized?

the baseflow period, also known as the summer base flow period, is the period characterized by low flows and minimul diurnal variation in discharge

What can happen to flow in smaller streams and rivers as melt season ends?

- Base flow in small streams and rivers dissapates and may cease entirely as the melt season ends

What contributes to baseflow after melt season ends?

- After the melt season ends, baseflow is sustained by ground ice melt, soil water drainage, and groundwater drainage(in discontinuous permafrost).

Does water from ground ice accumulate from the bottom up, or the top down?

- Water from ground ice accumulates from the bottom up, as opposed to snow and rain inputs which accumulate from the top down

What causes seeps and clay boils?

- Subsurface water may emerge as seeps and clay boils, but I don't know what a clay boil is

Glacier Hydrology

Why does glacial melt become more important in water flow mid-summer?

- Glacial melt becomes more important as snow wanes and energy available to melt reaches a maximum in mid-summer.

Where on the glacier does melt primarily occur?

- Melt primarily occurs on the surface of the glacier

What are the 3 main types of flows coming from glacial melt? Describe them.

- Supraglacial: may be pre-existing, and form long term efficient pathways for meltwater to flow. Like snow-filled channels on land, they become more efficient for flow after snow is cleared
- Englacial: may occur and require connections to the glacier surface to deliver meltwater. Englacial conduits are typically small and can close by ice deformation if they are not maintained through flow over longer time scales. Often englacial conduits drain onto the surface or to deeper flow paths.
- **Subglacial:** important for warm based glaciers. Meltwater from the surface and water released by basal melt support subglacial flows. Flow paths may be efficient conduits or linked cavity systems

What are *jökulhlaups*

- Ponding on the glacier may result in rapid or catastrophic release of water, can discharge several orders of magnitude until the storage is exhausted.

Rainfall

In general, is arctic rainfall of lower, or higher intensity than temperate systems?

arctic rainfall is of lower intensity than temperate systems.

What types of weather systems is arctic rainfall associated with?

- Frontal systems

- Convective storm systems

Why are antecedent soil water conditions an important control over the catchment response to rainfall?

- Antecedent soil water conditions are an important control over the catchment response to rainfall because if soil water storage is exceeded, excess rainfall will generate overland flow and downstream discharge.

How do low intensity rain events affect water discharge responses?

- Multiple low intensity events can prime the catchment by filling soil water storage

What areas in the arctic are affected by nival, glacial and pluvial water to river discharge? (the others are dominantly nival)

- Norway
- Iceland
- Alaska
- Baffin Island

6) Lakes, Ponds, and Wetlands:

March-24-15
6:02 PM

Arctic lakes:

- Lakes are a key aquatic environment in Arctic regions
    - Major source of fresh drinking water
- Support aquatic ecosystems and base flow in many river systems
    - Important geomorphic sinks for sediment and biogeochemical materials
- Critical as access for land use activities (*e.g., winter roads*)
- In many areas, they are one of the most common land cover types

Lake types:

- Due to recent and ongoing glaciation, substantial sea level changes and permafrost, there are a wide range of lake types in the Arctic:
    - **Ice-proximal (***proglacial***):**
        - immediately adjacent to glacial systems
    - **Ice-distal:**
        - lake still influenced by glacial inflow, but substantially downstream (**distal**)
    - **Ice-dammed:**
        - May be short term or long term, depending on ice dynamics
    - **Ice-scoured:**
        - Basins are formed by recent glacial erosion
- **Coastal isolation lakes:**

    - May be formed by progressive cut off by advancing river deltas or fans
    - May represent a pre-existing depression or scour
    - As coastal emergence occurs, these lakes are isolated
    - Depending on circumstances, these lakes may revert to freshwater, mixed, or remain saline
- Many smaller lakes and ponds are created in shallow depressions formed behind beach and other coastal landforms and are isolated during uplift

- **Uplift in Arctic regions is the result of:**
    - ***Glacioisostatic Emergence***- crustal rebound after the removal of ice loading
        - Net emergence ranges from 2-300m, depending on the thickness of the former ice cover
- Thermokarst lakes:
- formed by localized ground ice thaw
- Undergo growth by lateral capture
- May rapidly drain when tapped
- Hence, represent relatively short term features on the landscape

Physical limnology:

- Arctic lakes are characterized by short melt seasons
- Ice cover depends on severity of winter heat loss and snow cover
    - In low Arctic settings, ice cover may be 8 months, and in high Arctic as much as 11 months
    - In rare cases, multi-year ice cover may occur during some periods
    - Affects the development and seasonal characteristics of *water column* properties
- These key state variables affect most ecosystem, biogeochemical and sedimentary processes in a lake

Radiation:

- Solar radiation is highly attenuated by passage through water
- Red and infrared spectra are absorbed in the upper water column (*upper few metres*)
- Blue and shorter wavelengths penetrate to c. 10-15 m depth
- Snow and ice further reduces solar penetration
    - For example, under 0.5 m of snow and 2 m of ice, *photosynthetically available radiation* (PAR, 400-700 nm) is about 0.5% of incident
    - The same ice cover, without snow, increases PAR by 13 times, and biologically effective UV radiation by 16 times
- Dissolved coloured dissolved organic material (CDOM) in ice and water strongly absorbs UV and PAR, further reducing radiation in water column
- Where CDOM is in low concentrations, radiation attenuation is minimized and penetrates to greater depths

Thermal structure:

- The rapid absorption of most solar insolation in the upper 10 m or less of lakes is important for the vertical distribution of temperature
- As the melt season progresses, the upper part of the lake warms while the deeper water remains cooler
- If ice remains, this will limit warming substantially
- The maximum density of freshwater is 4°C, so as the surface waters warm above this level, they become less dense
    - This results in a *thermally stratified* water column
- The upper water is subject to wind stress and typically is well mixed
    - The lower water column is isolated by the *thermocline*, and is subject to reduced or no mixing

- In most Arctic areas, the density contrast between the upper *epilimnion* and the lower *hypolimnion* is not great as warming is limited
- Hence, during autumn cooling, the lake can return to *isothermal* conditions and wind-driven mixing of the entire water column
- In some stable lakes where mixing does not occur, radiation that reaches deeper waters may accumulate
- This results in higher temperatures at depth that may last for years, decades or longer
- Warmer conditions, together with low levels of PAR provide a suitable habitat for bacteria and some algae

Chemical conditions:

- Most freshwater lakes have little in the way of vertical variation in solute concentrations
- Diffusion of solutes from the bottom sediment during winter (under ice) may result in a shallow layer of high conductivity bottom water
    - In cases where the lake was isolated from the ocean, residual sea water can result in a *chemically stratified* lake, with a prominent *chemocline* separating the upper fresh water from the denser saline water
        - In these cases, the stratification is permanent, and in many cases, appears to have been in place for thousands of years

Dissolved oxygen:

- Oxygen is critical for most higher life forms (e.g. fish) in lakes
- **Dissolved oxygen** (**DO**) is derived from diffusion from the atmosphere, turbulent mixing of surface waters with waves, and photosynthesis in lakes, all of which lead to *aerobic* conditions
    - Persistent ice cover reduces atmosphere-water interactions substantially, and limits DO replenishment
- Stratification further limits DO replenishment in the hypolimnion
    - In chemically stratified lakes, the hypolimnion may be partially or completely *anoxic*
- Many lakes develop localized anoxia in the deepest locations during the winter
    - Result of microbial decomposition of organic material (BOD- biological oxygen demand)

