Hupfer, P. & A. Helbig (2007): Ocean and cryosphere and their effects on the global water budget and the climate. In: Lozán, J. L., H. Grassl, P. Hupfer, L.Menzel & C.-D. Schönwiese. Global Change: Enough water for all? Wissenschaftliche Auswertungen, Hamburg. Online: www.klima-warnsignale.uni-hamburg.de

1.4 Ocean and cryosphere and their effects on the global water budget and the climate

PETER HUPFER & ALFRED HELBIG

SUMMARY: *The water budget of the world ocean as well as of individual oceans is explained in their essential features. The Atlantic Ocean is the main water supplier for the surrounding continents. It is shown how the difference of evaporation minus precipitation influences the salinity as an outstanding oceanic property and thus the climatic relevant process of the thermohaline circulation in the ocean. Peculiarities of the water balance characterise the hydrographic regime of adjacent seas. During the Earth's history variable masses of water have been bound in the cryosphere. The main characteristics of the different kinds of ice are described. Especially the climatic importance of the large ice sheets of Antarctica and Greenland as well as of the sea ice is discussed. In connection with the present global warming the occurrence, area and thickness of sea ice is decreasing.*

The world ocean and the cryosphere with its different kinds of frozen water on the Earth are water reservoirs within the global water cycle. Together with the atmosphere they are of exceptional importance for the climate and its change. The ocean covers about 71% of the Earth's surface, where the main water turnover takes place. The ocean is the main source for the hydrological continental cycle. Important processes and states in the ocean are directly depending on the water budget. Ice occurred during the Earth's history in very variable volumes and forms. It varied in extent, thickness, time constants and it has therefore different effects with regard to external disturbances as well as to the climate system.

The oceanic branch of water cycle and its impacts

The water budget of the world ocean

Assuming the total water mass on the Earth being constant, the equation for the marine branch of the global water cycle is

$$\delta W = (E_O - P_O) + (F - M) + R_C + T \qquad (1)$$

with δW = change of water volume, E_O = oceanic evaporation, P_O = oceanic precipitation, F = gain of water by melting ice, M = loss of liquid water by freezing and R_C = runoff from the continents and islands. The term T takes into account the increase or decrease of water volume by thermal expansion or contraction. At present, its value is about 0.1–0.2% of E_O and the amount lies within the error limits of the evaporation values. In future T will become probably more important.

Investigating regional parts of the ocean, it is necessary to consider the inflow and outflow of water by currents. Restricting to long-term mean values and neglecting the thermal expansion, eq. (1) simplifies to (see also Chapter 1.3)

$$E_O - P_O = R_C. \qquad (2)$$

More detailed numbers of the marine water budget are presented in *Table 1.4-1*. The balance of 610 km³/year includes not only the resulting error of determination of

Table 1.4-1: Data on the mean annual properties of the marine water budget according to two different computations. For comparison volume rates being output of a climate model experiment (see also *Table 1.3-1*).

Oceanic water budget components	*Mean volume rate 10^3 km³/year after* KLIGE et al. (1998)	*Change of sea level mm/year*	*Mean volume rate 10^3 km³/year after* TRENBERTH **et al (2006)**	*Climate modell ECHAM4 (2001) for 1990–1999 10^3 km³/year*
Evaporation	507	- 1,401	413	453
Precipation	457	+ 1,264	373	411
River runoff	44	+ 122	40	46
Supply by melting ice	4	+ 11	Data not available	Data not available
Groundwater runoff	2,500	+ 7	Data not available	Data not available
Balance	***1***	***+ 2***	***0***	***4***

up.hupfer@freenet.de

the regional terms, but also the expansion of the ocean volume due to the world-wide increase of sea temperature in the upper layer (term T). The corresponding change of sea level agrees with the currently measured mean variation of sea level. *Table 1.4-1* demonstrates that deviations between empirical and climate model data on the one hand reaches more than 10% and on the other hand the data reflect the relative magnitude rather well.

Decisive significance has the surplus of E_O with regard to P_O. By this process water vapour reaches the air. After condensation this process strengthens the terrestrial water cycle and contributes to the water supply of the continents (see Chapter 1.6).

