Chapter 1 - Review Questions

(1) List five key components of the cryosphere.

Snow cover, glaciers, ice sheets and shelves, freshwater ice, sea ice, icebergs, permafrost and ground ice.

(2) Seasonally which component of the cryosphere undergoes the largest change, and the difference of the component (in ratio) between winter and summer?

Snow cover area in Northern Hemisphere varies typically from about 46.5 million km^2 in late January to less than 4 million km^2 in late August.

(3) Explain how the cryosphere is an integral part of the global climate system in terms of the five major influence it exerts on the climate system.

The cryosphere is an integral part of the global climate system in terms of the five major influences it exerts on the climate system: (1) linkages and feedbacks with the atmosphere and hydrosphere that are generated through its effects on surface energy partly because of the high reflectivity (albedo) of ice- and snow-covered surfaces with the ice - albedo effect amplifies climate sensitivity by ≈ 25-40%, (2) by the insulation of the land surface by snow cover and of the ocean (as well as lakes and rivers) by floating ice, which greatly modifies the temperature regime in the underlying land or water, (3) on moisture fluxes by releasing large amounts of fresh water when snow or ice melts (which affects thermohaline oceanic circulations), and by locking up fresh water when they freeze, (4) by the latent heat involved in phase changes of ice/water, and (5) by seasonally frozen ground and permafrost modulating water and energy fluxes, and the exchange of carbon, especially methane, between the land and the atmosphere.

(4) Globally what are the greatest potential source of freshwater, in terms of the estimated volume in km^3, and in terms of the global sea level equivalent in m?

The Antarctic ice sheet of volume ≈ 24.7 million km^3, which is equivalent to 57 m of the global sea level.

(5) How has the cryosphere been undergoing rapid changes during the 20th and the early 21st Century or what are key indicators of cryospheric change?

Since the mid- 20th and the early 21st century, the earth is undergoing potentially rapid changes in all cryospheric components, including Arctic Sea ice shrinkage, mountain glacier recession, thawing permafrost, diminishing snow cover, and accelerated melting of the Greenland ice sheet. This has significant implications for global climate, hydrology, water resources, and global sea level.

(6) What in your opinion is one of the most striking manifestations of climate warming in recent decades?

The recent significant changes observed in all cryospheric components, especially the Arctic perennial sea ice that has been decreasing in the summer at a rate of about 7.4 [5.0 to 9.8] % per decade since satellite images of the Arctic Sea ice become available from the DMSP Special Sensor Microwave Imager (SSMI) and SMMR of NASA since 1979.

(7) Explain possible implications to the future global cryosphere under the potential impact of climate change, and how will cryospheric changes impact the global climate system?

Most mountain glaciers will continue to diminish because of increased glacier melting, seasonal snow cover duration will continue to decrease except in high latitude regions such as the Arctic, and earlier onset of spring snowmelt have contributed to seasonal changes in streamflow in high latitudes areas. Runoff from small glaciers will typically decrease through mass loss, while runoff from large glaciers will likely increase until glacier mass becomes depleted. Arctic sea ice will continue to decrease, and the sea ice age will also become younger, with lesser multiple-year old sea ice and more sea ice that are less than two years old.

Sea level rise currently rising at about 3mm/year will likely accelerate, resulting in more coastal erosions. When the Arctic Sea ice (ASI) melts, ice that reflects away most incoming solar energy is replaced by ocean water that absorbs most solar energy, which enhances further warming. The diminishing ASI could affect the global heat distribution, oceanic circulations, storm tracks in the NH, the North Atlantic Oscillation (NAO), leading to more frequent weather extremes in northern mid-latitudes, severe winters, northward shift of the jet stream, and planetary waves. Distinct circulation responses to significant losses in sea ice and/or snow cover has been detected. ASI is affected by the Arctic Oscillation, NAO, Pacific-North America Pattern, and El Niño Southern Oscillation.

Chapter 2 - Review Questions

Snow Fall and Snow Cover

(1) Name three atmospheric conditions necessary for the process of snow crystals forming in the atmosphere to the occurrence of snowfall on land.

(a) Creation of saturation conditions necessary for the formation of water droplets or ice particles to occur mainly through convection or updraft, cyclonic cooling induced by circulation, frontal or non-frontal lifting of warm air, or orographic cooling by mountain barriers; (b) Snow crystals form primarily through heterogeneous nucleation. Under extremely low temperatures (below -40^{o}C), ice particles can also be formed through homogeneous nucleation; (c) Whenever snow crystals grow to a size when gravitational pull exceeds the buoyancy effect of air, snowfall occurs.

(3) List out five types of snowflakes under different combinations of temperature and super-saturation conditions with respect of ice. Do you believe that no two snowflakes are exactly alike?

Formation of snowflake types depend on combinations of temperature and saturation vapor pressure over ice, resulting in a wide range of snowflakes, such as pellets, dendritic plates, sector plates, needles, prisms. Personally, I don't really know if it is true that no two flakes are exactly alike.

(5) As one of two major hydrologic influences of wind transport of snow, blowing snow and sublimation, show that the amount of energy (latent heat) required for snow to sublimate is about 8.5 times that for snow to melt.

Snow sublimation involves both the latent heat of fusion l_{fs} ≈ 333 KJ/Kg (ice to water) and latent heat of vaporization (water to vapor), l_v ≈ 2501 KJ/kg while snowmelt only involves the latent heat of fusion of 333 KJ/Kg. Therefore, the amount of energy required for snow sublimation is about (333+2501)/333 ≈ 2834/333 ≈ 8.5 times that for snow to melt.

(7) Estimate the maximum snow load of the canopy of pine trees in kg m^{-2}, if the tree species coefficient S_p for pine is 6.6, the LAI of pine is 2, and the density of snow is 100 kg m^{-3}. What will likely happen to snow intercepted by canopy?

Snow intercepted by Canopy

Maximum snow load I* $= S_p LAI\left(0.27 + \frac{46}{\rho_s^f}\right) = 6.6x2\left(0.27 + \frac{46}{100}\right) = 9.64 \approx 10\ kg/m^2$

Snow intercepted by canopy is more likely to sublimate because wind tends to be stronger at the canopy level than on the ground.

(9) What are the advantages of remotely sensed snowpack data over *in situ* ground measurements of snowpacks? Briefly describe the properties of optical sensors of NOAA-AVHRR and MODIS satellites to estimate the spatial distribution of snow cover extent (SCE), and passive microwave sensors of SMMR, SSM/I and AMSR-E to estimate snow water equivalent (SWE) data at regional to continental scales? What are the limitations or possible errors of snowpack information retrieved from satellite data?

Remotely sensed snowpack data acquired from optical sensors such as NOAA-AVHRR and MODIS satellites provide frequent spatial distribution of snow cover extent (SCE) while in situ ground measurements of snowpacks are point measurements limited in space and in times because of the high cost of field work and a lack of manpower. In recent years, through new satellite sensors and imaging spectrometers, we have made progress in the interpretation of snow optical properties such as spectral and broadband albedo, fractional snow-covered area, grain size, liquid water content in the near-surface layer, and concentration of snow algae. The resolutions of optical sensors range from about 10-30 m per pixel (French SPOT, Landsat-TM) to about 1 km per pixel (NOAA-AVHRR). SWE estimated from the brightness temperature (T_D) data acquired by passive microwave sensors are of coarse resolutions ranging from about 10 km (AMSR-E) to 25 km per pixel and are subjected to uncertainties associated with the effects of vegetation cover on T_D data and the interpretation of such data.

(11) Estimate the daily snowmelt in mm per day of a snowpack located in a boreal forest environment of North America using the degree-day method, if the mean daily temperature T_a is 7 °C, the threshold temperature T_{thm} is 3.5 °C, and the recommended melt factor m_f is 1.83 mm per °C per day (Equation 2.22)?

M = 1.83(T_m – 3.5) = 6.4 mm/day = 0.64 cm/day of SWE

(12) For a homogeneous, 60-cm-deep (D) snowpack with a density ρ_p = 250 kg cm^{-3} that is in thermal equilibrium at a uniform temperature T_p of −5 °C, and the snowpack surface temperature $T_s = T_p$. What is the cold content (Q_{cc}) of a snowpack in J m^{-2} (Equation 2.37)? Note that C_s, the specific heat of snowpack, is 2,093 J kg^{-1}°C^{-1}.