- During the melt season, water inflow and wind mixing can flush the bottom and re-oxygenate these areas
    - Recent work has shown that in deeper lakes, this flushing process is quite variable, and is dependent on the intensity and density of inflow, especially while ice remains
- In freshwater systems, sediment load may be the main control over inflow density and hence, river discharge and sediment transport may affect bottom DO conditions
- In chemically stratified lakes, these processes are usually insufficient to flush the bottom due to the strong density contrast at the **chemocline**

- In some meromictic lakes, bacterial activity concentrated below the chemocline generates DO and may result in high DO levels
- These bacterial levels are often associated with thermal maxima as well, due to trapping of solar energy in the stable upper hypolimnion
- Collectively, these processes result in distinctive water stratification and water column properties that control other lake systems
- These properties are summarized by the character and frequency of water column mixing (or *turnover*)
- Many lakes with pervasive ice cover are ***cold monomictic***:
    - Due to limited warming, the water column remains largely isothermal all year, and mixing can occur whenever the ice is off
    - ***Dimictic* lakes** develop summer thermal stratification but are able to turnover in spring and fall when the water column is isothermal
    - ***Polymictic* lakes** can turnover at any time, and are typically shallow and subject to strong wind mixing
    - ***Meromictic* lakes** are chemically stratified and do not turnover
        - Many coastal lakes are meromictic and have marine water in the hypolimnion (S=34-35)
- In some cases, the hypolimnion may be diluted sea water due to some prior mixing (S less than 34)
    - Research suggests that meromictic lakes remain in settings where freshwater from the catchment is insufficient to gradually flush away the salt water at the chemocline
    - Hence, where freshwater inflow is high, lakes that were likely meromictic at one time, have become freshwater
- In other cases, the hypolimnion may be hypersaline (S greater than 50)
    - Hypersaline lakes are poorly understood, but the additional salt may arise from brine rejection during ice formation (crenogenic)
    - Alternatively, the additional salt may arise from brines rejected as permafrost advances around the lake (**cryogenic**)
- Recent work has suggested that during isolation, tidal replenishment of surface water enhances brine rejection during ice formation and can result in hypersalinity in a very short period of time (years to decades)
    - Notably, many hypersaline lakes in the Arctic appear to have isolated from open marine environments

    - By contrast, many known meromictic lakes isolated from settings behind ice shelves where freshwater surface layers may have already been in place during initial isolation

Hydrology-lake interactions- case study:

Cape Bounty Arctic Watershed Observatory, Melville Island, Nunavut

Question: How will climate change affect land and water processes in the High Arctic?

- Snow and meteorological observations
    - River discharge, suspended sediment, solute, stable isotope, nutrient and contaminant (Hg) fluxes in paired, nested watersheds
- Advanced biogeochemical analysis of soil and river organic matter
- Hydrological modelling
- Soil gas, nutrient, moisture and vegetation phenology
- Atmospheric and aquatic C/N gas fluxes
- Remote sensing of biomass, soil moisture
    - Sedimentary and hydrochemical dynamics in lakes
- Sedimentary paleoenvironmental work

Ponds:

- Ponds are essentially smaller lakes and the distinction between the two varies
- Generally, ponds are shallow (<5 m deep), relatively small
    - Widespread in the Arctic, and are formed by similar processes to lakes.
    - Thermokarst ponds are especially common in some areas
- Ponds may also be formed by highly localized slope and landscape processes
- Due to the reduced depth of ponds, solar radiation is typically available throughout the water column and on the bottom
    - Ice and snow reduce this radiation cover substantially
- Ice cover will vary from a winter ice pan in cases where ponds are deeper than typical ice thickness, to complete freezing in shallow ponds
- Due to the reduced volume of water and smaller extent of ice cover, the duration of ice on ponds is reduced compared to most lakes
    - **Multi-year ice is very unusual**

Thermal conditions:

- While the same density principles apply to ponds, the potential for thermal stratification is limited due to the limited depth
- In most cases, once ice is gone, ponds will mix fully with the wind and solar heat is distributed throughout the water column
    - The small volume of water results in rapid warming
- Measured pond temperatures can exceed 20°C in ponds
- The lack of volume means reduced heat storage in the pond
- Hence, ponds are subject to greater variability in thermal conditions

- Daily and synoptic weather changes affect pond thermal conditions

Water balance:

- Unlike lakes, where the volume of water changes are relatively limited, smaller ponds are significantly controlled by the water balance
  - The balance can be defined as:

Net = Inputs – outputs + storage changes

Inputs are:	Surface runoff, soil water seepage in the active layer, direct precipitation, direct snow melt
Outputs are:	Evaporation, soil water seepage, surface outflow

- Storage changes are essentially water level or depth
- This water balance is sensitive to conditions that vary between and during the year
  - Also depends on the hydrological connectivity of the pond to the surrounding land
  - Where the catchment area for inflow is relatively large, potential inflows are also high
  - Slopes, streams
- Where the pond has limited inflow catchment, water balance is more dependent on direct water inputs from snow and rain
- If snowfall is reduced, or soil is dry prior to winter, the impact of snow melt inflows are reduced
- Similarly, if winds accumulate or scour snow pack in the pond area, this may affect water level at the beginning of the melt period
- Slopes and streams sustain surface and soil water inflows
- Can provide ongoing water during the summer to maintain depth in the pond
  - Residual snow banks also represent an important potential input of water to ponds, where they are hydrologically connected
- Surface outflows from ponds may cease after inflows decline
- Thus, many ponds become closed basins during the summer season
  - Additionally due to low thermal capacity and a high surface to volume ratio, evaporation rates for ponds are higher than lakes
- Evaporation may vary from 1-10 mm per day during days with optimal conditions
  - **High heat fluxes** driven by positive radiative balance
  - **High latent heat** removal by strong winds
- Hence, seasonal evaporation may represent an appreciable proportion of the overall water in a given pond
- May result in complete drying of one pond and only water level drops in an adjacent pond
- Key issues to consider regarding water balance:
  - Declining pond water levels are not necessarily indicative of a simple change in hydroclimate
  - Warming climate, with attendant increased evaporation is one possible pathway to lower water levels

- Similarly, reduced inflows can also lower water level, without a change in evaporation
- A change in the seasonality in inflows can result in greater water loss through outflows
    - Intense rainfall
    - Large snowmelt period
- This is due to fixed amount of potential water storage in a pond

Water quality:

- Inflows and water balance changes are the primary controls over water quality in ponds, beyond normal background factors such as bedrock and chemical weathering
- The variable, but usually small water volume in ponds often means that water chemistry in the pond is subject to substantial changes during major inflows
- Hence, snowmelt or a large rainfall event can completely change the chemistry of a pond in hours to days

- Evaporation can substantially enrich the concentration of solutes and nutrients in ponds
- Given that ponds will evaporatively *enrich* as the water balance becomes negative
    - As further evaporation continues, the concentrations can increase in a non-linear way
- Small differences in volume and surface area between adjacent ponds can result in substantial differences in water chemistry and nutrient load

Wetlands:

