Chapter 1:
Introduction to Earth’s Cryosphere
1.0 INTRODUCTION

The word “cryosphere” is believed to have its origin from the Greek word “Kryos”, which means frost or icy cold. Cryosphere collectively defines the earth’s surface (land or ocean) where water is available in its solid form. It includes sea-, lake-, river ice, snow cover areas, glaciers, ice caps, ice sheets, frozen ground and permafrost. It forms an integral part of the earth’s climate system. Cryosphere affects the global climate through different feedback mechanisms and linkages, as it influences surface energy and moisture fluxes, clouds, precipitation, hydrology and atmospheric & oceanic circulations. Polar regions control some of the major atmospheric circulations and also affect the oceanic circulation. For most part of the year, considerable fraction of the high latitude global ocean is covered with sea ice. Sea ice forms a boundary between the atmosphere and the ocean. It considerably influences the heat, mass and the momentum fluxes between the atmosphere and the ocean. Also, it acts as a sensitive indicator of climate change. However, there exists a notable gap in the accurate and appropriate treatment of different cryospheric processes, their impact and response to the global climate system. The role of polar processes in global climate has not properly understood yet (Schmidt and Hansen, 1999). Also, the poor model description of the physical processes involved between ice formation and plum convection of heat lead to substantial climate drift or misrepresentation of the deep ocean in climate change studies using coupled atmosphere – sea ice – ocean global circulation models (GCMs) (Bryan, 1998; Gordon et al., 2000; Khodri et al., 2001; Barnett et al., 2001). An improved knowledge is needed of the broad scale as well as mesoscale time varying distribution of the physical characteristics of sea ice, particularly ice thickness and the over lying snow cover thickness, in both hemispheres, and the dominant processes of ice formation, modification, decay and transport which influence and determine ice thickness, compression and distribution. Cryosphere plays a significant role in the climatology and the hydrology of the earth and is also an important factor for ship navigation and oil exploration in the polar seas.
1.1 COMPONENTS OF THE CRYOSPHERE

We can define cryosphere into different categories like snow cover, sea ice, land ice, freshwater ice, frozen ground and permafrost.

1.1.1 Snow Cover

Among the different components of the Cryosphere, snow cover has the largest areal extent compared to any other component. Most of the earth's snow cover areas are located in Eurasia and North America. In northern hemisphere, the snow cover extent varies from $46.5 \times 10^6$ km$^2$ during January to 3.8 million km$^2$ (MSKM) in August (Robinson et al., 1993). The spatial and the temporal snow cover extent in a region are mainly affected by the seasonal cycle and the geographic location of the area. The global climate system is sensitive to the spatial and temporal variation in the snow covered regions. For example: Heavier than normal Eurasian snow cover in spring leads to a poor monsoon over Southeast Asia (Barnett et al. 1989)

1.1.2 Sea Ice

Another major component of the cryosphere is sea ice, which is found in polar seas/oceans. Freezing of seawater results in the formation of sea ice. During this process, brine is ejected into the water underneath. The rejection of brine increases the density of the seawater locally. The surface waters are becoming denser thereby driving oceanic convection and bottom water formation (Stossel et al. 2002). Over the continental shelf regime cold, dense and salty water is produced, which forms the major part of the bottom water, particularly Antarctic bottom water (AABW) (Orsi et al., 1999). Large areas of the polar oceans, in both the hemispheres, are covered with sea ice throughout the year. It exhibits regional, seasonal, annual and inter-annual variability in both the hemispheres. However, sea ice coverage in winter is much larger than in summer and exhibits temporal and regional variability in different sectors of both the hemispheres. In the Southern Hemisphere, seasonal sea ice extent varies by a factor of 5, from a minimum of 3 to 4 MSKM in February to a maximum of 17 to 20 MSKM in September (Gloersen et al., 1992), whereas in Northern
Hemisphere, seasonal sea ice extent varies by a factor of 2 from a minimum of 7 to 9 MSKM in September to a maximum of 14 to 16 MSKM in March (Gloersen et al., 1992). The months of maximum/minimum ice cover area lag behind the peak winter/summer by about 2 – 3 months in both the hemispheres.

