Polarforschung 66 (1/2), 11 - 18, 1996 (erschienen 1999)

Study on the Dynamics of Soil Moisture in an Ice-Free Area of the Fildes Peninsula, King George Island, the Maritime Antarctic

By Jie Chen[1] and Hans-Peter Blume[2]

Abstract: *In situ* observation of dynamic changes in free-water contents of soils at two sites (Eutri-gelic Regosol and Dystri-gelic Cambisol) was carried out in the ice-free area of the Fildes Peninsula, King George Island, the maritime Antarctic, by use of the specially developed moisture-sensing probes as sensors. The variation of freeze-thaw and moisture status of the soils, caused by site differences, is demonstrated. In addition, the possible differences of freeze-thaw cycle and moisture status of the soils between two years, resulting from variation of climatic factors etc., are discussed. Finally, several general conclusions on regimes and dynamic changes in free-water contents of soils in the studied area are tentatively drawn.

Zusammenfassung: Von zwei typischen Böden der eisfreien Fildes-Halbinsel der König-Georg-Insel (einem eutrophen Regosol und einer dystrophen Braunerde) wurden in verschiedenen Tiefen die nicht gefrorenen Wassergehalte im Jahreslauf durch die Messung der elektrischen Leiffähigkeit erfaßt. Die Ergebnisse von beiden Böden über zwei Messjahre werden miteinander und mit dem Temperatur- und Niederschlagsverlauf verglichen. Die Ergebnisse werden in ihrer Bedeutung für die Bodenbildung diskutiert.

INTRODUCTION

Since the earliest report on Antarctic soils (JENSEN 1916), numerous pedological investigations have been carried out in various localities of Antarctica, and a vast amount of information on weathering, formation, properties, distribution, zonalities and classifcation of Antarctic soils is available (e.g. BOCKHEIM 1980, CAMPBELL & CLARIDGE 1969, 1987, BOCKHEIM & UGOLINI 1990; BLUME et al. 1997). However, few studies focussing on soil moisture have been conducted in Antarctica because of technical problems and operative difficulties under the harsh conditions of Antarctica, although the formation, development, property and distribution of Antarctic soils could be reflected in soil-moisture availability due to its influences in periglacial movement and cryoturbance, biological activity and organic matter accumulation, leaching and illuviation, podzolization and rubification, salt situation and redistribution, other soil-forming and pedological processes etc. (BARSCH & STÄBLEIN 1984, BOCKHEIM 1995). As a result, little systematic and comprehensive data on soil moisture is available so that a number of appraisals on the basis of meteorological observation and of inferences in terms of theory are usually involved in Antarctic soil investigations which are related to soil moisture and its dynamic variation.

Besides, the distribution, thickness as well as properties of continuous or discontinuous permafrost, on which most of Antarctic soils rest, are also strongly characterized by the soil-moisture situation (MCCRAW 1967, MACNAMARA 1969). According to BOCKHEIM (1995), for a better understanding of characteristics of the upper permafrost layer and of active layer dynamics in the cold regions of the world, the related moisture and temperature data should be needed in advance.

In situ observation on dynamic changes of available soil moisture was made in the ice-free area of the Fildes Peninsula, King George Island, during the first author's stay in Antarctica for more than one year, from December 1992 to February 1994. In this paper some of the originally collected data and preliminary results are generalised and discussed.

STUDY AREA

The Fildes Peninsula (centred at 62° 12' S, 58° 58'S) belongs to King George Island, one of the South Shetland Islands located near the northeastern extreme of the Antarctic Peninsula in the maritime Antarctic climatic zone (BLUME et al. 1977). The Peninsula measures about 3.5 km from east to west, and 7.5 km from north to south. Situated more northerly and surrounded by sea masses, the Fildes Peninsula is one of the warmest and moistest regions in Antarctica. According to the records of the meteorological observatory in the Chinese Great Wall Station located there, from 1985 to 1990 the mean annual temperature was about -2.1 °C, while the mean annual precipitation reached about 635 mm (XIE 1993). Both temperature and humidity are higher on the Fildes Peninsula than the most regions of Antarctica, thus making the peninsula mostly ice-free and favourable to the growth of lower plant vegetation (CHEN & GONG 1995).

In contrast with the soils in the regions of continental Antarctica, the soils of the Fildes Peninsula are more influenced by available water due to the higher temperature and precipitation. Shallow permafrost table, deep seasonal thawing, remarkable freeze-thaw action, evident material translocation, little soluble salt accumulation together with considerable biological activity etc. make the soils of the Fildes Peninsula rather different from the rest at the regions of Antarctica (ALLEN & HEAL 1970, EVERETT 1976, TEDROW 1977, CUI et al. 1989; CHEN 1993, ZHANG 1990).

---

[1] Prof. Dr. Jie Chen, Institute of Soil Science, Chinese Academy of Sciences, PO Box 821, Nanjing 210008, P.R. China.

[2] Prof. Dr. Hans-Peter Blume, Institute of Plant Nutrition and Soil Science, University of Kiel, D-24098 Kiel, Germany

Manuscript received 21 April 1998; accepted 23 March 1999

According to Bockheim & Ugolini (1990), the soils of Fildes Peninsula could be grouped into the Subantarctic High Tundra and the Antarctic Sub-Polar Desert Zone. After the FAO-Unesco System (1994) the soils on the Fildes Peninsula could be classified as gelic subunits of Histosols, Leptosols, Cambisols and Regosols. Some soils developed on the rookeries and strongly influenced by sea bird activities could be classified as Ornithosols (Blume et al. 1997), whereas the main soil types of the peninsula could also be accommodated within Histosols, Cambisols and Entisols of Chinese soil taxonomy (Chinese Soil Taxonomy Research Group 1995).

