An Overview of the Rangelands Atmosphere-Hydrosphere-Biosphere Interaction Study Experiment in Northeastern Asia (RAISE)

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Abstract

Intensive observations, analysis and modeling within the framework of the Rangelands Atmosphere-Hydrosphere-Biosphere Interaction Study Experiment in Northeastern Asia (RAISE) project, have allowed investigations into the hydrologic cycle in the ecotone of forest-steppe, and its relation to atmosphere and ecosystem in the eastern part of Mongolia. In this region, changes in the climate have been reported and a market oriented economy was introduced recently, but their impact on the natural environment is still not well understood. In this RAISE special issue, the outcome is presented of the studies carried out by six groups within RAISE, namely, (1) Land-atmosphere interaction analysis, (2) Ecosystem analysis and modeling, (3) Hydrologic cycle analysis, (4) Climatic modeling, (5) Hydrologic modeling, and (6) Integration. The results are organized in five relevant categories comprising (i) hydrologic cycle including precipitation, groundwater, and surface water, (ii) hydrologic cycle and ecosystem, (iii) surface-atmosphere interaction, (iv) effect of grazing activities on soils, plant ecosystem and surface fluxes, and (iv) future prediction. Comparison with studies on rangelands in other parts of the world, and some future directions of studies still needed in this region are also summarized.

keywords: arid region, rangelands, environmental changes, climatic change

1. Introduction

Rangelands occupy some 30-50% of the earth's land area (World Resources Institute, 2000; Houghton et al., 2001), and they supply more than 80% of the feed of the livestock in Asia and Africa, about 25% in north and central America and some 50% in the rest of the world (Allen-Diaz et al., 1996). Thus rangelands are of vital importance for the production of live stock. Also for the global climate, rangelands have a strong impact. For example, they store 405-806 Gt of carbon (World Resources Institute, 2000) and absorb about 0.5 PgC per year (Scurlockand Hall, 1998). Given their large extent and importance, it is crucial to have a thorough understanding of the natural environments of the rangelands, in general, and of the mechanisms that maintain or change the ecosystem in response to the environmental changes in particular. Since many of the rangelands are located in areas classified as arid or semi-arid, the presence or lack of water is one of the key variables determining the fate of their ecosystem, and thus the understanding of the hydrologic processes is critically important. In addition, since water generally is brought into rangelands as precipitation, the atmospheric circulation is also a factor that should be understood. Moreover, changes of the ecosystem will eventually influence the atmospheric circulation and hydrologic cycle. This means that the ecosystem, the hydrologic cycle, and the atmosphere cannot be studied separately, but that their mutual interactions and feedbacks must also be considered.

Although there have been numerous attempts to study rangelands, most of them are limited within narrow traditional disciplines such as ecology or micrometeorology. Many of these studies have been very useful to understand several of the more important process occurring in rangelands. However, a full understanding of the complex nature of the rangeland environment and of the various interactions and feedbacks between the different processes are still lacking. Also, one should note that the rangelands in northeastern Asia have not received attention they deserve in contrast to some of the others. There are general features that are common to any rangeland, but at the same time there exist local characteristics which are relevant only in certain specific situations. Both types of characteristics must be studied, and it is only through comparison and integration of the results obtained in geographically diverse rangelands that a sufficient understanding of rangelands can be achieved.

In northeastern Asia around Mongolia, a climatic transition from humid conditions in the northern part to arid conditions in the southern part can be found over a relatively narrow, boundary zone (see, e.g., Fig. 1.1 of Simmers, 2003). As a consequence of the steep, meridional gradient in climate, a distinct ecotone of forest-steppe-desert is formed in this part of the world (Fig. 1). An ecotone in general is sensitive and susceptible to environmental changes (e.g., Pogue and Schnell, 2001) such as global warming even when the extent of the change is small. For example, in the interface region between the forest and the steppe in Mongolia, one can often observe the presence of a forest and a grassland located side by side. Forest is usually formed on the slopes facing north, while grasses can be found on the slopes facing south. This difference of vegetation cover within a small area appears to have been maintained by the slight difference in surface hydrology, evaporation and soil moisture in particular, and in meteorology in connection with the vegetation types that produce differences in

surface aridity (Yamazaki et al., 2004). Such small differences can easily be disturbed once the forest is destroyed by, e.g., human activities or forest fire. When that happens, it is not easy to recover the forest. In fact, it has been reported that winter and spring air temperatures have increased in this region (Yatagai and Yasunari, 1994) while the summer total precipitation appears to have increased, with also increased frequency of heavier rainfall in eastern and western Mongolia over the last four decades (Endo et al., 2006). It is possible that such climatic changes may have induced or will induce drastic changes in plant growth and vegetation distribution directly or indirectly through changes in hydrological cycle. However, this is merely a speculation and solid information or knowledge to support this scenario is not available yet for this region.

Another driving force of ecosystem changes results from human activities. In Mongolia, the number of livestock has increased drastically in the past decade or so (Fig. 2), as a result of the introduction of the so-called market oriented economy in 1990-91 after the change of the political system; the effect of the resulting overgrazing onto the ecosystem could be a serious problem. Currently, most of Mongolia is classified as being in a state of slight desertification (e.g., Dregne, 1986). However, until now no comprehensive scientific studies have dealt with this issue in this region.

In the light of the absence of interdisciplinary studies of rangelands, in general and in northeastern Asia in particular, a project called RAISE (the Rangelands Atmosphere-Hydrosphere-Biosphere Interaction Study Experiment in Northeastern Asian) has been initiated since 2001; more than 30 scientists with backgrounds in hydrology, meteorology, climatology, geomorphology, soil science, and plant ecology from Japan, Mongolia, China and Korea participated in this study to understand the ecosystem in this region with emphasis on the role of the hydrologic cycle. Its main intensive field observations took place in 2003 with supplementary observations in 2004-2005. The observed data have been analyzed and scrutinized through discussions among not only the RAISE investigators but also general scientific communities working on environmental issues in this region mainly through three international workshops, one international symposium and one domestic meeting. They were (i) the 1st International Workshop on Terrestrial Change in Mongolia (Dec 2-4, 2002, Tokyo, Japan), (ii) the 2nd International Workshop on Terrestrial Change in Mongolia (Dec. 2-4, 2003, Yokohama, Japan), (iii) a special session on “Interaction of atmosphere, hydrosphere, and biosphere in northeastern Asia” at the 2004 Japan Earth Planetary Science Joint Meeting (May 13, 2004, Chiba, Japan), (iv) the 3rd International Workshop on Terrestrial Change in Mongolia (Nov. 9-10, 2004, Tsukuba, Japan), and (v) the 1st International symposium on Terrestrial and Climate Changes in Mongolia (July 26-28, 2005, Ulaanbaatar, Mongolia).

This special issue is an outcome of the RAISE project and is designed to bring together recent findings relevant to environmental studies of rangelands, with particular emphasis on the integration of the studies of the hydrologic cycle, the ecosystem and the atmosphere. This issue is organized in the following key research areas: (i) hydrologic cycle including precipitation, groundwater, and surface water, (ii) hydrologic cycle and ecosystem, (iii) surface-atmosphere interaction, (iv) effect of grazing activities on soils, plant ecosystem and surface fluxes, and (iv) future prediction. In what follows, this overview paper includes a summary of the results of the RAISE project that have already been published elsewhere in addition to those presented in this special issue. This

special issue is intended not only to present the main findings from RAISE but also to serve as an archival reference for future studies of rangelands.

2. RAISE Project: Design and Implementation

2.1 Physical Setting and Location

The Khelren river basin located in eastern Mongolia with a catchment area of approximately $1.225\ 10^5$ km^2 (total area within Mongolia), $7.15\ 10^4$ km^2 (upstream area of Choybalsan,) or $3.94\ 10^4$ km^2 (that of Underhaan), was selected as the target of the intensive observations (Fig.1, Figs. 3-5). This selection was based on three major considerations. First, the watershed is part of the ecotone formed in this region and it displays a clear gradient in vegetation from forest in the north to steppe in the south. This allows an investigation of vegetation effects within the same watershed. The second consideration was that only small villages or cities exist within the catchment, and thus there is no need to be concerned with urbanization, which is not yet a major problem in Mongolia except for its capital city Ulaanbaatar (UB) and some larger cities. The third reason for the selection was that within this watershed, a relatively dense network of meteorological, hydrological and biology stations has been operated (see Fig. 5) by the Institute of Meteorology and Hydrology (IMH) of Mongolia, and the data prior to RAISE can be utilized to study inter-annual variations and to verify the model outputs.

As mentioned, the upper reaches of the watershed are covered by forest with montane Siberian larch as the dominant species and with scattered patches of white birch (Fig.3 and Table 1). As the altitude decreases from around 2000 m asl to around 1500 m, the vegetation changes from forest to steppe that consists mainly of C_3 plants such as *Stipa krylovii*. This corresponds well with the precipitation distribution in the watershed (Fig. 4), and partly with topography (Fig. 5). In this region, the amount of precipitation, not temperature, is the major factor that determines the dominant vegetation cover (Sugita, 2003). Annual mean temperature is around ±2 °C (Table 1). Only sporadic or discontinuous permafrost exists in this watershed except perhaps in the mountain region along the northern edge (Ministry of Water Economy of Mongolia, 1981; Tsujimura et al., 2006b).

2.2 Measurements and Data Collection

2.2.1 Continuous Observations

As mentioned, IMH deploys and maintains a network of observation stations throughout Mongolia. Their stations consist of the Meteostation, the Meteopost station, the Guging station and the Biostation (IMH, 1995, 1998, 2000, 2002). The Meteostation and the Meteopost measure the standard meteorological elements including air temperature, wind speed, air pressure, and precipitation. However, the Meteostation measures more variables with, in general, higher accuracy, and at finer time intervals of eight times a day from zero Mongolian Standard Time (MST) than the Meteopost stations which report measurements four times a day at 2, 8, 14, 20 MST, respectively. At the Gauging station placed along major rivers, the water level is measured twice daily

while the water velocity and the cross-sectional area to derive discharge are measured five times a month. The Biostation measures such variables as plant species, phenology and biomass. Some of these different types of stations are collocated.

In addition to the existing IMH stations, three flux stations and four automatic weather stations (AWSs) were set up for the purpose of obtaining continuous measurements within the experimental area (Figs. 3-5 and Table 1). One flux station (to be referred to hereafter as station FOR) was established in a mildly hilly area (see Fig. 6) some 25 km northeast of Mongenmoryt (MNG) village in the upper river basin (Li et al., 2005a) while two others were set up within an extensive steppe area in Kherlenbayan-Ulaan village (KBU) (see Fig. 7). Figs. 8-9 illustrate the long-term variations of precipitation and the normalized difference vegetation index (NDVI) at MNG and KBU, respectively. At KBU, one station called A1was located within the natural, pastoral steppe, while another essentially identical station called A2 was placed within a 200 m by 170 m fenced area to prevent grazing to take place since September of 2002 (Fig. 7). Station A1 is co-located with one of the IMH meteoposts. The instrumentations of these three stations are listed in Tables 2-4. Note that soil heat flux G was initially measured at A1 and A2 sites with a soil heat flux plate only at single location, and thus they may not have been representative of each area. In the April of 2005, additional 10 soil heat flux plates were buried at each of the stations to address this issue. Note also that mobile observations of the four radiation components of the net radiation Rn around A1 and A2 sites were carried out in 2005, which confirmed that the Rn values measured at each station are representative of those of the pastoral and the protected steppe. A footprint analysis for neutral atmospheric stability (Stannard, 1997) has indicated that 90% of the fluxes measured at these stations originate from upwind distances smaller than 3000 m and 750 m for the FOR and KBU sites, respectively. These distances are well within the extent of each vegetation cover for the dominant wind directions for the FOR site and A1 site at KBU. Although this distance extends beyond the fenced area for the A2 site of KBU, approximately 70% of the source fluxes still originate from within the fenced area. During daytime under unstable stability conditions, these distances should shrink because of the enhanced turbulence activity.

The AWS sites were co-located with existing IMH meteorological stations, so that inter-comparison and utilization of the pre-RAISE observations can be made. At four locations geographically spread within the steppe region of the experimental area (Table 1, Fig.3-5), basic variables of radiation, meteorology and hydrology listed in Table 5 have been observed since April of 2003.

In addition to the continuous measurements outlined above, several special measurements specific to particular investigations were also made. These included semi-continuous river water level measurements at MNG, BGN, and UDH to supplement the IMH station measurements, GPS measurements at KBU and Bayanchandmani (BCM) located about 110 km west of UB (Fig. 1) to study the mountain effects on cloud formation, small gauged watersheds near BGN and KBU stations for studies of hill slope processes and soil erosion (Nishikawa et al., 2005, Onda et al., 2006), water samplings for istopic studies at several locations (Table 1), and water table monitoring at MGM, KBU, UDH, and BGN.