1.1.3 Land Ice

Approximately 77% of globe’s fresh water is available in the form of ice sheets and glaciers, which therefore, serve as the greatest potential source of fresh water on the earth. Fresh water in ice bodies corresponds to 71 m of sea level equivalent, with Antarctica contributing about 90% of this and Greenland contributing almost 10%, and other ice bodies and glaciers contributing less than 0.5% (World Climate Research Program, 2001).

Glaciers/ice sheets have thickness of hundreds of meters and are found in the cold and temperate regions of the earth and sometimes at high altitudes in tropical regions also. The two major ice sheets of the earth are located in Greenland and Antarctica. Antarctic ice sheet comprises of a 3000 m – 4000 m high ice plateau, whereas Greenland ice sheet has lower elevations that exceed 3000 m in the center only. Both ice sheets play significant role in the global atmospheric circulation, especially in the global energy balance and in the movement of cyclonic systems in Polar Regions. There are large floating ice shelves in Ross Sea and Weddell Sea embayments and several smaller ones in other sectors, including the Antarctic Peninsula. Icebergs are released frequently into the sea through calving of ice-shelves and through outlet glaciers. These icebergs then slowly drift and melt away. Iceberg discharge from Greenland is estimated to be about $235\times10^{12}$ kg yr$^{-1}$, whereas that from Antarctica amounts to $2072\times10^{12}$ kg/yr (Church et al., 2001).

1.1.4 Fresh-water Ice/Lake Ice

The major cause of ice formation in rivers and lakes at high altitudes or at high latitude is, seasonal cooling. The interannual variability of the dates of appearance or disappearance of ice in lakes or rivers is affected by the local as well as large scale
weather processes/ phenomena occurring in that region. The indices (seasonally specific) of climatic perturbation can be inferred by studying the long time series of lake-ice observations.

1.1.5 Frozen Ground and Permafrost

Like snow cover, frozen ground covers a large expanse of the globe. Its areal expansion depends on seasonal effects. Its depth and distribution vary as a function of air temperature, snow depth, vegetation cover, ground moisture, and aspect with respect to solar illumination. Hence it shows a very high temporal and spatial variability.

Permafrost (perennial frozen ground) may occur where the mean annual air temperature is less than -1°C and is generally continuous in the regions where mean annual air temperature is less than -7°C (World Climate Research Program, 2001). It is estimated that permafrost underlies 24.5% of the exposed Northern Hemisphere land area (world climate research program, 2001), with a maximum areal extent between about 60°N to 68°N. Its thickness exceeds 600 m along the Arctic coasts of northeastern Siberia and Alaska, but thins towards the margin.

1.2 THE ROLE OF CRYOSPHERE IN CLIMATE SYSTEM: WITH SPECIAL EMPHASIS ON SEA ICE

The cryosphere is not only an integral part of the global climate system, but also a sensitive of any indicator change in that system. It affects the climate through complex processes. Cryospheric signatures of climate change are strong because of the nature of the melting process. Increase in air temperature increases the downward heat flux in both as sensible heat and as long wave radiation. Melting surface may not able to compensate the anomalous increasing incident heat flux by emitting more long wave radiations as that of the normal surface. Thus the surplus heat energy is used for more melting. On the other hand the formation of sea ice/snow cover reflects the incoming solar radiation, causing the surface cooling, which enhances the more and
more ice formation. This is why sea ice, snow cover and glaciers are more sensitive to temperature variation.