Cold content of snowpack $\boldsymbol{Q_{cc} = -\rho_p C_s D T_p}$

(13) Suppose the incoming solar radiation is 218 W m^{-2} while the surface albedo of the 60-cm-deep snowpack α_{sn} is 0.75, the fractional snow cover area A_{sn} is 0.8 (Equation 2.28), and the ground albedo α_g is 0.20, air temperature T_a is 8 °C, relative humidity of air is 50%, and wind velocity (U) is 9 km hr^{-1}. Rain, assuming with a temperature the same as T_a, falls on the snowpack at a constant rate of 1 cm hr^{-1}. Ignore the cloud cover effect and assume an atmospheric emissivity of 0.76, compute the advective heat (Q_v) of the rainfall event (Equation 2.36) occurring over the snowpack, and the time to overcome the Q_{cc} before melting begins? Note that melting begins as soon as Q_{cc} is overcome.

Advective heat of rain $\mathbf{Q_v = C_s\rho_w RT}$=4186 Jkg^{-1}°C^{-1} x1000 kgm^{-3}x1 cm/hrx1/(100 x 3600) x 8°C=93.02 Wm^{-2}

Average albedo $\boldsymbol{\alpha_{avg} = \alpha_{sn} \times A_{sn} + \alpha_g \times (1 - A_{sn})}$ = 0.75 x 0.8 + 0.2 x 0.2 = 0.64 (2.29)

Net radiation $\boldsymbol{Q_n = Q_{sn} + Q_{ln}}$ (2.28)
Assuming the snowpack temperature T_s is also -5°C.
$Q_n = (1 - \alpha_{avg})R_s + \varepsilon\sigma(T_a^4 - T_s^4)$ = (1-0.64)x218 + 0.76x5.67 x 10^{-8}W/m^{2-}°C^{-4}[(8+273)^4 – (-5+273)^4]
= 78.48 + 0.76 x 46.374 = 113.72 Wm^{-2}

Assuming the bulk transfer coefficients for sensible heat transfer, D_h = 2 J/m^3/°C, and for latent heat transfer, D_e = 0.1 J/m^3/Pa.

Sensible heat flux $\boldsymbol{Q_h = D_h U(T_a - T_s)}$ = 2 J/m^3/°C x 9 km/hr x (1000/3600) x[8 – (-5)] = 65 Wm^{-2} (2.32)
$e_s = 611xexp\left(\frac{17.27T}{237.3+T}\right) = 611exp\left(\frac{17.27x-5}{237.3-5}\right)$= 421.31 Pa, $e_a = 0.5x611exp\left(\frac{17.27x8}{237.3+8}\right) = 536.56Pa$

Latent heat flux $Q_e = D_e U(e_a - e_s)$= 0.1 J/m^3/Pa x 9 km/hr(1000/3600)[0.5 x 1073.12- 421.31]=28.813 Wm^{-2} (2.6)
$\boldsymbol{Q_o = Q_n \pm Q_h \pm Q_e + Q_v - Q_y + Q_f - Q_{cc}}$ (2.27)

$Q_o = Q_n + Q_h + Q_e + Q_v$ = 113.72 + 65 + 28.813 + 93.02 = 300.55 Wm^{-2}

Time needed to overcome the cold content Q_{cc} = 1,569,750 J m^{-2}/ 300.55 Wm^{-2} x 1/3600 hr/sec = 1.45 hours
Assume the energy available remains unchanged.

(15) Estimate the time to melt the snowpack completely **after** overcoming Q_{cc}, assuming the energy available for melting, Q_o (Equation 2.27) remains unchanged throughout the period of melting. Only consider Q_n, Q_h, and Q_e in computing Q_o (ignore Q_g and Q_v, rain has stopped) (Equations 2.30–2.35 and Equation 2.39). Note that after overcoming Q_{cc}, the snowpack temperature T_s will be 0 °C, not −5 °C. P_a is the atmospheric pressure (≈1,013 mb). The bulk transfer coefficients for sensible heat transfer, D_h = 2 J m^{-3} °C^{-1}, and for latent heat transfer, D_e = 0.1 J m^{-3} Pa^{-1}.

After overcoming Q_{cc}, T_p =0°C
Sensible heat flux $Q_h = D_hU(T_a - T_s)$ = 2 J/m^3/°C x 9 km/hr(1000/3600) x[8 – 0] = 40 Wm^{-2}

Latent heat flux $Q_e = D_eU(e_a - e_s)$ = 0.1 J/m^3/Pa x 9 km/hr(1000/3600)[0.5 x 1073.12- 611]=-18.61 Wm^{-2}

$Q_n = (1-\alpha_{avg})Rs+\varepsilon\sigma(T_a^4-T_s^4)=(1-0.64)x218 + 0.76x5.67 \times 10^{-8} W/m^{2-o}C^{-4}[(8+273)^4 - (0+273)^4]=107.794$ Wm^{-2}

Assuming rain has stopped, $Q_v = 0$

$Q_o = Q_n + Q_h + Q_e$ = 107.794 + 40 -18.61 = 129.184 Wm^{-2}

Melt rate $M=\frac{(Q_o\Delta t-Q_{cc})}{\rho_w l_{fs}\theta}=\frac{\frac{129.184 J/\sec m^{-2}\, x\, 86400 sec}{day} x100cm/m}{\frac{\frac{1000kg}{m3}x333000J}{Kg}x0.98} = 3.42 cm/day$ of SWE (2.39)

Time to melt the snowpack = 60 cm x 250/1000/3.42 = 4.386 days ≈ 4 days 9.3 hrs
This is an under-estimation because the energy available to melt the snowpack is assumed to remain unchanged which is not a realistic assumption.

Avalanches

(1) Define an avalanche. What natural factors and/or human activities that usually triggers an avalanche, and the range in size of an avalanche in terms of mass, path length, impact pressure, and slap depth (see Table 2.5)?

An avalanche involves the rapid flow of a mass of snow down a slope, triggered by either natural processes or human activity. The range in size of an avalanche in terms of mass, path length, impact pressure, and slap depth are <10 to 100,000 tonne, 10-3000m, 1-1000 kPa, and 0.15 to 3.5m, respectively.

(3) Name three common elements of avalanches, such as a trigger, and morphological characteristics used to classify avalanches, such as type of snow? Does the density of snow play a part in the failure of a snow layer on slopes of mountains?

Common elements of an avalanche: a trigger that initiates the avalanche, a starting zone from where the slide originates, a slide path along which the avalanche flows, a run-out zone where the avalanche comes to rest, and a debris deposit which is the accumulated mass of avalanched snow and associated debris once it has come to rest. The density of snow plays a part in the failure of a snow layer on slopes of mountains, e.g., loose snow avalanches occur in freshly fallen snow with low density.

(5) How does wind load, snow drift, formation of depth hoar under strong temperature gradients in snowpack, amount of snowfall in a few days, lee north- versus east-facing slopes, wet versus dry snow affect the bulk strength and overall stability of snow slabs, and the occurrence of avalanches?

External stresses include snowfall or rainfall, wind loading, and other factors listed in the question. The effect of a rise in temperature on snow stability is complex. There are immediate decreases in stability due to decreased hardness and increased toughness of the slab, on the one hand, and a delayed increase in stability due to an increase in bond formation and a temperature gradient decrease in the snow that leads to increased strength, on the other. Wind transport of snow generates differential loading on slopes. Top loading occurs when wind deposits snow perpendicular to the fall-line on a slope while cross loading occurs when wind deposits snow parallel to the fall-line. The proximate cause of most dry slab avalanches is overloading while that of most wet snow avalanches is internal changes in snow properties.

(7) Under climate change impact, would we expect increasing or decreasing trends in avalanche conditions across northern Europe and North America?

The frequency of destructive avalanches in the Swiss Alps for 1947–1993 show no evidence of trends, although at Davos their frequency declined over this period (Schneebeli et al. (1997). For the French Alps, Eckert et al. (2010) found that while the runout distance had not changed over 60 years, the runout altitude had decreased from ~1,400 m in 1948 to 1,350 m in 1977, and then recovered by 2006. Teich et al. (2012) found the number of potential forest avalanche days decreased at 11 of 14 snow and weather stations in the Swiss Alps for Type 1 avalanches and at 12 of 14 stations for Type 2 avalanches due to a decrease of snow and weather conditions associated with avalanche releases in forests under climate change impact. For the entire 1946–2005 data set near the southern Glacier National Park, Montana, USA, Sawyer and Butler (2006) showed a marked decrease in reported avalanches from the 1960s onward, compared with 1949–1957.

