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Responses of Energy Budget and Evapotranspiration to Climate Change in Eastern Siberia

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1. Introduction

The structure and functioning of the Arctic terrestrial ecosystems are greatly sensitive to climate change. Evidence continues to mount that warming experienced in the Arctic region during the past few decades has been affecting the structure and functioning of the Arctic terrestrial ecosystems (Oechel et al., 2000; Serreze et al., 2000). Observations indicate an increase in the number of shrubs in tundra regions (Chappin et al., 1995) and an increase in early greening of the Arctic vegetations (Buermann et al., 2003). Changes in the structure and phenology of vegetation act to modify energy and water budgets, because all components in the Arctic are interrelated through a network of linkages, feedbacks, and multi-dependent interactions. In fact, expansion of shrub cover has its own positive feedback on climate because of the lower albedo of shrubs compared to tundra, and consequently earlier snowmelt than snow-covered tundra (Chapin et al., 2005). In this manner, a change in one variable in a part of the system can initiate a cascade of regional effects and have global ramifications.

Soil moisture is the most important factor that links climate and vegetation. Climate influences the soil moisture via evapotranspiration (ET). Winter is the period of the lowest temperature in the Arctic, and hence, the low saturation of water vapour leads to less evaporation. Soil-freezing also controls plant water uptake. Snowmelt during the early spring releases the stored ice water causing higher soil moisture, subsequently increasing ET. Conversely, higher levels of ET cause a decrease in soil moisture content, resulting in soil water deficits. This soil water deficit in turn controls ET, stomatal conductance, and photosynthesis. ET rates at high-latitude are lower than at low-latitude. According to a recent review (Park et al., 2008), ET rates in eastern Siberia during the growing season were less than 3 mm day^{-1} whereas the corresponding rate at mid and low latitudes was 1–6 mm day^{-1}. The low ET rates in high latitudes can cause an extremely large seasonal variability in soil moisture. In Lena and Kolyma watersheds, for example, ET during the summer has often exceeded precipitation, resulting in a negative water balance (Park et al., 2008). The higher rates of ET during the summer subject the vegetation to frequent soil water stress. Unless the stress is settled by an increase in precipitation, summer water balances will become increasingly negative (Rouse, 2000). The active layer depth (ALD) increases during the summer. Plant roots penetrate beyond the immediate dry surface, providing a link to subsurface moisture. Therefore, the Arctic vegetation may not experience an immediate change in ET, and may ultimately experience less inter-annual variability of ET. In dry conditions, the increased ALD works as a buffer for transpiration. However, if the stage were reached when the water balance is considerably negative, this important interactive mechanism would no longer be active. In these manners, the Arctic presents a number of unique features that strongly influence their energy and water balances and their feedback to climatic and ecological processes.

Recently, changes such as early snowmelt (Nijssen et al., 2001), permafrost reduction (Jorgenson et al., 2006), and increase in runoff (Peterson et al., 2002) have been observed in the Arctic. These hydro-climatic changes influence the phenological and physiological functions of the Arctic ecosystems, thereby altering the exchange of radiation, water, and energy with the atmosphere. These changes may ultimately affect local, regional, and global climates (Bonan et al., 1992), which may in turn induce changes in the composition and distribution of vegetation. Global climate models (GCMs) also project increases in temperature and precipitation in the Arctic regions as global warming proceeds (IPCC, 2007). The increased temperature would lengthen snow-free periods, warm permafrost, and increase leaf area index (LAI), thus enhancing photosynthesis. Moreover, the high precipitation could also increase liquid water storage as the permafrost is warmed. Their interactions re-enforce both positive and negative feedback loops on ET, thus promoting ET. A summary of simulations by five GCMs indicates that ET rates from the major terrestrial Arctic watersheds will increase by a maximum of 10% in the years 2071-2090 relative to the 1981–2000 reference period (ACIA, 2005). The future projections by GCMs as well as historical field surveys (e.g., NOWES, BOREAS, NOPEX, and GAME-Siberia) are shedding new light on the interactions between the Arctic ecosystems and the climate system and suggest that the Arctic is highly sensitive to climate change. However, the issue of how the changes in air-surface energy and water exchange rates in eastern Siberia are influenced by the uncertainties of susceptibility and vulnerability of the boreal and Arctic ecosystems to future climatic changes remains unresolved. We attempt to resolve this issue by applying a land surface model (LSM) to two periods, 1986–2004 (Current) and 2081–2100 (Future). We also address the key factors affecting changes in their rates.

2. Model description

The land surface model used was developed by Yamazaki (2001), with the addition of a snow interception process (Yamazaki et al., 2007), and was then expanded to continental scale over eastern Siberia (Park et al., 2008). The LSM is a physically based process model dealing with thermal and hydrologic processes in an atmosphere-vegetation-snow-soil system. The major characteristics of LSM are briefly described. The vegetation canopy is divided into a 'crown space' and 'trunk space' (i.e., without leaves); the crown space is in turn subdivided into two layers. The energy budget is solved for the radiative and energy fluxes between the atmosphere and the two crown layers, considering both the heat storage within the canopy and the water or snow storage on the leaves. A multi-layer snow submodel is used to calculate the processes of snow accumulation and melting. The snow submodel calculates the profiles of snow temperature, density, and water content, incorporating depth hoar formed by the temperature gradient in snow layers. The model

also calculates heat and water fluxes in soil layers. In permafrost regions, soil seasonally freezes and thaws. The fusion of heat in frozen soil is estimated using a method that assumes the heat capacity to be large within a small temperature range near the freezing point. The effects of soil ice content on water and energy fluxes have not yet been incorporated. The snow-free condition energy balance equation that incorporates a surface resistance of ground and understory vegetation is applied to the soil surface and forest floor. Such a model structure makes it possible to evaluate the contribution of understory ET to the total ET rate. The LSM successfully simulated the understory ET rates at the different vegetation types (Yamazaki et al., 2004) and in eastern Siberia (Park et al., 2008).
The input data for the model simulation are daily air temperatures, humidity, precipitation, solar radiation, downward longwave radiation, and wind speed. The LSM calculates hourly water and energy fluxes using several empirical models and assumptions with the daily forcing data. The method that interpolates hourly meteorological variables based on the daily ones was well described in Park et al. (2008). Leaf stomatal conductance is estimated by an empirical model (Jarvis, 1976) composed of a function of solar radiation, air temperature, vapour pressure deficit, and soil moisture. Parameter values with each function are derived by aggregating the data of all the single leaves without classification of the vegetation type.