1.2.1 Cryosphere as an Indicator of Climate Change

Polar regions are the heat sinks of the great global heat engine. These regions play a major role in the interaction between the atmosphere, ice, oceans, biota and the land surface. These interactions will have effect on the total earth atmosphere system through feedback mechanisms, biogeochemical cycle, deep ocean circulation, change in ice mass balance and the atmospheric circulation. Many unique climate processes operate in these regions. Some involve complex interactions and feed back loops that may lead to glacial-interglacial climate transition (Petit et al., 1999; White and Steig, 1998). The contrast in the heat balance between the equator and the poles drives the atmospheric and the oceanic general circulation. Polar sea ice cover, ranging between 15 MSKM and 19 MSKM in areal extent, is an important component of the global climate system. Its growth and decay have significant impact on the world ocean circulation and the large-scale oceanic heat and mass transport (Park et al., 1998; Brix and Gerdes, 2003). The heat budget of the polar regions is dominated by the presence of sea ice, which reduces the amount of solar radiation absorbed at the earth’s surface by a factor of five or eight. This is due to the high albedo of sea ice, which ranges between <0.5 for melting bare ice and >0.85 for snow covered, cold ice. In contrast, the ice-free ocean has an albedo of below 0.1. The inclusion of melt ponds to different thermodynamic sea ice models significantly strengthen the sea ice-albedo feedback, while the sea ice thickness distribution decreases the strength of the modeled sea ice-albedo feedback (Curry et al., 1995). Also, ice cover in the sea (sea ice) serves as an effective insulator between the ocean and the atmosphere, limiting the exchange of heat, mass, momentum and chemical constituents between the ocean and the atmosphere. Ice has high albedo. It reflects almost total incoming solar radiation. As a result the sea surface cools and so does the air mass above the surface. This, in turn enhances the formation of ice. On the other hand, water absorbs most of the incoming solar radiation, which ice does not. This means that surface energy budget of an open polar ocean differs significantly from that of the ice covered one. The melting of ice leads to more and more absorption of the solar insolation providing more and more
latent heat of fusion to the remaining ice, thus accelerating the melting rate. This positive feedback affects the global climate in a significant way. A modeling study by Smith and Klinck (2002) showed that ice-melting in the spring is a two stage process. First, the open water is heated, by solar radiation, and then the warmer water leads to the melting of ice in contact with it. The direct melting for ice by solar heating is negligible (Smith and Klinck, 2002). Above all, the large seasonal variation of sea ice cover at the poles affects the energy balance of the globe in a significant way.

Cryosphere acts as a sensitive indicator of climate change. It is found from the model studies that the increase in temperatures in the polar regions would be substantially higher than that in the tropical and the temperate regions. For example, one estimate is that an average global temperature rise of 2°C would be accompanied by a 10°C increase in the Arctic (Editorial, Science, 1989). The global average surface temperature has increased by 0.6 ± 0.2 °C over the 20th century, where as in the Arctic, extensive land areas show a warming of as much as 5°C in air temperature. The model sensitivity study in doubling of CO₂ situation showed thinner ice amplifies the atmospheric temperature sensitivity by about 15% (to a warming of 4.8°C) (Rind et al. 1995). Over sea ice, there has been a slight warming in the 1961 – 1990 period. The analysis of in situ surface air temperature data from the Antarctic shows a predominantly positive trend, as high as 0.5°C per decade along the Antarctic Peninsula (Comiso, 2000). In the Antarctic, over the last five decades, there has been a marked warming trend in the Peninsula region. In the sea ice regions, the northern most positions of the ice edge are shown to be influenced by spatially alternating warm and cold anomalies around the continent (Comiso, 2000).

The response of each individual component of the cryosphere may vary both spatially and temporally. Some of them may grow with time where as others may shrink. For example, Greenland ice sheet is thinning day by day and sea ice extent in the Arctic is reducing by ~3% per decade, possibly due to Global warming (Maslanik et al, 1996; Parkinson et al., 1999). The thicknesses of some Antarctic glaciers are decreasing. In places, sea ice is actually advancing, and most of the Antarctic is not warming at all or is even cooling (Thompson and Solomon, 2002, Kerr, 2002). Whereas the response of the West Antarctic Ice Sheet (WAIS) is not very clear. A positive mass balance of
26.8 giga-ton per year is reported in Ross Ice Shelf region in the West Antarctic (Joughin and Tulaczyk, 2002). On the other hand breaking of ice shelves from Antarctic Peninsula is also being reported frequently.