Chapter 3 - Review Questions

(1) What are two key characteristics commonly used to classify glaciers?

Morphology and temperature characteristics.

(3) In high mountains, what are the typical elevations where Tropical glaciers are located, such as in Mount Kenya? Conversely, approximately how does the mean equilibrium line altitude (ELA) of glaciers rise with a decrease in latitude, or increase in m per degree in latitude? For example, ELA rises from 2,800 m in the Altai Mountain (49° N) to 6,000 m on the north slope of Mt. Everest (28° N).

The typical altitudes where Tropical or Equatorial glaciers are located are above 4,000 m. The ELA rises about 152 m per degree of latitude. On the south slopes of the central Himalaya the ELA drops to ~ 5,400 m as a result of the monsoon precipitation. The aridity of the Tibetan Plateau and the summer heat source causes the ELA to be highest in the west of the plateau where it is around 5,800–6,000 m.

(5) As glaciers worldwide are losing mass under the impact of climate warming, should the present global average accumulation area ratio (AAR) be larger or smaller than 0.5?

The present global average AAR should be smaller than 0.5.

(7) What are popularly used satellite images to map glaciers, and problems associated with automated mapping of glaciers from space such as shown in Figure 3.4?

Space platforms to map glaciers are optical, microwave and altimetry sensors such as Landsat, ASTER, Sentinel 1/2/3, SRTM, ALOS PALSAR, TerraSAR-X, ICESat, and CryoSat-2. Figure 3.4 (c) shows that proglacial lakes in northern Sikkim/China for the 2001 ASTER image could be misclassified as glaciers,

(9) Suppose the mean annual air temperature (T_A) of the Aletsch Glacier of Valais, Switzerland is about 3 °C, and its mean winter (NDJF) temperature (T_W) is −2 °C. First compute its the accumulative positive degree-days, $\sum \Delta T$, using Equation 3.18, assuming $\left(\sum \Delta T\right)\Delta t = 365T_A + 120T_W$. Then using the degree-day method, compute its average melt loss in m^3 per year, if its average degree-day factor (DDF) is 4.5 mm d^{-1} K^{-1}, and glacier melting occurs mainly between spring, summer and early autumn (March to October). Also, assume that on the average only 25% of the glacier (120 km^2 of ice area, 23.6 km long, 1.6 km width, and 1 km thick), undergoes ablation; and the accumulation is mainly due to an average winter precipitation of about 600 mm over the whole glacier. Compare the mass loss you computed with the observed glacier retreat in the last 30 years, estimated at about 27 m yr^{-1}. Based on the discrepancy between your estimate of net glacier mass loss (total ablation volume − accumulation) and the glacier retreat observed, estimate the amount of glacier thinning in m per year.

Temperature index method $\sum M = DDF \sum \Delta T \Delta t$ (3.18)

Where $\sum M$ is the estimated total melt over time interval Δt, *DDF* is the degree-day factor in mm day^{-1}°C, $\sum \Delta$T is the accumulated positive degree day or the summed values of the departure of the daily mean temperature above (below) a base value such as 0°C.

$\left(\sum \Delta T\right)\Delta t = 365T_A + 120T_W$ = 365 x 3 + 120 x -2 = 855 degree-day

Suppose DDF = 4.5 mm day^{-1}°C

Total Melt $\sum M$ = $DDF \sum \Delta T \Delta t$ = *4.5* mm day^{-1}°C x 855 degree-day = 3847.5 mm/year = 3.85 m/yr

Assuming 25% of Aletsch glacier undergoes ablation, mass loss ≈ 120 x 10^6 x 0.25 x 3.85 =1.155 x 10^8 m^3/yr

The Glacier mass loss due to a retreat of about 27 m/year

= 1.6 km x 1000 m/km x 1km x 1000 m/km x 27 m/yr = 0.432 x 10^8 m^3/yr

Winter precipitation of 600mm over the glacier = 0.6m/year x 120 x 10^6 m^3 = 0.72 x 10^8 m^3/yr
Net glacier mass loss due to glacier melting in Spring, Summer and Autumn
= (1.155 – 0.72) x 10^8 m^3/yr = 0.435 x 10^8 m^3/yr
The amount of glacier mass loss due to thinning ≈ (0.435 – 0.43) x 10^8 m^3/yr = 0.5 x 10^6 m^3/yr

(11) What are typical ranges of ice flow rates of moving glaciers in km per year? Explain the characteristics of surging glaciers (glaciers on the run), and what could have contributed to the sudden acceleration observed in some surging glaciers? For example, the Wahlenbergbreen glacier in Svalbard of Norway that began speeding up in September 2013. At the peak of the surge, beginning in 2015, the ice advanced at 9 m per day, bulldozing everything in its path.

Ice flow rates during the active phase may range from about 150 m a^{-1} to >6 km a^{-1}, and horizontal displacements may range from <1 to >11 km (Meier and Post, 1969). The sudden acceleration observed in some surging glaciers such as the Wahlenbergbreen glacier in Svalbard, Norway has been attributed to increased basal melt water.

Chapter 4 - Review Questions

(1) What is the definition of an ice sheet, and how many ice sheets are there on earth after the Pleistocene glaciations?

Arbitrarily, an ice sheet is defined as glacier ice extending over 50,000 km^2 in area. After the Pleistocene glaciation, two remaining continental ice sheets are the Greenland and the Antarctica.

(3) What information about the paleoclimate record can we obtain from ice core data recovered from the Greenland and Antarctic ice sheets, and what is the longest climate record recovered from the European Project for Ice Coring in Antarctica (EPCIA)?

Retrieval of CO_2, CH_4 and $\delta^{18}O$ isotopes concentrations dated back to the past hundreds of thousands of years from layers of ice cores recovered from both ice sheets. EPICA (European Project Ice Coring in Antarctica) core goes back to 720,000 years (8 glacial cycles).

(5) Explain the possible key factors contributed to the surface mass loss and melting for Greenland in 2019 such as clear sunny weather related to high pressure conditions, ice–albedo feedback, low snowfall, or warm summer conditions. What is the average surface mass loss of the Greenland ice sheet in Gt of ice per year in recent years?

Key climatic factors for surface mass melting for GIS in 2019 are persistent anticyclonic summer conditions (high geopotential height), resulting in dry and clear sky conditions conducive to surface melt enhanced by the ice–albedo feedback, and low snowfall in the 2018–2019 fall/winter seasons, particularly in the western Greenland. The average surface mass loss of the GIS over 2002-2016 is about 270 Gt/year (3750/14)

(7) If the Antarctic Ice Sheet (AIS) of about 24.7 km^3 in volume were to undergo major melting in the next several decades, how could the sea-level rise affect coastal cities worldwide? If AIS were to melt completely, how high will the global sea-level rise?

Significant coastal erosions are expected in coastal cities worldwide due to SLR. If AIS were to melt completely, the global sea level is expected to rise by about 57m.

(9) Explain how the Atlantic Meridional Overturning Circulation (AMOC) that transports heat northward in both hemispheres could be a possible link between the snowmelt variability of both ice sheets?

When AMOC becomes stronger (weaker), northward oceanic heat flux increases (decreases), which could warm (cool) the Arctic, but cool (or warm) Antarctica, and then cause the snowmelt to increase (decrease) in GIS and decrease (or increase) in AIS.

(11) Since early 1990s, what high-precision altimeter satellites have been used to measure global sea-level rise (SLR)?

Since early 1990s globally distributed sea-level measurements and SLR has been measured by high-precision altimeter satellites, the TOPEX/Poseidon (T/P), Jason-1, Jason-2, and Jason-3 altimeter satellites, and so on. Six groups (AVISO/CNES, SL_cci/ESA, University of Colorado, CSIRO, NASA/GSFC, NOAA) provide altimetry-based GMSL time series.