3. Dataset preparation

An area of 40–72°N, 90–180°E was selected as the study area covering eastern Siberia, which included the Lena and Kolyma watersheds. Inhomogeneous topography and land cover may produce a very high spatial variation in meteorological variables. The climate data of 66 stations within the study area are available. The station data during 1986–2004 were interpolated to the grid of 0.5° x 0.5° using a minimum curvature technique (Park et al., 2008). To generate the data sets for predictions of climate change for Future (i.e., 2081–2100), outputs from 11 GCMs based on a scenario (i.e., SRES A1B) of IPCC (2007) were selected. The climate outputs from each GCM were linearly interpolated to 0.5° resolution for the use of LSM, and the interpolated values of 11 GCMs were averaged to all grid cells. The averaged data sets were used as the forcing data of the LSM for the future simulations.

4. Model simulation

Leaf area index is closely correlated to land surface processes. LAI is known to be a large source of uncertainty in the specification of the global time-series fields. The current LSM does not consider vegetation dynamics, implying that it cannot express the spatiotemporal variations of vegetation structure under the future climatic changes, as well as their effects on land surface processes. This can seriously affect the calculation of land surface processes. Therefore, it is assumed that the prescribed vegetation type at each grid does not change under the future climate. Instead, LSM considers the seasonal and inter-annual variations of LAI. The variations of LAI are estimated by a modified phenological model (Park et al., 2008) as

$$\mathrm{LAI} = LAI_{\max,i} \times \left(T_{\min,i} \times VPD_i \times Photo_i\right) \quad (1)$$

where $LAI_{\max,i}$ is a maximum LAI over grid i determined from June to August based on MODIS image data; T_{min}, the minimum temperature indicator; VPD, the vapour pressure deficit indicator; and $Photo$, the photoperiod indicator. The three indicators in eq. (1) are respectively bounded between 0 (inactive) and 1 (unconstrained) and their equations can be found in Jolly et al. (2005). The scenario SRES A1B estimates the air CO_2 concentration to reach 700 ppm in 2100. The increased CO_2 concentration will cause higher photosynthesis, so that LAI will also be increased. To reflect the effect of CO_2 concentration on LAI, $LAI_{\max,i}$ in Future is assumed to 1.5 times higher than that in current. In the period of each calculation, the LAI is calculated as a 10-day moving average for all grids.

The LSM also takes into consideration eight soil types, assuming them to be constant with time. The treatment of the initial and boundary layer values is an important problem in the model simulation. In the calculation of current, the initial water content of soil layers was set to 0.3 for all grids. The soil surface and lower boundary layer temperature was set to the air temperature of the first day and annual mean air temperature, respectively. The temperature of soil layers was interpolated linearly between the surface and the lower boundary layer temperature. A spin-up computation was performed over five calculation years for the stabilization of soil temperature and water. The two modelling periods of this study are not continuous. Thus, values of individual variables at the final time step of the calculation period were used as the initial values of the next modelling period.

5. Results and discussion

5.1 Spatial fields

5.1.1 Air temperature and precipitation

The mean fields of air temperature and precipitation for the two periods over eastern Siberia are compared in Fig. 1. Air temperature exhibits considerable spatial variation between the two periods. The comparison also illustrates the significant increase in the temperature in Future across all areas of eastern Siberia, as compared to Current. In particular, it is found that the temperature increment migrates in a northward direction. In the years 1986–2004, the regions with temperature <-10°C are distributed over a wide area. However, this area is significantly decreased in Future. Above all, the increase in temperature is remarkable in regions with >140°E and >65°N, where it is classified as tundra under the current climate. In those regions, temperature in Future is increased by a minimum of 5°C as compared to Current.

The increase in temperature in the Arctic had already been addressed by previous observations and simulations (IPCC, 2007). Data coverage during the early part of the twentieth century is sparse, especially at high latitudes. During the twentieth century, however, averaged annual temperatures have exhibited an overall increase of approximately 1°C, but with large variability (Serreze and Barry, 2005). The temperature in eastern Siberia has risen by 1–2°C on an annual basis during the past few decades (Dolman et al., 2008). Moreover, the five ACIA-designated GCMs projected a warming in the annual mean air temperature of approximately 4–5 °C by 2080 (ACIA, 2005).

Indeed, precipitation exhibits similar spatial distributions in the two periods (Fig. 1). However, the absolute amount of precipitation obviously increased in Future as compared to Current. The increase was especially significant in the regions with >140°E, similar to what was observed for air temperatures. The Future precipitations in northern regions also indicated significant increases. A comparison of precipitation between Current and Future shows spatially large differences in ranges of approximately 50–200 mm.

Based on analyses from 1900 through 2002, annual precipitation, averaged over terrestrial regions over the 55–85°N band, exhibited a general increasing trend (Serreze and Barry, 2005). In general, GCMs had projected modest increases in precipitation by the end of the

21st century. The five ACIA-designated GCMs projected that precipitation in the major terrestrial Arctic watersheds will increase by approximately 10% in the years 2071–2090 relative to the 1981–2000 baseline (ACIA, 2005).