The determination of the water budget components, especially for short time intervals of averaging, is still afflicted with considerable errors. The most exact data are those of river runoff based on measurements. Usually the evaporation is computed from oceanic climatological data like surface air temperature, sea surface temperature, water vapour pressure and wind velocity. Most critical is the determination of the precipitation above sea, despite of use of radar and satellite based methods. For long time intervals of averaging the data are mostly derived from observed precipitation frequencies above sea and of data from stations on islands and at the coast. From such data the values of P_O can be estimated.

Above the oceans P_O (see Chapter 3.1-1) and E_O (see Chapter 1.5-1) are irregularly distributed. The annual means of E_O show areas with maximum values in the subtropics. These are described as source areas of the water cycle. In contrast the precipitation shows high values in the middle latitudes (see *Fig. 1.4-3*) and especially near the equator. These zones are the sinks of the water cycle.

The spatial inhomogeneity is superimposed by temporal changes of the oceanic components of the water budget in a broad range of periods. Beside of the daily and yearly variations (KESSLER 1985, p. 97ff) and irregular fluctuations there are climatic alterations of different amplitudes and periods. *Fig. 1.4-2* presents the course of the properties since 1880. The curves for E_O and P_O show a well defined maximum about 1940. This time coincides with the peak of the first global warming in the 20th century (HUPFER & KUTTLER 2005, HUPFER & TINZ 2006). This makes clear, that a global warming is connected with an intensification of the marine water cycle. Such intensification is also expected as a part of the global climate change in the 21st century (see Chapter 3.1.4). Those long-term variations of the oceanic water budget components are equally cause and effect of interactions and feedbacks within the climate system of the Earth (HUPFER & KUTTLER 2005).

Atlantic Ocean as water supplier

A view on the water budget of the individual oceans (*Table 1.4-2*) is also of interest. Depending on the size of

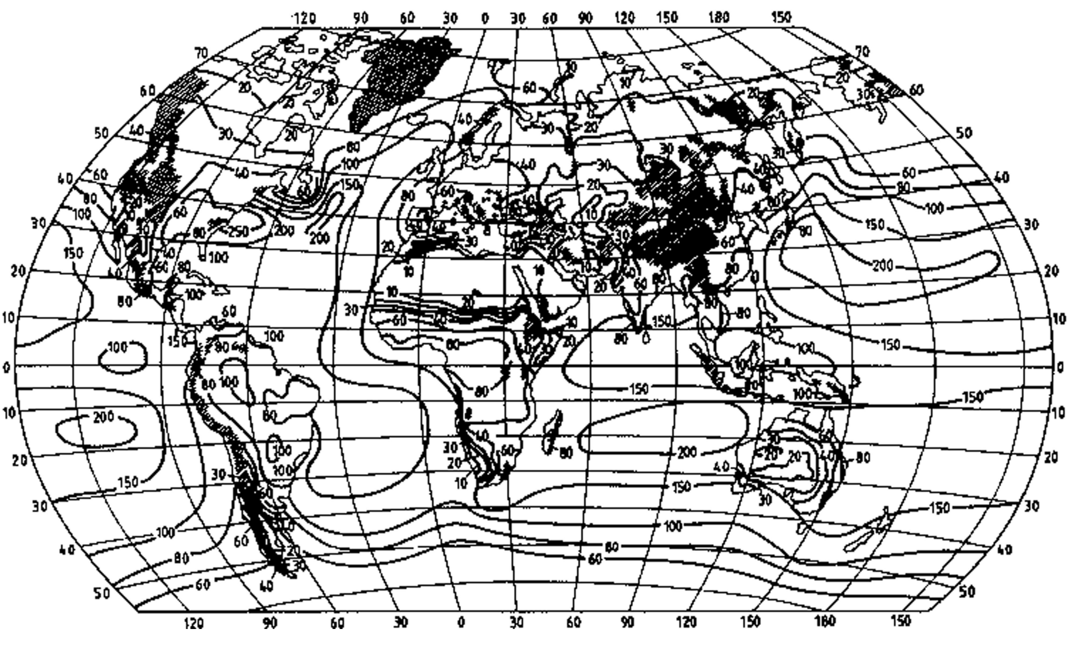

Fig. 1.4-1: Global distribution of the annual mean values of evaporation in cm/year (from the multiplication of the values with 0.72 follows the latent heat flux in W/m^2 (data after Budyko, here from HUPFER & KUTTLER 2005, p. 65).

their evaporating areas, the oceans contribute in a different way to the water supply of the continents. In contrast to the Pacific Ocean, the Atlantic Ocean is not surrounded by high marginal mountains. Water vapour enriched Atlantic air masses can spread out relatively unhindered above large continental areas. After condensation the rain precipitates. If air masses flow from the Pacific to the surrounding continents then the rain precipitates already near the coasts.