2.2.2 Intensive Observations

In order to obtain more detailed information which the continuous, routine observations outlined above may not be capable to provide, five intensive observation periods (IOPs) were scheduled in 2003 to capture the different stages in vegetation growth (Fig. 10). Unfortunately, following the outbreak of a severe acute respiratory syndrome in this region in April-May of 2003, the first planned IOP was canceled. This corresponds to the period when the vegetation growth just started. According to the phenology report of the Biostations in this region, April 24 was the first day when the vegetation started its growth in 2003. However, most of the relevant data that cover this growing stage were obtained in 2004 by a subsequent continuous observation.

For each IOP, investigators participated in the field campaigns mainly in three groups. The first group stayed either at the KBU site or at the FOR site to gather detailed information at each site. The second group traveled to all relevant RAISE sites during or shortly after each IOP to obtain data and samples such as the leaf area index (LAI), biomass, soil and spectral reflectance at all sites and fluxes at the AWS sites where fluxes were not measured constantly (Table 6). The third group used an aircraft in order to obtain variables in and above the atmospheric boundary layer (Kotani and Sugita, 2006), to make remote sensing of the surface spectral reflectance (Matsushima, 2006), and to capture water vapor samples for the isotopic analysis (Yamanaka et al., 2006). The flight passes and dates are listed in Table 7 and Fig.11.

At the A2 and A1 Sites in KBU, the same biology and soil observations were carried out each year since 2002 in order to monitor the year-to-year changes in the ecosystem following its exclosure from grazing activities.

2.2.3 Other Data Sets Used for the Studies

In addition to the IMH routine observation data and the RAISE special observations, several data sets from other sources have been utilized. These included DEM and satellite images around KBU, FOR and BGN areas produced as part of the ASTER 3D data set (Abram, 2000), a GIS data set of vegetation, topography, soil, and ecosystem (Saandar and Sugita, 2004), statistical data such as the number of live stock for each year (gathered as part of the annual domestic animal accounting survey by the local administration staff under the supervision of the Ministry of Agriculture and compiled by the Statistical Office of Mongolia for each *soum,* a Mongolian administrative unit, equivalent of a county), other satellite data such as Landsat TM/ETM+ and ADEOS/MODIS data, the NCAR/NCEP reanalysis data set (Kalnay et al., 1996), near continuous doppler radar data at UB, and miscellaneous atlases and maps published in Mongolia (e.g., State Administration of Geodesy and Cartography, 1996; Ministry of Water Economy of Mongolia, 1981; Tuvdendorzh and Myagmarzhav, 1985, Ministry of Geodesy of Russia, 1990, among others).

2.3 Construction of RAISE Models and Future Prediction

For purposes of further study and possibly future prediction, mainly three models were developed, namely a regional climate model TERC-RAMS (Sato and Kimura, 2005a, 2005b, Sato et al., 2006), a grassland ecosystem model Sim-CYCLE Grazing (Chen et al., 2006) and a distributed hydrological model. The TERC-RAMS model was based on the Regional Atmospheric Modeling System (Pielke et al., 1992) but some modifications were made to improve its ability to reproduce the hydrometeorological regime, especially precipitation, in this region. The Sim-CYCLE Grazing model was based on the Sim-CYCLE model of Ito and Oikawa (2002) and a foliation model of Seligman et al. (1992) which allows the evaluation not only of the CO_2 fluxes and carbon accumulation within the ecosystem but also of the effect of the grazing activities which would consume the above-ground biomass and impact soil surface conditions, and eventually the below-ground physical condition and biological activities as well. The distributed hydrologic model is based on Lu et al. (1996). Since the thaw and freezing processes are particularly important in this region, they have been incorporated into the model (Doi et al., 2005), together with some refinement of the treatment of various hydrologic processes.

These models have been calibrated against the data obtained by the IMH for the past 10-30 years, and also against the more detailed observations that were carried out by RAISE for 1-2 years. Once the calibrations were completed, each model was made to produce outputs for 10 years including the year 2003. These products were and will be used as additional information, since the observations were often made only at discrete time intervals or for a limited time period, and the horizontal coverage may not have been adequate. Also, their means will serve to characterize the present conditions which can be compared against the means of the future conditions.

3. Interactions of Hydrologic Cycle With Atmosphere and Ecosystem in Arid Region: Some Findings From RAISE Project

Based on the analysis of the observational and modeling studies, some interesting findings have already emerged. While details have been, and will be presented as individual papers both in this special issue and other scientific journals, some of the findings are summarized below.

3.1. Hydrologic Cycle

A first natural question to ask would be why this region is so dry. Although there have been some theories and discussions of this issue, there is still no agreement on the exact reason(s) for the aridity of this region. Sato and Kimura (2005a) have successfully demonstrated through numerical experiments with their TERC-RAMS model that the presence of the Tibetian plateau, which heats the atmosphere and creates the upward convective motion of the air which in turn induces the downward flow in northern part of the plateau, is the main cause of the dryness of this area. Another question is where the origins of the precipitation are located. An isotopic analysis by Yamanaka et al. (2006) gives a partial answer on this issue. They collected rain water through an extensive sampling network in Mongolia, and were able to show that the observed δ values of the rainfall agree quite well

with the predictions of a Rayleigh-type model except for July, for which δ values are significantly lower than those of the prediction. This tends to suggest that there is a contribution of evaporated water in the rainfall in this region in July. Such evaporated water is likely to come from Southeastern China with its widespread rice paddy fields and higher temperatures in summer.

In traditional and textbook views of arid land hydrology (e.g., Simmers, 2003), the amount of precipitation is usually too small to maintain a constant river flow, and thus most perennial rivers flowing in arid- or sub-arid regions originate from more humid adjacent regions. This has been partially confirmed with our studies. For example, Tsujimura et al. (2006a) indicate from a regression analysis between altitude and $\delta^{18}O$ in the precipitation that the main stem of the Kherlen river is fed by precipitation fallen in the headwater region above 1650 m asl, where the annual precipitation is larger around 250-300 mm. Water balance considerations of the Kherlen river watershed (Kamimera et al., 2005) tend to support this idea. Note that there was a possibility that the melted water from the permafrost could also be the source of the river water in this region. However, a figure of $\delta^{18}O$ vs δD (Tsujimura et al., 2006b) has successfully shown that this is not the case, and that the precipitation is the major source of the river water.

Isotopic analysis of shallow groundwater, springs, and rivers by Tsujimura et al. (2006a) has indicted that there is essentially no interaction between the river flow and the surrounding area and that the shallow groundwater and the river water are essentially uncoupled from each other over most of the middle to lower parts of the watershed. This is quite in contrast to the traditional view of river flow in arid areas in which river water is supposed to disappear as it flows because of losses due to recharge into the riparian groundwater aquifers and to river surface evaporation. Since the shallow groundwater circulates within a local system, and is replenished only by high intensity precipitation events (Tsujimura et al., 2006b), it is quite important to evaluate the water balance of each shallow local groundwater system to avoid over-exploitation, since it is the main source of water for grazing and daily nomadic life.

3.2. Hydrologic cycle and ecosystem

In arid and semi-arid regions, the hydrologic regime undoubtedly exerts a strong influence on the fate of the ecosystem. This has been studied in this project with particular emphasis on soil, soil erosion, and grasslands. In general, soils tend to reflect a longer term hydrologic history, while grasslands respond more quickly to the recent hydrology.

In the central part of the Mongolian steppe, Miyazaki (2004) already found prior to the RAISE project that precipitation and the changes in soil moisture content in the early growing season before July had the largest influence on the grass growth as measured by LAI. Similarly, Iwasaki (2005, 2006) have shown through analysis of the meteorological data at 97 IMH stations that there is a fairly strong correlation between vegetation activity and the monthly averages of the temperature and the precipitation. These results tend to indicate that the primary factors that determine the rangelands biomass are indeed precipitation and temperature in early summer season

but that there are probably other factors in some locations that need to be addressed. Kojima (2004)'s result that there is a negative correlation between the magnitude of the changes in biomass over a one month period and the grazing pressure suggests that grazing activity is one of such factor. However, more studies will be needed to quantify such effects.

Asano et al. (2006) made a detailed survey of soil profiles at five locations with annual precipitation ranges from about 130 to 200 mm. Their study shows that there are differences in soil chemistry and physics that clearly reflect the characteristics and amount of the precipitation and infiltration at each location. The presence of the different soil in turn means that the same environmental impacts or disturbances could result in quite different consequences in soils, even though the general soil class within the experimental area is classified as essentially the same Calcic Kastanozems and Calcic Hyposodic Kastanozems (Asano et al., 2006). Mariko et al. (2006) studied experimentally the effect of water on the CO_2 and CH_4 fluxes at the soil surface at KBU. Immediately after an artificial rainfall, CO_2 emission from the soil to the atmosphere increased while the CH_4 absorption by the soil decreased. It is suspected that the rainfall activated the microorganisms and resulted in changes in the fluxes due to respiration. Thus the soil respiration depends not only the soil temperature but also the soil water content. This is another example of the profound relevance of water in controlling fate of the rangelands in various ways.

3.3. Atmosphere-surface Interactions

One of the main topics of interest here is the difference between the montane larch forest and the steppe within the ecotone in this region. A more thorough knowledge of this difference should allow a better assessment of the possible impact on the environment when, for example, the vegetation changes from forest to grassland. A series of studies (Li et al., 2005a, 2005b, 2005c, 2006a, and 2006b) have shown that there is a distinctive difference in the interaction features between the larch forest in the upper watershed and the steppe grassland, although the general seasonal trend is essentially the same. For example, the magnitude of the latent heat fluxes are larger in the forested area, with an annual evaporation of about 225 mm in the forest at FOR and 163 mm in the grassland at KBU. Another contrasting feature of the forest and the grassland is the source of the evaporative fluxes. A Keeling plot analysis with stable isotopes (Tsujimura et al., 2006a) has indicated that 60-70% of the total evapotranspiration is the transpiration at FOR while it is only 30-60% at KBU. Also at FOR, it was found (Li et al., 2005c) that water used by the larch trees originate from the upper 30-cm surface layer of the soil when the precipitation input was large and the soil moisture was relatively high while it came from the deeper layers when the water supply in the upper soil layer was limited. Soil water itself was found to come mainly from summer precipitation (Li et al., 2006b) at the FOR site located on a hilly terrain. The stable isotope analysis carried out on samples taken along a transect from the FOR site toward the Kherlen river indicated that as the land surface elevation decreases toward the river, the trees indeed begin to use river water.

Another aspect one needs to consider is the variability of the surface fluxes. Although rangelands are relatively homogeneous in comparison with other types of surfaces, they still exhibit heterogeneity resulting from

small topographic features, changes in dominant vegetation, etc., with horizontal scales ranging from 10^0 to 10^2 m or more. For example, a preliminary study presented in Sugita et al. (2005) has shown that the instantaneous sensible heat flux *H* exhibits a horizontal variation of 20-50 W/m^2 around a mean *H* of about 100 W/m^2 over a distance of several kilometers even under clear sky conditions. Therefore measurements at a given station may not necessarily represent the average conditions of the entire experimental area. This issue was studied by Asanuma (2006) who utilized a large aperture scintillometer which allows evaluation of the sensible heat flux *H* averaged over a distance of up to 5 km near the A1 station at KBU. His results indicate that fluxes from the A1 station and those from the scintillometer are indeed comparable with each other, and thus a station measurement of the fluxes averaged over appropriate time can probably taken as representative over a steppe region. However, a more detailed analysis has also shown that the choice of empirical formula has a large influence on the uncertainty in *H,* and further studies are required to reduce the uncertainty associated with this problem.

Another common challenge is how fluxes can be estimated over a large area, particularly in a remote region such as that of where the RAISE project took place. Kotani and Sugita (2006) explored this through the application of variance methods with data observed by the aircraft in the convective boundary layer (CBL). Their results indicate that while a calibration is needed, the variance methods can produce surface fluxes *H* with an accuracy of the order of 30 W/m^2. This accuracy could be further improved by including additional variables describing large scale atmospheric features such advection or baroclinicity. Another approach to evaluate the regional distribution of the surface fluxes makes use of satellite remote sensing in conjunction with a model. This was carried out by Matsushima (2006) who utilized the GOES9 and MODIS satellite data to estimate the solar radiation, the surface temperature and LAI. These derived products were then put into the surface heat budget model which allowed the estimation of the surface fluxes with an error <30 W/m^2 on a daily basis during the growing season. The derived map of evaporation that extends horizontally over a distance of the order of 10^2 km indicates that there is a considerable horizontal variation, for example, in the ragne of 0.5-4.0/mm/day on a sunny summer day even though the general class of vegetation is the same grassland.