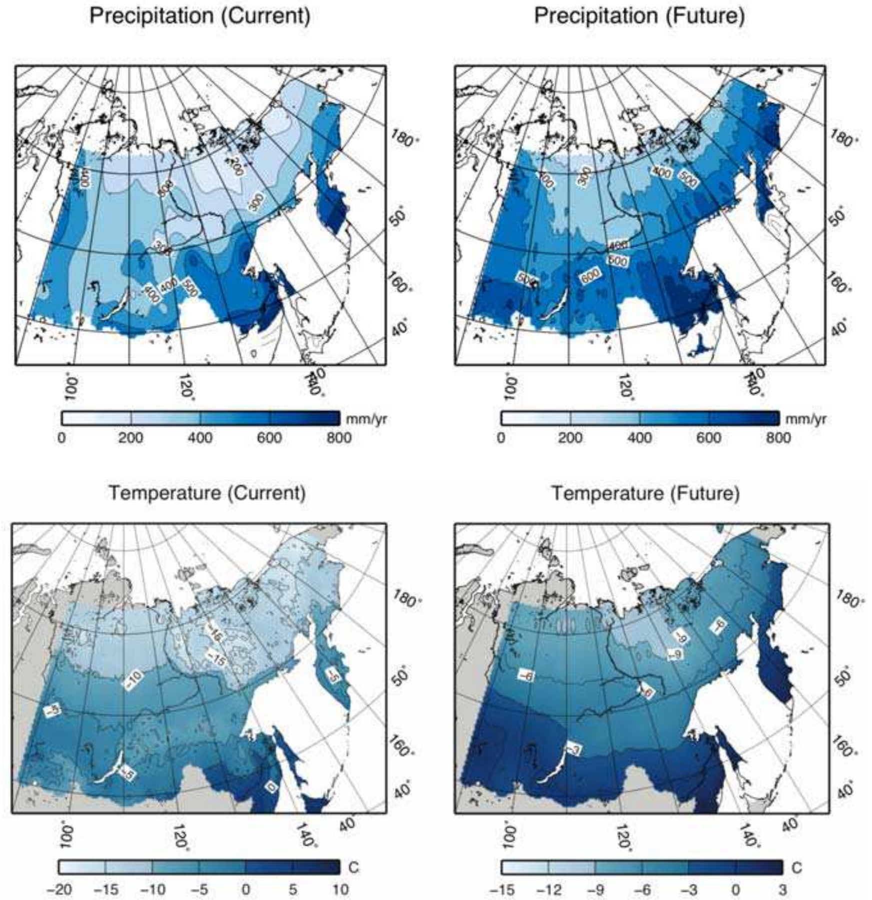

Fig. 1. Comparison of spatial distribution of mean annual precipitation (top) and mean annual air temperature (bottom) between Current (1986-2004, left-hand side panel) and Future (2081-2100, right-hand side panel).

5.1.2 Energy budget and evapotranspiration

Partitioning of net radiation (R_n) into sensible (H), latent heat (LE), and ground heat (G) fluxes reflects the different properties of vegetation and climate over the surface. Figure 2 illustrates the spatial distribution of averaged annual energy budget components in the two periods. Fig. 2 also shows the largest increase in R_n in forested area in Future as compared to Current. Consequently, in Future, LE and H also increased in the same area. LE is a major component of the energy budget during summer in Current as well as Future, especially in the boreal forest. A clear contrast in LE between the two periods exists along the boreal forest-tundra transition. In Future, the forest-tundra transition line migrates further northward than Current. This means an increase in evaporative rates in tundra regions. The increase in *LE* in tundra regions may be closely related to the increased air temperature, precipitation (Fig. 1), and LAI. Warming would cause increases in productivity and leaf areas, thus increasing *LE* (Eugster et al., 2000). Field surveys (Sturm et al., 2001) and satellite observations (Jia et al., 2003) had shown the increase in the biomass within ecosystems in tundra regions. The increased biomass, especially LAI, is a likely contributor to higher evaporative rates. LAI in Lena watershed was 2.0 in Current and 2.8 in Future.

A notable fact is that *LE* dominates the energy balance in northern regions (i.e., tundra). The absolute value of *LE* in the tundra region is lower than that in forest areas, but *LE* in Future is larger than that in Current. Relative to the differences among biomes, Arctic tundra is remarkably homogeneous in land surface parameters, with low values for canopy height, surface roughness, LAI, etc. However, measurements showed that significant differences exist among tundra ecosystem types in surface energy partitioning and moisture exchange (Eugster et al., 2000). Therefore, climatically induced changes in ecosystem structures can greatly affect regional energy exchanges. This is because during summer, large areas of the Arctic tundra and boreal zone are actually heat and moisture sources rather than sink deposits.

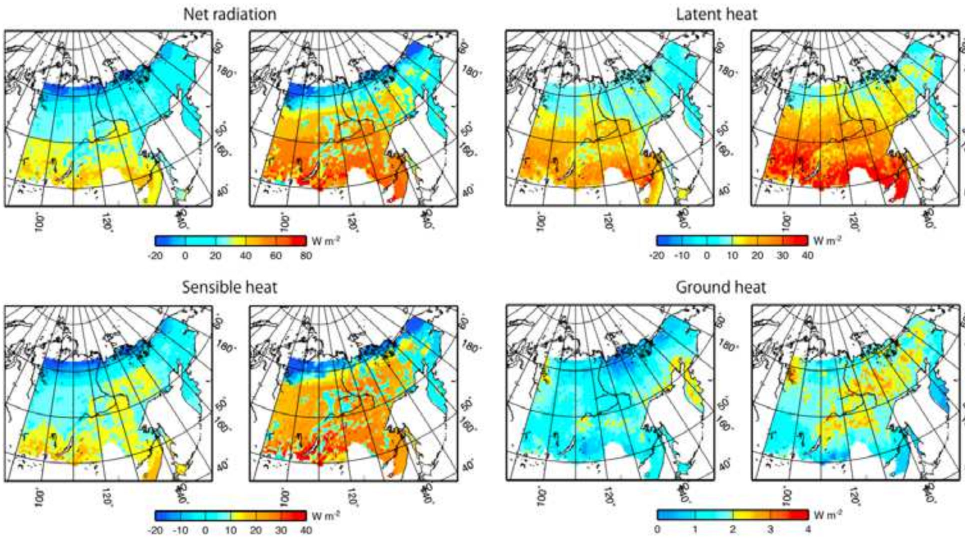

Fig. 2. Comparison of spatial distribution of averaged annual energy budget components between Current (left-hand side panel) and Future (right-hand side panel)

The spatial difference in *H* is as large as that of *LE* (Fig. 2); *H* in Future is larger than that in Current. The increase in *H* is majorly correlated to the increased R_n. Warming increases LAI, enhancing the absorption of radiation with low albedo. As a result, the temperature gradient between canopy surface and the overlying air increases, thereby resulting in higher *H*. Potential shifts of vegetation in the future would also have various climate feedbacks. According to a simulation dealing with vegetation change, transition from moist to shrub tundra increased near-surface temperature by 3.5°C during summer because of increased *H* (Chappin et al., 2000). Higher LAI also increases surface roughness, which decreases aerodynamic resistance, generating turbulence and ultimately higher *H*. The large *H* over boreal forests is likely to contribute to the diurnal growth of a very deep planetary boundary layer (PBL) (McNaughton and Spriggs, 1989). It is known that PBL in Siberia does not grow to the depths observed in Canada (Hollinger et al., 1995) because of the existence of the Siberian High Pressure zone. However, the formed boundary layers entrain a substantial amount of dry air, which makes it difficult to humidify the air. This response can have a negative feedback on stomatal conductance and a positive feedback on *H* and PBL growth (McNaughton and Spriggs, 1989).