1.2.2 Role of Sea Ice in Global Climate: Importance to Antarctic Sea Ice

1.2.2.1 Effect of Sea Ice on the Energy Balance and the Atmospheric Circulation of the Antarctic

The differential heating between the poles and the equator is one of the major causes, which drives the hemispheric circulation. In polar region the retreat of the sea ice edge during the summer is mostly controlled by the solar heating of the ice (though the melting of ice due to direct heating is negligible (Smith and Klinck, 2002)), upper ocean and the atmosphere over the ice and the ocean. In mid-1980’s, the extent of the perennial ice in the Bellingshausen and Amundsen seas began to decline, mostly due to the regional warming in the vicinity of the Antarctic Peninsula ( Jacobs and Comiso, 1997; Jacobs and Comiso, 1993)

The impact of the high latitude surface conditions on the atmospheric circulation is mainly determined by the ice albedo feed back (Curry et al., 1995; Rind et al., 1997) and the heat fluxes between the open water within the sea ice packs (i.e. leads and polynyas) and the atmosphere (Andreas and Murphy, 1986; Andreas and Cash, 1999; Grotzner et al., 1996; Moore et al., 2002; Smith and Klinck, 2002). Both the albedo and heat fluxes depend on the percentile area covered by sea ice or by the concentration of the sea ice. As derive from satellite passive microwave radiometers, climatological sea ice data are commonly based on ice extent, defined as the area enclosed a certain minimum threshold (usually taken as 15%) concentration contour. Even in winter, the ice concentrations are mostly below 100% due to the constant opening of cracks and leads between ice floes. During austral winters of 1974-76, a large polynya (large region of open water surrounded by ice) persisted in the ice-covered Weddell Sea (Gordon, 1978; Carsy, 1980). Polynya affects the surface meteorology of the region in a great way. In a polynya, the absence of sea ice exposes the relatively warmer surface of water to the cold polar atmosphere, which can lead to
intense exchange of heat and moisture between the ocean and the atmosphere (Smith et al., 2002; Moore et al., 2002; Wu et al., 2003). A study by Moore et al., (2002) showed that surface air temperatures over the polynya are 20°C higher than the climatology. They also reported that the cloud cover over a polynya is 50% higher than the climatological value. During winter months, the sensible and the latent heat fluxes over the polynya are of the order of 150 and 50 watt/m² (Moore et al., 2002).

Study of different models (Semtner level-3, Maykut and Untersteiner, Curry and Ebert “slab” model) showed that models are very sensitive to warming perturbations (Curry et al., 1995). These models show that a complete summer time melting of the sea ice perturbed the surface flux within a range of 3 to 5 watt/m² (Curry et al., 1995). Where as the ice thickness distribution model and Semtner level-0 model showed that during the summer time melting the surface heat flux perturbation ≥ 8 watt/m² (Curry et al., 1995). They also suggest that the ice albedo feedback mechanism appears to be particularly sensitive to melt ponds, the ice thickness distribution and the treatment of conduction within the ice (i.e. vertical resolution, temperature and salinity dependence of thermal diffusivity).

An analysis of 20 years (1979-1998) of monthly sea ice concentration, sea ice drift and sea level pressure data in the Weddell Sea by Venegas and Drinkwater, (2001) showed that anomalous atmospheric patterns reached Weddell Sea periodically from the west. This effect may be attributed to the Antarctic circumpolar wave as described by White and Peterson (1996). This anomalous atmospheric modification perturbs the sea ice circulation and distribution in the Weddell Gyre through changes in the intensity and the direction of the winds. Sea ice margin responds actively to atmospheric forcing. For example: the low pressure system developed modified the regional distribution of sea ice, which leads to enhance the sea level and thermal gradients, thus providing a favourable condition to cyclogenesis (Yuan et al., 1999)