Chapter 5 - Review Questions

(1) Which of the followings is the correction definition of a permafrost: It is a frozen ground in which temperature remains below (a) −30 °C for 5 or more years, (b) −15 °C for 10 or more years, (c) −40 °C for 3 or more years, (d) 0 °C for 2 or more years, and (e) 0 °C permanently?

The right answer is (d) Temperature remains below 0°C for 2 or more years.

(3) In the Northern Hemisphere, what is the MAAT that approximately represents the respective southern limits of continuous and discontinuous permafrost? Also, what is the respective percent of area underlain by frozen ground for these two types of permafrost in NH?

In NH, discontinuous permafrost may occur where the mean annual air temperature (MAAT) is less than –1°C and is generally continuous where MAAT is less than –7 °C. They respectively occupy about **24** % and **50** % of exposed land of Northern Hemisphere (NH).

(5) Name two types of satellite data, one of high and another of low resolutions, commonly used to map the occurrence of frozen ground in the upper surface soil layer. What are the expected changes in the following properties of soils under frozen and unfrozen states measured by the SAR or passive microwave sensors: (i) thermal temperatures, (ii) dielectric constant, (iii) emissivity, and (iv) brightness temperatures?

The occurrence of frozen ground in the upper surface soil layer can be determined using (1) SAR data, and (2) Passive microwave radiation (PMR) data of lower spatial resolution. SAR & PMR data can provide the timing, duration, and spatial progression of near-surface freeze–thaw of surface soil layer in autumn and spring. Freezing results in a large increase in the dielectric of soil and vegetation, which causes a large decrease in L-band (15–30-cm wavelength) and C-band (3.75–7.5-cm wavelength) radar backscatter (~3 DB). Frozen soils relative to unfrozen soils exhibit (i) lower thermal temperatures, (ii) higher emissivity, and (iii) lower brightness temperatures.

(7) Compute *Z* (Equation 5.2), the thickness of the active layer in meters of a permafrost composed of predominantly silt and clay at the end of a thawing season of 4-month duration when the average seasonal air temperature is 7 °C, if the water content is about 30%, and dry soil density is about 1,400 kg/m^3. Should you use the K_t (thermal conductivity) of unfrozen or frozen silt and clay shown below? Compute the rate of descent d*z*/d*t* (Equation 5.3) of the thawing front in m per month.

Fig 148	Fig 149

You should use the K_t of unfrozen silt and clay.
If T = 7°C, K_t = 1.18 W/m °K, t = 4 month, find Z (m/4 month) using Stefan's equation, where K_t = Thermal conductivity of unfrozen soil, L_f = Latent heat of fusion of water (Jm^{-3}).

$$Z=\left[\frac{2TK_t t}{L_f}\right]^{0.5}=\left[\frac{2x7x\dfrac{1.18J}{Sec\ m^{-o}K}x4\ mon.\dfrac{x\dfrac{30.5days}{mon}x86400sec}{day}}{\dfrac{333{,}000J}{kg}x1000kg/m^3}\right]^{0.5}=0.72m$$

dz_t/dt = Rate of descent of a thawing front
T_f/z_f is the freezing temperature gradient (°Km^{-1})
θ_z is the volumetric fraction of soil moisture content at depth z

$$\frac{dz_t}{dt}=\frac{K_t\left[{}^{T_f}/_{z_f}\right]}{L_f\theta_z}=\frac{\dfrac{1.18Jm^{-1}s^{-1}\,{}^oK^{-1}x\dfrac{7^oC}{m}}{333x10^6Jm^{-3}x0.45}x30.5day}{mon}x\ 86400\sec day^{-1}=0.145m/mon$$

$dz_t/dt = 0.145 m/month$

(9) Despite of the extent and rapidity of observed changes to permafrost due to climate warming, such as the significant and rapid permafrost thaw from the top in recent years, and the projected warming of 2.8–7.0 °C in the Arctic by 2100, why is the projected degradation in ice-rich permafrost in response to strong high-latitude warming over the twenty-first century remains highly uncertain?

Even though permafrost thaw responds quickly to climate warming, deep permafrost would persist for a long time because degradation of permafrost in response to high-latitude warming remains highly uncertain, partly due to its dependence on changes in snow cover which is difficult to predict.

(11) As highly dynamic landforms in ice-rich permafrost areas attributed to the thawing of ice-rich permafrost, name three climatic factors that affect the formation and dynamics of retrogressive thaw slumps (RTSs) such as the retreat of headwall, and three terrain factors that can also exert significance influence on RTS dynamics in high Arctic?

Three climatic factors that affect the formation and dynamics of RTSs are warm summers, sparse vegetation, and climate warming. RTSs preferentially develop at locations with gentle slopes (four to eight degrees), and in areas lower than the surroundings and receiving less solar radiation (i.e., north-facing slopes).

Chapter 6 - Review Questions

(1) Name two climatic factors that contribute to the formation of lake ice of certain thickness. How are white and black ice formed in lakes? According to the Stefan relation for black ice (curve of maximum ice thickness shown in Figure 6.2), how thick in cm will the black ice grow out of accretion under a cumulative freezing degree day (FDD) of 400, and the corresponding white ice thickness under the same FDD? Why lake ice thickness increases with latitude, for example, in Russian Far East and eastern Siberia, lake ice thickness increases from ~100 cm at latitude 45° N to 180 cm at 65° N?

Formation of lake ice depends on the cooling of surface water to supercooled water where ice is formed on its nuclei, with the thickness of lake ice primarily depending on the amount of heat lost to the atmosphere estimated in terms of accumulated freezing degree day (FDD). According to Figure 6.2, the black ice could grow up to about 70cm thick, while white ice could grow to slightly over 20 cm, under a FDD of 400. Lake ice thickness increases with latitudes mainly because FDD increases with latitudes.

(3) Several 1-D energy balance models of lake ice growth have been developed and applied to lakes in Europe and North America. Briefly explain the four sub-models of the 1-D energy balance model of Liston and Hall (1995a) and the thermal energy balance at the ice-water interface shown in Equation 6.3. Name five climate variables typically needed to run a 1-D energy balance lake ice model.

The four sub-models of the 1-D energy balance model of Liston and Hall (1995a) are: (i) the evolution of lake water temperatures and the lake stratification; (ii) a snow sub-model that describes the depth and density of the snow cover; (iii) a lake ice sub-model that forms ice by clear ice grows at the ice, and snow ice forms through the freezing of water-saturated snow; and (iv) a surface energy balance sub-model. Equation 6.3 shows that the thermal energy balance at the ice-water interface depends on the vertical temperature gradient, convective heat transfer and the thermal conductivity of layers of ice, snow, snow/water mix and water, respectively. Climate variables needed to run a 1-D energy balance lake ice model are precipitation, wind speed, air temperature, water surface temperature and water freezing temperature.

(5) Explain how lake ice characteristics such as the timing of lake ice break-up, freeze-up, and ice cover durations are useful indicators of climate variability and change, particularly to environmentally sensitive, Arctic lakes? For example, the long-term average maximum ice covers of Lake Erie vary from 95% in severe winters to only 14% in mild winters. Also explain how large lake ice variability is linked to climate anomalies such as Pacific North American Pattern and Arctic Oscillation.

In recent years, many lakes especially lakes in the Arctic show earlier melt onset, experienced earlier summer ice minimum, water-clear-of-ice, or some lakes may be transitioning from a perennial/multiyear to a seasonal ice regime. Trend analysis of in situ measurements and satellite images such as AVHRR record shows earlier break-up (e.g., 0.18 days to 1 day yr^{-1}) and later freeze-up (e.g., 0.12 to 0.8 days yr^{-1}) for majority of Canadian lakes analyzed. The above observed changes are clear indicators of climate change, while the large variability of lake ice cover is linked to anomalous atmospheric circulation patterns, such as the Pacific North America pattern, La Niña, and the Arctic Oscillation, which would affect the precipitation/snowfall, temperature, duration and depth of snow cover which affect lake ice covers.

(7) What is river ice jam, typical river sites that are prone to ice jamming, and how could ice jam cause a higher flood risk?

A river ice jam is the rise in river stage caused by the break-up or freeze-up of a river ice cover. The most common sites of ice jams are sharp bends in the river, abrupt reductions in slope, and channel constrictions that reduce flow velocity. The increase in water level height associated with ice jams causes a higher flood risk.