3.4 Effect of Grazing Activities on Soils, Plant Ecosystem and Surface Fluxes

One of the main concerns in this region is the influence of grazing. This has been studied mainly in two aspects in this study. First, possible effects on the surface-atmosphere interaction have been evaluated by comparing the vegetation, the surface fluxes and other meteorological and hydrologic variables in a pastoral steppe and in a fenced, protected steppe. The protection of the fenced area from grazing animals started in 2002 as mentioned above and since then three years of data had been collected as of the end of 2005. Thus the results obtained so far (Kato, 2006, Kato et al., 2005, Urano et al., 2005) are still preliminary in nature, but they already show a remarkable difference between the two sites. Results of field surveys of the vegetation differences between these two sites have been presented by Urano et al. (2005), Li (Unpublished data, 2005) and Hoshino (2006). Even in July of the summer of 2003, merely one fall-winter season after the fence construction, the peak

aboveground biomass (AB) and the amount of litter were found to be larger by respectively some 33% and 133% within the fenced area while the belowground biomass (BB) remained essentially the same. The maximum and mean height of vegetation were also found higher by 26-30% inside the fence. These differences became even larger in the summer of 2004 particularly for the AB. Toward the third year in 2005, major changes were observed in the difference of litter. The litter is usually consumed by grazing during the dormant season since live biomass is not available. This was even more so at KBU where animals as many as around 97 10^4 sheep equivalent unit (SEU), in which the numbers of different animals are translated into sheep equivalent numbers by the ratios given by Asian Development Bank (2002), are brought to this area during winter season due to its milder climate (Mr. Gerelsuren of the KBU village mayor, Personal communication, 2004). From spring through fall, the average animal number is 46 10^4 SEU in this village of 1.982 10^4 ha. These numbers can be translated into the stocking rate or the grazing pressure of 2.3 (winter) and 7.3 (spring-fall) SEU/ha. This large stocking rate has clearly contributed to the loss of litter in this pastoral steppe and has resulted in almost twice as much litter accumulation inside the fenced area as on the outside.

The fact that amount of the BB remained roughly the same is not surprising since it usually takes more time for the BB to respond to environmental changes. Nevertheless, in 2003, the cumulated growth of the root system in the pastoral lands was smaller already in 2003 by some 20% on a dry weight basis than in the protected area (Liu et al., 2004). Since the AB constitutes only 9% of the total biomass (Chen et al., 2006), it is more important to study the effect of grazing activities on the BB in the longer term. This was further studied by means of an ecological model (see below).

Soil surveys (Hoshino, 2006) during three years of 2002-2005 have shown that there are not substantial changes in soil physical properties. In terms of chemical properties, however, notable changes were observed which can be explained in terms of grazing activities. For example, pH value was some 250% higher in the pastoral steppe and this is probably linked to the increase of BB inside the fenced area as the root systems are known to discharge the organic acid.

Grazing activities should affect the surface condition and thus should also have a large influence on the surface-atmosphere interactions. This was studied by comparing the fluxes at the A1 and A2 sites in KBU. A preliminary analysis (Kato et al., 2005, Kato, 2007) has indicated that already after one fall-winter season, G of the natural, pastoral grasslands was much larger than that of the fenced area by a factor of 2.5 approximately. In contrast, Rn showed only a small difference at the two areas. At peak vegetation strength the latent heat and H fluxes were found larger inside the fenced area. This difference apparently comes from larger available energy inside the fence with the smaller G value, and also from the enhanced turbulence exchange as a result of taller and denser vegetation.

A second important aspect of grazing is the possible inducement of soil erosion. It is generally argued that grazing activities reduce surface vegetation coverage and thus make the soil more vulnerable to erosion. Studies of Onda et al. (2006) and Nishikawa et al (2005) have estimated the runoff generation and the sediment discharge, i.e., the amount of water erosion of soils at two contrasting small experimental watersheds at KBU and BGN in

terms of grazing pressure. The overall discharge during the observation period was higher at the BGN than at the KBU watershed for the same size of rainfall. This is somewhat surprising given the sparse vegetation with heavier grazing at the KBU watershed. However, investigation of the sediment discharge over the past 40 years or so by using ^{137}Cs and $^{210}Pb_{ex}$ have shown that indeed the mean soil erosion rate in the past at the KBU has been larger than that at the BGN watershed. This probably means that at KBU, surface soils that can be easily eroded had already been discharged and now there was a smaller soil discharge even though the potential of the erosion was still quite high. Thus not only the current status of the grazing activities but also the past activities are important to investigate the soil erosion and the land degradation of an area. Note that wind erosion in this area has been found to be smaller in a preliminary study of Nishikawa et al. (2005).

3.5. Future Predictions

It is often necessary and required by local governments and policy makers to provide predictions of the future evolution of the environment. This task has been and will be worked out mainly by three models as mentioned above. Although not all tasks have been completed, some relevant results are reported in this special issue. Sato et al. (2006) have estimated the current and future regional climate, with the main focus on the summer precipitation, of this region by means of the dynamical downscaling method (Houghton, et al., 2001) with the GCM outputs and reanalysis data as two means of inputs into a computational model. The target years were 1991-2000 for the hindcast and 2071-2080 for the prediction based on the A2 scenario (Nakicenovic and Swart, 2000) run of a GCM experiment. The comparison between the mean precipitations observed by the IMH stations and those hindcasted by the model indicated that the distribution patters of the precipitation agrees fairly well although the absolute values were found underestimated in the southern and eastern parts, overestimated in the western part, and in agreement in the southern and in mountainous regions. The difference between the current 10-year means and future 11-year means were studied, and it was found that both predictions based on the two inputs produced similar results with a rainfall decrease of 15% in the NW and NE regions, while in the SE and SW regions the changes can be considered negligible. On average over the entire region of Mongolia, the rainfall will appear to decrease. Since major rivers in Mongolia have their origins in the NW and NE regions, the decrease in rainfall could become a serious concern for water resources management.

Chen et al. (2006) studied the sustainable grazing pressure on the grasslands by means of their ecosystem model for a range of stocking rates and for the climatological conditions given as the 10-year averages of the IMH Meteopost at KBU. Their results based on model runs over 250 years at one month time steps demonstrated that, as the grazing pressure increases, the AB and the above-ground net primary production (ANPP) decrease significantly. For example, for an assumed condition without any grazing activities, the AB and the ANPP values remain about the same. For a stocking rate of 0.4-0.7 sheep/ha, the ANPP value initially decreases but eventually reaches an equilibrium. However, for a larger stocking rate, the ANPP decreases all the time and should eventually result in the loss of the grasslands ecosystem. Thus the Mongolian steppe region,

represented by KBU, could be classified as "overgrazed" for a stocking rate in excess of 0.7 sheep/ha, as "moderately grazed" for 0.4-0.7 sheep/ha, and as "lightly grazed" whne it is grazed by less than 0.07 sheep/ha. Since current grazing pressures in Mongolia lie in the range of 0.25-1.50 sheep/ha (Fig. 12), the grazing pressure in some areas is already too extensive, as it exceeds the critical rate of sustainable land use. Moreover, the above statistics represent averages obtained for each *soum* over a relatively large area. Locally, higher stocking rates have been reported. For example, the stocking rate at KBU is as high as 7 sheep/ha in winter due to the migration of animals to this area as mentioned above. Thus, more specific estimate of such local stocking rates is probably needed to make full use of the model predictions.

4. Concluding Remarks

The observations, analyses and modeling activities of the RAISE projects have provided unique opportunities to study the hydrologic, atmospheric and ecological processes and interaction among them in the rangelands-forests ecotone located in northeastern Asia. There is still a profound lack of understanding of these processes and thier mutual interactions and of information in this area in comparison with other rangelands in the world. Thus the results presented in this special issue and elsewhere from the RAISE projects should contribute to fill this vacuum and should provide the general scientific community with information needed to compare and integrate the results obtained here with those obtained elsewhere. For example, among the papers presented in the special issue on the Semi-Arid land-Surface-Atmosphere (SALSA) program (Goodrich et al., 2000) whose observations took place at the semi-arid Mexico-U.S. border region, several can readily be compared with our results to gain insight into the generality and the differences of the processes and features these rangelands. One finding that appears to be general relates to surface-atmosphere interactions. Both projects utilized and have demonstrate potential and the difficulties involved in the use of large aperture scintillometer to infer the area-averaged fluxes. At the same time, one can easily identify subjects that are quite area specific. For example, in the SALSA experimental area, shrub or mesquite invasion of the grassland and its influence on the hydrologic cycle appear to be an important subject, while in the RAISE experimental area, grazing activities are still within the limited range and the grasslands degradation may not yet be of a high priority environmental problem, except for sites with locally high grazing pressure. Nevertheless, a comparison should allow results obtained at a particular area to be put into perspective, and thus should be carried out more extensively with results obtained in areas with diverse climatic, hydrologic and social conditions.

Although the results obtained in RAISE cover a wide range of subjects, there are still numerous relevant issues that remain to be studied. Actually this becomes even more so, as newer findings become available. Below such issues are summarized that need to be studied in the coming years within the RAISE project area.

Among water cycle and water resources problems in arid- and semi-arid regions, the role of groundwater is crucial. Within the framework of the RAISE project, it has become clear that the shallow groundwater is recharged and consumed essentially locally, except for the higher elevations of the watershed and for the vicinity

of the streams channels. Thus an estimation of the recharge rate and the optimal water withdrawal from each groundwater system based on water balance considerations are essential to allow sustainable use of the shallow groundwater resources. Tsujimura et al. (2004, personal communication) have initiated such a study to estimate the groundwater recharge rate in a small watershed where the surface water does not exit and where the shallow groundwater, which accumulates in the lower part of the watershed, is used for grazing and daily nomadic activities through a hand-dug well. This type of study should be extended to other watersheds to determine the spatial and inter-annual variability of the water balance and the recharge rate.

Another issue that needs to be studied relates to the flow and storage on the deep, confined groundwater. Until now, most of the groundwater use in Mongolia has been limited to the shallow, unconfined aquifers, and not much is known on the properties of the confined groundwater system. This is potentially a rich source of water resources. Also in this region, interaction with the permafrost may become an important issue with the increase of the air temperature and possibly resulting in thawing of the permafrost.

In the general category of surface-atmosphere interaction studies, some new techniques such as the use of the scintilometer, the CBL variance methods, the energy balance model with remote sensing data as inputs, to evaluate regional fluxes have been made within RAISE. Each of them appears to be promising. However, they are still in the research phase, and the utilization of these novel techniques or their products in other research areas or in an operational system is still not ready for full implementation, and their actual usage needs to be explored further. One obvious option would be the usage of these products as inputs or validation data for models of climate, hydrology and ecosystem simulation. The surface-atmosphere interaction processes are a common interface which all models include as a relevant feature. Perhaps through off-line comparison or eventually on-line coupling, new findings and newer approaches of the atmosphere-interaction studies can be fully utilized.

In the general area of interaction among the hydrosphere, atmosphere, and biosphere, new findings and insights specific to this region or common to the general rangelands have been obtained. However, these are obtained as a separate process of some specific parts of the complicated interaction. Within the RAISE project, grazing activities have been modeled to some extent and this has produced a useful prediction of the sustainable grazing pressure. Naturally further studies are desired to take into account processes that have become evident through observations but are not yet incorporated in the models. An example is the reduction of the C and N inputs into the soil by the prohibition of grazing. Also the combined use of the models for future prediction (Fig. 13) is a natural target of the study.

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Figure caption

Fig. 1 A map showing the vegetation coverage in northeastern Asia with the location of the Khelren river basin and major rivers and lakes. Vegetation classification by DeFries and Townshend (1994) is used. Open circles represent RAISE observation points (Tables 1 and 6). Location names are as follows. SHB: Sukhbaatar, MDG: Mandalgobi, UDH: Underhaan, and CHB: Choibalsan, and UB: Ulaanbaatar. The names of the points within Kherlen river basin, whose boundary is shown by white lines, are shown in Figs. 3-4. For the detailed vegetation within the Kherlen river basin, see Fig. 4.

Fig. 2 Changes in annual mean grazing pressure in sheep/ha at selected *soums* (Mongolian administrative unit equivalent of county) from 1984 to 2003. Circles represent grazing pressure in Darhan (DH) soum (with an area of 4.4 10^5 ha), squares in Bayandelger soum (2.3 10^5 ha) that included Baganuur (BGN), triangles in Jargalthaan (JGH) soum (3.0 10^5 ha), asterisks in Kherlen soum (2.5 10^5 ha) that includes Underhaan (UDH), crosses in Mongenmorit soum (6.7 10^5 ha) (MNG), and diamonds in Delgerkhaan soum (3.0 10^5 ha) that includes Kherlenbayan-Ulaan (KBU) village. See Figs. 3-5 for the exact locations of these soums.

Fig. 3 Distribution of vegetation in the Khelren river basin on the basis of data provided by Saandar and Sugita (2005). The black color indicates forest, the gray colors the mountain steppe, and the bright gray the steppe region. Note that vegetation data are not available outside the Mongolian border toward the north of the Kherlen river watershed, and their area is left blank. Circles denote the location of the IMH and RAISE stations. BGN: Baganuur, BGN (hillslope): hillslope observation site in Baganuur, KBU: Kherlenbayan-Ulaan, DH: Darhan, UND: Underhaan, JGH: Jargalthaan, FOR: forest stie near MNG, MNG: Mongenmorit, and CHB: Choibalsan. White thick lines represent the basin boundary while the white thin lines indicate major rivers.