1.2.2.2 Effect of Antarctic Bottom Water on Global Ocean Circulation

Sea ice formation/depletion also affects the ocean circulation. When sea ice is formed, the brine (more concentrated saline water) is ejected to the seawater under neath.
Thus, the salt concentration in the upper layer of the ocean in that region increases. The seawater becomes denser than the surrounding water masses and therefore, sinks down to form intermediate and deep water. The spreading paths of newly formed Antarctic deep and bottom waters over the slope regime, and their subsequent oceanic circulation patterns were analyzed by Orsi et al. (1999). Orsi et al. (1999) did two experiments on chlorofluorocarbon (CFC) budget estimation in the Southern Ocean. In their first experiment, they neglected the loss of CFC-bearing waters across the top isopycnal, and in their second experiment they assumed the bottom layer to be well mixed. From these two experiments they calculated the total Antarctic Bottom Water (AABW) production rate to be about 8 Sv (8×10^6 m^3/sec) and 9.5 Sv (9.5×10^6 m^3/sec) in first and second experiments respectively. Another important phenomenon occurs under the divergent sea ice condition (i.e. leads and the polynyas) is air-sea interaction. The reduced ice concentrations, in the leads, enhance the air-sea heat fluxes. Over the leads there is strong coupling between atmosphere and the ocean. This phenomenon is mostly associated with the surface cooling and the formation of new ice. New ice formation yields strong brine rejection to the water underneath. Similar process happens in polynas also. Within the polynya there is a vigorous air-sea interaction resulting in the densification of the surface water. This brine rejection process or the densification, which accelerates with the sea ice growth, acts to destabilize the upper water column (Martinson and Iannuzzi, 1998). Especially in Southern Ocean, this results in the entrainment of warm, deeper water into the mixed layer and possibly deep penetrating overturning in case of open ocean convection (Martinson, 1990; Gordon and Huber, 1990; Akitomo et al., 1995). This buoyancy flux activates the over turning of the water column and thus more heat starts getting delivered to the surface to be vented to the atmosphere. Such convective process or upwelling condition leads to large quantity of heat release to the atmosphere, but require persistent ice divergence to remain active. During the winter season the average buoyancy flux within the polynya is negative. This indicates that the surface waters are becoming more denser, thereby driving oceanic convection and the Antarctic bottom water formation.

Seasonal and interannual variation of the sea ice cover significantly affects the water mass modification in the Weddell Sea and the Ross Sea basins (Jacob and Comiso, 9
1989; Comiso and Gordon, 1998; Markus et al., 1998). In these two key regions of Antarctic, ice formation and melting influence the upper ocean stability by changing the salinity and buoyancy gradients (Martinson and Iannuzzi, 1998). Both mechanisms may have an impact upon the water mass modification process leading to profound impact on global thermo-haline circulation patterns. Using a global three-dimensional ocean general circulation model coupled to a dynamic-thermodynamic sea ice model, Brix and Gerdes (2003) found that buoyancy changes in the Weddell and Labrador Seas exert a direct effect on the overturning cells of the respective hemisphere. They also found that buoyancy changes in the above regions influence the density structure of the ocean and thereby leading to alterations in the strength of the Antarctic Circumpolar Current (ACC).

The bottom water formation near the ice shelves is more significant. The eventual down slope flow of cold and high salinity shelf water, incase of near boundary condition (with respect to open water) determines the deep and the bottom water formation (Gordon, 1998; Killworth, 1983; Whitworth et al., 1998; Jiang and Garwood, 1995; Orsi et al., 1999). An important role is played by the bottom water produced from the continental shelf surrounding Antarctica in high latitude physical processes in global GCM (Kim and Stossel, 1998).

The growth and melting processes of ice have direct implication on the mass balance of sea ice. A fundamental difference exists between the growth of ice in the Antarctic and in the Arctic. In Antarctic, frazil ice occurs where the open ocean wave field interacts with the growing ice cover, quickly expanding the ice edge by lateral accumulation. Whereas in the Arctic, most ice growth occurs via bottom accumulation, offsetting vertical heat conduction through the ice. Sea ice dynamics involves the ice motion and deformation (World Climate Research Program, 2001). Sea ice dynamics directly contributes to the energy and moisture exchanges by creating the open water regions within the ice (which are described above). Ice transport plays an important role in redistributing the fresh water and thereby influencing ocean water mass properties, deepwater production rates and circulation. The bottom water slowly moves equator-ward, due to the temperature gradient and the salinity gradient, affecting the ocean circulation over the climatic time scale (Brix
and Gerdes, 2003). Melting ice near the edge of the Antarctic continent produces low salinity water that mixes with the upwelling from the southward moving Atlantic deep current (see fig 7.8 of Pickard and Emery, 1993). This mixture is then divided into two components. The first component appears in the form of the northward flowing Antarctic surface current. The second component sinks to become the Antarctic intermediate current, and then finally turns into Antarctic bottom current, which is relatively more saline and cold.