As compared to forests, low leaf area in tundra regions results in more radiation reaching the ground surface, and thus, higher values of *G*. *G* in Future is slightly higher than in Current, in the tundra regions as well as in forests (Fig. 2). The increase in *G* in Future is not as large as the accompanying temperature increase. This can be attributed to soil surface shading caused by the increased LAI. Eastern Siberia is covered with permafrost. A considerable amount of *G* is consumed in the melting of permafrost during summer. The energy used for the melt of permafrost is therefore not available for increasing surface and soil temperature, thus restricting the increase in *H* or *LE*. It is known that in forested areas, the influence of *G* on the energy partitioning is weak because of the low absolute value. However, the effect of *G* on the energy budget in tundra is not negligible. In tundra regions, for instance, *G* accounted for 25% of R_n during 1986–2004 (Park et al., 2008). Therefore, the increase in *G* in tundra regions caused by the future warming could reduce *H*. The change in the distribution of energy partitioning, especially in the northern region can be explained through an analysis of the reported results (Fig. 3).

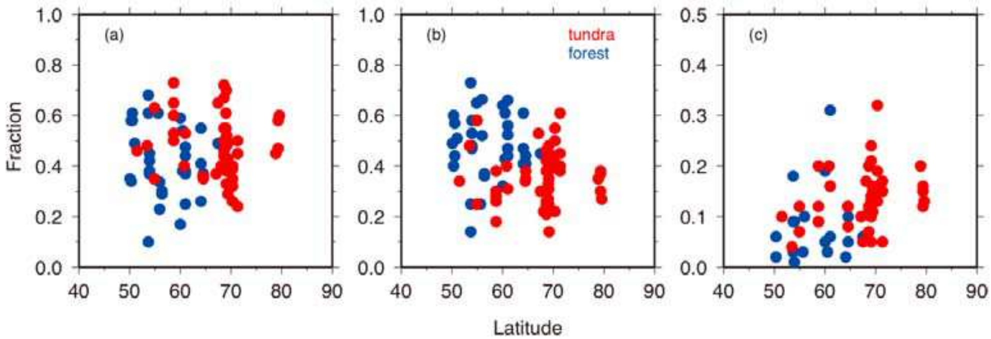

Fig. 3. Distribution of LE/Rn (a), H/Rn (b), and G/Rn (c) of different vegetation types across a latitudinal range. They are arranged based on the data of Eugster et al. (2004), Baldocchi et al. (2000), Beringer et al. (2005), and Bernhofer et al. (2003)

The rate at which R_n is partitioned into energy components is dependent on climatic conditions, species composition, vegetation structure, soil, topography, etc. If vegetation changes, the energy balance of the surface will be greatly changed. Latitudinal energy partitioning rates are plotted in Fig. 3, based on the data observed at various arctic land types. The rate LE/R_n exhibits a large scattering. No specific tendency in the rate is observed along latitudes and between latitudinal vegetation types (Fig. 3a), implying that LE/R_n does not obey simple scale laws. Eugster et al. (2000) suggested that the complex pattern of LE/R_n is associated with moisture gradient, LAI, and plant physiological controls over stomatal conductance. In particular, Eugster et al. (2000) stressed the roles of soil moisture in describing the complex LE/R_n ratio between vegetation types.

The rates of both H and G exhibit a latitudinal trend (Fig. 3). H/R_n tends to decrease with latitude. In the same latitude, H/R_n is higher in boreal forests than in tundra regions. Higher LAI, in addition with tree biomass, contributes disproportionately to roughness length, and therefore, the efficiency of convective exchange. This leads to the conclusion that under the future warming, the migration of forest into tundra regions will cause higher H. Observations over a vegetation transition from tundra to tall shrub and then to forest concluded that the transition could result in an increase in H during the growing season (Beringer et al., 2005). A similar result was obtained in a simulation associated with vegetation change (Chapin et al., 2000). A consistent latitudinal trend is found in G/R_n (Fig. 3c). In particular, higher G/R_n is found in tundra regions. In contrast, the low G/R_n in forests represents the effect of canopy shading. These results also imply that in the future, vegetation shift into tundra can reduce G due to increased soil shading by the canopy. The conclusion drawn from Fig. 3 is that if climatic warming causes the transition of vegetation from tundra to forest, the transition could result in a significant increase in the atmospheric heating due to the increased H.

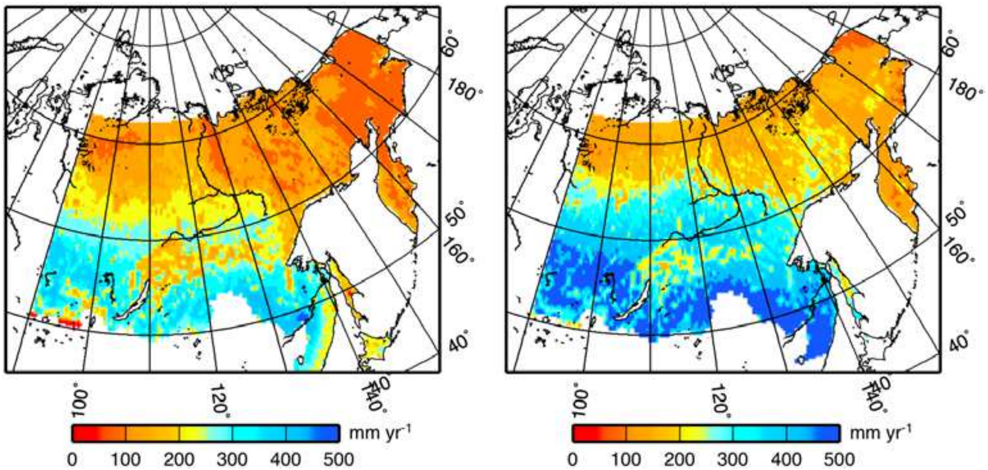

Fig. 4. Comparison of annual mean evapotranspiration in Current (left) and Future (right)

Figure 4 shows the spatial variability of ET in the two periods. In most areas, ET is considerably larger in Future than in Current. The spatial distribution of ET in Future indicates some remarkable characteristics. ET presents a clear latitudinal contrast. The increasing tendency of ET migrates northward as previously mentioned, implying an increase in ET in tundra regions. Finally, the significant increase in ET occurred sporadically in the southern forest area. The increase in ET in Future across all areas of eastern Siberia is closely correlated with the increase in temperatures, precipitation, and LAI. Higher precipitation is likely to be made available for soil moisture and canopy interception. Furthermore, higher LAI increases the absorption of radiation that interactively generates ET.

In Future, the remarkable increase in ET is found in tundra regions. In some of the tundra regions, for instance, ET in Future increased by approximately 50–100 mm when compared to Current. The increase in ET in tundra areas is attributable to higher evaporation rates from the soil surface. Evaporation from the soil decreases nonlinearly with increasing leaf area, whereas soil evaporation is a linear function of available energy. When the soil surface is wet, evaporation rates can exceed available energy (Lindroth, 1985). Therefore, increased precipitation is favourable for high soil evaporation.