Fig. 4 Distribution of the annual mean precipitation in the Khelren river basin; the contour lines were created from the IMH meteostation network data for the period of 1993-2003. Small triangles denote locations where the soil samples were taken for laboratory tests of physical and thermal properties (see Table 6.) Other symbols and the name conventions are the same as those in Fig. 3.

Fig. 5 Topographic map of the Khelren river basin. Symbols and name conventions are the same as in Figs. 3-4. Additional small squares indicate the location of the IMH stations in and around the Kherlen river basin. Contour lines at 500 m intervals are shown based on the DEM provided by GTOP30 data set (http://edc.usgs.gov/products/elevation/gtopo30.html)

Fig. 6 Topographic map with a Landsat ETM+ true color image of the FOR site. Contour lines are shown at 30 m

intervals, except for the upper side of the map as this is outside the ASTER image from which contour lines were created. The flux station is indicated by a circle. Also shown at the upright corner is aerial photograph of the site.

Fig. 7 Topographic map with a Landsat ETM+ of the KBU site with location of the stations, fenced area, and a former agricultural field indicated. Details of the stations' setting are also shown as a separate map. At KBU, agriculture was initiated in 1962 to produce pasture. In 1982, the agricultural area was expanded to 5,000 ha with irrigated water from the Kherlen river to produce wheat, corn, sunflower, etc. until 1992; the field has been abandoned since then, but the vegetation is still different from surrounding steppe area (Hoshino, 2006) although LAI is about the same.

Fig. 8 Changes of annual precipitation measured at the IMH Meteostation at Mongenmoryt (circles in panel (a) and in panel (b)), those provided by Willmott and Matsuura (2001) (triangles in panel (b)) and seasonal variation of NDVI derived by the NOAA AVHRR sensors (inverted triangles in panel (c)) and the SPOT satellite (triangles in panel (c)). The thick horizontal lines represent the mean precipitation for panels (a) and (b) during the period shown in each panel , and the mean peak NDVI value derived from the NOAA AVHRR sensors (panel (c)).

Fig. 9 Same as Fig. 4 but for KBU site.

Fig. 10 Seasonal variations of Normalized difference vegetation index (NDVI) at six RAISE observation sites with the timing of four IOPs indicated by the shaded bars. The location abbreviations are the same as in Table 1, and their locations can be found on Figs. 3-5.The thin NDVI lines indicate annul changes for each year from 1981 to 2002, and the thick line shows the NDVI changes in 2003. The NDVI values derived from AVHRR/NOAA were processed by CEReS (2001), while the SPOT NDVI values were from VGT-S10 products of the Image Processing and Archiving Centre, VITO (http://www.vgt.vito.be/)

Fig. 11 Flight paths of aircraft measurements. Thick line represents the Khelren river.

Fig. 12 Distribution of the grazing pressure in Mongolia. Unit is BOD/ha.

Fig. 13 Schematic diagram showing strategy of the future prediction in RAISE

Table 1 List of Observation Stations of the RAISE Project.

Name/Location	Abbreviations	Type	Measured items	Annual mean precipitation (mm/year) Annual and summer mean temperature (°C)	Maximum LAI, aboveground biomass, and plant height in 2003 Dominant plant species
Forest site 25 km NE of Mongonmorit (MNG) 48° 21'6.7"N 108° 39'15.6"E 1630 m asl	FOR	Flux	Fluxes, general meteorology and hydrology Water and water vapor sampling Biological parameters	282 mm/y 283 mm/y -2.9 °C 11.3 °C	2.2-2.7 (Overstory, July 23) 1.7 (Understory, July 11) 117 g/m^2 (Overstory) *Larix sibirica* *Betula platyphylla* (Overstory) *Carex spp.* *Koeleria spp.* *Chamaenerion angustifolium* (Understory)
Baganuur 47° 46'59"N 108° 21'45"E 1360 m asl	BGN	AWS	General meteorology and hydrology, fluxes by a bulk method	213 mm/y 263 mm/y -2.4 °C 12.7 °C	0.34 (June 27) 38.0 g/m^2 (Aug.25) 10.0 cm (July 25) *Stipa krylovii* *Carex sp.* *Caragana stenophylla* *Cleistogenes squarrosa* *Artemisia frigida*

Kherlenbayan-Ulaan 47° 12'50.3"N 108° 44'14.4"E 1235 m asl	KBU	Flux	Fluxes, general meteorology and hydrology of protected and unproteced area	181 mm/y 240 mm/y 1.3 °C 16.8 °C	0.57 (Aug. 19) 81.2 g/m^2 (Aug. 19) Dominant species: same as in BGN
			Water and water vapor sampling		
			Biological parameters of protected and unproteced area		
			GPS		
			Sintilometer measurements		
Underhaan 47° 18'30"N 110° 37'20"E 1040 m asl	UDH	AWS	General meteorology and hydrology, fluxes by a bulk method	226 mm/y 250 mm/y -0.1 °C 15.5 °C	0.26 (Aug. 30) 38.3 (Aug. 30) 7.0 (June 22, July 29) Dominant species: same as in BGN
Darhan 46° 37'58"N 109° 24'38"E 1270 m asl	DH	AWS	General meteorology and hydrology, fluxes by a bulk method	216 mm/y 206 mm/y 1.6 °C 15.2 °C	35.9 (Aug. 28) 0.27 (June 20) 6.0 (June 20) Dominant species: same as in BGN
Jargalthaa 47° 29'13"N 109° 28'24"E 1335 m asl	JGH	AWS	General meteorology and hydrology, fluxes by a bulk method	187 mm/y 240 mm/y 0.9 °C 15.4 °C	162.8 (Sep.1) 0.50 (July 30) 9.0 (Sep. 1) Dominant species: same as in BGN

AWS: Automatic Weather Station

Dominant plant species: from Li et al. (2005a), Li et al. (2005b) and Li (2004, unpublished data)

Mean annual precipitation

Upper row: means for 1993-2003 observed at the IMH station, except for the FOR station for which observations at Mongenmoryt station is listed

Lower row: means for 1950-1999 at a nearest 0.5×0.5°grid by Willmott and Matsuura (2001).

Annual and summer mean temperature

The annual mean and means from May through September, both for the period of 1993-2003 observed at the IMH stations.

LAI and aboveground biomass: from Kojima (2004) for grasslands and Li et al. (2005a) for the FOR site.

Note that JGH and KBU stations are the meteopost and only the data three times a day (8, 14, 20 MST) were available and were used for the calculation, while others are the meteostation. Also in some months, data are completely missing in some stations. At KBU, this is the case for 23 months, 1 month at BGN, 6 months at DH, and 25 months at JGH, and thus the listed values should be treated with caution.

Table 2 Observed elements at the FOR site

Category	Item	Instrument (manufacturer and model)	Height (m)	Sampling interval	Averaging time
Radiation	Downward short-wave radiation	Net radiometer (Kipp & Zonen, CNR1)	29	5 sec	30 min
	Upward short-wave radiation				
	Downward long-wave radiation				
	Upward long-wave radiation				
Flux	Sensible heat flux	Sonic anemometer (Kaijo, SAT540)	30	10 Hz	30 min
	Latent heat flux	Sonic anemometer (Kaijo, SAT540) and CO_2/H_2O analyzer (LI-COR, LI-7500)			
	CO_2 flux				
	Friction velocity	Sonic anemometer (Kaijo, SAT540)			
Meteorology/ Hydrology	Wind speed				
	Wind direction				
	Air temperature	Humidity and temperature probe (Vaisala, HMD45D) in a ventilated radiation shield		5 sec	
	Relative humidity				
	Surface temperature	Infrared radiation thermometer (Climatec, CML303F)			
	Air pressure	Barometer (Vaisala, PTB101)	1.5	30 min	0
	Precipitation	Tipping bucket rain gauge (R. M. Young, 52202)	0	30 min	total amount over 30 min
Soil	Heat flux in the soil	Heat flux plate (REBS, HFT-1.1)	-0.05	10 sec	30 min
			-1		
	Soil tempetature	Platinum resistance thermometer	-0.05		
			-0.1		
			-0.2		
			-0.3		
			-0.5		

	Volumetric water content	TDR sensor (Campbell, CS616)	-0.1	10 sec	
			-0.2		
			-0.3		
			-0.7		
			-1		
		TDR sensor (IMKO, Trime-IT)	-0.05	30 min	0
			-0.5		
	Matric potential	Tensionmeter (Irrometer, RA24LT)	-0.05	10 sec	30 min
			-0.1		
			-0.3		
			-0.5		
			-0.7		
			-1		
		Gypsum block sensor (Irrometer, Watermark 200)	-0.05		
			-0.1		
			-0.3		

Table 3 Observed elements at the A1 flux station at KBU.

Category	Item	Instrument (manufacturer and model)	Height (m)	Sampling interval	Averaging time
Radiation	Downward short-wave radiation	Net radiometer (Kipp & Zonen, CNR1)	2.5	5 sec	30 min
	Upward short-wave radiation				
	Downward long-wave radiation				
	Upward long-wave radiation				
Flux	Sensible heat flux	Sonic anemometer (Kaijo, SAT550)	3.5	10 Hz	
	Latent heat flux	Sonic anemometer (Kaijo, SAT550) and CO_2/H_2O analyzer (LI-COR, LI-7500)			
	CO_2 flux				
	Friction velocity	Sonic anemometer (Kaijo, SAT550)			
Meteorology Hydrology	Wind speed				
	Wind direction				
	Air temperature	Humidity and temperature probe (Vaisala, HMD45D) in a ventilated radiation shield	2.5	5 sec	
	Relative humidity				
	Surface temperature	Infrared radiation thermometer (Climatec, CML303F)			
	Air pressure	Barometer (Vaisala, PTB101)	1.3	30 min	0
	Precipitation	Tipping bucket rain gauge (R.M. Young, 52202)	0	30 min	total amount over 30 min
Soil	Heat flux in the soil	Heat flux plate (REBS, HFT-1.1)	-2	10 sec	30 min
			-10		
	Soil temperature	Platinum resistance thermometer	-0.05		
			-0.1		
			-0.2		
			-0.3		
			-0.5		
			-0.7		

			-1		
			-1.5		
	Volumetric water content	TDR sensor (Campbell, CS616)	-0.1		
			-0.2		
			-0.3		
			-0.7		
			-1		
			-1.5		
		TDR sensor (IMKO, Trime-IT)	-0.05	30 min	0
			-0.5		
	Matric potential	Tensionmeter (Irrometer, RA24LT)	-0.05	10 sec	30 min
			-0.1		
			-0.3		
			-0.4		
			-0.6		
			-1		
		Gypsum block sensor (Irrometer, Watermark 200)	-0.05		
			-0.1		
			-0.3		

Table 4 Observed elements at A2 station in KBU.

Category	Item	Instrument (manufacturer and model)	Height (m)	Sampling interval	Averaging time
Radiation	Downward short-wave radiation	Net radiometer (Kipp & Zonen, CNR1)	2.5	5 sec	30 min
	Upward short-wave radiation				
	Downward long-wave radiation				
	Upward long-wave radiation				
Flux	Sensible heat flux	Sonic anemometer (Gill, R3A)	3	10 Hz	
	Latent heat flux	Sonic anemometer (Gill, R3A) and CO_2/H_2O analyzer [2003/3-2004/3] (ADC BioScientific, OP2) [2004/4-present] (LI-COR, LI-7500)			
	CO_2 flux				
	Friction velocity	Sonic anemometer (Gill, R3A)			
Meteorology /Hydrology	Wind speed				
	Wind direction				
	Air temperature	Humidity and temperature probe (Vaisala, HMD45D) in a ventilated radiation shield		5 sec	
	Relative humidity				
	Surface temperature	Infrared radiation thermometer (CLIMATEC, CML303F)	2.5		
Soil	Soil Heat flux	Heat flux plate (REBS, HFT-1.1)	-2	10 sec	30 min
			-10		
	Soil tempetature	Platinum resistance thermometer	-0.05		
			-0.25		
	Volumetric water content	TDR sensor (Campbell, CS616)	-0.05		
			-0.25		

Table 5 Observed elements at four automatic weather stations (AWSs)

Category	Item	Instrument (manufacturer and model)	Height (m)	Sampling interval	Averaging time
Radiation	Downward short-wave radiation	Solar and infrared radiometer (EKO, MR-40)	3.10 (UDH) 2.98 (BGN) 3.00 (JGH) 2.90 (DH)	10 sec	10 min
	Upward short-wave radiation				
	Downward long-wave radiation				
	Upward long-wave radiation				
Meteorology/ Hydrology	Wind speed	3-cup anemometer (R. M. Young, 03002)	2.92 (UDH) 3.15 (BGN) 3.00 (JGH) 2.90 (DH)		
	Wind direction	Wind vane (R. M. Young, 03002)			
	Air temperature	Platinum resistance thermometer	2.60 (UDH, JGH) 2.63 (BGN) 2.50 (DH)		
	Relative humidity	Humidity probe (Vaisala, HMP45D) in radiation shield			
	Air pressure	Barometer (Vaisala, PTB210)	1.3		
	Precipitation	Tipping bucket rain gauge (EKO, MW010)	0	30 min	total amount over 30 min
Soil	Heat flux in the soil	Heat flux plate (EKOl, MF-81)	-0.05	10 sec	10 min
	Soil tempetature	Platinum resistance thermometer	-0.03		
	Volumetric water content	TDR sensor (IMKO, Trime-IT)		1 min	