The Atlantic Ocean has a negative total balance with a maximum mean difference between E_O and P_O. The Indian Ocean behaves in a similar way. Due to the high precipitation, the Pacific Ocean with its large tropical areas has a water surplus. The compensation takes place in the large, oceans linking circumpolar current around Antarctica.

Thermohaline oceanic circulation

The global oceanic circulation is mainly wind-driven. But it has an important thermohaline component, too. The thermohaline circulation is defined as that part of all ocean currents, which is caused by the variable spatial and temporal deviations from the mean horizontal density distribution. Such deviations are primarily caused by E_O and P_O (Willebrand 1993).

The density of seawater depends on temperature and salinity and at a lower degree on the hydrostatic pressure, too. A statistically significant linear correlation exists between the zonally averaged salinity value immediately below the frequently disturbed surface layer and the difference E–P. This relation has discovered at first the German oceanographer Georg Wüst (1890–1977). The greater E, the higher is the salinity. The more precipitation is falling on the sea surface, the smaller is the salinity (*Fig. 1.4-3*). The density of seawater is increased by E_O both due to the salt enrichment of seawater and to the cooling by withdrawal of heat of vaporisation. In the case of precipitation the density is reduced in connection with the decrease of salinity. In addition, inclinations of sea level are produced by the corresponding decrease (in the case of E_O) and increase (in the case of P_O) of water volume, respectively. By these processes barotropic currents are generated.

The thermohaline circulation plays a very important role for the climate and its variability by its contribution to the heat transport from the tropics into the sub-polar and polar regions. The reduction or even the total break down of the meridional heat transport in the North Atlantic can lead to dramatic cooling effects in extended regions of Europe. This emphasises that the marine branch of the global water cycle has also a great importance with regard to climate change.

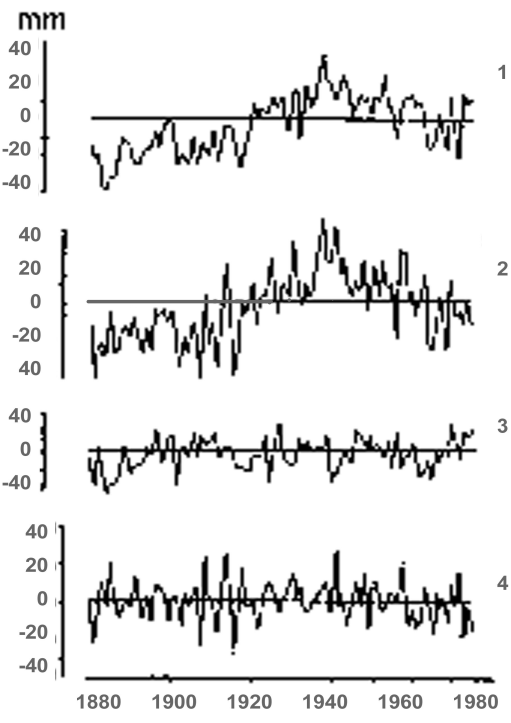

Fig. 1.4-2: Anomalies of annual mean values of evaporation E_O (1), precipitation P_O (2), water supply by river runoff and melting ice R_C (3) as well as water balance $P_O+R_C-E_O$ (4) for the ocean after Klige et al. (1998, p. 344).

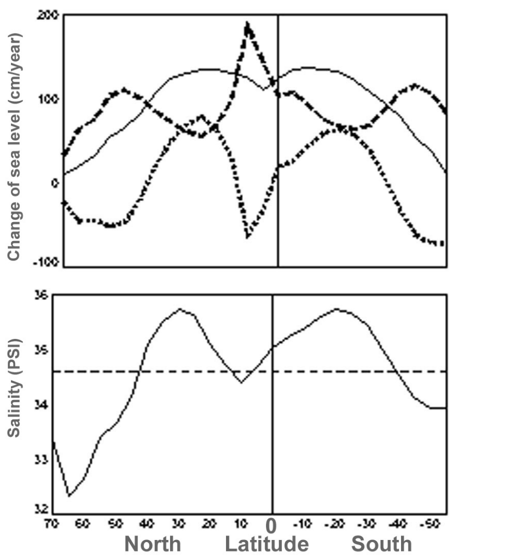

Fig. 1.4-3: Zonally averaged annual means of evaporation E_O (*above, drawn*), precipitation P_O (*above, broken*), difference E_O–P_O (*above, dotted*) as well as salinity S (*below*) for the oceans (including adjacent seas). Data after Wüst et al. (1954).