- Widespread, particularly in continental, low-relief areas
- Essentially represent a shallower or more ephemeral water balance than pond systems
- Typically, very shallow depths result in complete freeze conditions in winter
- In summer, water balance conditions dictate if water levels are maintained or decline during the season
- Hydrologically connected wetlands will often sustain water levels, while closed, or isolated wetlands will respond to the same factors that control shallow ponds

- Due to the shallow water depths, most wetlands have vegetation that grows throughout
- This vegetation may be emergent all year, or only during low water levels
- Due to increased vegetation compared to ponds, wetlands often have additional water losses through plant transpiration
    - Similarly, due to higher accumulation of organic material, wetlands often have higher microbial decomposition rates
- Results in potential for microbial consumption of oxygen to exceed replenishment from the atmosphere- local or widespread anoxia

7) Terrestrial and Aquatic Ecosystems:

Tuesday, March 17, 2015
3:38 PM

Aquatic ecosystems:
- River, lake, pond and wetland settings form the basis for a variety of aquatic ecosystems
- All are controlled by the strong seasonality of Arctic climate, ice cover, water availability, temperature cycling, and availability of resources
- Aquatic ecosystems contribute to water quality, and represent an important component of the overall biogeochemical cycling in the Arctic
- Important as well for northern communities, and understanding the function and dynamics of these systems is necessary for land and water management

Food webs:
- In general, there is not a specific or typical food web characteristic of Arctic aquatic systems
- Food webs are better described as a continuum from more temperate webs, to simpler webs in the High Arctic
- In the Low Arctic, the food web can have well developed zooplankton and fish communities
- In the High Arctic, the food web may be topped by flagellates, rotifers and other small organisms
- Web structure depends on the physical and chemical context for the water body
- These in turn control the availability of nutrients and necessary to support the food web

Controls over productivity:
- Water supply is a fundamental need for aquatic systems
- In many Arctic aquatic settings, liquid water is available for a short period of the year (weeks to months)
- Limitations to the availability of water are reflected in the structure of aquatic systems

- Hence, while some systems may have limited water all year, this limits production to microbial populations
- Larger water masses like deep lakes may support aquatic webs throughout the year
- Ephemeral systems like small ponds and wetlands may only host microbial and primary producers for the brief period of water availability

- **Solar irradiance** is another key control over aquatic productivity
    - Arctic regions receive less solar irradiance than lower latitude locations
    - Ice and snow further attenuate the amount of irradiance found underwater, often to very low levels (<1% incident)
        - This reduces the overall level of photosynthesis in aquatic systems
    - Further, the seasonality of irradiance is a controlling factor

    - Despite these controls, Arctic aquatic ecosystems frequently show early spring photosynthesis and phytoplankton biomasses, even under ice
    - These are often followed by reductions in primary productivity during summer when ice is no longer present, but when nutrient levels are lower

- **Nutrient supply** is a key constraint on aquatic ecosystems
    - Primarily related to N, P and dissolved organic matter (DOM)
    - Arctic catchments are typically less productive than temperate equivalents
    - Chemical weathering is also typically reduced
    - Results in lower nutrient delivery to aquatic systems
    - Further, the high discharge intensity of many Arctic systems (especially nival systems) results in rapid flow-through rates and reduced retention of nutrients in water bodies

- **Nutrient availability** in a water body is characterized as the *trophic status*
    - This is an important state to consider as an over-arching control over food web structure and productivity
    - Most Arctic water bodies are **oligotrophic**, where key nutrients N and P are limited and constrain primary productivity
    - N and P are sourced from the watershed as inflows, or may be cycled in the sediments of water bodies
    - **Dissolved organic matter (*DOM*)** contributes N and P to the aquatic system through *microbial decomposition*

    - Elevated levels of N and P are found in Eutrophic aquatic systems
    - These are comparatively rare, and are found where nutrient inflows are high
        - Ponds near shore bird colonies
        - Anthropogenic waste discharge
- In general, lakes and ponds may gradually become eutrophic through accumulation of organic material in the sediment the cycles N and P in the food web
- However, this concept develops over the long term (millennia) in temperate systems
- The lower overall productivity in most Arctic systems limits this progression and few examples of natural eutrophication can be found

Benthic communities:

- In shallow ponds and wetlands, or where water column conditions are **stable** due to ice cover, benthic communities can dominate
- Benthic habitats and food webs are characterized by primary producers, intensive cycling of nutrients
- At the **micro**-scale, benthic habitats may have locations of elevated nutrients, warmer water or other characteristics that encourage *benthos*
- Benthic organisms are composed of a range of *algae*, *cyanobacteria* and other *primary producers*
- In contrast, overlying water may be too nutrient poor to support much in the way of primary producers
- Generally, the relative role of the benthic production declines southward, as nutrient levels increase and overall production increase

Pelagic production:

- In higher nutrient conditions, deeper water or where ice is removed, production of pelagic or planktonic communities are more important
- Radiation limitations may also result in a planktonic community, especially where CDOM or ice limit benthic radiation
- Planktonic communities are represented by photosynthetic algae (*diatoms, chrysophytes, chlorophytes*) and bacteria, including *cyanobacteria*, *green sulphur* and *purple sulphur*
- These *primary producers* support herbivores including *zooplankton* and *chironomids*
- Productive or larger aquatic systems can further support larger invertebrates

- Although life histories are often poorly studied, rapid development and maturation are normal and optimize the limited period of favourable conditions present during summer

- Lakes that support fish have substantially altered food webs
- Predation by fish on invertebrates and primary producers result in a typical shift towards smaller zooplankton which cascades down the food web
- Additionally, life-cycle habits of fish may produce specific feeding patterns
    - Juvenile fish may frequent deep water to avoid predation from larger fish and where food competition is reduced
    - Adult fish may reside in the shallower littoral zone, where feeding is rich and the larger fish are able to withstand higher predation and competition pressures

- *Anadromous* fish species like *Arctic Char* and *salmon* may live part of their life cycle in marine environments
- Migrations from freshwater to marine sites occur during summer and allow feeding in productive marine waters
- In more northerly areas, a fish may undertake 2-5 summer feeding migrations before reaching maturity
- Migration may be limited by a number of physical barriers, some of which, like outflow, may vary year to year
- *Anadromous* fish may co-exist with resident freshwater individuals and limited breeding between the groups may establish distinctive *ecophenotypes* within a lake

Thresholds:

- Finally, due to the *substantial limitations* on aquatic productivity and sensitivity of these systems to physical and chemical controls, Arctic aquatic ecosystems are subject to key thresholds in function and productivity
- **Key physical thresholds** include:
    - ice cover,
    - permafrost landscape disturbance,
    - stratification and mixing regimes
- **Biogeochemical thresholds** include:
    - changes in nutrient availability,
    - changes in penetration of light due to CDOM,
    - anoxia,

    - anoxia-related increases in sedimentary P release

- Hence, feedbacks between these environmental controls can result in rapid and profound changes in aquatic ecosystem structure
- This is perhaps best exemplified by recent (*post industrial*) changes to diatom communities observed throughout the Arctic
    - Rapid transition from dominantly benthic to planktonic communities
    - Increased productivity
    - Attributable to climate change-induced nutrient, ice cover, light and thermal effects on highly sensitive aquatic systems

Terrestrial ecosystems- *vegetation*

- Arctic vegetation reflects the wide range of conditions found across the region
- As is the case elsewhere in world, vegetation productivity, communities and species attributes reflect prevailing environmental controls
- These are primarily climate and soils, with additional controls at the local scale