Table 6 Observed elements by means of mobile and other observations

Category	Item	Method/instruments	locations	Remarks
Biology	LAI	In-situ sampling and laboratory work (steppe area) litter fall collection and all-sky camera (for the FOR site)	KBU, BGN, UDH, JGH, DH, and FOR	For steppe area, a linear regression equation between LAI and biomas was established after IOPs and were used to derive LAI from biomass measurements since then.
	Biomass	In-situ sampling and laboratory work		
	Vegetation height	In-situ determination		
	Vegetation coverage			
	Vegetation species			
Radiation/Remote Sening	Spectral reflectance	Spectral radiometer (Analytical Spectral Devices, FieldSpec Pro FR)	KBU, BGN, UDH, JGH, DH, FOR, and aircraft	See Fig. 11 for the aircraft paths
Flux	Sensibel heat flux	Sonic anemometer (Gill, R3A)	KBU, BGN, UDH, JGH, and DH	
	Latent heat flux	Sonic anemometer (Gill, R3A) and CO_2 /H_2O analyzer (ADC BioScientific, OP2)		
	CO_2 flux			
	Momentum flux	Sonic anemometer (Gill, R3A)		

	Temperature and humidity variances	fine thermocouple and a crypton hygrometer (Campbell, KH-20)	aircraft	See Fig. 11 for the aircraft paths
	Soil and vegetation CO_2 flux	chamber method	KBU	
Soil	Physical, chemical and thermal properties	In-situ sampling and laboratory test	Total of 46 locations	See Fig. 4 for locations
	Soil profile examination	FAO/ISRIC (1990)	KBU, BGN, UDH, JGH, DH, and FOR	
	Horizontal distribution of soil water	10-m interval measurements along a 100-m transect by a Portable TDR meter (Campbell, Hydrosense)	KBU, BGN, UDH, JGH, and DRH	
Groundwater and spring water	Water level	Automatic water level sensor In situ determination	MNG, BGN, KBU and UDH (automatic) 74 wells and 7 springs (in situ)	
	Chemistry and temperature	In-situ sampling and laboratory test	74 wells and 7 springs	
	Isotope	In-situ sampling and laboratory test		
River water	Water level (& discharge)	Automatic water level sensor and periodic discharge determination	MNG, BGN, UDH, CHB (automatic) 30 locations (in situ)	
	Isotopes	In-situ sampling and laboratory test		
	Chemistry	In-situ sampling and laboratory test		

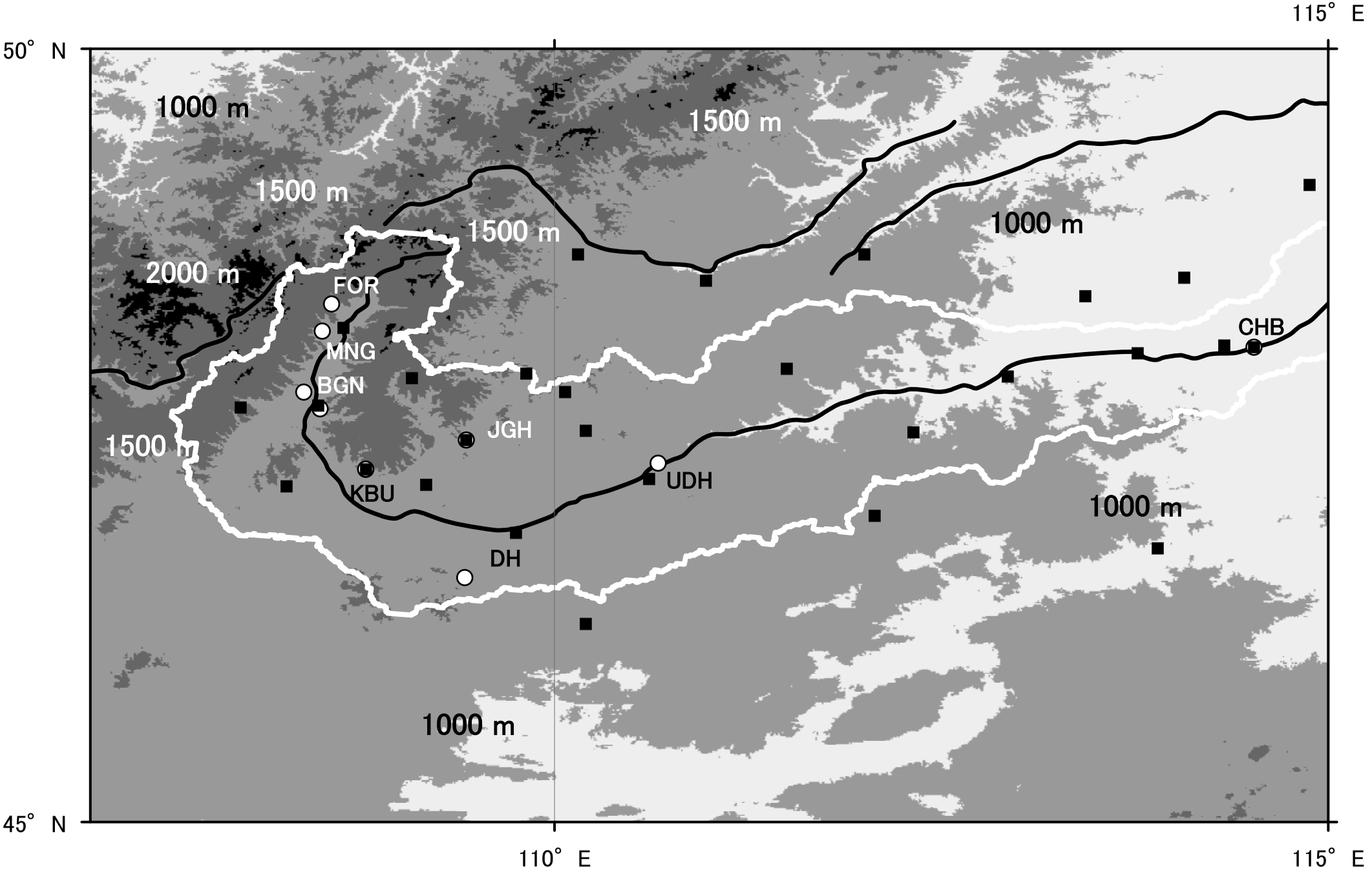
Precipitation	Isotopes	In-situ sampling and laboratory test	MNG, KBU, UDH, UB, MDG, and SHB	
Precipitable water	GPS	High resolution GPS	BCM and MNG	
Water vapor	Isotope	In-situ sampling and laboratory test	FOR, KBU (near surface) FOR, BGN, KBU, UDH, JGH, DH (0.2-2 km above surface by Aircraft)	

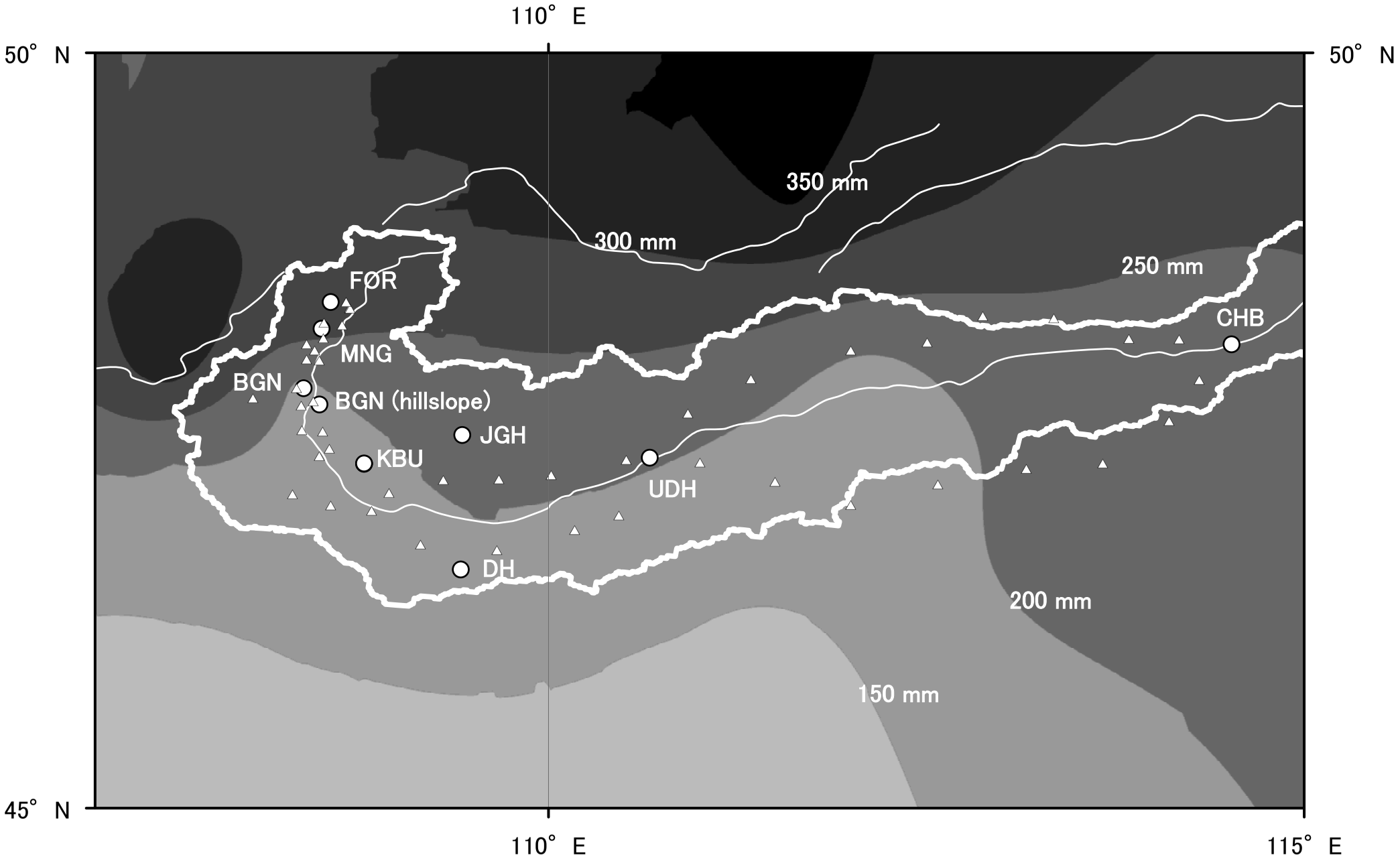
SHB: Sukbaatar, MDG: Mandalgobi, CHB: Chibalsan, BCM: Bayanchandmani. Other location abbreviations are listed in Table 1. Locations are graphically shown in Figs. 1, 3-5.

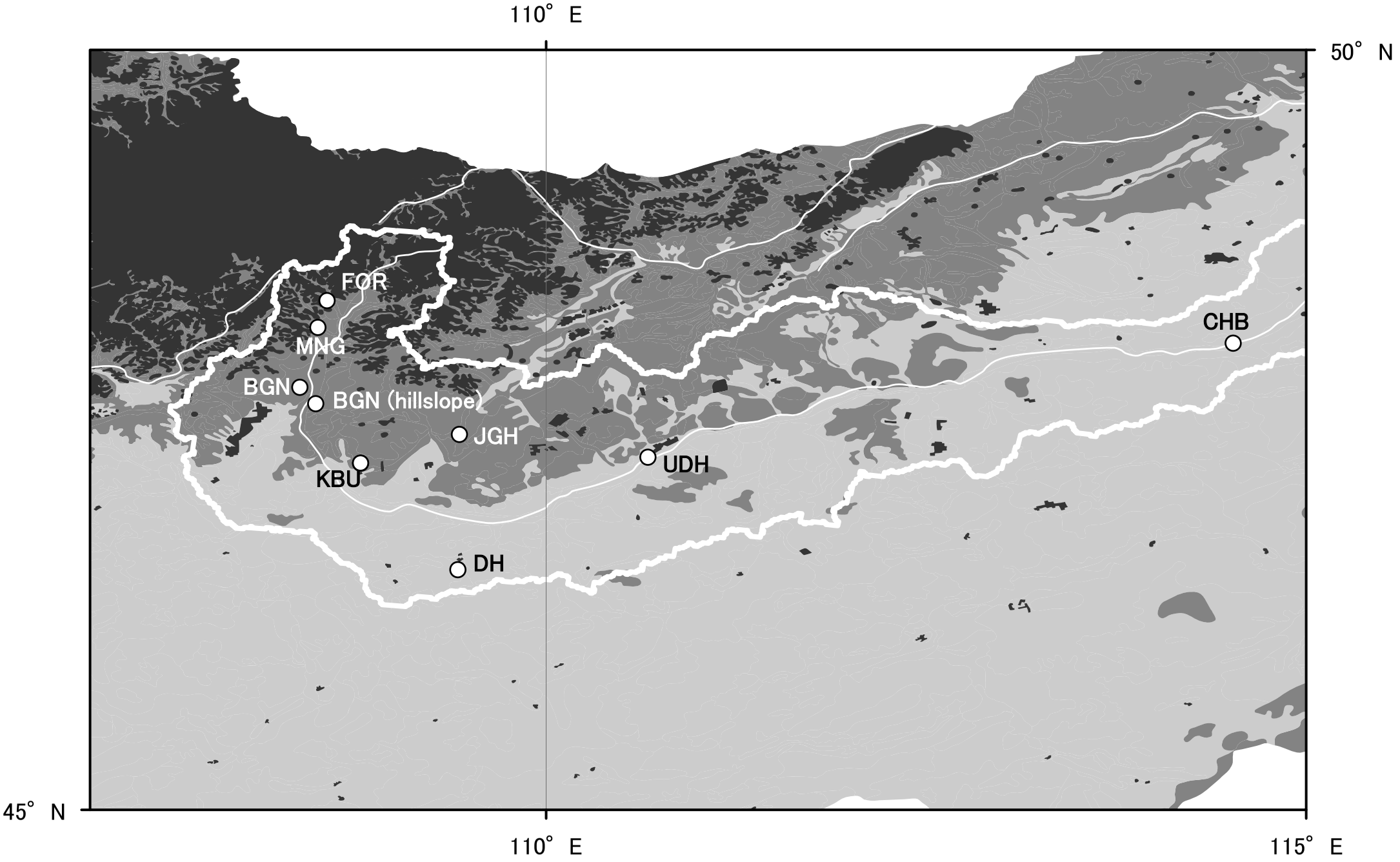
Table 7 Summary of aircraft observations