5.2 Seasonal variations

5.2.1 Climatic variables

Figure 5 shows mean seasonal variations of air temperature and precipitation in Lena watershed for the two periods (Current and Future). Air temperature exhibits a seasonality, showing a maximum in summer followed by a sharp decrease (Fig. 5a). A significant difference in air temperatures between summer and winter can be observed. The difference in Current was 42.8°C. The air temperature in Future significantly increased as compared to Current, especially during winter. In December, air temperature in Future was on maximum higher 5°C than in Current. IPCC (2007) had projected the increase in air temperature in winters at high latitude under global warming conditions.

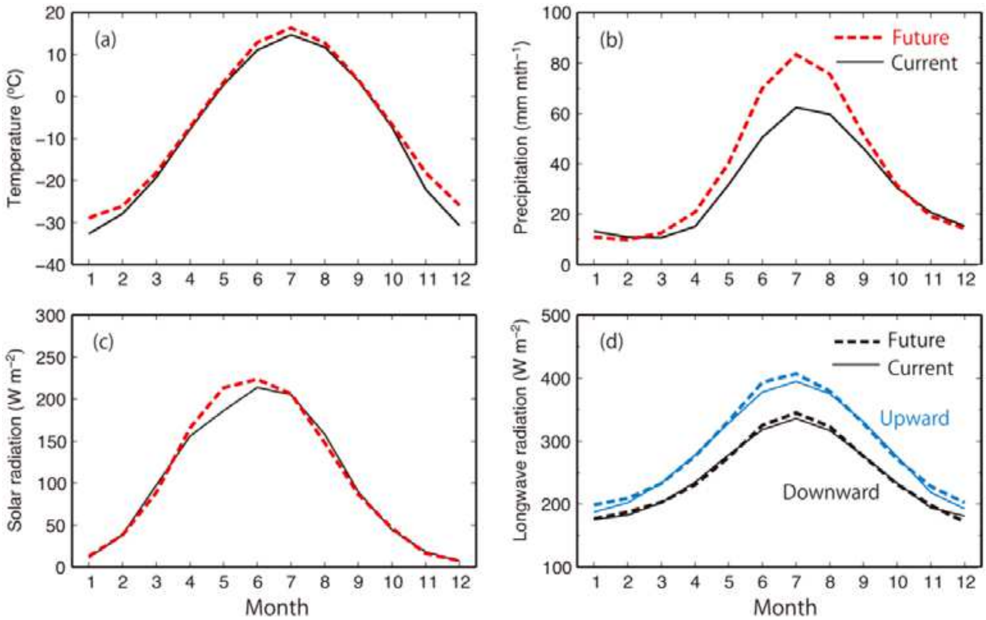

Fig. 5. Monthly variations of temperature (a), precipitation (b), solar radiation (c), and longwave radiation (d) in Lena watershed in Current (straight lines) and Future (dotted lines).

Precipitation also exhibits a clear seasonal pattern in that it is high in summer and low in winter (Fig. 5b). In Current, summer precipitation accounted for 47% of the annual value. As compared to Current, precipitation in Future was higher during spring and summer. The difference in summer precipitation between Current and Future was 59 mm. However, precipitation during October to February was higher in Current than in Future. The low precipitation directly resulted in lower snow depths during the specified period. Annual

mean precipitation was higher by 79 mm in Future than in Current. IPCC (2007) had projected increases in the amount in precipitation in high latitudes of as much as 20% in 2100.
Solar radiation during May through July was higher in Future than in Current (Fig. 5c). However, the solar radiation in the early spring and late summer tended to be rather lower in Future than in Current. Longwave radiations over spring to autumn also exhibited similar seasonal patterns with solar radiation (Fig. 5d). However, longwave radiations during summer and winter were larger in Future than in Current.

5.2.2 Energy budget

Energy exchange at land surface affects the local and seasonal climates through the transfer of heat and water to the atmosphere. The energy exchange is greatly dependent on the surface conditions varying temporarily and spatially. A change in land surface can therefore alter energy exchange ratios, leading to distinctly different local and seasonal climates. Table 1 summarizes the mean seasonal variations of energy components in Lena watershed for the two periods. In both Current and Future, energy exchanges are strongly active in spring and summer. In Current, R_n during spring is almost completely consumed for LE and G. The fraction of G to R_n is higher than that of LE. Prior to leaf-opening, high solar radiation gives rise to higher soil evaporation from the wetted soil surface that is formed with snowmelt. Moreover, frozen soil contributed to the large G by creating a strong thermal gradient between the ground surface and the soil depth. G is therefore not available for increasing the surface temperature, and hence, derives less H. On the other hand, in Future, energy fluxes in the spring exhibit considerably different patterns in comparison with Current. Most noticeably, the increase in R_n is significant, which is strongly associated with the increase in solar radiation (Fig. 5c). Simultaneously, H considerably increased, being 75% of R_n. The increased biomass, especially LAI, is useful for higher H, while reducing G. Evaporation rates over boreal forests and tundra regions are relatively low in the spring, despite higher solar radiation with high evaporative demand. The low evaporation rates during spring are due to cold or frozen soils restricting root uptake of soil moisture (Teskey et al., 1984).

	Current				Future			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
R_n (W m^{-2})	11.8	104.3	-7.8	-16.3	62.8	111.4	-2.9	-8.4
LE (W m^{-2})	4.9	47.9	2.5	0.1	11.4	58.1	7.7	5.7
H (W m^{-2})	0.9	43.7	-4.0	-9.4	46.8	39.5	-4.7	-8.6
G (W m^{-2})	6.0	12.8	-6.2	-7.0	4.7	13.8	-5.0	-5.5
E_T (mm)	1.8	93.6	6.0	0.0	3.3	94.8	0.2	0.0
E_I (mm)	0.3	33.0	3.0	0.0	20.4	70.1	26.2	8.4
E_S (mm)	11.8	40.0	5.9	0.0	5.3	22.9	2.4	0.0
ET (mm)	13.9	166.6	14.9	0.0	29.0	187.8	28.8	8.4

Table 1. Summary of seasonal variations of averaged energy budget and cumulated evapotranspiration components in Lena watershed in Current and Future. Spring denotes March to May, Summer is June to August, Autumn is September to November, and the remaining months are Winter

In summer, energy fluxes steeply increased in both Current and Future. In particular, there was a marked increase in LE in Future. The increase was accompanied by increased precipitation, deriving higher ET. During summer, soil water deficits can restrict ET by forcing stomata to partially close. Increased precipitation can reduce the restriction of the soil water deficit to ET. In contrast, the presence of clouds and higher atmospheric humidity as fronts passed limited transpiration through their association with low radiative forcing. The autumnal decline in *LE* is covariant with available energy and air temperature, which decrease after the summer. However, the autumnal *LE* in Future is larger than in Current, which can be attributed to the influence of canopy interception. A large increase in winter *LE* in Future is observed, owing to snow interception and sublimation. In dense coniferous canopies, for instance, interception can result in up to 40% of sublimation (Pomeroy and Gray, 1994). The sublimation reduces snow on the ground during the winter, consequently affecting ground heat flux in spring.