- Due to reduced solar insolation at high latitudes, photosynthetic production in the Arctic is substantially reduced
    - Increasing length of the freeze period progressively shortens the growth season with latitude
- In the most extreme cases like the High Arctic, the growth period may only be a number of weeks, and can be interrupted by frost at any time
- Where slopes are steep, variations in the aspect of the slope may affect these radiative and climatic factors and result in different vegetation types on different slopes

- Water availability is a key constraint on vegetation structure in most Arctic areas
- Excess water in wetlands and ponds represents one end of this spectrum
- Soils that dry out in rooting zone for much of the growing season is the other extreme
- In most Arctic settings, persistence of water supply results in a clear vegetation community structure at local and larger scales
- Exposure to wind is also an important factor for plant type and growth habit in Arctic regions
- This is especially the case in areas of tundra vegetation, where the absence of tall vegetation increases wind exposure
- Wind affects the surface temperature of the plants
- Increases transpiration and water losses
- May cause damaging loading by rime ice or wet snow
- Wind scouring of snow can alter the soil thermal regime
- Vegetation may protect snow from scour, locally enhancing snow accumulation
- In many instances, long lived species like trees can deform to reflect prevailing winds
- May form more compact or lower plant habits
- Branches and trunk may be displaced downwind

Biomes:

- Arctic vegetation can be divided in to broad biomes that reflect climatic and other factors
- The southern margins are characterized by boreal forest cover
- The primary species are spruce (black and white) and jack pine that are adapted to cold conditions and short growing seasons
- Deciduous species include primarily birch and poplar species
- There is considerable variation in ground cover, typically mosses and low shrubs dominate and thick accumulations of partially decayed plant biomass are found

- The boreal species that dominate forest communities varies across the Arctic, particularly at the northern or altitudinal limit
- In North America, spruce is most common, while larch is more common in Russia and birch is common in Scandinavia

Treeline:

- Latitudinal treeline is a key division between the boreal biome and the tundra to the north
- It varies in location substantially, and reflects long term patterns of climate and the distribution of permafrost
- In North America, it nearly reaches the northern coast in the Mackenzie delta region, while it is located along the southern coast of Hudson Bay in the eastern areas
- Despite the term, treeline is not a sharp boundary in vegetation cover
- It is often gradational, representing a decline in the density of tree species
- Clusters of tree cover may occur hundreds of kilometres north of treeline, in particular in optimal locations like river valleys
- Similarly, altitudinal treeline reflects the same climatic and soil factors inherent at higher elevation sites
- The elevation of treeline progressively drops northward in the Arctic, until the elevation of tree limit is essentially at the level of the region
- In the southern margins, treeline may approach 2000 m asl
- It declines substantially to below 500 m asl at the Arctic Circle in western North America
- As is the case with treeline elsewhere, the actual change is gradual

Tundra vegetation:

- Tundra vegetation varies considerably in structure and species composition
- Generally, as the environment becomes more extreme, the productivity declines, resulting in lower vegetation biomass, lower canopy, and reduced density of plants
- Highly localized conditions related to soil type, availability of moisture and microclimate may affect the specific community
- Results in a patchy cover in may areas where growth conditions vary substantially
- Tundra vegetation is characterized by cold winter conditions, cool to cold summers
- The brief growing season results in plant-specific strategies for growth and reproduction
- This may include rapid seed development, altered growth habit to maximize photosynthesis and infrequent seed production

- Shrub tundra is found in southern margins and is characterized by extensive cover of shrubs up to 1 m height
- Many of the shrubs are dwarf varieties of alder, birch and spruce species, although taller individuals may sporadically occur
- Generally, this is a wetter biome and relatively productive
- Tussock and dwarf shrub tundra is found in middle Arctic regions
- Birch and willow are common as low shrub forms, and moss and sedges cover the soil surface
- Shrubs are under 0.5 m height, and represent colder, moist conditions
- Plants may form into tussocks, or low organic mounds that give this tundra community its distinctive appearance
- Prostrate shrub and herb tundra is found in dryer, colder settings, particularly the High Arctic
- Shrubs of willow and dryas are less than 10 cm high, and the sedge and grass cover varies, depending on moisture availability
- Mosses and lichens may represent up to 60% of the ground cover in wet sites, and much less in dryer locations

- Cryptogram and herb barrens are found in the most extreme settings, where bedrock dominates substrate or climatic conditions are especially harsh
- Community is composed of scattered herbs, mosses, lichens and liverworts, all with heights less than 5 cm
- Local variations in moisture result in higher plant density and some elements of more productive tundra biomes
- The strong control over local environmental conditions is reflected in the distribution of communities along slopes (or cantenas) and due to variations in bedrock and surface sediment

Animals and birds:

- Despite the harsh environment, a number of *mammals* and *insects* are found in Arctic regions, as well as a wide range of *bird species*
- The distribution of species across the Arctic reflects the structure of food webs, environmental stresses on individual species and competition between species
- As primary production of plant biomass is lower than temperate regions, this provides an overall limitation to animal ecosystem productivity
-
- In many cases, individual species are central elements of food webs
- In particular, the *herbivores* depend on *vegetation* cover for food resources and are ***limited*** by these resources
- They also represent prey for predators

- Hence, the population dynamics of herbivores are key drivers of other components of the food web and major population changes cascade to other web components

- Notably, the northward expansion of many temperate species is limited by temperature and other aspects of environmental harshness
- However, it is interesting to note that the southern limit of many Arctic species is not constrained by temperature, but rather, likely by the limitations of competition with other species, food resources and pressures from enemies
- Hence, while there may be substantial barriers to southern migration of Arctic species, if conditions improve in the Arctic, temperate species may migrate northward
- For example, there has been a notable northward migration of red fox onto Baffin Island during the 20th century, at the expense of the range of arctic fox

Adaptations to the physical environment:

- Many Arctic species are well known for adaptations to the conditions found in their extreme habitats
- Warm-blooded mammals have thick fur that retains heat
- Their body shape is rounder with shorter appendages to minimize heat loss
- Appendages like ears and tails are shorter or rounded to minimize heat loss as well

Warm blooded mammals, ungulates, predators have variations in fur that encourage retention of heat. Eg. Muskox have very thick fur, arctic fox has shorter tail, rounded ears, etc that minimize heat loss from appendages.

Because they are active year round, they need to survive particulary in winter.

- However, there are few specific physiological adaptations found in Arctic species
- Exceptions to this include the accumulation of body fat for winter survival in some ungulates like muskoxen and caribou
- Some species can alter their winter metabolism to lower levels, like arctic fox
- Animals that do not have these traits may utilize alternative strategies
- Lemmings and voles, which have large surface to volume body ratios, will remain active in tunnel systems in snow to reduce exposure to winter extremes
- In a few cases, they may hibernate, but this is rare in Arctic species
- Breeding habits are similarly altered in many species
- Mating patterns may be altered compared temperate species
- The breeding season can be substantially shortened to adapt to the shorter period of tolerable conditions in the Arctic
- Few specific recognizable metabolic adaptations.
- Key is, a lot of these animals don't have traits that are specifically different. Some small rodents are specifically vulnerable to heat loss, their adaptation is to remain in the snow.