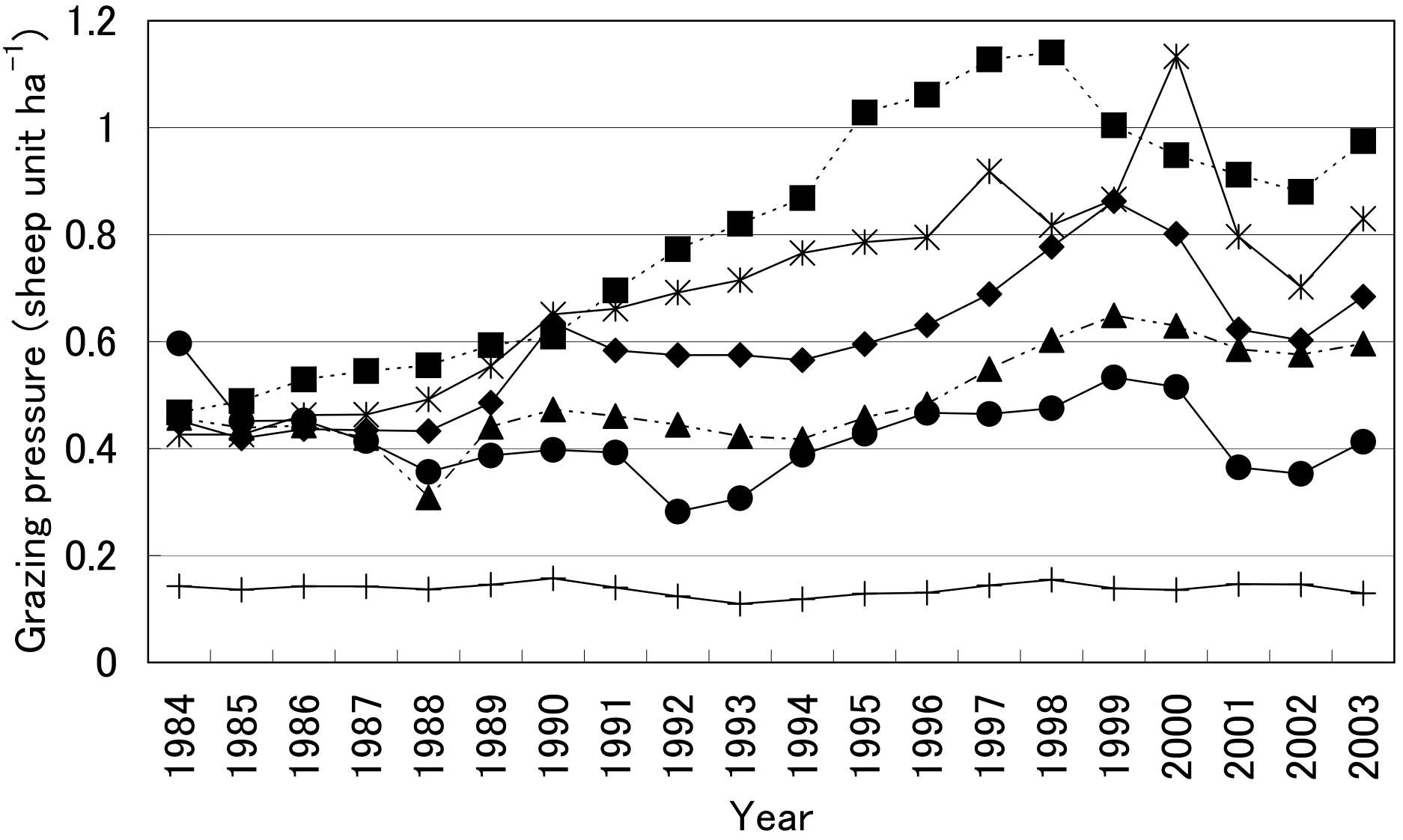
Date	Time (MST)	Flight path	general weather condition
June 17	18:20 - 20:29	UB - BGN - UB	Clear with light haze due to forest fire
June 18	9:35 - 12:55	UB - BGN - KBU -UB	Clear with slight haze due to forest fire
July 19	13:11 - 16:47	UB - BGN - FOR - BGN - KBU -UDH	Clear, but hazy at BGN-FOR-KBU
July 20	9:39 - 13:44	UDH - KBU - BGN - FOR - BGN - UB	Generally clear and clear/cloudy at UDH-KBU
July 23	10:22 - 13:56	UB -FOR - BGN - KBU - UB	Clear
August 21	9:40 - 14:14	UB - BGN -FOR - BGN - KBU - JGH - UDH	Mostly cloudy near UDH, BGN, and UDH, and clear/cloudy at other locations
August 22	10:45 - 15:37	UDH - DH - KBU - BGN - FOR - BGN - UB	Generally clear except for UDH where morning clouds prevailed
August 23	9:57 - 14:00	UB - FOR - BGN - KBU -UB	Generally clear except for sporadic cloudiness near FOR
October 2	13: 40 - 18:00	UB - FOR - BGN - KBU - JGH - UDH	Generally clear except for cloudy condition at FOR and JGH-UDH
October 3	11:00 - 15:49	UDH - DH - KBU - BGN - FOR - UB	Generally clear except for partial cloudiness at UDH and DH
October 4	10:40 - 14:39	UB - FOR - BGN - KBU - UB	Generally clear

UB: Ulaanbaatar. Other locations are listed in Table 1. Flight paths are graphically shown in Fig. 11.


115° E
50° N
1000 m
1500 m
1500 m
1500 m
1000 m
2000 m
FOR
MNG
BGN
CHB
JGH
1500 m
KBU
UDH
1000 m
DH
1000 m
45° N
110° E
115° E


110° E
50° N
50° N
350 mm
300 mm
250 mm
FØR
MNG
BGN
BGN (hillslope)
JGH
KBU
UDH
CHB
DH
200 mm
150 mm
45° N
110° E
115° E