Climatic warming resulted in significant increases in both *LE* and *H* during spring and summer. These increases strongly responded to the enhanced available energy and precipitation, in conjunction with biomass. The increase in energy fluxes in summer is a general pattern, although their increasing magnitude depends on a number of factors. A unique change under the Future climatic warming is the promoted atmospheric heating due to greater *H* in spring (Table 1). Above all, the increased solar radiation is primarily associated with the higher *H*. The rise of spring temperature over high latitudes has been observed during the past few decades. The major reason is early snowmelt due to increased air temperature (Groisman et al., 1994; Chapin et al., 2005). As a result, the snow-free period lengthens and sequentially causes summer warming (Chapin et al., 2005). However, snowmelt in Future was somewhat late as compared to Current, which was on average 4 days. Snow depth was lower during October through February in Future than in Current due to lower precipitation and higher sublimation caused by higher temperatures. However, higher precipitation in March and April in Future (Fig. 5b) induced later snow depth with high albedo. After snowmelt, therefore, strong solar radiation and higher air temperature is likely to have caused the higher *H*.

5.2.3 Evapotranspiration

Evapotranspiration in Lena watershed occurred mainly during summer (Table 1). Most of the precipitation in summer is used for ET, and transpiration is a dominant factor of ET in Current and Future. In spring, soil evaporation exceeds transpiration. This is closely correlated with the strong solar radiation observed during spring. Radiation contributes to snowmelt and soil thawing. As a result, increased soil moisture is available for higher soil evaporation. On the other hand, transpiration in spring and autumn is relatively low, despite higher soil moisture. Even though snow is completely melted, the thawing of frozen soil does not occur rapidly. The frozen soil during spring causes the hydraulic conductivity of the roots to be low, reducing leaf turgor and forcing the closing of stomata, thus restricting root uptake of soil moisture (Teskey et al., 1984). The drop in air temperatures below 0°C during spring and autumn results in leaf chilling and freezing. These stresses on the plants affect transpiration through interaction with stomatal conductance and photosynthesis.

When LAI increases, soil evaporation is reduced, but transpiration from the leafy canopy simultaneously increases. The seasonality in interception generally follows the pattern of precipitation, but is closely correlated to LAI. Higher LAI in Future resulted in higher interception. Greater amounts of leaf are aerodynamically rougher. This enhances the transfer of mass and energy to the atmosphere by generating more turbulence and increasing the aerodynamic conductance (Jarvis and McNaughton, 1986). In Future, the increase in interception was significant, especially in summer. Most of the increased precipitation in summer was used for interception, which relatively reduced the contribution of precipitation to transpiration.

Evapotranspiration rates in autumn are low, despite the considerable precipitation. In general, active layer depth in the Arctic reaches the deepest layers between August and October. However, water uptake by trees in these times is relatively low. This is probably related to the decrease in air temperature and available energy that decrease after summer solstice. In autumn, interception in Future is considerably high. ET from wet forests sometimes exceeds available energy. In general, ET rates from wet forests also exceed values over dry forests by factors of 50% and above (Lindroth, 1985). Under climate warming, higher sublimation is a marked change in ET components. The increase in sublimation can decrease snow depth, resulting in a feedback loop that decreases G between the snow layer and the soil surface, while heating the atmosphere.

The climate warming greatly changed the partitioning of ET components in Lena watershed. Transpiration was a major contributor to ET in Current and in Future. However, the weight of canopy interception to ET remarkably increased in Future, correlating to the increased precipitation and LAI. In contrast, soil evaporation significantly decreased in Future.

5.3 Inter-annual variations

Annual ET and mean energy budget between Current and Future in Lena watershed is compared in Fig. 6. The comparison shows significant increases in energy budget in Future. R_n increased twofold in Future compared to Current. The increase in R_n caused LE and H to increase. However, the evapotranspirative fraction (LE/R_n) was higher in Current (0.55) than in Future (0.45). In Lena watershed, transpiration was the major contributor (52%) to ET in Current (Table 1). Baldocchi et al. (2000) also found that across spruce forests, between 50 and 62% of LE comes from transpiration. In Future, however, the fraction of transpiration to ET was lower than Current (Table 1). Transpiration is partly controlled by stomatal and boundary resistances to water vapour transport which are in turn related to atmospheric conditions (Oke, 1987). Soil moisture has been considered an important factor in controlling LE. Precipitation in Future was higher than in Current (Fig. 5). The increased precipitation in Future contributes to reduce soil water stress and can support transpiration. However, the frequent precipitation can enhance canopy interception with the increased LAI in the Future climate. The increased interception means less contribution of precipitation to the soil moisture. When the canopy is wet, stomata may be temporarily closed, thus limiting transpiration (Park and Hattori, 2004).

The sensible heat fraction (H/R_n) in Future was larger (0.44) than in Current (0.30), which is can be attributed to the contribution of the increased H in spring in Future (Table 1). The Bowen ratio (H/LE) is a good factor for comparing the surface energy balance in climates and vegetation types with differing R_n. The Bowen ratio was 0.65 and 0.90 in Current and Future, respectively. According to observations conducted at the same climate zones, the Bowen ratio increased across the vegetation sequence from the low leaf tundra (0.94) to the high leaf forest (1.22) (Beringer et al., 2005). Both LE and H are sensitive to aerodynamic resistance and surface temperature, but LE depends on bulk surface resistance to water vapour flux from the surface. In Future, higher canopy interception reduced soil moisture and higher LAI helped to increase canopy shading. These resulted in higher bulk surface resistance, restricting LE. In fact, ET during the dry period was 30 mm lower in Future than in Current (Table 1). Most of this 30 mm was sourced from the decrease in soil evaporation, implying an increase in bulk surface resistance, especially during the dry periods. Boreal woodlands are mostly open, allowing a disproportionate amount of solar radiation to reach the understory, in turn leading to *H* and *LE* exchange at the forest floor. In contrast, the increase in LAI is able to limit this exchange. On the other hand, the increased LAI also enhances aerodynamic conductance. Therefore, the higher Bowen ratio in Future seems to be related to the change in LAI.