SITES

Two sites for *in situ* observation were chosen in a hilly, ice-free area in the middle of the Fildes Peninsula. Giving consideration to the local factors causing a variety of soil moisture such as relief, vegetation, snow cover etc., Site 1 is situated in the north-facing slope bottom of an igneous rock hill, Site 2 is located at the top of the hill with an elovation of about 50 m. The soil of Site 1 is formed on a young slope deposit fan and belongs to Gelic Orthic Entisol of Chinese soil taxonomy (Chinese Soil Taxonomy Research Group, 1995), and to Eutri-gelic Regosol of FAO system (FAO-Unesco 1994). The surface of Site 1 is devoid of vegetation and mostly covered by rounded, subangular, irregular pebbles, boulders and rock fragments in various sizes (from tens to half centimetres). Strongly affected by cryoturbance, the genetic horizons and structures are weakly developed within the soil profile of Site 1. The texture in the column varies from gravely coarse sand to sandy loam, mixing with fresh, unstained rock fragments. The occurrence of ice wedges indicates that the permafrost table is at a depth of 67 cm. Around Site 2, about 40 percent of the surface area is covered by outcrops which are partly colonized by the lower plant community dominated by lichen species *Usnea fasciate* and *Cornicularia aculeata.* The soil of Site 2 is developed from weathered bedrock, classified as "Umbric Pergelic Cambisol" (Chinese Soil Taxonomy Research Group, 1995) or as "Dystri-gelic Cambisol" according to FAO-Unesco (1994). The soil of Site 2 has a much shallower solum (less than 45 cm) than that of Site 1. Only a surface horizon ranging 5-10 cm, containing around 2 % organic matter is preliminarily formed within the soil. The lower part of the solum is weakly developed because of pattern ground activities, sometimes discontinuous due to intrusion of big rock fragments. No permafrost is found within the profile of Site 2.

METHODS

Data of soil moisture dynamics were collected and recorded with a special freeze-tolerant instrument developed for this study by the Soil Physical Department and Scientific and Technological Developing Company of the Institute of Soil Science, Academia Sinica. The equipment includes the moisture-sensing electrical conductivity probes and electrical conductivity gauge, both connected by coated copper wires (see Klute 1986). Before probes were used in the field observation, the relation between the electrical conductivity and moisture suction had already been standardized in the laboratory, so that the dynamic changes of soil moisture could be determined quantitatively through the conversions immediately after the data were collected in the field.

Totally 10 moisture-sensing electrical conductivity probes were installed into both the investigated sites. Beginning at a depth of 10 cm and with a vertical separation of 10 cm, 6 probes (from No. 1 to 6) were used for Site 1 and 4 (from No. 7 to 10) for Site 2. Thus, the probe arrays within the two soil profiles extend 60 cm and 40 cm respectively (Fig 1).

The electrical conductivity gauge, here used as the record-counter, collected the data on electrical conductivity of the soils at different depths within the two investigated profiles

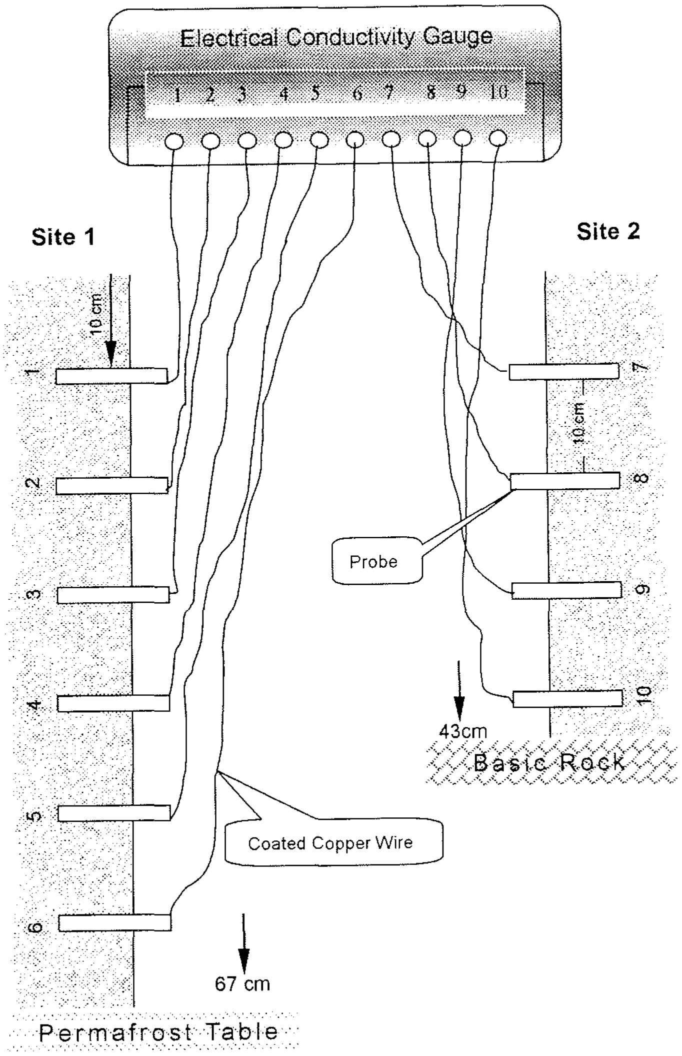

Fig. 1: Sketch of equipment installation in soil profiles at the two investigated sites.