(9) Name heat fluxes occurring at the water–ice and ice–air interfaces, and two prerequisites for the formation of frazil ice.

Latent heat, radiation and convection heat fluxes occur at water–ice and ice–air interfaces. Prerequisites for the formation of frazil ice are (1) the formation of snow ice that contains small and spherical air bubbles in turbulent flows of supercooled water either from snow falling into cool water (≈0 °C) or when snow on an ice cover gets wet and then freezes; (2) Frazil particles adhere together forming slush, or snow may form snow slush, that aggregates into slush balls, which through collisions grow into ice pancakes with upturned rims and eventually amalgamate in ice floes and an ice sheet.

(11) Briefly explain the mechanisms behind the formation of icings in high-gradient alpine streams and in flat braided streams, and the effects of terrestrial factors such as continuous/discontinuous permafrost boundaries, and winter baseflow on the occurrences of river icings, and a shift in their distributions.

River icings develop after a seasonal ice cover has formed and when water seeps from a river onto the ice surface during periods of subfreezing temperatures and accumulates in successive layers of ice. Water flowing below the ice cover may be forced up onto the river ice by channel restrictions or ice dams. In catchments with continuous permafrost, icings occur preferentially at the foothills of heavily faulted karstic mountainous regions, where winter baseflow and its contribution to the annual discharge was lower than in discontinuous permafrost. As icing conditions are sensitive to degrading permafrost, a northward shift in the continuous permafrost boundary would likely reduce icing occurrences or perhaps a shift in their distribution if northerly regions become more conducive to icing development.

Chapter 7 - Review Questions

(1) Define sea ice extent, and why is sea ice extent inevitably larger than sea ice area?

Sea ice extent is the area of ocean where there is at least 15% or more of sea ice concentration while sea ice area is the ocean area covered with sea ice which is inevitably smaller than sea ice extent.

(3) Based on passive microwave SMMR and SSM/I data of DMSP satellites collected since 1979, what is the average decreasing annual trend in Arctic perennial sea ice extent in percent decade^{-1}, and decreasing trend in summer (in late September) in percent decade^{-1}? What was the lowest summer sea ice extent ever recorded in million km^2 and when did it happen?

Parkinson and Cavalieri (2008) show that annual averages in Arctic perennial sea ice extent for 1979–2006 had an overall negative trend of -3.7 ± 0.4%decade^{-1}. For September 1979–2009, the trend was -11.9%decade^{-1} (Stroeve, 2010). Based on 85 GHz SSM/I data, Kern et al. (2010) detected reductions in ice area in the Irminger Sea (west of Iceland) between 1992–1999 and 2000–2008 by 17% in winter and 45% in summer. In the Barents Sea the corresponding reductions were 20% and 54%, respectively. The lowest summer sea ice extent ever recorded was in 2012 at 3.39 million km^2, which was 44 % below the 1981–2010 average (Vaughan et al., 2013).

(5) Why changes in Antarctic Sea ice have received less attention than changes in Arctic Sea ice? Explain the contrast between changes to Antarctic and Arctic Sea ice in recent years, such as the average trend in Antarctic Sea ice observed in recent years.

Arctic Sea ice has received much attention because it has been declining significantly at about 400,000 km2/decade (-2.64%/decade) over 1979-2019. In contrast, Antarctic Sea ice has marginally increased over the same period by about 0.8%/decade.

(7) How have large-scale climate anomalies such as NOA and AO contributed to the southward sea ice flux through the Fram Strait?

Positive AO with a stronger vortex is shown to increase the export of ice from the Arctic (Rigor and Wallace, 2004). Similarly, the export of sea ice through the Fram Strait were maximal when the NAO index was near its peak (Kwok, 2009).

(9) What are the key mechanisms behind the formation of leads and polynyas in the Arctic and Antarctic in terms of ice drift and local melting? Why are they a major source of brine and how have they affected the regional exchange of sensible heat, latent and longwave radiation fluxes in the Arctic and Antarctic?

A large-scale divergent wind field can create a divergent stress over sea ice. Since ice has little strength under tension divergence can open up cracks, which widen to form leads (linear water openings) or polynyas (irregular shaped water openings) produced by ice motions. Along the Siberian shelf the ice motion is commonly directed offshore forming large and persistent polynyas between the landfast ice and the moving pack ice. By the formation of sea ice, brine is released to the cold, dense, water. As large offshore openings in blankets of sea ice, they release large amount of heat stored below the ocean surface to the frigid atmosphere, resulting in loss of surface buoyancy which may lead to convective overturning, modify the ocean interior, with significant implications for large-scale ocean circulations. The heat release can affect the regional climate and possibly global climate patterns through atmospheric teleconnections. In coastal regions of Antarctica, latent-heat polynyas are a major source of the world’s bottom waters, a warm upwelling ocean water that influences the process of thermohaline circulation.

(11) Since the Arctic Sea ice has been getting younger and thinner, what has happened in summers to most of the Arctic Sea ice recovered in recent past winters? How much has 4+-year-old ice shown in Figure 7.20 lost in percentage from 1984 to 2019?

Figure 7.20 shows the almost complete loss of 4+-year-old Arctic Sea ice in recent years. The 4+-year-old Arctic Sea ice which made up about 30% of the Arctic Sea ice in 1984, made up only 1.2% of the ice cover by mid-April 2019. On the other hand, 3 to 4-year-old ice increased slightly, increasing from 1.1% in 2018 to 6.1% in 2019.

(13) Explain possible ecological implications of diminished Arctic Sea ice, and new commercial opportunities, such as creating new shipping lanes and increased access to natural resources in the Arctic region.

Possible ecological implications of diminished Arctic Sea ice are such as the existence of polar bears could be threatened by the melting of Arctic Sea ice, but phytoplankton thrive in open water because overturning ocean water brings nutrients to the surface, e.g., during the summer, Antarctic polynyas are one of the most biologically productive regions in the world's oceans. A possible ice-free Arctic say in the summers of mid- 21st century will create new shipping lanes and increased access to natural resources in the Arctic region in the future.

Chapter 8 - Review Questions

(1) Name the classic tragic accident involving an iceberg that happened in the northwest Atlantic leading to the establishment of the International Ice Patrol in 1914, and the accident was featured in numerous films, TV movies and notable TV episodes for over a century?

The tragic loss of the RMS *Titanic* in the northwest Atlantic and over 1,500 lives, due to a collision with an iceberg in April 1912.

(3) Define an ice shelf. Who discovered the world's largest, Ross Ice Shelf in the Antarctic, the size of this ice shelf in area (km^2), length (km), and thickness (m), and the rate it is advancing to the sea in m/day?

An ice shelf is a sheet of very thick ice, with a nearly level surface that is attached to the land, but most of which is floating on the ocean. It is bounded on its seaward side by a steep ice cliff. The Ross Ice Shelf was discovered by Sir James Clark Ross on 28 January 1841. The Ross Ice Shelf is roughly 500,809 km^2 in area (as of 2013), about 800 km across, several hundred metres thick, and the nearly vertical ice front to the open sea is more than 600 km long. The Ross Ice Shelf pushes out into the sea at between 1.5 and 3 m a day.

(5) Explain the key contributing factors behind the dramatic breaking off of Larsen A on January 1995, Larsen B on January–March 2002, and Larsen C on July 2017. What is the approximate total amount of ice lost in km^2 from the Antarctic Peninsula since the 1950s?

The rapid breakup of Larsen A on January 1995, Larsen B on January–March 2002, and Larsen C on July 2017 has been attributed to the effects of liquid water; melt water ponds formed on the surface of the shelf during the 24-hour-long days, then drained down into cracks and, by acting like a multitude of wedges, levered the shelf into pieces.
Sea level rise and weakening of ice material due to warm meltwater percolation can also contribute abrupt and catastrophic large-scale disintegrations of ice shelves. The total area of ice shelf lost from the Antarctic Peninsula from the 1950s is 28,117 km^2.

(7) Radar altimeters of satellites have been employed to study ice shelf altimetry. Name three such satellites, and what are the approximate range of ice-shelf elevation change rate ($\Delta h/\Delta t$) of the Ross Ice Shelf over 2003–2008 (see Figure 8.8) estimated by Pritchard et al. (2012) using radar altimeter data and modeling of the surface firn layer?