Migration:

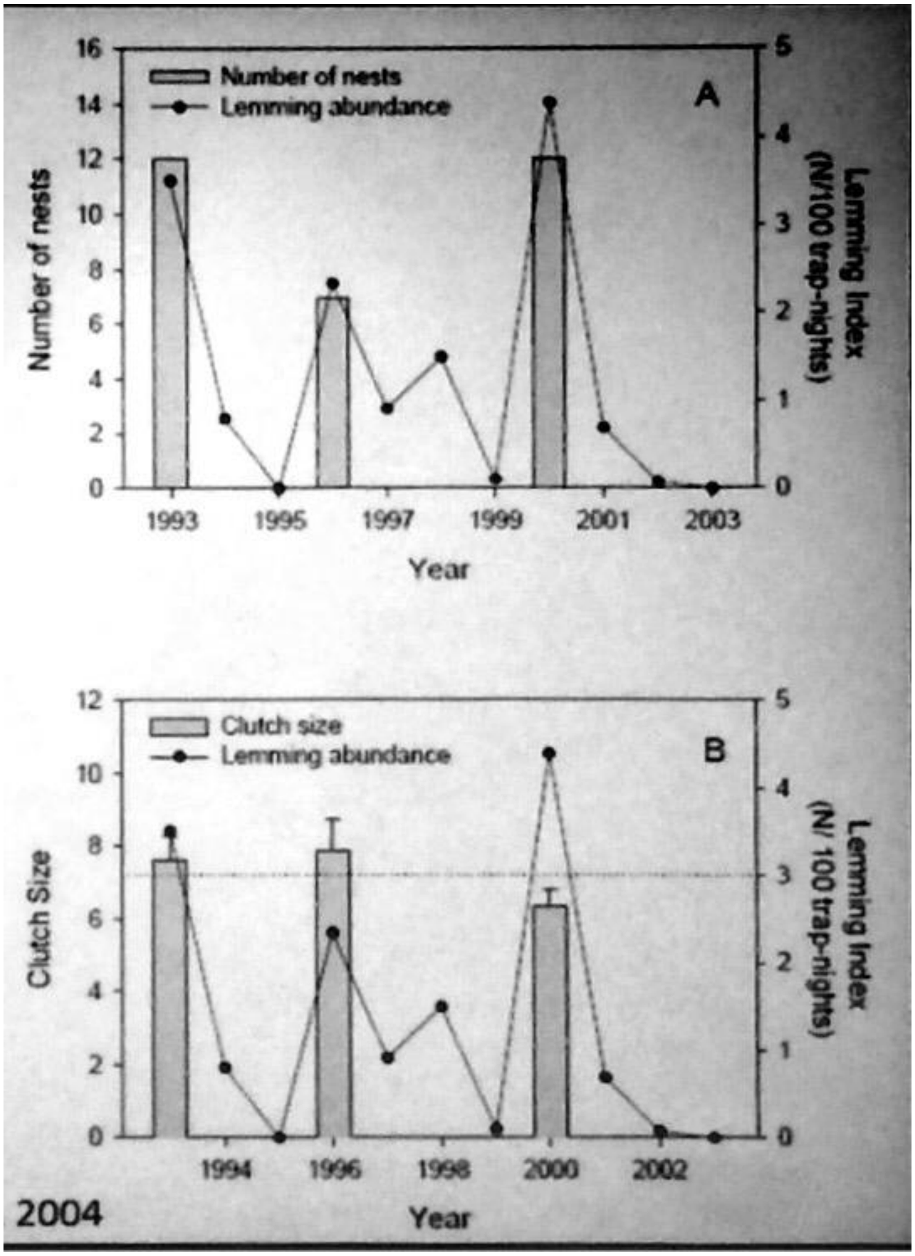
- Many species move seasonally to optimize available resources and to reduce exposure to extreme conditions
  - Move into the forest for shelter during winter, then out into the plains in summer, etc.
- Most Arctic mammals do not migrate with a predictable pattern, although many are highly nomadic and may travel long distances during the course of the year
- Others, like caribou, may have important migrations that are predictable

- Caribou move from breeding grounds, often in the protection of the northern boreal forest, to summer calving and feeding grounds in the tundra
- Most Arctic bird species migrate, in some cases, from distant winter habitat in the tropics and southern hemisphere
- These migrations expose them to additional pressures of competition for resources, predators, environmental stresses and overall energy consumption
- Relatively few Arctic bird species are year-round residents
- Notable exceptions include: snowy owl, ptarmigan and gyrafalcon

Adaptations to the biotic environment:

- For the most part, Arctic species are **generalists**
- Consistent with varied and limited resources of food
- Some **notable exceptions** to this pattern exist:
  - *Lemmings* are the primary food of *snowy owls* and *weasels*
  - Herbivores typically remain in areas with good grazing, but not exclusively

- Hence, most animals can be found in a wide range of habitat settings
- Many bird species have specific habitat preferences, particularly water birds like geese
- Some species show **adaptations** to changes in their habitat, particularly food resources
  - For example, arctic foxes litter sizes and body mass vary as the population of lemmings cyclically varies



  - Interactions between reproductive success of snowy owls and lemming populations.
  - Snowy owls are fairly common, but rare to see because their population is so widespread., so it's rare to see.

Population dynamics:

- Many animal species have *multi-year cycles* where populations wax and wane
- In the case of **predators**, this largely reflects the *availability of prey* and the predator cycles will lag those of the prey
- Small mammals like *lemmings* and *arctic hare* have cycles that tend to be well developed
- The cycles vary geographically, and are often out of phase over a region

  - **Lemmings**, for instance, have a well-defined population cycle of 2-5, which is characterized by an increase in population, reaching a peak and a “crash” in the subsequent year
  - When you are in a lemming peak, you can't not notice. They are literally everywhere, but in the crash you can go years without seeing one.
- The reasons for the cycles are poorly understood, but **climate variations** may represent one aspect.
- *Feedbacks* with *predator populations* may also play a role
- These species-specific cycles may impact other species due to diversion of predation
  - For instance, when **lemming** populations plummet, *predation* by **foxes** and **ermine** is directed towards **geese** and other **birds**
- Larger herbivores may undergo periodic or irregular population cycles driven by high winter mortality rates due to unusual weather conditions
  - For instance, late autumn freezing rain or deep snow may prevent caribou and muskoxen from accessing their food sources and cause widespread starvation
  - Depend on access to food year round, including through snowcover. One strategy is to paw through the snow to get to the grass.
  - This makes it very difficult to determine population size/dynamics sometimes, creating tensions with hunters and conservation experts.
- Documented cases have revealed up to 95% of the regional population may die in a winter with these circumstances

Microorganisms:

- A wide variety of bacteria, cyanobacteria, algae and fungi show remarkable tolerances to Arctic conditions
- Represent one of the foundations of the ecosystem in land and in the water
- Show remarkable resistance to arctic conditions. Some bacteria can remain unfrozen and productive in as low as -40 degrees celsius! (*antifreeze*)
- Window for microorganism community is much wider than you would think. There is no environment on the planet where microorganisms cannot survive.