Abb. 1: Instrumentarium zur Messung der elektrischen Leitfähigkeit in den verschiedenen Tiefen der beiden untersuchten Bodenprofile.

twice a day, at 8:00 a.m. and 20:00 p.m. local time. Based on the original data obtained from *in situ* observations during the year from the beginning of January 1993 to the beginning of January 1994, the dynamic changes of electrical conductivity of the soils at the investigated depths within the two profiles are shown in Fig. 2.

As mentioned before, dynamic changes in soil moisture suction could be easily obtained through the conversion curves obtained in the laboratory. However, for a better understanding of the moisture status of the soils, quantitatively calculation of free-water content of the investigated depths was made through soil moisture suction. As known, moisture suction is characterized by soil moisture-holding capacity which is dominated by several soil properties such as soil texture, percentage of rock fragments >2 mm, bulk density as well as organic matter content (AK Bodenkunde 1994). Soil properties differ not only from different soils but also different depths within the same soil. Thus, on the basis of quantitative data on the soil properties obtained at different depths of both the sites, the soil free-water content at each investigated depth within the two profiles can be reckoned through the related calculational parameters (Fig. 3).

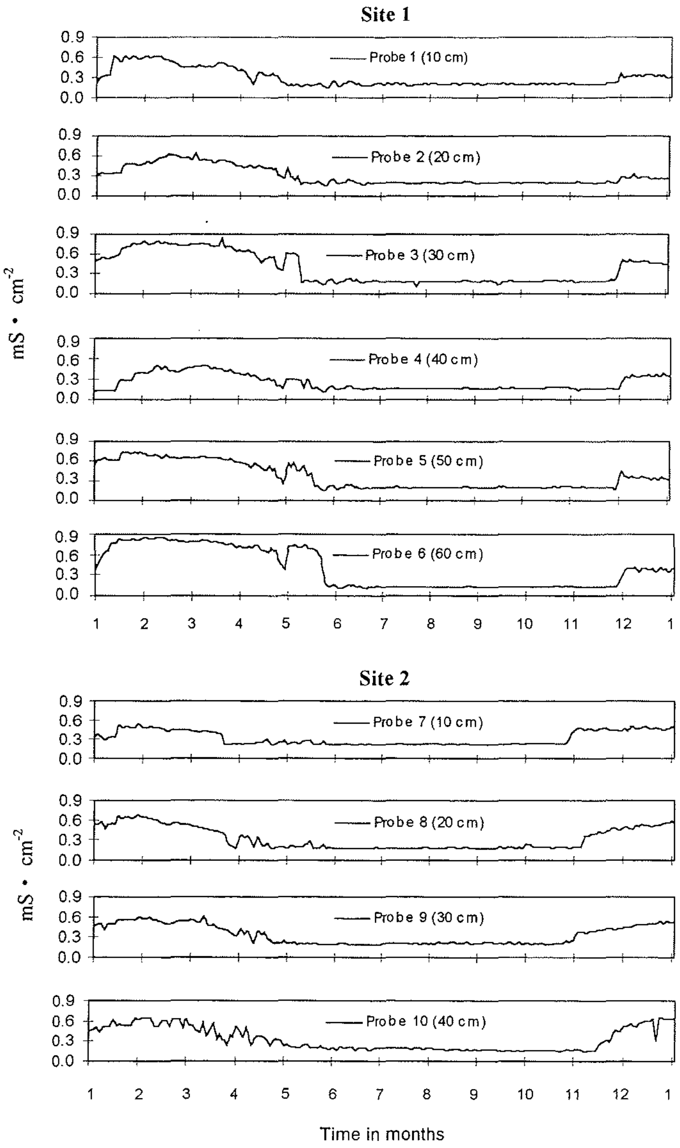

Fig. 2: Yearly dynamic changes of electrical conductivity (mS x cm^{-2}) at the investigated depths within the soil profiles at Site 1 and Site 2.

Abb. 2: Jahreszeitlicher Wechsel der elektrischen Leitfähigkeit (mS x cm^{-2}) in verschiedenen Tiefen der Böden 1 und 2.