Peculiarities of adjacent seas

The adjacent seas show oceanographic peculiarities depending on their climatic situation. It is a decisive condition whether the adjacent seas and their catchment areas are located in a humid or in an arid climate zone. We have humid conditions, if the precipitation exceeds the evaporation, and vice versa in the case of arid conditions. The most representative adjacent seas of these two types are the Baltic Sea and the Mediterranean Sea, respectively. They have the following mean water budget numbers, for comparison expressed in relative units:

outflow – inflow = precipitation + runoff – evaporation
Baltic Sea: 100.0 = 49.3 + 89.0 – 38.3 (%)
Mediterranean Sea: -100.0 = 36.8 + 14.5 – 151.3 (%)

In humid conditions precipitation and river runoff dominate, in contrast to that in the arid case the evaporation dominates. This leads to principally different hydrographic basic states. The humid adjacent seas have low salinity (brackish water) in the surface layer and inflow of water with higher salinity in the lower layer. In the gates between ocean and an arid adjacent sea the situation is opposite (*Fig. 1.4-4*). The most inner parts of the Baltic Sea have a very low salinity, whereas the absolute maximum of salinity is observed in the most eastern part of the Mediterranean Sea (the same is valid for the arid adjacent seas Persian Gulf and Red Sea). In the neighboured oceans the high saline deep water can be pursued over long distances.

Ice occurrence

The global ice masses and snow deposits in form of the Antarctic and Greenland ice sheets, snow covers, sea ice, mountain glaciers as well as in form of ground ice compose the cryosphere. Already since the Precambrium the development of the Earth and its climate is characterised by interruptions of the existence of a cryosphere. Extent and thickness of the ice masses in its different forms have always been subjected to strong fluctuations. The Quaternary ice age was characterised by the alternating occurrence of glacial and interglacial periods with corresponding spread and retreat of the ice masses relative to the polar region. Today it is well-known that these time periods were connected with a high climate variability which caused these extensions or retreat of the cryosphere. The recent extent and volume of all components of the cryosphere is shown in *Table 1.4-3*.

In the global survey the water budget of the cryosphere is not separately shown. Depending on the location of ice and snow the corresponding values were assigned to the continental or oceanic water balance. As listed for the Arctic Ocean in *Table 1.4-2*, the precipitation, but even more the evaporation is much smaller as it is the case for the ocean in general and for the continents.

Interaction between cryosphere and atmosphere

For all components of the cryosphere it is common that they are highly differentiated in structure, volume and extent. Due to their physical properties (albedo, emissivity, heat conductivity, specific heat capacity, surface roughness, density) and their areal coverage they cause significant changes of the energy balance of the Earth surface. Beyond this they control the interaction at the interface between continents or oceans and the atmosphere crucially.

The seasonal variation of snow cover and of sea ice extent is mostly variable and therefore it is most sensitive against climatic change. As a result the reflectivity of short-wave radiation (albedo) of snow and ice surfaces plays the most important role. Although in Antarctica the observed global radiation fluxes in summer are much higher than in the Arctic (480 W/m² and 305 W/m² resp.), the high albedo of the Antarctic ice plateau has the consequence, that the short-wave net radiation in the Arctic is higher.

The sea ice cover controls the interaction between ocean and atmosphere. Therefore anomalies and variations of sea ice coverage modify the regional and even global climate through the concomitant variation of the energy balance. Significant effects can be induced by