- Many are able to withstand sub-zero temperatures without cellular damage, and some show evidence of productivity at temperatures as low as -40°C
- Others have *cellular mechanisms* to adapt to *physical* stresses such as **high solar irradiance, moisture extremes** and **mechanical disturbance**
  - For example, recent research has shown that microbial activity actually increases in locations of permafrost disturbance
- This suggests that microbial organisms are sensitive and adaptive to changing Arctic conditions and play an important role in the overall terrestrial ecosystem

8) Marine Ecosystems:

March-19-15
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Oceanography:

- The **marine system** is an integral part of the *Arctic environment*
- It represents most of the north polar region
- The pervasive sea ice cover affects **ocean**, **atmosphere** and **biological processes**
- Ice cover also affects **coastal processes**
- Conditions in the *Arctic Ocean* are exchanged with other ocean basins and affect the larger northern hemisphere climate
- There is a large potential store of **natural resources** under the *Arctic Ocean*
- The *Arctic Ocean* is of military and geopolitical significance

Physical oceanography:

- **Density:**
  - The primary measure of ocean properties.
  - Factors controlling density:
    - Temperature
    - Salinity
    - Depth
    - Suspended sediment concentration
- **Salinity** in the oceans is characterized by a near constant ratio of **chlorine** *(55%)*, **sodium** *(30.6%)*, **sulphate** *(7.7%)* **magnesium** *(3.7%)* and **potassium** *(1.1%)*.
- The *total dissolved concentration* of **salts** in the ocean averages about *35 g/kg*, and is typically indicated as *35%*
  - Normally, we refer to salinity as S and without units (e.g., S=35)
- Increased **salinity** results in *higher water **density***
- **Temperature** affects **density** as well, and increases in saline water as the freezing point is reached

- Water is also slightly compressible, so at depth (under great pressure), the density increases
- Finally, if there is substantial suspended sediment in the water, this can increase density as well
- In settings where sediment inflow is high, this effect may dominate (e.g., river mouths)

Geography:

- The Arctic Ocean is *relatively small and shallow*
- It is made up of the **Canadian**, **Eurasian basins**, and the **Greenland Sea**
- Additionally, there is an extensive and shallow **Eurasian shelf** that includes the **Barents Sea**

- Connections to other oceans are through **Fram** and **Bering Straits**, and to a lesser extent, through the channels of the **Canadian Archipelago**

- **Fresh water** inflow comes from the **Bering Strait** (*1500-2000 km3*)

- Additionally, the **Arctic Ocean** is unique in that it receives a large amount of river inflow (*c. 3500 km3*) each year
    - Most of this comes from the *Eurasian* landmass
- Evaporative losses from the *Arctic Ocean* are relatively low due to ice cover and limited energy inputs
- The result is that the *Arctic Ocean* is *relatively fresh* (S=30) compared to other marine settings

- Circulation of the *Arctic Ocean* is dominated by the persistent surface high pressure that generates the clockwise-flowing *Beaufort Gyre*
- Water from the **Bering** *Strait*, along with *freshwater* from **Eurasia** and **North America** combine and move at ***2-5 cm*** per second
    - This affects water in the uppermost 150-300 m in the ocean
- Most of this water crosses near the north pole and exits via *Fram Strait*, in what is referred to as the *Transpolar Drift*
- This exodus of cold, relatively fresh and ice-rich water becomes the **East Greenland current**

- The **Beaufort Gyre** also directs some flow towards northern **Greenland** and **Ellesmere Islands**, where it circulates *southward* towards the **Beaufort sea** or exits via the inter-island channels
- The **Canadian Arctic Archipelago** contains over 600 islands and several of the channels are subject to *outflow* from the *Arctic Ocean* towards **Baffin Bay** and **Hudson Bay**
- The most important outlets are **Nares Strait** and **Lancaster Sound** that are up to **250 m** deep at controlling sills
    - *Limited flow* through **Fury** and **Hecla Strait** allows *Arctic water* to flow into **Foxe Basin**, **Hudson Bay** and **Hudson Strait**

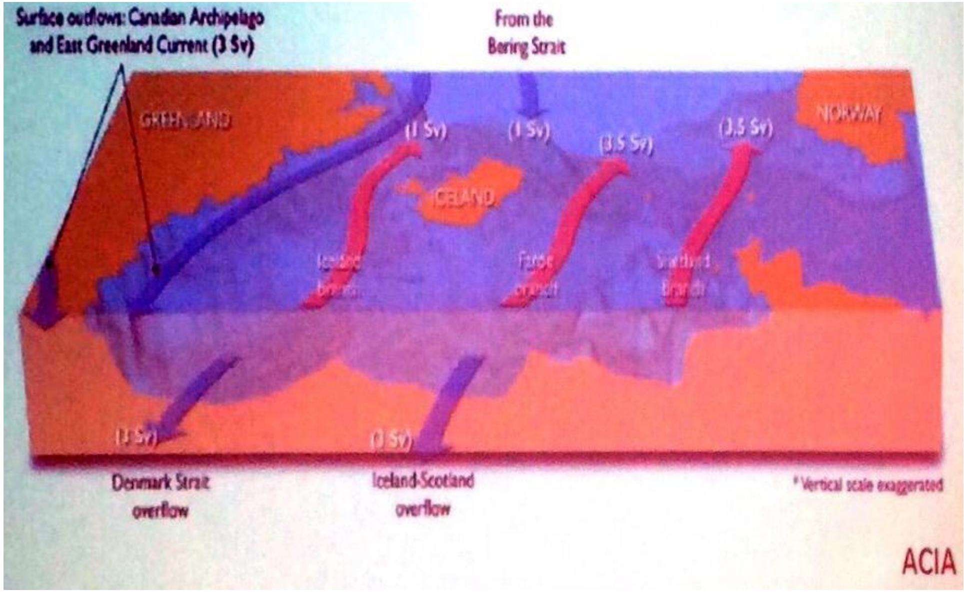
- **Baffin Bay** is linked with the circulation of the *North Atlantic* via ***West Greenland current*** and the cold ***Baffin*** and ***Labrador currents***

- The surface circulation of the *Arctic Ocean* controls the movement of water and ice
    - The ice pack is effectively following currents and is in near-constant motion

- The slow movement of the *Transpolar drift* results in ice crossing the **Arctic Basin** and exiting **Fram Strait** in 3-6 years
- Ice trapped in the **Beaufort Gyre** is recirculated and may thicken if it becomes shore-fast along **Ellesmere Island** and the northwestern islands

- Relatively warm, saline (S=35) *north Atlantic* water enters the Arctic between Iceland and Norway in the Norwegian Current
- This water is denser, and spreads at depth in the Arctic Ocean as intermediate water
- Below about 900 m depth, the Arctic Bottom water is cold and saline, and remains relatively separate from the intermediate water

- The exchange of flow between the Arctic and Atlantic oceans is a critical series of processes that result in deep circulation of the Arctic Ocean
- Warm, saline water entering the Arctic at depth cools and as it approaches the interior of the Arctic basin, is subject to brine rejection during sea ice formation
- This results in denser water that sinks and accumulates as Arctic Bottom water
- This water `spills` over controlling sills and returns to the Atlantic as deep water
- Represents a major ventilation of the deep Arctic and a major source of energy to the Arctic region
- This circulation is sensitive to the input of energy from the Atlantic, and the freshwater flux that forms the surface waters of the Arctic
- Reduced heat fluxes from the Atlantic may persist for 10+ years (as can the opposite situation)
- Similarly, increased freshwater flow from the continents can cap the Arctic Ocean, cool the surface, expand ice cover and reduce brine rejection and deep water ventilation



- Ice circulation can be affected by seasonal changes in the winds
- The main flow of the Transpolar drift can respond to longer term changes in circulation
- Causes changes in ice export through Fram Strait
- Can be affected by short term and long term fluctuations

- Longer term changes in circulation arise from persistent changes in atmospheric circulation that are linked to the AO and NAO
- These result in key changes in ice flow, seasonal ice cover and conditions in the surface layer of the Arctic Ocean
- Shift in climate changes persistence of winds, and wind directions
- Positive phase - enhanced outflow of ice from fram straight
- Negative - backflow in gyre?