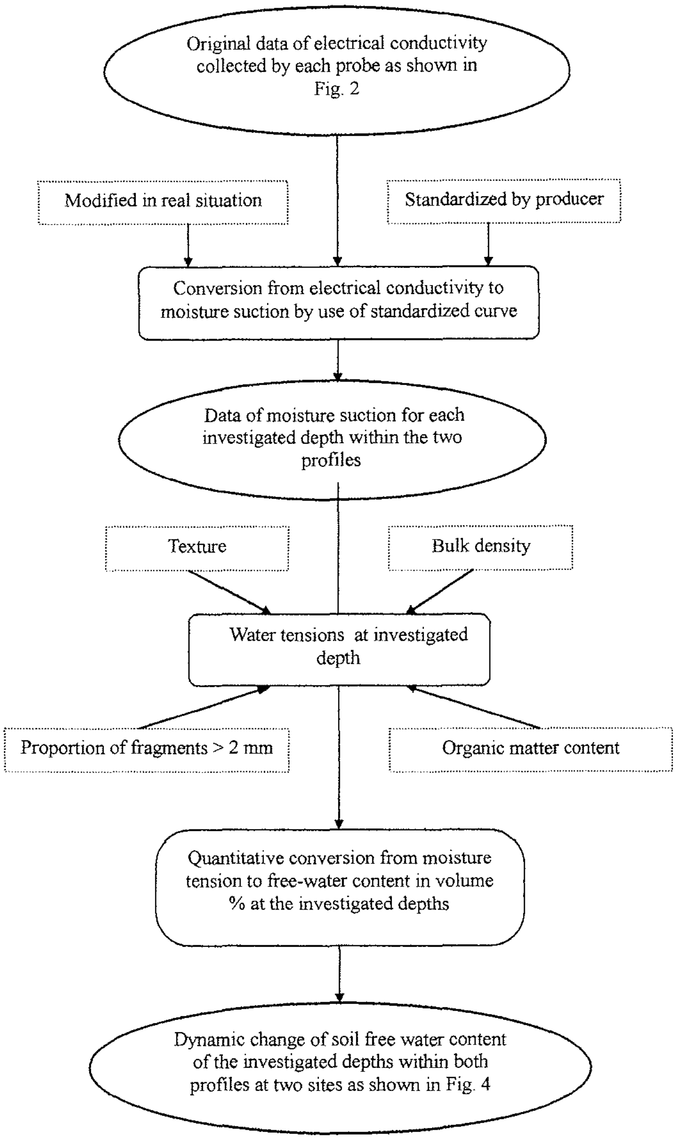

Fig. 3: Flow chart of data processing and conversion from original electrical conductivity to free-water content in vol. % at the investigated depths.

Abb. 3: Schema der Datenermittlung und Umwandlung der elektrischen Leitfähigkeit in Gehalte ungefrorenen Wassers in den untersuchten Bodentiefen.

RESULTS AND DISCUSSIONS

Using the data transferred from moisture suction of the different depths, the dynamic changes of the free-water content in volume at two investigated sites are shown in Fig. 4.

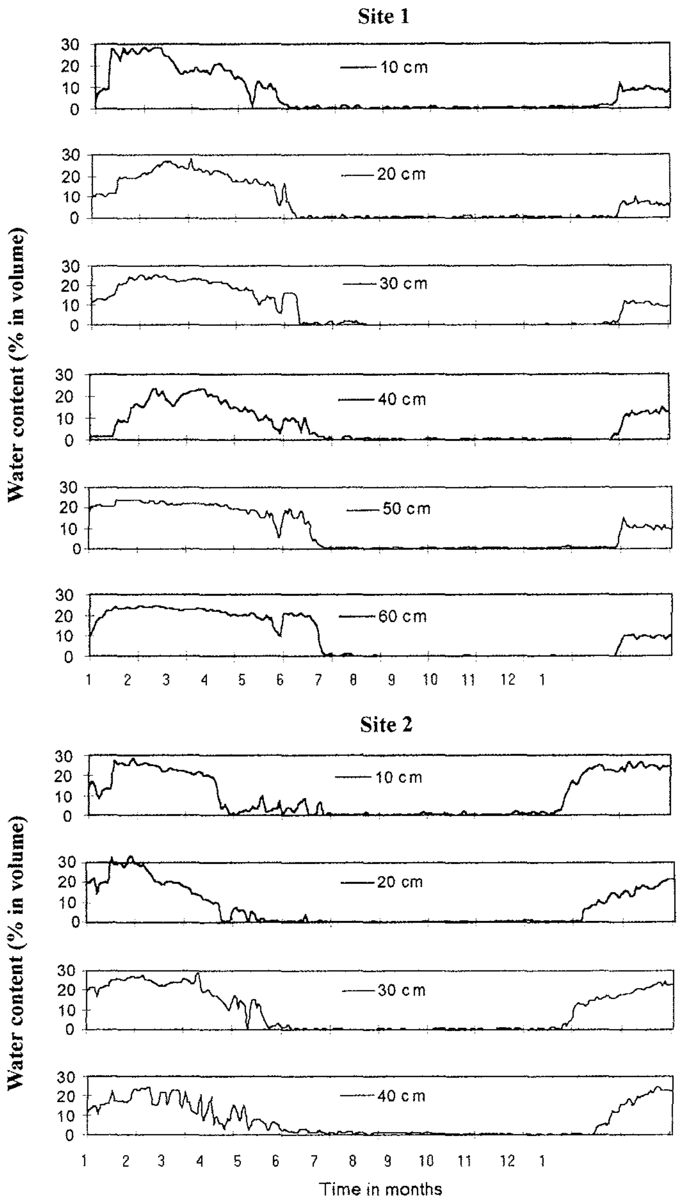

Fig. 4: Annual dynamic changes of soil free (unfrozen)-water content (in vol. %) at the investigated depths within the soil profiles at Site 1 and Site 2..

Abb. 4: Jahreszeitlicher Wechsel der (nicht gefrorenen) freien Wassergehalte in verschiedenen Tiefen der Böden 1 und 2.

Soil freeze-thaw cycle

One of the most important features of the maritime Antarctic soils is that they are always influenced by strong freeze-thaw action. As a result, the soil free-water content is dominated to a great extent by soil temperature variation and the freeze-thaw alternation. Therefore, the examination of the curves of dynamic changes on soil free-water content shown in Fig. 4 make it possible to easily figure out the freeze-thaw pattern of the investigated profiles at two sites.