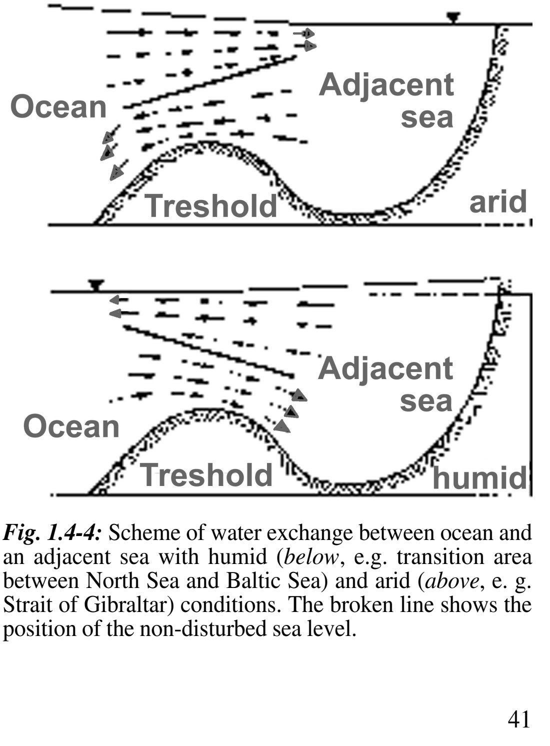

Fig. 1.4-4: Scheme of water exchange between ocean and an adjacent sea with humid (*below*, e.g. transition area between North Sea and Baltic Sea) and arid (*above*, e. g. Strait of Gibraltar) conditions. The broken line shows the position of the non-disturbed sea level.

macroscale changes of salinity of the ocean water as it appears during sea ice melting processes.

The ice cover changes the albedo and the aerodynamic roughness of the ocean surface. It forms a separate interface between atmosphere and ocean and maintains the salt exchange between the oceanic water bodies. These changes affect the radiation regime and the turbulent exchange of energy, momentum and water vapour, the salt balance and the thermohaline circulation in the world ocean (see above).

The water stored in the cryosphere is about 2% (approx. 30,000×10^3 km³) of the world storage of water. Without sea ice the storage amounts approximately to 1.7%. The freshwater supply of the Earth consists at 68.7% of the volume of the ice sheets of Antarctica and Greenland, all mountain glaciers and the continuously laying snow cover (Dyck 1980, Marcinek 1980). In the atmosphere ice occurs at a portion of 0.01%, which plays an important role in the global water and/or ice cycle (see Chapter 1.5). Thus the annual increase of the glaciers and ice sheets is produced nearly completely by the deposit of atmospheric ice. On average 11% of the land surfaces of the Earth and 7% of the world ocean are covered with multiyear snow and ice. During the year the coverage of ice and snow varies within a wide range. At the maximum the ice and snow-covered surface is twice as large on the Northern Hemisphere as on the Southern Hemisphere and the intra-annual fluctuation even three times as large (Untersteiner 1984).

Ice sheets

The ice sheets and mountain glaciers develop and exist in areas of land, on which more solid precipitation falls than it can melt and evaporate. Contrary to these regions with accumulation, in areas where melting and evaporation prevails ablation exceeds the snow accumulation. The velocity of the glacier growth depends on its thickness, on the supply and on the slope gradient of the glacier bottom. The inland ice and glaciers move from the accumulation areas into ablation areas and find their equilibrium line, where mass loss and supply hold themselves the balance. Every year 25×10^3 km³ water falls on the Earth surface in the form of snow, which is about 5% of the total precipitation. A third portion melts immediately again in the ocean, the remaining portion forms a snow cover on the continents, glaciers and on the sea ice.

Over the continent Antarctica an enormous ice sheet arches covering 98.6% of the continental surface. It acts as the most important factor on the climate regime of South Polar Region. The central part of the ice sheet has a maximum thickness of 3.5 km and possesses a mean topographic surface height of 2,450 m. The mass balance of Antarctica consists of the following components (in water equivalent): the accumulation amounts currently between 2,200–2,600 km³/year fed by atmospheric precipitation and sublimation of water vapour. The ablation is very small, amounting to 15–16 km³/year, since

Table 1.4-2: The mean water budget of the oceans. Numbers in mm/year after Baumgartner & Reichel (1975). 1 mm corresponds to 361 km³.

Ocean	***Precipitation*** P_o	***Evaporation*** E_o	***Difference*** $E_o - P_o$	***Runoff*** R_c	***Balance*** $P_o + R_o - E_c$
Atlantic Ocean	760	1,130	370	200	-170
Pazific Ocean	1,290	1,200	- 90	70	160
Indian Ocean	1,040	1,290	250	70	-180
Arctic Ocean	100	50	- 50	310	360

Table 1.4-3: Areas and volumes of all components of the cryosphere (after Hartmann 1994, Peixoto & Oort 1992).