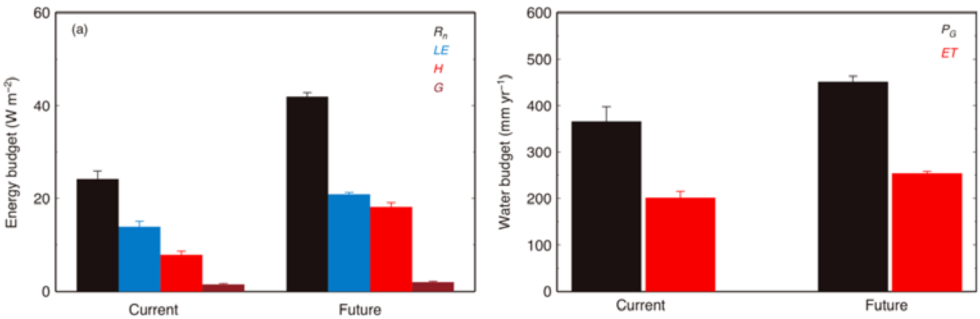

Fig. 6. Comparison of energy (a) and water (b) budgets in Lena watershed between Current and Future

The model specified the ET components over two periods in Lena watershed (Table 1). There have been almost no previous studies that have evaluated ET components on the Arctic watershed scale, making a useful comparison of the estimate ET components impossible. However, Serreze et al. (2003) estimated annual ET of 182 mm in Lena watershed by water budget using measured runoff. Fukutomi et al. (2003) reported annual ET of 160 mm by atmospheric water budget. The values are similar to those estimated by the model for Current ET (196 mm) (Fig. 6b).

The climate warming caused ET to increase by 58 mm in Future (Fig. 6b), which is the value corresponding to the increased precipitation in summer (Table 1). The increase in ET is considerably large, as compared to a projection that ET from the major Arctic watersheds will increase on maximum 10% in the years 2071–2090 relative to 1981–2000 (ACIA, 2005). GCM simulated that in Alpine regions, ET in 2071–2100 will increase by approximately 20% relative that in 1961–1990 (Calanca et al., 2006). Karpechko and Bondarik (2003) also estimated that if warming up of 2°C occurs, ET from a forested catchment in northwest Russia will increase by 15–20 mm per year. The Arctic regions are vulnerable to global warming. Trees may expand into tundra regions, and increased disturbance from fire and logging alters ecosystem structures. Climatic forcing arising from these disturbances may be comparable to that arising from biome shifts (Liu et al., 2005). The most important changes in surface energy partitioning, and hence in the feedback to larger scales, is expected from a combined decrease in precipitation and in fire frequency that would more than double *H* by reducing *LE* to roughly 70% of today's value (Eugster et al., 2000).

5.4 Variables affecting evapotranspiration

Ecoclimatic diversities across the Arctic regions mean that the evaporative rates of the boreal forests present the greatest heterogeneity (Fig. 7). Fig. 7 shows the relationships between annual precipitation (P_G) and annual ET in different types of boreal plants. Classification into 3 regions of continuous permafrost, discontinuous permafrost, and non-permafrost is made. The smallest values of ET are found in plants of continuous permafrost, whereas plants in non-permafrost generally exhibited higher ET. However, the rates of ET to P_G are in contrast the highest in plants of continuous permafrost, in which most of P_G available is used for ET. The rate of ET/P_G tends to decrease with the reduction in permafrost. In non-permafrost regions with low annual P_G (particularly areas with less than 500 mm y^{-1} of P_G), the annual amount of ET has been found to vary linearly with the annual P_G with a very slight deviation (Zhang et al., 2001). The difference between our analysis and the result of Zhang et al. (2001) may represent the specific roles of permafrost on hydrological processes in high latitudes.

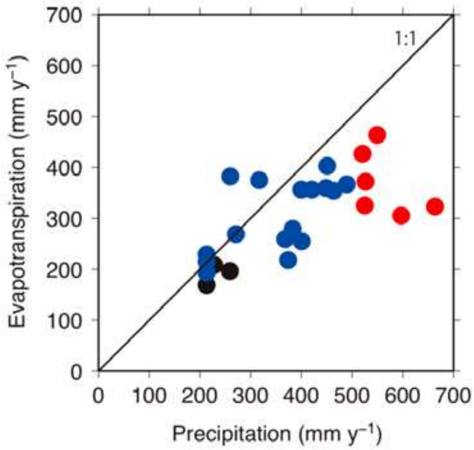

Fig. 7. Relationships between annual precipitation and evapotranspiration in various types of plants in high latitudes. The different colours represent continuous permafrost (black), discontinuous permafrost (blue), and non-permafrost (red). The data are sourced from Amiro (2009), Amiro et al. (2006), Arain et al. (2003), Black et al. (1996), Bond-Lamberty et al. (2009), Grell et al. (1999), Hamada et al. (2004), Nijssen et al. (1997), Nijssen and Lettenmaier (2002), Ohta et al. (2008), Schulze et al. (1999), Wever et al. (2002), and Yuan et al. (2010)

In the Arctic regions, land surface processes are primarily controlled by the presence or absence of permafrost. Land surface processes are also influenced by the thickness of the active layer and the total thickness of the underlying permafrost. As permafrost becomes thinner or decreases in area, the interaction between ET and sub-permafrost groundwater gains in significance. The inability of soil moisture to infiltrate to deeper groundwater zones owing to ice-rich permafrost results in very wet upper soils. The wet soil water is favourable for ET. Even though soil is dry due to small P_G, the melted soil water also helps to alleviate soil water deficit. Sugimoto et al. (2002) examined the water usage of larch forests near Yakutsk, Russia, using a stable isotope of oxygen, δO^{18}. They showed that trees took up precipitation water in wet years, but transpired permafrost melt-water in drought years. Therefore, the active layer plays an important role in the Arctic regions, because most ecological, hydrological, biogeochemical, and pedogenic activity occur within it (Hinzman et al., 1991).