Extremely low contents of soil free-water at different depths within the soil profiles indicate that the soils are frozen during a period which lasts 6-7 months per year at both the investigated sites. The freezing period begins and ends differently not only between the two sites, but between the investigated depths at the same site, as shown in Fig. 4.

Generally, the soil at Site 2 has the freeze-thaw transition, whether from freeze to thaw or from thaw to freeze, about one month earlier than the soil at Site 1. As known, the freeze-thaw transition in soil results from thermal exchange between soil and atmosphere. Site 2, located at the top of a towering hill, is exposed to strong winds which effectively prevent snow from accumulating on the surface. Thermal diffusivity from the soil to the atmosphere occurs directly and rapidly. Thus, when winter comes, the transition from thaw to freeze in the soil of Site 2 takes place earlier than Site 1 which is devoid of strong winds and has a thick snow cover on the surface. With the warm period, the soil of Site 2 is first to receive solar radiation and to have a more convenient thermal exchange with the atmosphere because of its open surface and thinner snow cover. Therefore, the transition from freeze to thaw in the soil there occurs earlier than at Site 1. Within each investigated profile, there is later freeze-thaw transition in the deeper part. Because the soil in the interior of the profile has no immediate interface to the atmosphere, thermal exchange could only take place with the overlying and underlying soil media, where the thermal conductivity is much lower than open air. The different patterns of the freeze-thaw transitions amongst the investigated depths are demonstrated by the change tendency of soil temperature on the Fildes Peninsula (Fig. 5).

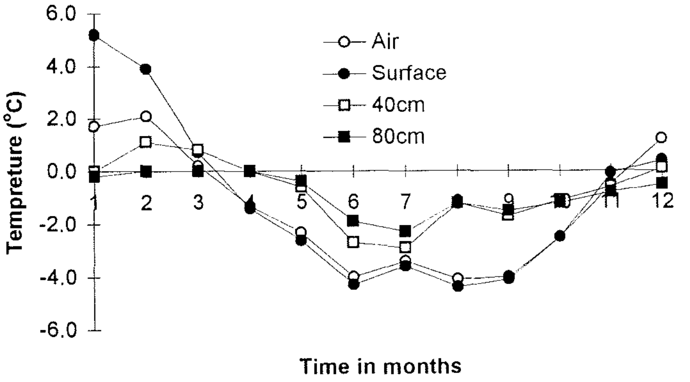

Fig. 5: Mean monthly air and soil temperatures at different depths in the ice-free area of Fildes Peninsula in 1993 (on a flat ground with an elevation of approximately 20 m, without vegetation cover on the surface).

Abb. 5: Jahreszeitlicher Wechsel der Luft- und Bodentemperaturen im eisfreien Bereich der Fildes-Halbinsel im Jahre 1993 (Verebnung 20 m NN, vegetationsfrei).

Summarizing, the periodic freeze-thaw in the soils of the ice-free Fildes Peninsula could be described as follows: Freeze lasts a period of 6-7 months while thaw takes the remaining 5-6 months of the year. Variations in soil freeze-thaw transition occur due to local site differences such as slope aspect, exposure, and snow cover etc. Besides, within a profile the lower part of the soil always has later freeze-thaw transition.

Dynamic changes of soil moisture status at different depths of the profile

The moisture status at different depths may be reasonably variable as a result of the variation of temperatures, mechanical composition, organic matter content etc, of alternate of active layer of permafrost within the soil profile. Fig. 4 shows that the soil at every investigated depth has its biggest free-water content in the middle of the thawing period. A careful examination of the curves in Fig 4, however, indicates that soil free-water content in surface layers (with maximum depth of 10 cm) of the profiles reaches its peak value much earlier, then rapidly decreases when an obvious increase of the free-water content occurs in the underlying layer. This fact suggests that snow-melting water on the surface and soil free-water from the thawing action form a downward flow when the surface soil becomes saturated, which penetrates the surface layer and contributes to the available moisture of the underlying layer. Step by step, similar contributions to free-water contents from the downward flow may occur in the deeper layers of the profile as time goes on. Even, along with the depth the maximum values of the free water contents of the soils become smaller and smaller.

Exceptionally, the gentle curves of soil moistures at the depths of 50 cm and 60 cm at Site 1 indicate that the dynamic moisture status differs from that at the shallower depths. This may be due to the occurrence of permafrost at the bottom of the profile (permafrost table at Site 1 is found at the depth of 67 cm) and will be discussed in detail later.

During the transition from thaw to freeze, frequent variations of free-water content at smaller scales in surface soils are indications of mechanisms of short-term freezing and thawing, which demonstrate the direct influence from the variation of air temperature and the intermittent snow-melting water on the surface during the early winter. This phenomenon is more obvious at Site 2, due to its more open surface ground.