			Area (10^6 km^2)	***Volume (10^4 km^3)***	***Portion of Total Ice (%)***
Land ices	Ice Sheet Antarctica		13.9	3,010	89.3
	Ice Sheet Greenland		1.7	270	8.6
	Mountain glacier		0.5	24	0.76
	Permafrost	permanent	8	20–50	0.95
		temporary	17		
	Snow cover	Eurasia	30		
		America	17	0.2 – 0.3	
See ice	Southern Ocean	Maximum	18	2	
		Minimum	3	0.6	
	Arctic Ocean	Maximum	15	4	
		Minimum	8	2	

the climatic snow border lies at the sea level and coincides with the coastal line. Basal melting due to the ice pressure supplies about 450 km³/year. Nearly one order larger is the iceberg production with 2,200 km³/year. An uncertain component in the mass balance is the amount of the snow transported with the katabatic wind across the coastal line, which can reach up to 20 km³/year. Altogether the mass balance is estimated as balanced or weakly positive on a long-term basis (DEWRY & MORRIS 1992).

The Greenland ice sheet is located at the margin of the Arctic region. Its extent amounts to $1{,}806\times10^3$ km², which is 82.5% of the surface of Greenland. The mean thickness of the ice sheet in the central part parallel to 72° N amounts to 2,300 m, the maximum thickness reaches between 3,300 m to 3,400 m, and decreasing to North and South. The ice volume amounts to 2.7×10^6 km³. The mean ice mass balance is characterised by accumulation from 600 to 620 km³/year with melting from 360 to 375 km³/year and an iceberg production of 251 km³/year (HOINKES 1968, STAUFFER 1980).

Permafrost and glacier

The ground ice is stored in seasonally and in permanently frozen ground, whereby the latter one covers an area of 32×10^6 km². The distribution of permafrost on the Northern Hemisphere, in the sub-polar latitudes of North America and Eurasia is particularly large. The thickness of the permanent frozen soil reaches in Siberia 1,300–1,500 m, in North Canada 400–600 m. The permafrost reacts in complex way very slowly to variations of climate.

Because of the total area of the mountain glaciers and its volume (smaller than 1% of the present ice volume) no considerable feedback is to be expected on the global climate. They are however very sensitive indicators for climatic change (see Chapter 1.6).

Sea ice

The formation of the sea ice and its physical properties are closely connected with the salinity of the sea water. In the world ocean with salinity over approximately 25 PSU*, the density of the sea water increases continuously with cooling. Therefore the convection-driven vertical circulation is not prevented and the entire water column cools. At the freezing point small ice particles form, which rise upward due to their lower density and create the ice cover there. As soon as sea ice exits, reciprocal effects of four components begin in a complex way: air, snow, ice and water. The salt withdrawal connected with the ice formation increases the stability of the upper ocean layer and suppresses at the same time the turbulent mixing and the exchange of radiation energy and latent heat with the atmosphere. In the shallow shelf waters around Antarctica, which are ice free in the summer, conditions with salinity of 33.5 PSU* represent the typical case. In contrast in the central Arctic Ocean exits a sharp pycnocline in 25–50 m depth, which represents the lower limit of Arctic surface water with temperatures near the freezing point and a salinity of 30 PSU. This lower salinity is maintained by the continental discharge of annually 3,300 km³ of freshwater (see also *Table 1.4-2*) (UNTERSTEINER 1984, BAREISS 2003). This density profile in the surface water is caused by the salt distribution – not temperature – and it is essential for the continuous existence of an almost closed cover of multiyear drifting and pack ice in the inner Arctic. The Arctic sea ice consists to 70% of multiyear ice. Openings in the ice cover – Polynjas – represent the places of ice production and formation of the cold deep water and constitute 2–15% of the total area. The maximum ice extent achieves the double amount in relation to their minimum. The pack ice possesses a mean thickness of 3 m. The disturbance of these conditions leads to a systematic decrease of the Arctic sea ice.

The decrease of the snow cover and land ice extent by approximately 10% since 1960 is positively correlated with the rising surface air temperature. The sea ice extent decreased in the Arctic since 1950 in the spring and summer by 10–15% concomitantly with a decrease of the sea ice thickness in late summers and early autumn by 40% in the period 1958–1976 (HOUGHTON et al. 2001).