Satellites deployed to study ice shelf altimetry are such as ICESat and ICESat-2 of NASA, European Remote-sensing Satellite-2 (ERS-2) and Envisat. The approximate range of ice-shelf elevation change rate ($\Delta h/\Delta t$) of the Ross Ice Shelf over 2003–2008 was ± 0.05m/year.

(9) Why is buttressing – holding back the glaciers that feed them – important in the disintegration of the Larsen B but not the Larsen C ice shelves?
Scambos et al. (2004) find a two- to six-fold increase in centerline speed of four glaciers flowing into the now-collapsed section of the Larsen B Ice Shelf. On the other hand, basal melt rates near Bawden Ice Rise, a major pinning point of Larsen C Ice Shelf, showed large increases, which will lead to substantial loss of buttressing of Larsen C Ice Shelf, which does not provide strong buttressing forces to upstream basins.

(11) What are the six size categories for icebergs according to the International Ice Patrol? What is the most common shape of icebergs formed from ice shelves, and the average width to length ratio of such icebergs? How large was the world's largest recorded B-15 Iceberg in terms of surface area in km^2?

The six size categories for icebergs according to the International Ice Patrol are: The smallest ones are called growlers (<5 m long, ~1 m high). The next larger size is 5–14 m long and 1–5 m high. The remaining four size categories are: small (15–60 m long and 5–15 m high), medium (60–120 m long and 16–45 m high), large (120–210 m long and 46–75 m high) and very large (>210 m long and >75 m high). Tabular icebergs, flat sheets of floating ice formed from ice shelves with a length/height ratio of ≥5:1, are most common shape of icebergs formed from ice shelves. Icebergs have an average width to length ratio of about 1:1.6. The world’s largest iceberg B-15, which broke off the Ross Ice Shelf in March 2000, measured 10,800 km^2 in surface area.

Chapter 9 - Review Questions

(1) Name six major Ice Ages over the geological time starting from the NeoArchean–Paleoproterozoc (~2,700 to 2,200 million years ago, Ma) to the Holecene (12,000 years to present). Approximately during what period (Ma) was the earth believed to be entirely covered with ice, the Snowball Earth?

The major ice ages were the Huronian/Makganyene glaciations in the NeoArchean–Paleoproterozoc (~2,700 to 2,200 million years ago, Ma), the Sturtian, Marinoan, and Ediacaran glaciations of the Neoproterozoic (~730–700 Ma, 665–635 Ma, and 635–542 Ma), the late Ordovician glaciation (460 Ma), the late Devonian glaciation (360 Ma), the Permo-Carboniferous glaciation (320–250 Ma), and the Late Cenozoic glaciation (beginning ~40 Ma). The latest glacial period occurred between about 120 ka and 11 ka ago. Since then, Earth has been in the interglacial period called the Holocene. During about 730–540 Ma, cooling due to a dimmer early sun (~0.94 of today's value) and lower CO2 levels, may have produced a Snowball Earth in which permanent ice covered the entire globe.

(2) The three geologic events attributed to major temperature fluctuations are the Plate tectonics, large-scale ocean currents and thermohaline circulations, and Milankovitch cycles. Explain how has glacial/interglacial cycles identified in paleo ice core data collected from, say, the Vostok Station of Antarctica, supported the orbital hypothesis of the Milankovitch cycles, such as the eccentricity of the Earth's orbit around the Sun has a periodicity of ~100,000 years?

Given glacial (Interglacial) cycles identified in paleo ice core data collected from the Vostok Station of Antarctica, which tend to occur during periods of less (more) intense summer solar radiation in the NH, show a periodicity of ~100,000 years, it supports the orbital hypothesis of the Milankovitch cycles, that variations in Earth's orbit has a periodicity of about 100,000 years.

(3) In your opinion, which of these hypotheses provides more plausible explanation(s) that the global glaciation period between 730 and 540 Ma ended abruptly because of major volcanic eruptions that lead to a drastic increase in atmospheric CO_2 (350 times the modern level), or significantly lower the tropical surface albedo, or methane released from melting permafrost in low latitudes, or some oceans remained ice free permitting free exchange with the atmosphere?

I believe the hypothesis that the global glaciation period between 730 and 540 Ma ended abruptly because of major volcanic eruptions that lead to a drastic increase in atmospheric CO_2 should be more plausible than the hypothesis of significantly lower tropical surface albedo, or methane released from permafrost in low latitudes, or free exchange between ocean and the atmosphere because of the significant radiative forcing expected from a very high atmospheric CO_2 concentration.

(4) What were the characteristics of the Phanerozoic glaciations modes in the late Ordovician (445–440 Ma), the late Devonian (375–368 Ma), the Permo-carboniferous (360–263 Ma), and the Cenozoic (beginning ~40 Ma) glaciations, with respect to atmospheric CO_2, biogeographic changes and continental drifts?

The late Ordovician (445– 440 Ma) and late Devonian (375–368 Ma) glaciations typify short-duration, high atmospheric CO_2 events, characterized by cosmopolitan faunal distributions and episodes of catastrophic extinction. The Permo-Carboniferous (360–350 and 330–263 Ma) and Cenozoic glaciations typify long-duration, low atmospheric CO_2 events, characterized by abundant biogeographic differentiation and stable or rising biotic diversity. The late Devonian witnessed a reduction of CO_2 levels giving rise to global cooling and a harsh continental climate with a major mass extinction. The onset of glaciation in Antarctica was probably related to the continuing breakup of Gondwana, poleward drift of the Antarctic continent, and the opening of ocean passages around it.

(5) What evidence has been identified about the full glaciations of the East Antarctica in the earliest Oligocene (37–24 Ma), West and East Antarctica during the Miocene (24–5 Ma), and which hypothesis regarding the formation of the ice sheets, such as breaking-up of Gondwana, ocean passages or ocean current such as the Antarctic Circumpolar Current and orbital forcing are more convincing to you and why?

The formation of the Antarctic Circumpolar Current (ACC) in the Southern Ocean was attributed to the development of an ice sheet in East Antarctica at about 33–34 Ma (instead of the breaking-up of Gondwana), as ACC is the strongest ocean current on our planet extending from the sea surface to the bottom of the ocean. It encircles Antarctica, keeping it cool and frozen. There is also strong evidence for the presence of large ice sheets on both West and East Antarctica during the Miocene (Hambrey et al., 1989). Decreases in pCO2 were apparently synchronous with major episodes of glacial expansion during the late Middle Miocene ~14 to 10 Ma. Between 14.1 and 13.9 Ma, there was a rapid cooling of about 8 °C in mean summer temperatures in the McMurdo Dry.

(6) Approximately when did the glaciations in the Northern Hemisphere begin, and what evidence has been found that support or against the traditional belief that glaciations in Greenland and the Arctic began in the late Miocene, much later than the glaciations of the Antarctic?

The earliest recorded glaciation in the NH is in the Late Miocene involving a significant buildup of ice on southern Greenland around 7 Ma. However, recently ice-rafted detritus has been identified as early as the Eocene, ~45 Ma, in the Arctic Ocean. According to Stickley *et al.* (2009), episodic sea-ice formation in marginal shelf areas of the Arctic started around 47.5 million years ago and the onset of seasonal sea-ice formation in offshore areas of the central Arctic about half a million years later.

(7) For the Quaternary period, among various speculations on the cause of glacial cycles of the Pleistocene glaciations of the last 2 Ma that shifted from a 41,000-year to a 100,000-year signatures, do you agree with the argument that a progressive removal of a deforming sediment layer, that maintained thin ice sheets responding to dominant 23 and 41 ka orbital forcings, had caused the transition to thicker ice sheets of dominant timescale of change of ~100 ka?

This shift has been attributed to a nonlinear response to small changes in external boundary conditions, but we don't really know it was due to small or major changes in external boundary conditions. A progressive removal of a deforming sediment layer is a possibility, but I don't quite agree that itself had caused the transition to thicker ice sheets of dominant timescale of change of ~100 ka. I believe other factors, or a combination of factors had resulted in increasing volumes of glacier ice.

(8) What were the range of CO_2 levels obtained for the most severe glacial intervals of marine isotope stages (MIS) 2, 12, and 16 from ice cores of the European Project Ice Coring in Antarctica (EPICA) in Dome C, to the warmer interglacial intervals, say, MIS 11, 9, 7, 5, and 1? Are the current, much higher global CO_2 levels (>400 ppm) mainly caused by the burning of fossil fuels worldwide since the industrial revolution began in about 1760?