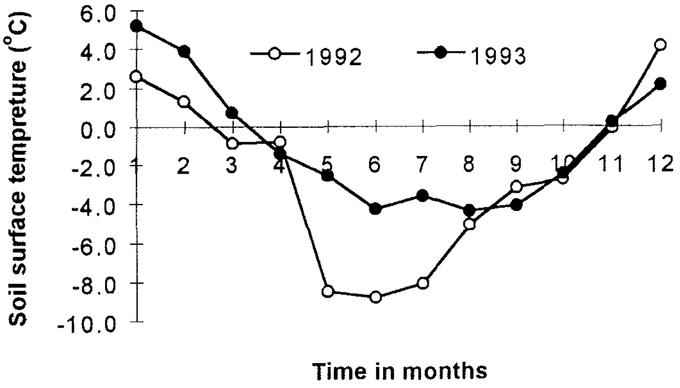

Fig. 6: Mean monthly temperatures on soil surfaces of the Fildes Peninsula in 1992 and 1993.

Abb.6: Monatliche Mitteltemperaturen der Jahre 1992 und 1993 im eisfreien Bereich der Fildes-Halbinsel.

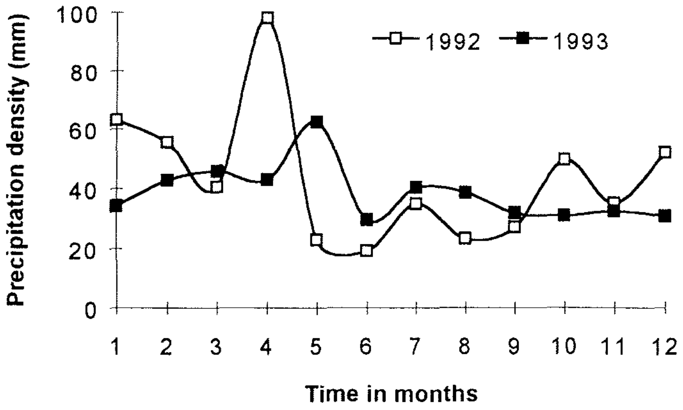

Fig. 7: Monthly distribution of precipitation on the Fildes Peninsula in 1992 and 1993.

Abb.7: Monatsniederschläge der Jahre 1992 und 1993 im eisfreien Bereich der Fildes-Halbinsel.

Yearly variation of freeze-thaw and soil moisture status

The freeze-thaw processes and the dynamic of soil moisture status at the same site between two years could be different. This is partly confirmed by Fig. 4, in which most of the moisture curves of the investigated depths have rather different shapes between the beginnings of January 1993 and 1994. In other words, the heads and the tails of most soil moisture curves fail to coincide with each other. The yearly variation in freeze-thaw processes and soil moisture status may result from many causes including yearly differences of the climatic factors.

The comparisons of soil surface temperature and precipitation between 1992 and 1993 are illustrated in the curves of Fig. 6 and Fig. 7, from which it is seen that obvious differences of the mean monthly temperature of soil surface and precipitation distribution occur between these two years. However, it is impossible to make a comparison of the status of the soil moisture in the same period of the different years only from the variations of the surface temperature and precipitation between the years, because the climatic influences could be variable at the different sites. For instance, micro-relief and surface conditions play their important roles in redistribution of the snow-form precipitation by the winds. As a result, the differences of snow-cover thickness may occur over distances of a few meters. As known, snow cover is not only the potential source of soil moisture but also an important factor strongly affecting the thermal exchange behween the underlying soil and the atmosphere. This may be why Fig. 2 shows different pictures of the yearly variation of soil moisture status between the investigated sites.

Comparisons of dynamic changes in free-water content between two sites

It has been repeatedly described that wide variations in moisture status of the soils occur due to the local site differences. The soils with greatly different moisture status may occur alongside each other (e.g. CAMPBELL & CLARIDGE 1987). The variation in freeze-thaw processes of the two investigated sites has been discussed in the preceding part of this paper. In the following paragraphs, comparisons of the free-water contents at several interesting depths between two sites are made.

Fig. 8 shows the dynamic variations of free-water content at the depth of 10 cm in the investigated profiles at the two sites. It can be seen that there is much more free-water available in the surface soil at Site 2 than at Site 1 during the beginning of the thawing period. This may result mainly from two reasons. One is that more convenient thermal exchange with open air at Site 2 causes an earlier strong thawing in its surface soil. Another is that rain-form precipitation occurring in the early summer contributes directly to the free-water in the surface soil, because