The Antarctic sea ice covers over the course of a year up to 85% of the corresponding ocean surface and possesses a highly variable portion of ice-free channels created by divergent currents. Along the coastal line of Antarctica large quasi-permanent Polynjas exist. The coverage of Antarctic waters with sea ice varies seasonally between 18×10^6 km² in September and 3×10^6 km² in March. Already small shifts have consequences for the circulation of the atmosphere, because the changes take place most rapidly at that time, where the global radiation at the Earth surface reaches the maximum. Hence it follows that a modification (temporal shift) of the yearly variation of sea ice extent largely influences the solar radiation absorbed by the ocean.

The courses of the sea ice coverage both in the Arctic and in the Antarctic are displayed in *Fig. 1.4-5*. While in the Arctic the sea ice extent shows a negative trend, the Antarctic sea ice extent in the same period increases particularly in the summer months.

The ice drift produces heterogeneous sea surfaces with large variations of the surface properties at the margin between sea ice and water surface, which leads to local disturbances of the energy balance. Globally, an asymmetry exists between formation and melting of the

*PSU Practical Salinity Unit equals formerly used »parts per mille«

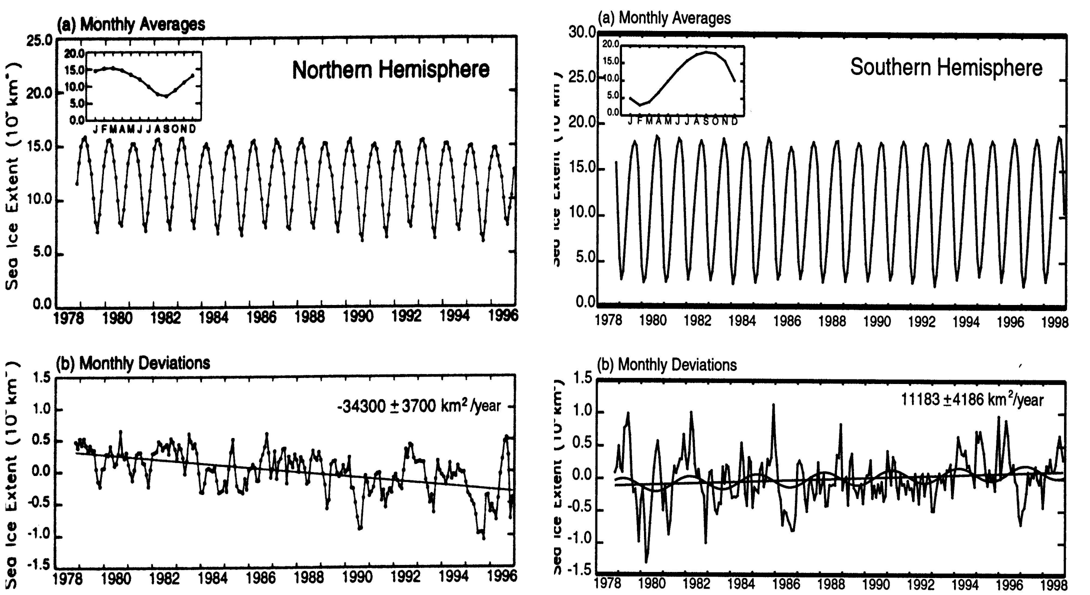

Fig. 1.4-5: Time series of the sea ice coverage in the Arctic (A) in the period 1978–1996 (after PARKINSON et al. 1999) and in the Antarctic (B) in the period 1979–1998 (after ZWALLY et al. 2002).

polar sea ice surfaces. The ice formation takes in the Arctic 5 months, in contrast in the Antarctic 7 months; the melting takes 7 months in the Arctic and 5 month in the Antarctic.

Quantifying the energy exchange at the interfaces atmosphere – sea ice and atmosphere – ocean is the challenge for resolving the discussed above effects of sea ice on climate. This applies also to all processes, which are effective at the margin of sea ice.

Final remarks

The oceanic branch of the global water cycle strengthens the terrestrial cycle and contributes crucially to the water supply of the continents and thus the human society. On the other hand the ocean is recipient for the water of the rivers and streams including its suspended materials. The oceanic water cycle exerts direct influence on important oceanic processes, which are responsible for climate and its change. Since billions of years the varying storage of water in form of ice and snow is a typical feature of the geologic history. Total quantity and extent of the frozen water are very variable in a large temporal scale. The climatic effects of the cryosphere are various. For the more exact knowledge of the oceanic and cryospheric processes further internationally co-ordinated research is required.