110° E
50° N
FØR
MNG
BGN
BGN (hillslope)
JGH
KBU
UDH
CHB
DH
45° N
110° E
115° E


Grazing pressure (sheep unit ha^{-1})
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0.6
0.4
0.2
0
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1985
1986
1987
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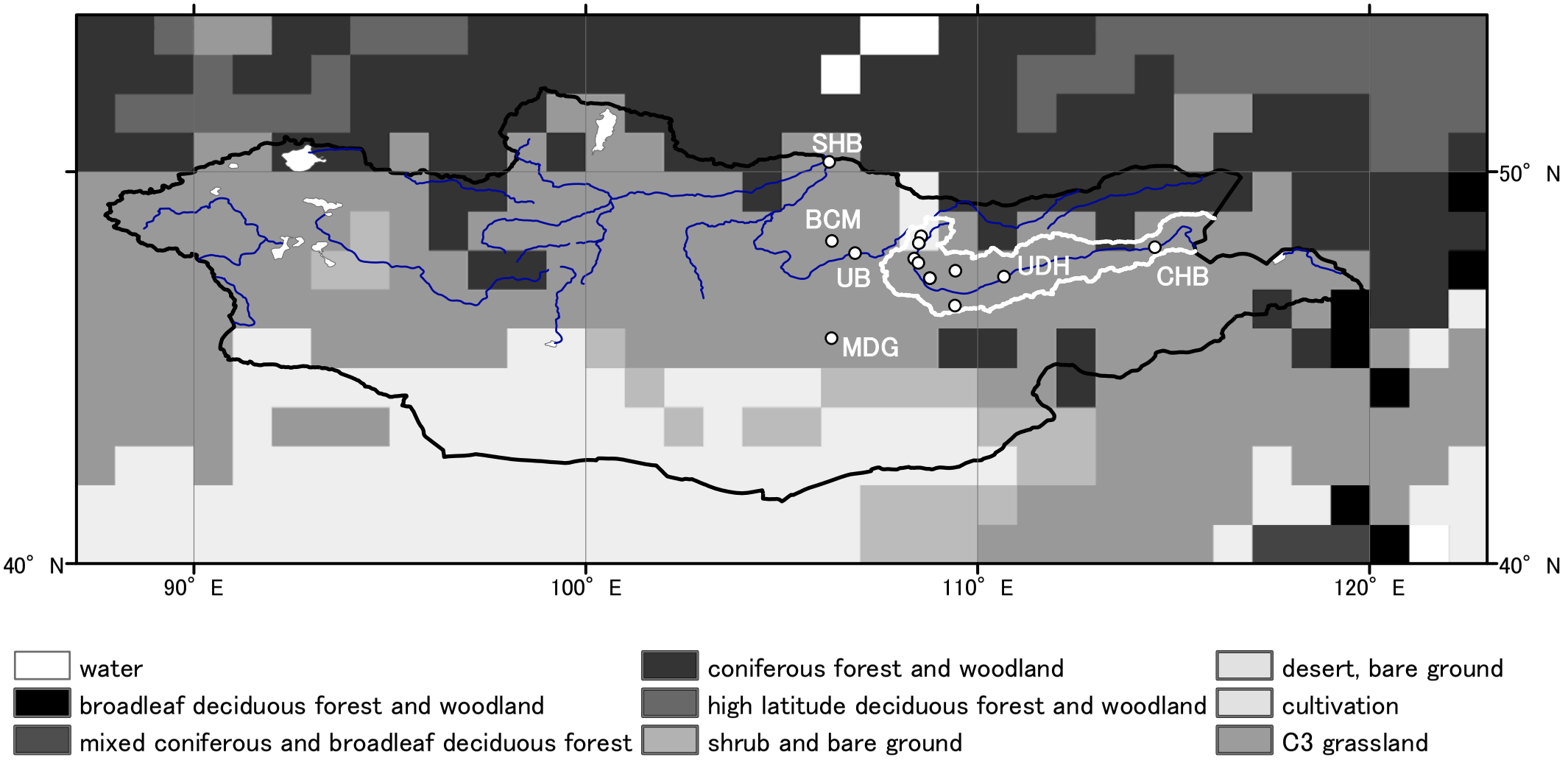
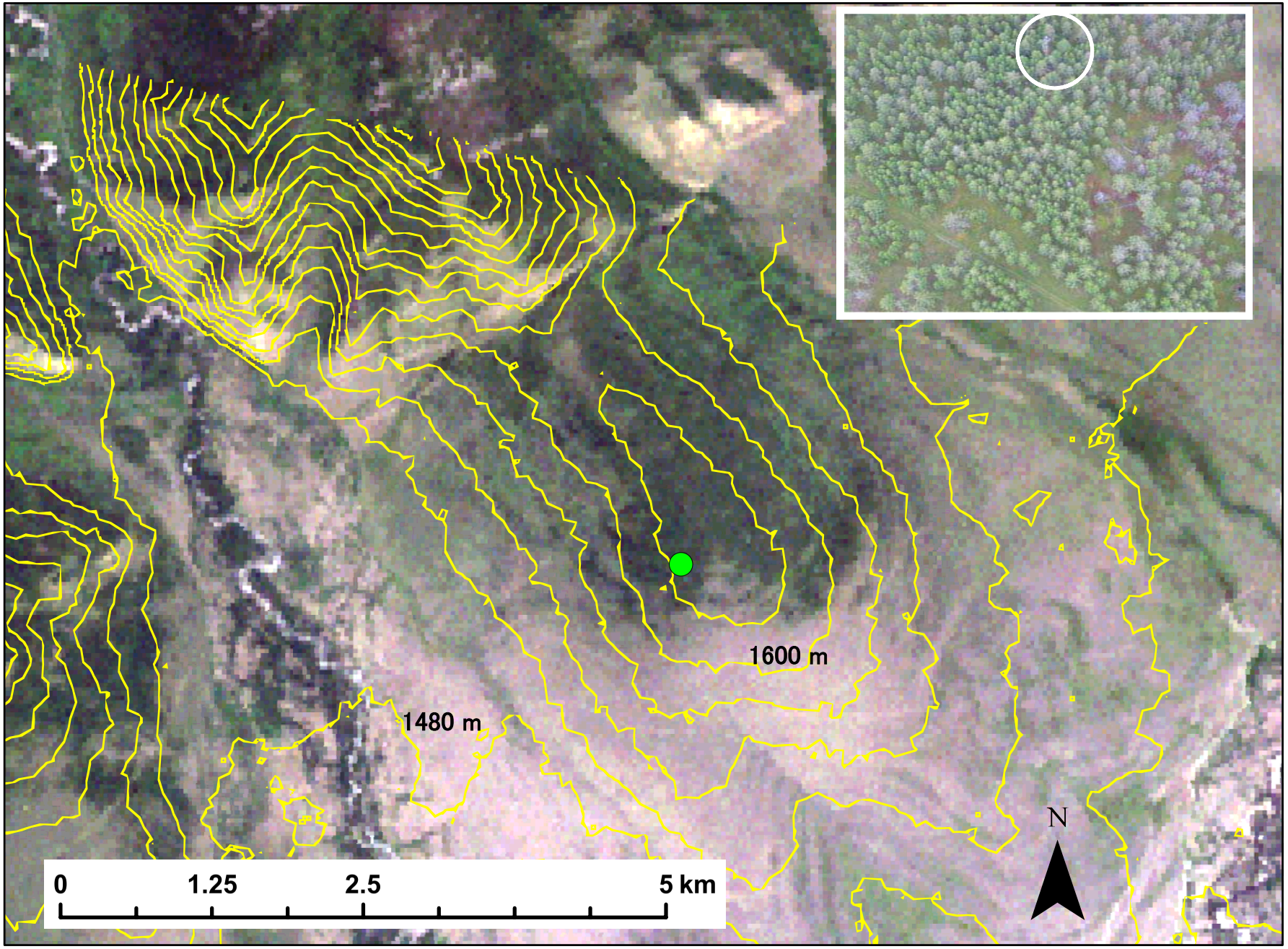
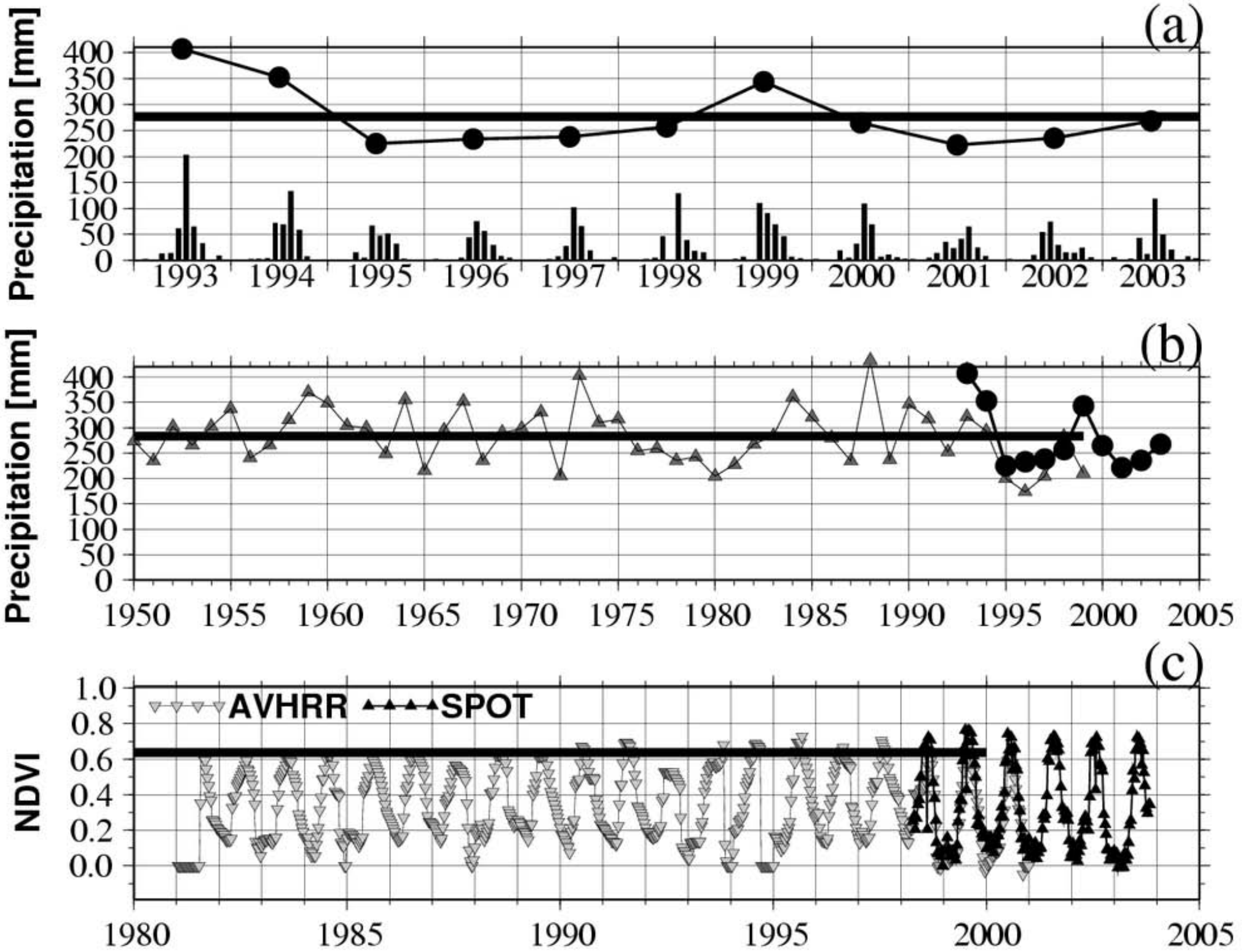
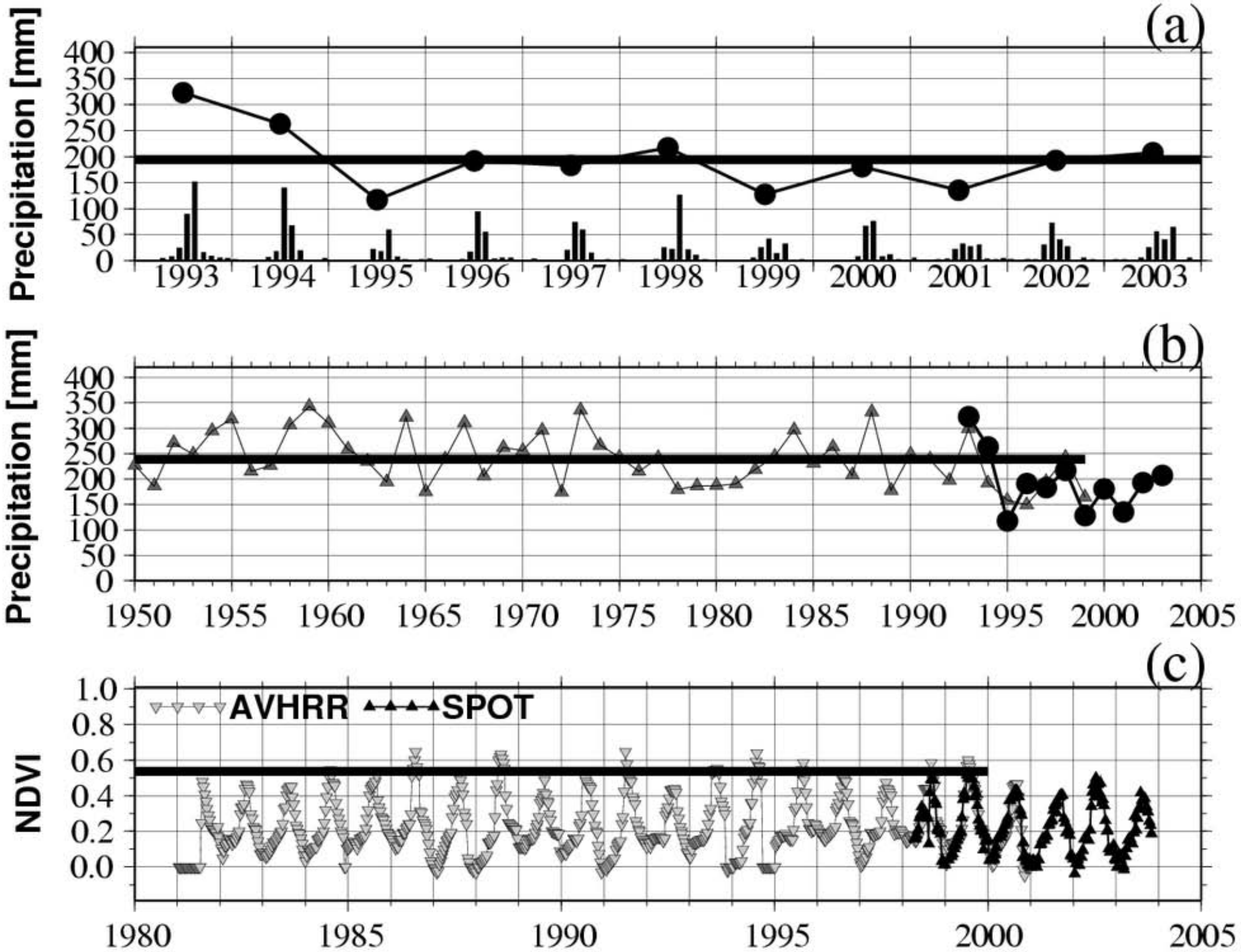
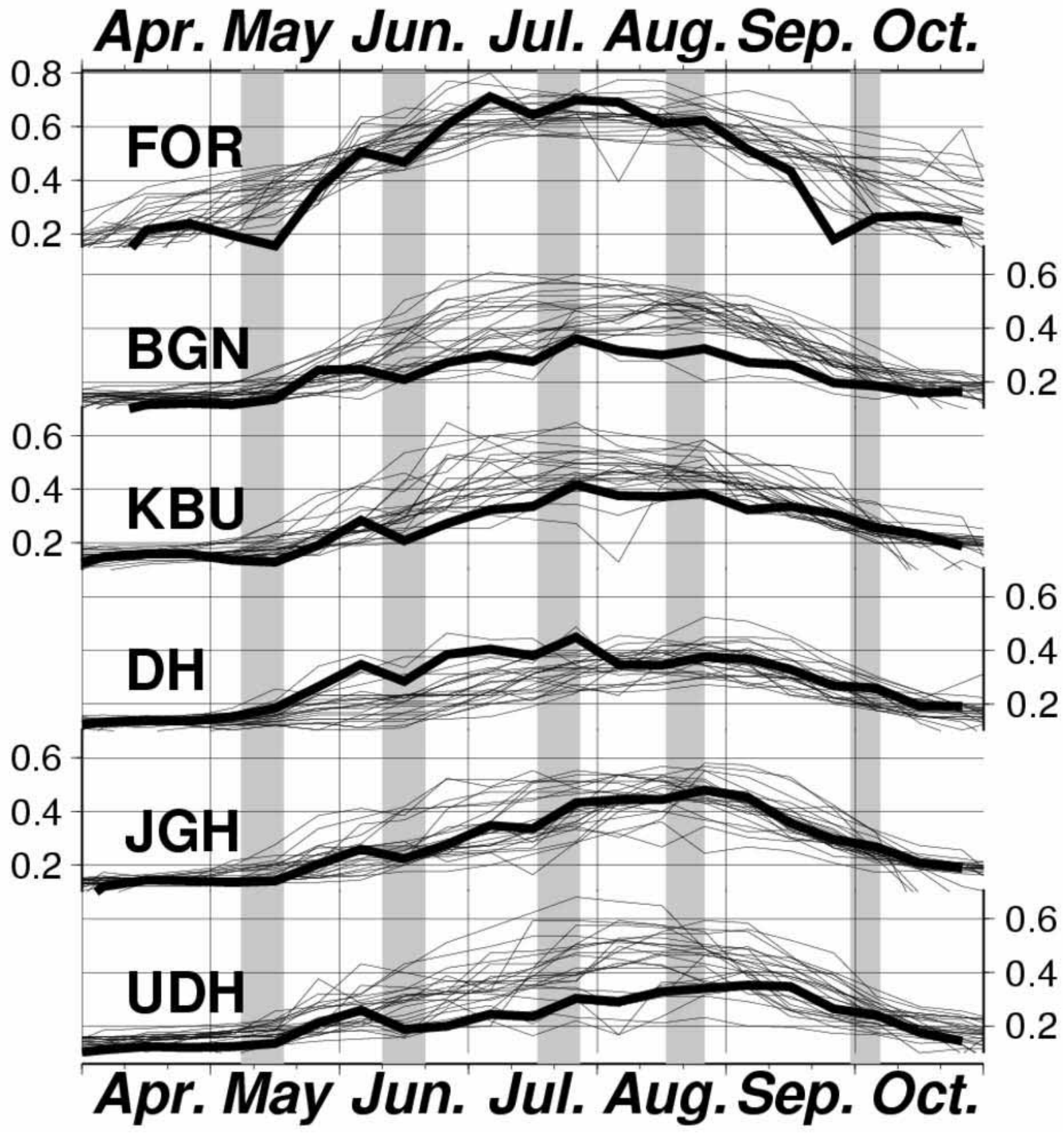
2001
2002
2003
Year