Marine ecosystems:

- Marine ecosystems are important elements to the Arctic
- Widespread productivity, including considerable winter food web activity
- Important for global biogeochemical cycling, particularly carbon sequestration
- In polynyas and other oceanographic settings that have high resources, they represent hot spots of productivity
- Migrations of some Arctic species contribute to marine ecosystems elsewhere
- Inuit culture is based on harvesting marine animals
- Most communities are on the coast
- This traditional and contemporary land use represents a key sensitivity to ice cover and changes to climate Food web structure:
- Human populations have a much closer connection to marine ecosystem
- Marine productivity is usually radically higher than terrrestrial
  - Everything on land and aquatic pales in comparison
  - Much of the research refllects an interest in land and aquatic, but we should be looking at marine.
- Persistent open water areas are hotspots of marine activity, food sources are available year round, etc.
- Because a lot of arctic species migrate widely, we have great interest in what is going on in terms of their dynamics.
- Polar bear: marine animal! Fisheries and seabirds are also marine
- Food web structure: primary resources, nutrients, not worried about presence of water like we were in aquatic and terestrial ecosystems. In particular, primary productiity which feeds a food web in terms of biomass in respective trophic levels, or in carbon sequestered.

- Unlike the terrestrial ecosystem, the majority of biomass in the marine system is animal
- Most marine systems are composed of trophic levels that include primary producers, and several levels of animal feeders
- Production at lower levels is only partially transferred into the biomass of higher levels
  - Respiration and sedimentation result in about 75-80% losses to the biomass between levels
  - Lost either as waste or sediment
- In the marine environment, there may be distinctive pelagic and benthic communities
  - Represent contrasting environments, both of which can be very productive depending on circumstances
- The latter depend on sedimentation from shallower levels
- Together, bacteria and phytoplankton constitute the bulk of the biomass in the ecosytem
- As we work our way up to various grazers, productivity at each individual level declines, and biomass varies quite a bit.
- Whales, seals, birds, bears are very small in terms of biomass contribution and productivity of the ecosystem, but they are a critical indicator of the health of the system
  - Norway, japan are the only countries that routinely take part in whaling

Limitations on production:

- To some extent, water temperature represents a limitation on the overall productivity
- However, even at low temperatures (near 0°C), most phytoplankton are able to bloom and photosynthesize
- Rare to see temperatures higher than 2 degrees in the artcic, so we're not very interested in temperature, as opposed ot other resources like nutrients and light.
- More critically, light and nutrient supply represent important limitations to productivity
- Pervasive sea ice cover reduces light in the upper photic zone of the water column
- Similarly, nutrient supply (N, P, micronutrients like Fe, organic matter) may be a substantial limitation to primary productivity
    - Critical at the bottom of the food chain, not the top

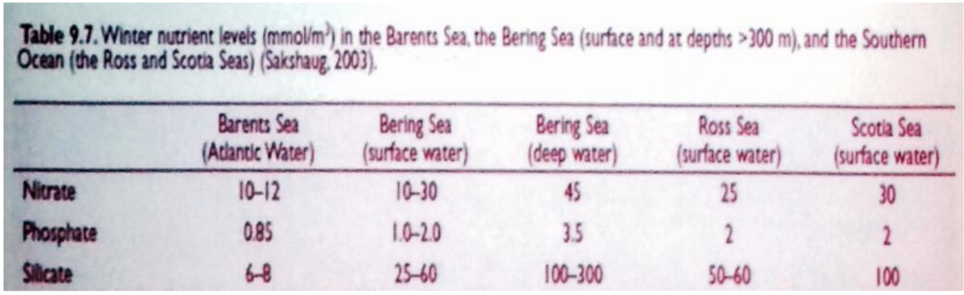


Table 9.7. Winter nutrient levels (mmol/m^3) in the Barents Sea, the Bering Sea (surface and at depths >300 m), and the Southern Ocean (the Ross and Scotia Seas) (Sakshaug, 2003).

	Barents Sea (Atlantic Water)	Bering Sea (surface water)	Bering Sea (deep water)	Ross Sea (surface water)	Scotia Sea (surface water)
Nitrate	10–12	10–30	45	25	30
Phosphate	0.85	1.0–2.0	3.5	2	2
Silicate	6–8	25–60	100–300	50–60	100

- Areas where deeper, “older” water upwell and mix with surface waters tend to have higher nitrogen and phosphorus levels
- Encourages high productivity in these areas, notably the Barents, Chukchi and Bering Seas and polynyas
- In ice covered areas, the reduction and loss of ice results in a phytoplankton bloom in spring that follows the ice edge
- The timing of the bloom is further constrained by solar insolation, and if sufficient light is not available, this will delay the bloom
- Stratification of the water column will result in nutrient depletion during the bloom, which will result in cessation of the bloom
- Nutrients are brought to the surface, where there is radiation energy available, leading to the blooms.
- The timing of the life cycles for zooplankton and fish relative to the phytoplankton blooms dictate the extent to which the latter is consumed or sediments to deeper levels
- The degree of “match” is important and represents a key oceanographic constraint on transfers of energy from the lower to higher trophic levels
- Water temperature plays a critical role in the life cycle of fish and zooplankton, and can drive the food web in terms of limiting consumption of primary producers and reproductive success of higher species
- Timing of their lifecycle becomes imprtant

- If we have a scenario where ice comes off earlier and phytoplankton bloom earlier, but zooplankton don't, this leads to a detatchment and a mismatch between these two groups, and the energy of the food web is dimished
- If ice off is early or late, it affects the organization of different classes
- If resources and use are not synchronized, energy is wasted.