Ice bergs drifts into the southern ocean, slowly break up and continually melt, resulting in widely extended water masses cooled noticeably and so the air above the water also gets cooled. The effect of the coolness on the weather in and around the field of the icebergs is felt almost immediately as fog forms and persists tenaciously. The iceberg cooling effect on the climate of much wider areas is potentially even more important, in particular those observed in the southern Atlantic. This is more important not only for the ice budget problem, but also for the understanding and the forecasting of sub-Antarctic temperatures.

On the other hand, the ocean influences the sea ice processes mainly through the oceanic heat advection and the entrainment of heat at the base of the mixed layer. This heat flux has large spatial gradients (near the coastlines, sea ice margins and new ice formation zones) and large temporal variations (larger values occurring in early and the mid winter). Experiments conducted with coupled sea ice–ocean models illustrate the importance of ocean currents and oceanic heat flux on the simulated ice cover.

1.2.2.3 ENSO and Sea Ice

El-Nino Southern Oscillation (ENSO) is a phenomenon, which affects the global climate system in a significant way. El-Nino is associated with monsoon failure and droughts in South-east Asia, heavy rains in the eastern part of North America, Heavy rain fall in Brazil etc. El-Nino is the major climatic variation having a periodicity ranging from 2 to 7 years. El-Nino is marked by the increase in the sea surface temperatures (SST) in the Eastern Equatorial Pacific. The cause of El-Nino is the failure of trade winds, which can be attributed to Southern Oscillation. Southern
Oscillation is referred to the seesaw in the surface pressure anomalies between the Indian Ocean -Australian region (Darwin) and the southern tropical Pacific Ocean (Tahiti) on a seasonal and inter-annual time scale.

Many studies have been carried out to explore the possible teleconnection between ENSO and Antarctic sea ice extent. Gloersen, (1995) found quasi-biennial and quasi-quadrennial periodicities in both the Arctic and the Antarctic sea ice extent, which he associated to the ENSO variations. For this he used the multiple window harmonic analysis technique. White and Peterson (1996) analyzed the Antarctic sea ice extent and the anomalies in Sea surface temperature (SST), surface pressure and wind speed, and found a wave like behaviour to be quasi-periodic with an approximate periodicity of 4 – 5 years. These anomalies move eastward with ACC and take 8 – 10 years to encircle Antarctica. They named it as Antarctic Circum-polar Wave (ACW). They suggested that the ACW is associated with the ENSO related activities in the Equatorial Pacific. White, et al. (1998) tried to explain this teleconnection by the transfer of ENSO signal from the sub-tropical South Pacific through vertical convection and an overturning cell in the troposphere. Also, the lengthening/shortening of sea ice seasons in different sectors of the Southern Ocean were related to variability of the ACW (Parkinson, 2002). Yuan and Martinson (2000) reported that the Antarctic sea ice edge anomalies in Amundsen, Bellingshausen and Weddell Seas are strongly linked with the extra-polar climate. They also showed that 34% variation in sea ice edge anomalies are related to ENSO indices. Recently, a study by Kowk and Comiso (2002) depicts the strong correlation between the Southern Oscillation Index (SOI) and the polar climate anomalies found in the Bellingshausen & Amundsen and Ross seas. They also reported that significant retreat in ice cover of the Bellingshausen and Amundsen seas were observed showing a unique association of this region of the Antarctic with the Southern Oscillation.

1.3 SOCIAL AND ECONOMIC IMPACTS OF CHANGES IN THE CRYOSPHERE

Changes in the extent and the characteristics of global snow and ice cover will have a broader impact on the climate system. It may modify the major modes of atmospheric
circulation such as ENSO, the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), Antarctic Oscillation (AAO) and others. Which, in turn, may modify the temperature and precipitation anomalies throughout the globe. Thus, the perturbed climate system may cause extreme events such as storms, floods and droughts. Cryosphere has direct or indirect socio-economic impacts, which may have both, the beneficial and the detrimental consequences. The improved knowledge to detect and predict regional climate and environmental change patterns is very important for various socio-economic activities thriving in different parts of the world.