Changes in active layer thickness are influenced by many factors, including surface temperature, physical properties of the surface cover and substrate, soil moisture, and duration and thickness of snow cover (Zhang et al., 2005). In Lena watershed, the average maximum active layer depth was larger in Current (0.94 m) than in Future (0.91 m). The lower active layer thickness in Future is likely to have affected, in some part, the lower ET in dry period (Table 1). Despite higher air temperature and P_G in Future, the low active layer depth in Future seems to be closely associated with higher LAI (2.8), as compared to LAI of Current (2.0). Higher LAI shades the soil, thus countering the effect of warmer air temperature on the active layer. Walker et al. (2003) also found a similar relationship between LAI and active layer depth when observing various types of vegetation in Alaska. These results indicate that changes in surface conditions can produce significant changes in permafrost, which in turn feeds back to surface processes.

Temperature is one factor influencing ET in the Arctic. In Lena watershed, mean air temperature during the growing season exhibited high correlation with ET (Park et al., 2008). This is because sufficient, but not excessive, heat is a prerequisite for physiological, biological, and biogeochemical reactions. Therefore, boreal vegetation that experiences a short warm summer seems to be more sensitive to low temperatures rather than higher temperatures. The low temperature results in chilling and freezing. Chilling mainly occurs in spring and autumn when ET is relatively low. On the other hand, freezing is often found during night of the growing season. This can cause a non-reversible reduction in photosynthetic capacity and stomatal conductance, consequently limiting transpiration (Schulze et al., 1977).

Soil moisture is an important factor that can greatly influence ET (Ohta et al., 2008). Soil moisture from the previous autumn was highly correlated to ET of the following year (Park et al., unpublished). In the permafrost-covered regions, the soil moisture in autumn is stored as ice until the next melting season. Higher soil moisture in the autumn likely augments soil moisture with the melted snow water during the following spring. The combined higher soil moisture in the spring may largely affect soil evaporation rather than transpiration, because cold or frozen soil in the spring restricts root uptake of soil moisture. However, higher soil water is favourable to soil thawing. Therefore, the speed-up of the soil thawing could enhance root water uptake because considerable amounts of roots in boreal forest are relatively distributed in the upper soil layers.

6. Future model developments

In atmosphere-land systems, vegetation is a dynamic component that exhibits spatiotemporal variations. The representation of vegetation dynamics incorporated thus far is extremely simplified, and most existing LSMs do not consider vegetation as a dynamic component. In most current LSMs, the seasonal variation of LAI is prescribed or defined to be constant. This treatment implies that the effect of climate variability in modifying the structure and physiological properties of vegetation cannot be satisfactorily evaluated. However, this study estimated seasonal LAI in each grid with a semi-empirical formula, based on both prescribed $LAI_{\max}$ and climate variables (eq. 1). The formula is simple, and is dependent on the prescribed $LAI_{\max}$. When actual values of LAI exceed $LAI_{\max}$, eq. (1) can underestimate LAI and can explicitly cause errors in energy and water fluxes.

Plants exposed to elevated levels of CO_2 exhibit increased growth and photosynthesis rates. A number of studies have reported higher soil moisture under elevated CO_2 (e.g., Volk et al., 2000). A decrease in transpiration and an increase in carbon uptake under elevated CO_2 imply increased water use efficiency by plants. Root distribution and maximum rooting depth exhibit seasonal and inter-annual variations depending on plant carbon uptake and soil moisture (Arora and Boer, 2003). The preferential use of moisture from different soil depths by plants highlights the control of vegetation on soil moisture. The spatial structure of soil moisture and its evolution in time are also affected by the root distribution. However, the LSM of this study used an empirical parameterization that roots uptake water from soil layers of 0–22 cm. This parameterization does not consider root dynamics, and thus, it may not be appropriate to simulating the interactions between vegetation and soil moisture, via the control of transpiration by vegetation and the effect of soil moisture on vegetation. Having deeper roots, trees are able to extract water from deep soil layers. When soil is dry, roots tend to grow for extracting water. These processes require a new parameterization for root distribution, or the incorporation of a photosynthesis model into LSM.

7. Summary

This study evaluated the effects of future climate changes on energy and water fluxes over eastern Siberia using a LSM. According to simulations, energy budgets and ET rates in Future considerably increased in comparison with Current. These increases in Future are correlated to the increased temperature and precipitation. The Future climates preferentially yielded higher LAI, increasing the absorption of radiation, in turn leading to higher R_n and consequently to higher *LE* and *H*. The increases in *LE* and *H* were significant in spring and summer and at tundra in the regional distribution. Considerable increases in ET were found in Future. The increased ET was mainly due to the increase in canopy interception associated with higher LAI and increased precipitation. In contrast, the higher LAI limited soil evaporation. The increase in sublimation during winter in Future is also a remarkable result, caused by higher temperatures and less precipitation. Northward spatial migration of ET was found from the comparison between Current and Future. In conclusion, it is possible to state that tundra regions are susceptible and vulnerable to climate changes.

It has been previously observed that ET is influenced by air temperature during the growing season and date of complete snowmelt (Park et al., 2008). Changes to ET in the Arctic are intimately linked to permafrost levels. As permafrost warms, the active layer thickens. A deeper active layer seems to have the capacity to attenuate soil water deficit owing to increased storage, causing higher ET rates, and vice versa. When permafrost is degraded or absent, ET is completely dependent on precipitation, and thus, the ET rate is decreased.

The Arctic regions are known to be susceptible and vulnerable to climate changes. This study will be useful for decreasing the uncertainties surrounding the susceptibility and vulnerability of the Arctic ecosystems to future climatic changes, especially with regard to water and energy budgets. Further study is needed to examine the details of interactions of vegetation dynamics and climate system and the likely consequences of such changes.

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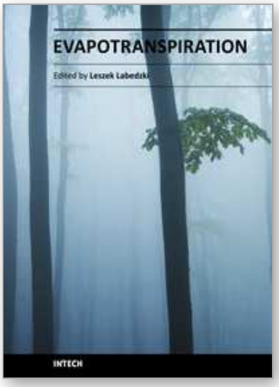

Evapotranspiration

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Evapotranspiration is a very complex phenomenon, comprising different aspects and processes (hydrological, meteorological, physiological, soil, plant and others). Farmers, agriculture advisers, extension services, hydrologists, agrometeorologists, water management specialists and many others are facing the problem of evapotranspiration. This book is dedicated to further understanding of the evapotranspiration problems, presenting a broad body of experience, by reporting different views of the authors and the results of their studies. It covers aspects from understandings and concepts of evapotranspiration, through methodology of calculating and measuring, to applications in different fields, in which evapotranspiration is an important factor. The book will be of benefit to scientists, engineers and managers involved in problems related to meteorology, climatology, hydrology, geography, agronomy and agricultural water management. We hope they will find useful material in this collection of papers.

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