Phytoplankton and algae:

- Very small, primary producers
- Plankton of various sizes constitute the primary producers in the marine ecosystem
- Most production is by diatoms, a siliceous-shelled algae represented by over 150 species
- Other producers include dinoflagellates, cyanobacteria, and nanoplankton
  - Extrordinarly numerous acrosss the planet
  - Tend to be focused in the uppermost photic zone
- Plankton are found in a wide variety of settings and in the water column throughout the Arctic basin
- They represent a key source of lipids and protein (up to 50% by mass) that is critical for higher trophic levels
- Plankton are known to occur as isolated individuals, or joined together as extensive blooms
  - Can join together and behave as a mat

Micro-heterotrophs:

- Non-photosynthetic microorganisms that are found in high concentrations in the marine environment
- They are poorly understood in terms of their role in the marine food web
- Some, like phages, are viruses that likely modify populations of algae and bacteria
- Others may graze bacterial
- These organisms are consumed by a number of zooplankton
- May represent a key pathway linking bacterial and higher food webs
- Play very important role in moderating other levels of the food web
- Can be consumed by larger organizms

Zooplankton:

- These intermediate sized organisms represent up to 50% of the marine pelagic biomass
- They are a key link in the food web between primary producers and higher trophic levels
- Due to their life cycle habits, they store a large amount of lipids for overwintering
- Important source of food for some fish species
- The main groups include copepods, krill and amphipods
- Copepods may represent 70-90% of the zooplankton biomass
- During the spring and summer, they are found in surface waters where they graze on primary producers
- In winter, copepods in particular, they often descend to depths of several hundred metres
  - To a much more cooperative environment

- Consumers: intermediate, most important part of the system. Key link between primary producers and larger organizms
    - Importance speas to that trophic level
- Can survive on lipids over winter when food is scarce
-

Benthic fauna:

- Benthos may be highly productive in Arctic waters, particularly below areas of high surface productivity like polynyas
- Other areas of high productivity like mixing zones (temperate and Arctic) support rich benthos
- Unlike aquatic systems, benthic fauna are not limited to shallows. In the ocean, you can find them very deep
    - This is because surface areas deliver energy in the form of organic sediment falling to the bottom
- Shallow littoral substrates may be too variable in terms of environmental conditions to support a diversity of organisms, compared to deeper, more stable conditions
    - Shoreline areas, often active in wave action, dynamic conditions, may see water stress, tides, etc. Leads to considerable diversity of organisms when compared to deeper conditions
- High surface productivity results in reliable sedimentation of organic material to the deep ocean to support benthic food webs
- These deep food webs are important for many bottom-feeding mammals, fish and sea birds
    - Large mammals on the surface will dive to benthic communities to feed
- Typical benthic organisms include bivalves, barnacles, nematodes, gastropods and amphipods
- Crustaceans include prawns, crabs, (including king, red and snow crab), scallops and several mollusks

Fish:

- A large number of fish species are found in Arctic waters, up to 150
- Few are endemic and can be found elsewhere in boreal and temperate waters as well
- All depend on lower trophic levels and associated productivity, and hence tend to be found in regions of higher primary productivity
- As a result, seasonal migration is common and result in generally well know winter and summer areas

Capelin:

- Capelin are small pelagic fish that feed from plankton, copepods, krill and amphipods
- They are found in cooler waters, and are particularly abundant in the north Atlantic and Bering Sea

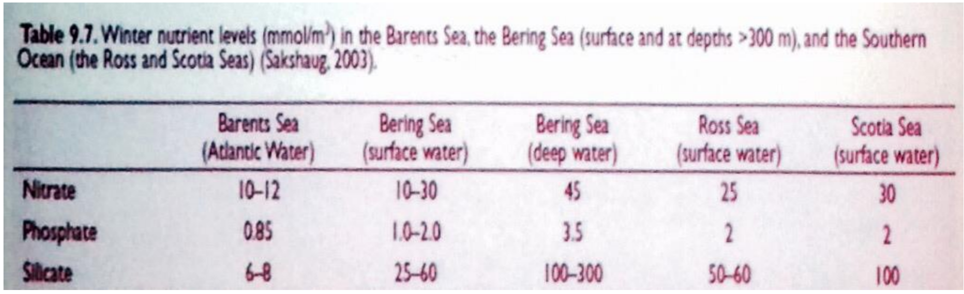
- Populations of capelin are highly variable and this impacts their distribution and abundance considerably
- They are a primary prey fish for sea birds and larger fish like cod
- Fluctuations in capelin thus affect productivity of these higher consumers

Cod:

- Polar cod are a crucial part of the Arctic foodweb
- They feed primarily on plankton while larger individuals may feed on fish
- They are widespread across the circum-Arctic and are important prey for larger fish and mammals
- Pacific and Atlantic cod are important in the north Atlantic and Pacific oceans
- They are mixed feeders of smaller fish, invertebrates and shellfish
- Cod spawning in the Norwegian Sea has historically supported large populations, some of which have or were commercially significant
- Notably, cod populations near Newfoundland collapsed in the 1990s due to overfishing, and other populations have undergone similar stresses

Marine mammals:

- Mammals are the top predators in the marine ecosystem
- There are a wide range of forms and they are all characterized by high mobility and colonizers
- They have undergone substantial hunting pressures by humans, particularly whale and walrus
- Some notable species were nearly driven to extinction (bowhead whale)



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Polar bear:

- Polar bears are the top of the marine food web
- Their habitat is primarily on sea ice, but they can revert to land as necessary
- They are excellent swimmers and have been known to cover distances up to 100 km
- Their primary food source are seals hunted from the ice
- Availability of hunting drives polar bear movements and success
- Female bears den for 5-7 months and typically have two cubs
- The emergent bears critically depend on hunting success for survival
- The cubs remain with the mother for approximately two years

Walrus:

- Walruses are large mammals that are found throughout the Arctic, but the largest populations are in the Bering Sea region
- They maintain breathing holes in ice during winter, and haul out to rest on the ice at all times of the year
- Their ecological niche is relatively narrow, based primarily on relatively shallow water and the availability of mollusks and other bivalves
- Most common in the bering sea
- Active year round, must maintain a breathing hole so they can breathe under the ice
  - Will maintain multiple holes through winter, in the rest of the year they will haul out onto the ice
- Even polar bears think twice before attacking a walrus
- Very narrow ecological niche - molluscs, bivalves
  - Root around in the sediment, bring prey to the surface and crack the shells
- Only found where there is rich benthic fauna
- Very rare to see them anywhere that productivity is low

Seals:

- There are three primary seal species in the Arctic: ringed, bearded, and harbour
- Ringed seals are the most common, and are found across the entire region
- They maintain winter breathing holes and carry out all resting and rearing activities on the ice
- Bearded and Harbour seals are found in a wide range of conditions, but are not as well suited to continuous activity near pervasive ice
- Seals are either benthic or opportunistic feeders, depending on fish, crustaceans and bivalves
- Seals are a keuy predator within the broad marine ecosyste,m high biomass, found throughout the arctic. Walrus are active year round, but have to maintain breathing holes. This leaves them vulnerable to freeze-over. It is not uncommon that the ice holes will freeze over and they will asphixiate, or freeze on the surface if they are out of the water at the time.
- Most seals are benthic feeders, but will feed on fish as well

Whales:

- Bowhead and white whales and narwhal are found in the High Arctic
- They are associated with the ice edge, leads, and polynyas and they migrate to follow changing ice conditions
- They feed on planktonic crustaceans, small fish and cephalopods
- Other whale species are observed, but their presence is seasonal or irregular
- Narwhal has a unicorn tooth, hunted for meat and ivory from the tooth.

Seabirds:

- Arctic seabird populations are amongst the largest in the world
- There are over 60 seabird species in the Arctic, and over 40 species breed in the region
- Some migrate from the southern hemisphere, while others stay in proximity to the ice edge and open water

- They tend to nest in large colonies, the largest of which comprise millions of birds
- Favoured locations vary by species, but include sea cliffs and isolated rocky islands
- Seabirds feed mostly on polar cod and large copepods
- Eiders feed in shallow waters, or even from the surface
- Other species may feed at depths of hundreds of metres
- They can remain underwater for long periods of time and travel long distances underwater
- Often mistaken for terrestrial, but because they feed on fish, they are marine animals.