The EPICA ice core data in Dome C shows that the most severe glacial intervals were MIS 2, 12, and 16 when CO_2 levels fell to 180–200 ppm, to the warmer interglacial intervals, MIS 11, 9, 7, 5, and 1, when the CO_2 levels were higher at 260–285 ppm. According to the AR6-WGI report of IPCC (2021), it is indisputable that the current much higher global CO_2 levels (>400 ppm) is mainly caused by the burning of fossil fuels worldwide since the industrial revolution began in about 1760.

(9) Name several ice sheets in North America and the Scandinavia during the Quaternary periods and the postglacial Holocene, of which some have been reconstructed by geodynamical models ICE4G and ICE5G, and how they have retreated over postglacial warming or deglaciation periods, say ~21–9.6 ka?

The Laurentide ice sheet was reconstructed by ICE5G and Fennoscandian Ice Sheet was reconstructed by ICE4G. Large ice streams at the northwest margin of the Laurentide Ice Sheet underwent major retreats during deglaciation (~21–9.5 cal ka), resulting in intermittent delivery of icebergs into the Arctic Ocean

(10) Among a series of Heinrich events that interrupted the postglacial warming, what could have caused the abrupt Younger Dryas cold interval that resulted in massive environmental changes to occur and lasted ~1,300 years?

The abrupt YD cold interval that lasted ~1,300 years and interrupted postglacial warming could has been attributed to multiple cometary airbursts that impacted at least North America at the onset of the YD, triggering massive environmental changes, or the YD was caused by a significant reduction of the North Atlantic thermohaline circulation in response to a sudden influx of fresh water. However, the evidence for the proposed multiple cometary airbursts or the source of this water remains unresolved.

(11) In the postglacial Holocene epoch, among the four minor Neoglaciations, what were the characteristics of the Little Ice Age (LIA) dated around 1550–1850, besides the most substantial glacier advances over the last Millennium observed in the European Alps and in mountain regions worldwide, and disparity in the maximum ice extent between Southern and Northern hemispheres?

Besides the most substantial glacier advances over the last Millennium observed in the European Alps and in mountain regions worldwide, and disparity in the maximum ice extent between Southern and Northern hemispheres, the other characteristics of the LIA are such as: Glaciers in northern Sweden reached their maximum extent between the 17^{th} and the beginning of the 18^{th} centuries, whereas most Norwegian glaciers attained their maximum extent during the mid-18^{th} century. Glaciers in the Alps attained their maximum extents in the 14^{th}, 17^{th}, and 19^{th} centuries, with most reaching their greatest extent in the final advance about AD 1850/1860. There is evidence of ice cap growth in northeastern Arctic Canada between AD 1250 and 1300 and around AD 1450, with the ice remaining in an expanded state until the last few decades. In southern Tibet, maritime glaciers were 30% larger during the LIA than at present, while continental glaciers in the western part of the plateau were <10% larger.

Chapter 10 - Review Questions

(1) Name five key elements of the global cryosphere. For example, snow cover.

Snow cover, glaciers, sea ice, ice sheets, permafrost.

(3) Why is the global warming impact more pronounced in high latitudes, especially the Arctic, or why does global warming affect the cryosphere more than the hydrosphere?

Global warming impact is more pronounced in high latitudes, especially the Arctic, likely because of several feedback mechanisms that are accelerators of Arctic warming: (1) temperature feedback that results from the effect of rising temperatures on outgoing longwave radiation at the top of atmosphere; (2) Planck feedback due to the contribution from vertically uniform warming of the surface and troposphere; (3) lapse-rate feedback due to the contribution from tropospheric warming that deviates from the vertically uniform profile; (4) ice–albedo feedback due to the increase in surface absorption of solar radiation when snow and ice retreat because the albedo of seawater is much lower than sea ice; (5) water vapor feedback due to the greenhouse effect of additional atmospheric water vapor; (6) cloud feedback due to effect of clouds on the Earth's radiative balance, and others.

(5) In terms of the radiative forcing in W m^{-2}, the CO_2-eq concentration in ppm, and the projected temperature change in 2100, explain differences between several Representative Concentration Pathways climate projections, RCP2.6, RCP4.5, and RCP8.5 of CMIP5. Given the global CO_2 concentration is about 410 ppm in 2020, and CO_2 concentration is increasing at about 2 ppm yr^{-1}, in your opinion which of the above three RCPs is a more realistic projection for 2100?

RCP2.6: Radiative forcing is projected to peak at about 3 W m^{-2} and then declines to 2.6 W m^{-2} in 2100, with CO_2-eq concentration of 430–500 ppm.
RCP4.5: Radiative forcing is projected to peak at about 4.5 W m^{-2} in 2100, with CO_2-eq concentration of 500–650 ppm.
RCP8.5: Radiative forcing is projected to >8.5 W m^{-2} in 2100, with CO_2-eq concentration of 851–1,370 ppm.
Given the global CO_2 concentration is about 410 ppm in 2020, and CO_2 concentration is increasing at about 2 ppm yr^{-1}, in my opinion RCP4.5 should be a more realistic projection for 2100 when the global CO_2 concentration should be about 570ppm unless we radically reduce the emissions of GHG over the 21st century.

(7) According to simulations of GCMs of CMIP5, how will the Northern Hemisphere snowpack projected to change with respect to winter snowfall, annual snowfall, maximum snow depth, and the duration of snow season, and latitudes? Even though GCMs generally simulated representative twentieth-century snowfall, what are the possible deficiencies of GCMs of CMIP5?

As climate warming increases the atmospheric moisture-holding capacity at about 7% per °C rise in temperature, the total precipitation is projected to increase but the fraction of precipitation falling as snowfall decreases and spring snowmelt tends to occur earlier with warming. The annual snowfall is projected to decrease across much of the NH during the twenty-first century but projected to increase at higher latitudes where the transition zone corresponds approximately to the −10 °C isotherm of the late twentieth-century mean surface air temperature, e.g., positive trends prevail in winter over large regions of Eurasia and North America. Even though snowfall decreases across most NH, increases in total precipitation typically contribute to increases in snowfall, especially in DJF. Based on simulations of the Community Earth System Model (CESM) for 1.5 °C and 2 °C warming and CMIP5 RCP2.6 and RCP4.5 climate scenarios, the projected change in annual snow area extent (SAE) over NH between 1971–2000 and 2071–2100 divided by the mean of 1971–2000 are −8.02 ± 0.78%, −10.92 ± 0.52%, −8.5 ± 5.58%, and −14.47 ± 5.71%, respectively, with the NH average SAE changes to be -1.69×10^6 km^2 in 1.5 °C and -2.36×10^6 km^2 in 2.0 °C. CMIP5's GCMs tend to over simulate the amount of precipitations.

(9) Name a few satellite missions that remotely observed the melting trends of land ice such as glaciers, Arctic Sea ice, Greenland Ice Sheet (GIS), and Antarctic Ice sheet (AIS). According to the RCP2.6 and RCP8.5 scenarios of AR5 (IPCC, 2013), what will likely be the range of global mean sea-level rise (SLR) for 2081–2100 relative to 1986–2005?

Data of Landsat satellites, such as Landsat 7 with the Enhanced TM (ETM), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument, are used for mapping mountain glaciers. Synthetic aperture radar (SAR) data of the European Space Agency's (ESA) Earth Remote Sensing (ERS)-1 and ERS-2 has been used to determine ice-sheet mass balances. The Canadian RADARSAT-I and RADARSAT-II data, and NASA's QuikSCAT have been used to map Arctic Sea ice extent. NASA's ICESat and ICESat-2 data was used to measure ice-sheet elevations and changes in elevation and sea ice thickness, land topography, vegetation characteristics, and clouds. ESA's CryoSat data was used to monitor changes in the thickness of sea ice in the polar oceans and variations in the thickness of the Greenland and Antarctic ice sheets, and GRACE data of NASA and German Aerospace Agency is used to monitor ice-sheet dynamics, land-ice response, and sea-level change to climate warming. According to AR5 (IPCC, 2013), the global mean SLR for 2081–2100 relative to 1986–2005 will likely be between 0.26 and 0.55 m under RCP2.6, and between 0.45 and 0.82 m under RCP8.5 scenarios.