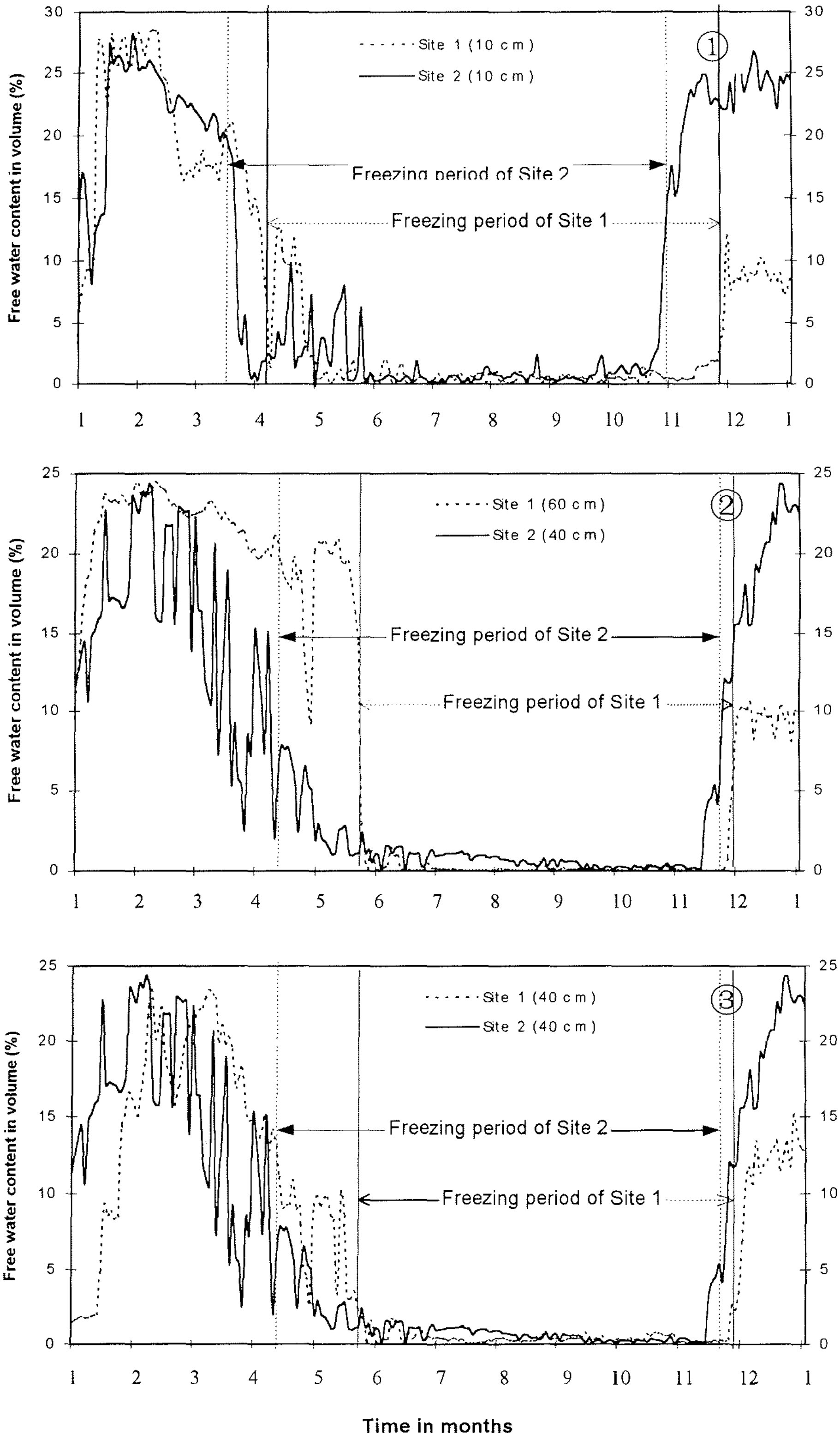

Fig. 8: Comparison of free (unfrozen)-water contents of the soils between investigated depths of Site 1 and Site 2.

Abb. 8: Jahreszeitliche Schwankungen der Wassergehalte in verschiedenen Tiefen der Böden 1 und 2.

there is no obstruction of snow cover on the surface of Site 2. However, as time goes on, the surface soil at Site 1 would theoretically have more and more free-water available because of its higher water capacity and a thicker snow cover on the surface as a source of potential moisture. Additionally, in the middle of summer when the snow is fully melted and the soils along the slope are saturated, slope runoff and lateral seepage also are expected to enrich free-water of the soil at Site 1 as a result of its location at the bottom of the north-facing slope.

An obvious difference between the curves of moisture status in the lower part of the investigated profiles is demonstrated in Fig. 8. A much higher content of free-water at the bottom of the profile of Site 1 is mainly due to the occurrence of the permafrost at a depth of 67 cm, which acts as a barrier to stop the downward flow of free water from the surface and the upper layers. Additionally, a possible shift of the active layer of permafrost may also contribute to the content of soil free-water to a certain extent. Because there is no occurrence of permafrost within the soil profile of Site 2, where the soil is developed on the broken rock and has a much shallower solum, the downward flow of free water, if it occurred, would suffer a big percolation loss through the rock cracks. This could have been reflected in the frequent and strong fluctuations of the moisture status curve. Thus, a comparatively lower content of free-water at the bottom of the profile of Site 2 during the thaw is explicable.

At the depth of 40 cm the curves of soil free-water at the two investigated sites have a comparatively similar change trend of free-water content as shown in Fig. 8, possibly suggesting general influences of soil temperature change in this region. However, at the beginning of thawing period the soil of Site 2 contains a higher free-water than of Site 1 at this depth. But, after the strong thawing period the free-water content at Site 2 decreases more rapidly and more strongly. Such a strong and frequent variety of free-water at the 40 cm depth (the bottom of profile) of Site 2 indicates a percolation loss downward through the big rock cracks, as is discussed in the above paragraph. At Site 1, also the downward flow of free water from the upper profile may only use the middle of the profile as a pathway to go deeper; the change of soil moisture at Site 1 is more gradual and the free-water content is more stable. This suggests that the mechanical composition and soil structure at 40 cm depth in the two investigated profiles are obviously different. And, it is reasonable that the soil of Site 1 has a higher water capacity than the soil of Site 2 at this depth.

CONCLUSIONS

Broad generalization valid for the dynamic changes of moisture status in all the soils of the whole ice-free areas in the Fildes Peninsula are quite difficult to draw from this study alone. The dynamic change of moisture within soils is a complex process, not only site specific but also time independent, as discussed in this paper. It is obvious that one-year data of the two investigated sites are not enough to comprehensively describe the dynamic variation and regimes of soil moistures in the region. However, the following phenomena related to the dynamic changes of soil moisture should reccive more attention.