1.3.1 Role of Cryosphere in the Hydrology of the Region

Cryosphere has a large effect on the hydrology of a region. For many dry climate regions like the western United States, northwest China, Central Asia and Andean countries, cryosphere serves as the source of water. The changes in the amount and the timing of the snow cover area, snowmelt run off from mountain snow packs and glaciers have significant impact on the water resource management of the above countries. This also impact on hydropower projects due to the changing inflow of water in rivers, having glacial origin. For example the hydropower operation in the Himalayas, Alps, Canada, New Zealand etc. would be affected by any modification in the cryosphere in those regions. The changes in the amount and the distribution of continental snow cover will directly impact the magnitude of spring runoff and the characteristics of annual runoff hydrology. This would affect the nature and the occurrence of floods and droughts, irrigation needs (for example Ganga Basin in India), community water supply, wetland recharge and moisture supply for the spring planting. This also would have a direct impact on the functions of ecosystems in these regions.

1.3.2 Effect of Cryosphere on Navigation and Oil/Mineral Exploration in Polar Regions

Navigation in the polar seas is significantly affected by the sea ice extent, concentration and thickness. For example persistent reduction in Arctic or Antarctic sea ice cover will allow marine operations through normally ice covered regions, such
as the North-West passage. It is a benefit to marine transport. Snowfall frequency and magnitude directly affect road and rail traffic and aircraft operations. River and lake ice provide winter road to remote areas. Freshwater ice can have significant influence on aquatic and riparian ecosystems, geo-chemical processes and sediment transport (Ferrick and Prowse, 2000)

The building design in the seasonally frozen ground faces lot of challenges and results into higher building costs. The changes in permafrost regions have direct impact on construction of buildings, pipelines, roads and railways in the Arctic and the sub-Arctic regions. Improved observation and prediction of sea ice variability will lead to increased operational ability for the exploitation of potential hydrocarbon resources in the Arctic region.

### 1.3.3 Sea Level Rise and its Impact

Cryosphere attracts human attention more and more due to its direct effect on sea level rise. Sea level rise poises diverse range of threats to human settlements, natural ecosystems and landscape in coastal zones. Relative sea level scenarios (i.e. sea-level rise with reference to local land surfaces) are of great interest for the impact and the adaptation assessments and for the future of human race living along the coastal tracts. Tide gauge and wave height records of about half a century or more are required along with information on severe weather and coastal processes to establish the base line levels and trends.

Rising of the concentration of CO$_2$ and other greenhouse gases in the atmosphere will cause the air temperature to increase leading possibly to changes in precipitation patterns. These changes would direct impact on the great ice sheets, ice caps and the glaciers all around the globe (Rind et al., 1995). However, the response to climate change/sea level rise depends on several regional factors. Some glaciers or ice sheets may grow (a positive mass balance of 26.8 giga-ton per year is reported in Ross ice streams in the west Antarctic (Joughin and Tulaczyk, 2002)) whereas others may shrink (thinning of Greenland ice sheet, the breaking of ice shelves from Antarctic Peninsula are reported). We get mixed response from the Antarctic regions. The
thickness of glaciers in the eastern part of the Antarctic is increasing possibly due to heavy precipitation in that region, whereas the response of the West Antarctic Ice sheet (WAIS) is not very clear. These studies suggest that the effect of global warming on different glaciers show regional dependence. The over all confidence about their contribution to sea level rise is positive with glaciers and Greenland ice sheet shrinking. The contribution from Antarctica to sea level rise is still uncertain.

1.4 SUMMARY OF THE CHAPTER

In this chapter we have given a brief description of the different components of the cryosphere and the importance of the cryospheric studies. We have also mentioned about the model deficiencies in representing the cryospheric processes. We have also briefly described the climatic, social and economical importance of sea ice studies. In our next chapter we will describe the principles of remote sensing and different types of remote sensing (i.e. visible, IR, microwave remote sensing) studies of the cryosphere.