(11) What have been the observed changes in lake and river ice in response to climate warming impact, such as the timing river ice breakup, freeze-up, and river ice season and how would such changes affect possible flooding caused by river ice-jams during the breakup season? Besides climate warming, what large-scale climate anomalies have been observed to contribute to earlier ice-off dates for lakes and rivers across NH?

Freshwater ice duration in lakes has been decreasing and the average seasonal ice cover shrinking, such as lakes in Scandinavia and northern USA, where freeze-up occurring 1.6 days decade^{-1} later and breakup 1.9 days decade^{-1} earlier, with abrupt changes in mean ice breakup for 53% of lakes across NH. In the North American Great Lakes, the average duration of ice cover declined 71% over 1973–2010. For northern rivers, an almost universal trend toward earlier breakup dates in the last few decades of the 20th century was observed but with considerable spatial variability in those for freeze-up. Later freeze-up, shorter river ice season and breakup periods were found across Canada. In Yukon, there is an increasing frequency of overlapping river ice breakup events and freshet peaks. River ice breakup over northern Canada is projected to occur earlier by 15–35-day, while the duration of river ice over most of Canada by AD 2050 will show a 20-day decrease relative to 1961–1990, e.g., in the Peace-Athabasca delta it will be 2–4 weeks shorter by AD 2100. The frequency of mid-winter thaws will increase with a northward shift in their occurrence and fewer dynamic river-ice breakup events, and the frequency of major ice jams during the spring breakup will decrease. Short-term behavior of ice-off dates are found to be affected by NAO, Pacific-North American Pattern (PNA), and El Niño-Southern Oscillation (ENSO).

(13) According to Vaughan et al. (2013), what was the total mass loss from all glaciers globally, excluding those on the periphery of the two ice sheets, in Gt yr^{-1} in 1993–2009, and in 2005–2009, and predominantly from which regions? Based on RCP scenarios of multiple GCMs, what were the projected glacier-volume changes from North and South America, Europe, and Asia between 2010 and 2100 under RCP2.6, RCP4.5, and RCP8.5? Will the glacier runoff continue to increase, or will they decline after reaching the peak runoff due to glacier mass loss? Will the maximum glacier runoff tend to occur earlier or later in basins with larger glaciers and higher ice-cover fractions, and why?

According to Vaughan et al. (2013), worldwide total mass loss from all glaciers globally, excluding those on the periphery of the two ice sheets, was estimated at 275 ± 135 Gt yr^{-1} in 1993–2009, and 301 ± 135 Gt yr^{-1} in 2005–2009. Based on RCP emission scenarios of GCMs, between 2010 and 2100, for large-scale glacierized drainage basins selected from North and South America, Europe, and Asia., the total glacier volume in all the investigated basins is projected to decrease by 43 ± 14% (RCP2.6), 58 ± 13% (RCP4.5), and 74 ± 11% (RCP8.5). The glacier runoff of the drainage basins will likely decline after reaching the peak runoff due to glacier mass loss. The maximum glacier runoff tends to occur later in basins with larger glaciers and higher ice-cover fractions because surface melting tends to peak later in glaciers with larger mass and ice-cover fractions.

Chapter 11 - Review Questions

(1) What are three main types of snow fence used to prevent snow from drifting across highways in many US states? Briefly explain how each of these fences are designed to reduce snow drift.

The three main types of snow fence are a collecting fence, a solid fence and a blower fence. A collecting fence is used upwind and adjacent to the highway to reduce the wind speed, collecting and depositing the snow before it drifts onto the road. A solid guide fence is aligned at an angle to the prevailing wind direction to deflect the snow laterally. A blower fence is aligned at an angle to the wind vertically to accelerate the local flow and transport the snow elsewhere.

(3) How ice storms/freezing rain disrupt traffic, damage properties, and result in the loss of power and communication? Provide your explanations with reference to a recent major ice storm.

Ice storms with freezing rain can cause severe problems by depositing a glaze layer of black ice that brought down power lines and disrupts traffic by causing loss of traction, loss of stability/maneuverability, lane obstruction, impaired mobility, and loss of visibility in highways, leading to road damage, loss of life, property damage, loss of communications and power. The January 5–9, 1998 ice storm in eastern NA shut down much of southern Quebec, Maine, New Hampshire, parts of New York, and Vermont. A wide area received 50–100 mm of freezing precipitation. About 32,000 km of transmission lines and 96,000 km of distribution lines were brought down by the storm. Over 4 million households in Canada and in the USA lost power for weeks. Losses totaled $6 billion in Canada and $2 billion in the United States. A fifth of Canada's maple syrup trees suffered severe damage.

(5) Before making a trip, from where and what information should backcountry skiers and snow boarders collect to assess the risk of an avalanche? Given about 100 people lost their lives each year in the Alps in last four decades, roughly what is the odd that a skier will encounter a fatal avalanche in the Alps?

Backcountry skiers and snow boarders should check the daily danger scale for public avalanche warnings issued by the nearby or the closest backcountry avalanche forecast center of the country, funded by various private and public funding sources, and which typically provide daily avalanche advisories and a variety of avalanche education for the public.

(7) Globally what is the approximate fraction of people relying on spring snowmelt, and how their water supply will be affected by changes to the hydrologic cycle in response to global warming?

Globally more than one-sixth of the Earth's population relying on glaciers and seasonal snowpacks for their annual water supply. Global warming has important consequences particularly in northern regions with annual runoff dominated by spring snowmelt because with higher surface temperature, less winter precipitation falls as snow, and the spring snowmelt will occur earlier. Both effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when the water supply demand is the highest. Where storage water capacities are lacking, much of the winter/spring runoff will discharge to the oceans, which could severely impact the future water supply dominated by spring snowmelt.

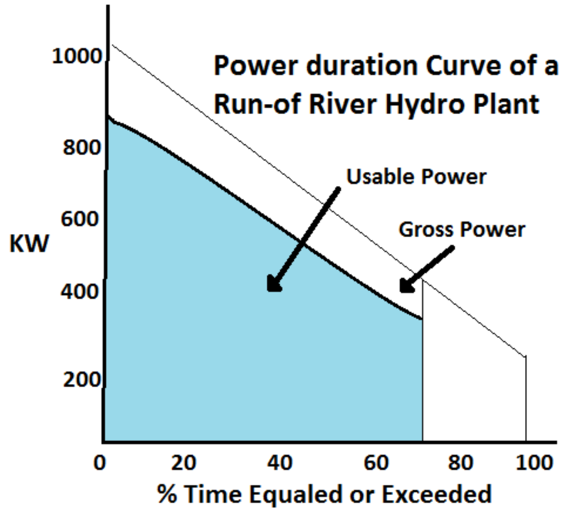
(9) As Arctic Sea ice continues to decline, discuss the new future opportunities in a more accessible Arctic and risks, such as oil and mineral extraction in the Arctic, the northern route: shipping and transportation, and tourism at the Arctic?

According to climate model simulations, future reduction of Arctic Sea ice will be continuous and amplified, with ice-free summers occurring as early as the 2030s, and an ice-free year occurring as early as the 2050s. As Arctic becomes more accessible in the summer, new future opportunities such as oil and mineral extraction in the Arctic, the northern shipping and transportation route, and even tourism at the Arctic will be possible. We could expect some countries trying to extract oil and mineral in an ice-free Arctic in future, especially during summers.

(11) Which parts of North America are more prone to ice-jam flooding (IJF)? How have shifts in magnitude of IJF in Canada vary between unregulated and regulated rivers, and size of river basins?

North America is one of the most prone regions to ice-jam flooding (IJF), particularly in eastern NA. In Canada, shifts in magnitude of ice-jam floods varies from + 3.5% to −5% yr^{-1} in unregulated rivers and ±3.5% yr^{-1} in regulated rivers which are more dominated by negative trends. The trends in IJF are also correlated with size of the basins in unregulated rivers with small basins showing larger variabilities.

(13) Using the power duration curve of a run-of-river hydro plant, estimate the annual usable power of the hydropower plant in kWh.



Annual usable power = $= \frac{[860+340]Kw}{2x\ 1000} x0.7x8760hr = 3679MWh$