1. Thawing action takes 5-6 months or more, quite a bit longer than formerly recorded and reported in the ice-free area of the maritime Antarctic. The soil development on the Fildes Peninsula is more strongly influenced by freeze-thaw and other periglacial actions than usually expected.

2. During the thawing period, the free-water available in the soils comes mainly from melting of potential sources on the surface and in the soils themselves. However, the contributions from other moisture sources, for instance, from slope runoff and lateral seepage may be also important for free-water contents and the dynamic changes of moisture status of the soils, especially for the soils developed in the valleys, depressions and footslopes.

3. The occurrence of permafrost at the bottom of a profile can play an important role in the dynamic change of soil moisture. The shallow soils formed on the hills without the influence of permanently frozen ground have quite different moisture conditions with the soils resting on permafrost during some certain periods. Therefore it is necessary that illustrations of the moisture regime of the soils at different localities should be dealt with in different ways.

4. Starting time, lasting period, and the strong degree of freeze thaw action in soils all are yearly dependent as a result of the variations of climatic and other factors. For a more systematic and comprehensive understanding, data on soil freeze-thaw and moisture dynamics through several years are needed.

References

AK (Arbeitskreis) Bodenkunde (1994): Bodenkundliche Kartieranleitung.- 4. Aufl., Hannover, pp. 108-141, 298-310.

Allen, S.E & Heal, O.W. (1970): Soils of the Maritime Antarctic zone.- In: M.W. HOLDGATE (ed.), Antarctic Ecology, Vol. 2, New York, Academic Press, 693-696.

Barsch, D. & Stäblein, G. (1984): Frost dynamics and permafrost in ice-free areas of the Antarctic Peninsula.- Polarforschung 54: 11-119.

Blume, H.-P., Beyer, L., Bölter, M., Erlenkeuser, H., Kalk, E., Kneesch, S., Pfisterer, U. & Schneider, D. (1997): Pedogenic zonation in soils of the southern circum -polar region.- Advances GeoEcology 30: 69-90.

Bockheim, J.G. (1980): Properties and classification of some desert soils in coarse-textured glacial drift in the Arctic and Antarctic.- Geoderma 24: 45-49.

Bockheim, J.G. (1995): Permafrost distribution in the southern circumpolar region and its relation to the environment: a review and recommendations for further rescarch.- Permafrost Periglacial Pro. 6: 27-45.

Bockheim, J.G. & Ugolini, F.C. (1990): A review of pedogenic zonation in well drained soils of the southern circumpolar region.- Quaternary Res. 34: 47-66.

Campbell, I.B. & Claridge, G.G.C. (1969): A classification of frigic soils – the soils of the Antarctic continent.- Soil Sci. 107: 105-131.

Campbell, I.B. & Claridge, G.G.C. (1987): Antarctic: soils, weathering processes and environment.- Amsterdam. Elsevier Science Publisher, 330-334.

Chen, J & Gong, Z. (1995): Role of lichens in weathering and soil-forming processes in Fildes Peninsula, Antarctic.- Pedosphere 5: 305-314.

Chen, X.B. (1993): Permafrost around CGWS, Antarctica.- Proceedings of the 6th International Conference on Permafrost, Vol. 1.- Guengzhou: South China University Technical Press, 82-90.

Chinese Soil Taxonomy Rescarch Group (1995): Chinese Soil Taxonomy – Revised Edition (in Chinese).- Beijing: Chinese Agricultural Scientific and Technological Press, 58-147.

Cui, Z., Xie, Y. & Liu, G. (1989): Antarctic periglacial environment and the formation mechanism of sorted circles' in the Fildes Peninsula.- Proceedings of the International Symposium on Antarctic Research, Beijing, China Ocean Press, 82-90.

Everett, K.R. (1976): A survey of soils in the region of the Southern Shetland Islands and adjacent parts of the Antarctic Peninsula.- Ohio State Univ. Inst. Polar Stud. Rep. 58.

FAO-Unesco (1994): Soil map of the world, revised legend with corrections.- ISRJC, Washington.

Klute, A. (1986): Methods of soil analysis. Part I, Physical and mineralogical methods, 2nd ed.- Soil Science Soc. America, Madison, Wisconsin.

Jensen, H.I. (1916): Report on Antarctic soils.- Repts. Sci. Invest. Brit. Antarct. Exped 1907-1909, Geology 2: 89-92.

MacNamara, E.E. (1969): Active layer development and soil moisture dynamics in Enderby Land, Antarctica.- Soil Sci. 107: 345-348.

McCraw, J.D. (1967): Some surface features of McMourdo Sound region, Victoria Land, Antarctica.- N. Z. Journ. Geol. Geophys. 10: 394-417.

Tedrow, J.C.F. (1977): Soils of the polar landscapes.- Rutgers University Press, New Brunswick, 639 pp.

Xie, Y. (1993): Geomorphology and deposition of the area around Great Wall Station (Fildes Peninsula), Antarctica (in Chinese).- China Occen Press, Beijing, 3-50.

Zhang, Q. (1990): Comparison of periglacial landforms on the Vestfold Hills, East Antarctica, and on the Fildes Peninsula, West Antarctic.- Antarctic Res. 2: 1-9.