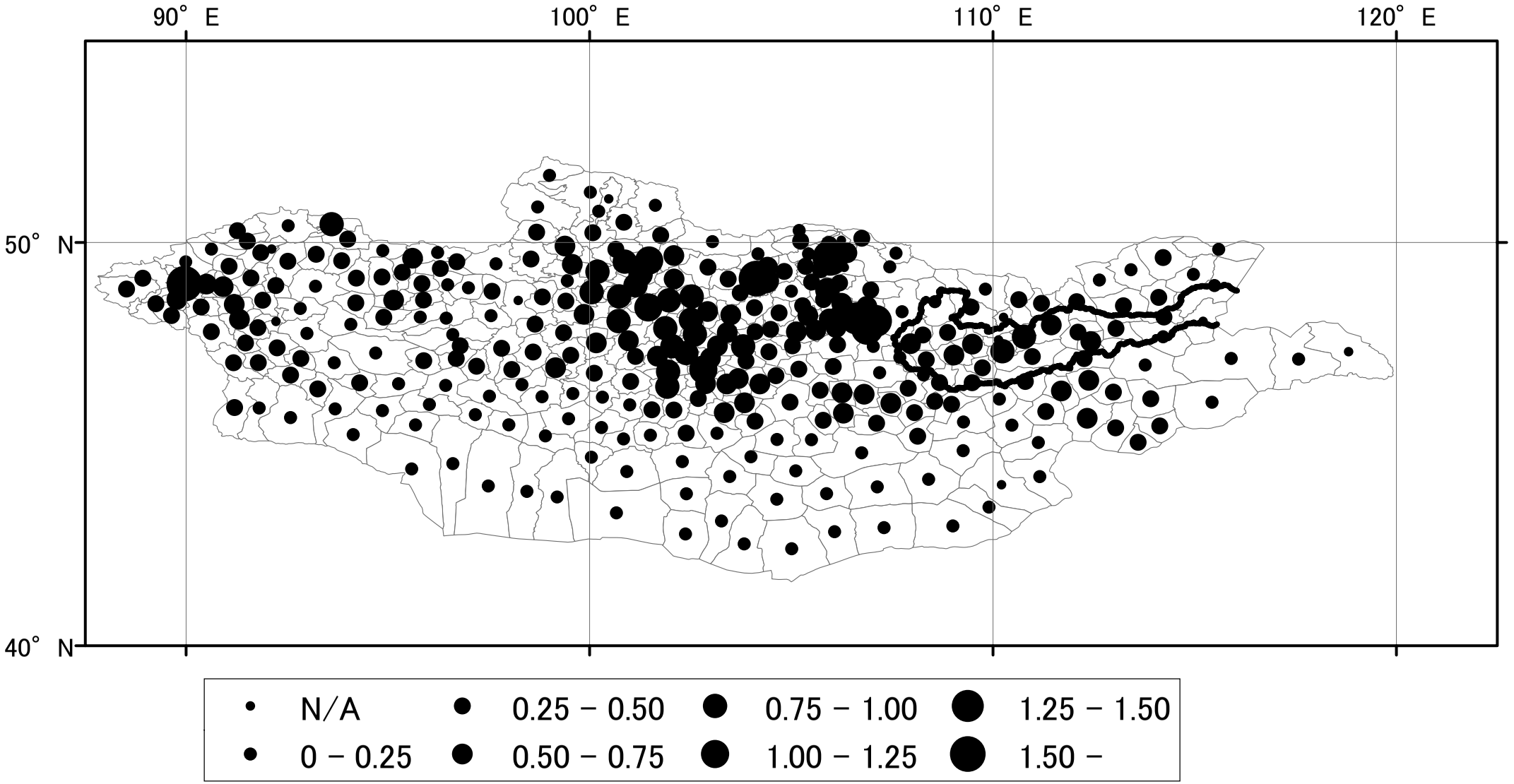

SHB
BCM
UB
UDH
CHB
MDG
50° N
40° N
90° E
100° E
110° E
120° E
water
broadleaf deciduous forest and woodland
mixed coniferous and broadleaf deciduous forest
coniferous forest and woodland
high latitude deciduous forest and woodland
shrub and bare ground
desert, bare ground
cultivation
C3 grassland


1600 m
1480 m
0
1.25
2.5
5 km
N


(a)
Precipitation [mm]
400
350
300
250
200
150
100
50
0
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
(b)
Precipitation [mm]
400
350
300
250
200
150
100
50
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
(c)
NDVI
1.0
0.8
0.6
0.4
0.2
0.0
AVHRR
SPOT
1980
1985
1990
1995
2000
2005


(a)
Precipitation [mm]
400
350
300
250
200
150
100
50
0
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
(b)
Precipitation [mm]
400
350
300
250
200
150
100
50
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
(c)
NDVI
AVHRR
SPOT
1.0
0.8
0.6
0.4
0.2
0.0
1980
1985
1990
1995
2000
2005


Apr. May Jun. Jul. Aug. Sep. Oct.
0.8
0.6
0.4
0.2
FOR
BGN
KBU
DH
JGH
UDH
Apr. May Jun. Jul. Aug. Sep. Oct.


90° E
100° E
110° E
120° E
50° N
40° N
N/A
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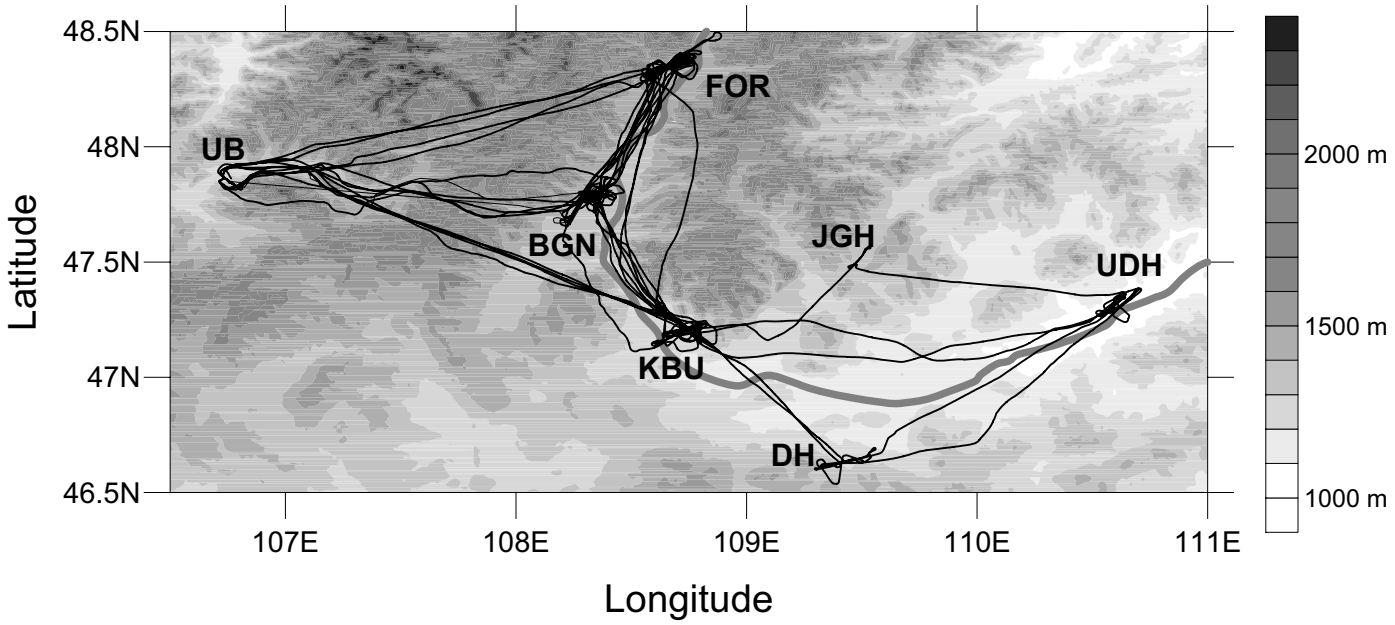
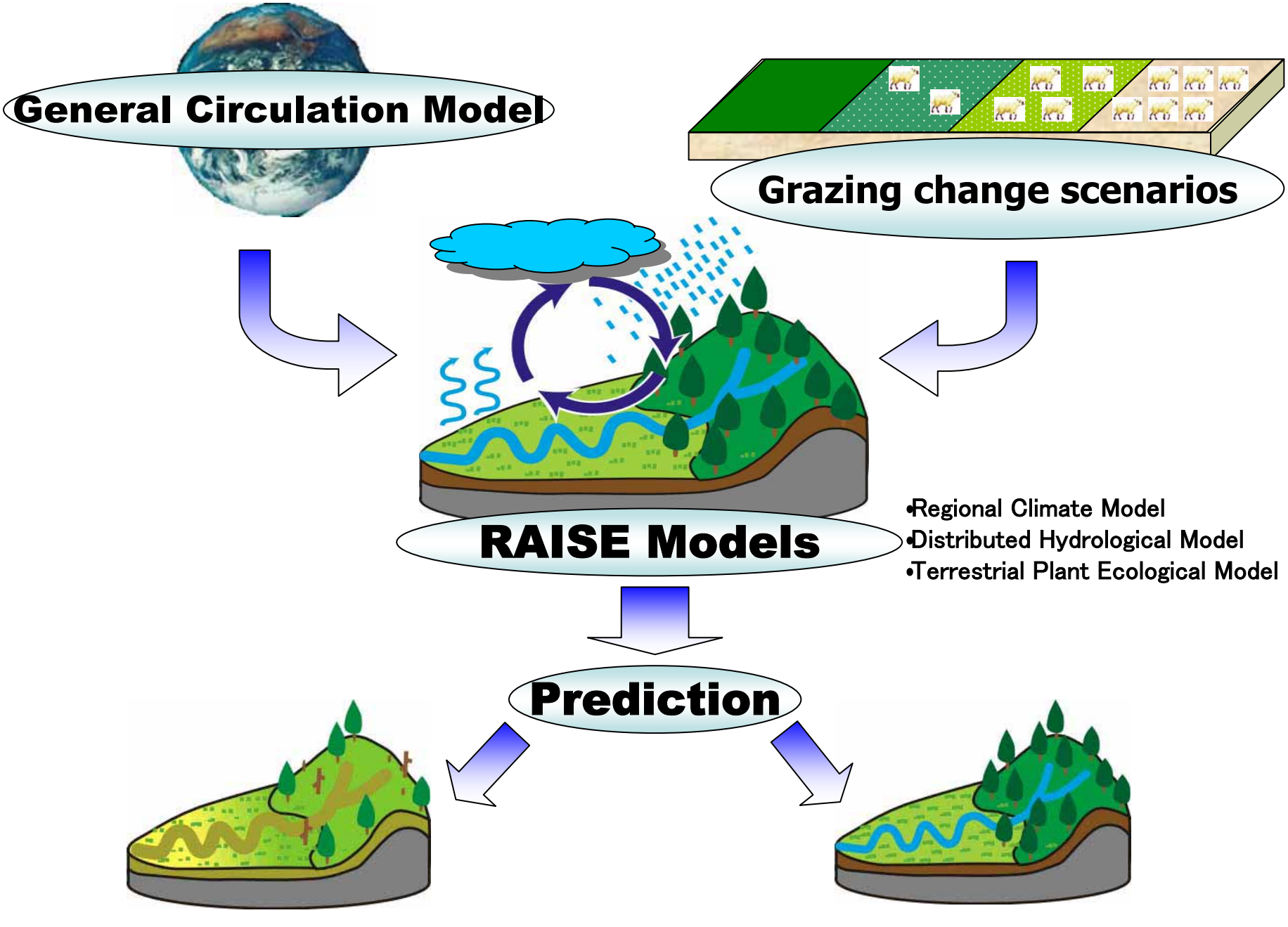
0.25 – 0.50
0.50 – 0.75
0.75 – 1.00
1.00 – 1.25
1.25 – 1.50
1.50 –


48.5N
48N
47.5N
47N
46.5N
Latitude
107E
108E
109E
110E
111E
Longitude
FOR
UB
BGN
JGH
UDH
KBU
DH
2000 m
1500 m
1000 m


General Circulation Model
Grazing change scenarios
RAISE Models
•Regional Climate Model
•Distributed Hydrological Model
•Terrestrial Plant Ecological Model
Prediction