Chapter 3
Water Cycles in Forests

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3.1 Introduction

Forests play an important role in the terrestrial water cycle. The rainfall brought to forest ecosystems is drained via surface and ground flow and partially transported into the atmosphere via evapotranspiration. These water balances are expressed in Eq. (3.1), in which precipitation (P) is distributed between evapotranspiration (ET), which includes transpiration by plants and evaporation from wet surfaces (e.g., soil and wet plant surfaces), change of storage (ΔQ), and runoff (outflow/inflow calculated as the residual component of the water balance, R):

$$P = ET + \Delta Q + R. \tag{3.1}$$

This water balance is linked to the heat balance via the evapotranspiration in the same domain:

$$R_n = H + LE + G, \tag{3.2}$$

where R_n is the net radiation as a budget of the shortwave and longwave radiation, H is the sensible heat flux, LE is the latent heat flux, which is ET multiplied by the latent heat of evaporation, and G is the heat flux into the ground. Evapotranspiration ET, which appears in Eqs. (3.1) and (3.2), plays a role in both the forest water cycle and the climate via the surface energy balance.

In boreal regions, the ecosystem has adapted to the environment, which is formed by the high latitude climate, snow, and frozen ground processes. Particularly, in eastern Siberia, the characteristics of the continental climate appear more strongly in comparison to other boreal regions (Schulze et al. 2002). The climate has strong

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continental characteristics, with a low precipitation of approximately 200–300 mm y^{-1} and an annual range of daily mean air temperature of more than 60 °C. The growth period of the plants is approximately the three summer months. The establishment of the forest is primarily composed of deciduous conifer, larch, which is enabled in spite of the small amounts of precipitation because permafrost is distributed continually over the area and the seasonally thawing ground supplies water for plant use (Chap. 1). The plant cover prevents rapid thawing of the frozen ground, while plants gain benefits from the water in the thawed ground. The forest ecosystem adapted to the environment of eastern Siberia in this way via frozen ground processes and plays a role that is important to the formation of the local water cycle.

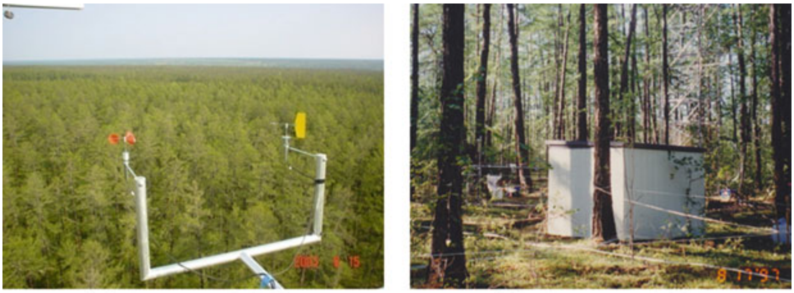
In recent years, the ecosystem has faced an intensification and an increased frequency of occurrences of extreme precipitation and temperature phenomena (Groisman and Soja 2009; Groisman and Gutman 2013). In the last decade, environmental changes on various scales have been observed in Eurasia at high latitudes, for example, increases in river discharge into the Arctic Sea (e.g., Shiklomanov and Lammers 2009), increases in atmospheric water vapor transport to high latitudes (Zhang et al. 2012), increases in snowfall over Siberia (Bulygina et al. 2011), increases in subsurface water storage over the Lena watershed (Chap. 11, Muskett and Romanovsky 2009; Velicogna et al. 2012), and increases in the area of surface water (Chap. 8, Fedrov et al. 2014; Boike et al. 2016). It is important to examine how the responses of the forest ecosystems of eastern Siberia to the changes in the water environment and sequentially the water cycles will change.

This chapter introduces observational studies of the water and energy balance primarily of forest ecosystems during the plant-growing season. Evapotranspiration over the larch forest and its biophysical responses are focused on and the recently observed wet climate environment is presented.

3.2 Study Area

The Spasskaya Pad Scientific Forest Station (62°15′N, 129°37′E, 214 m a.s.l.) is located on a terrace of the Lena River in the Central Yakutia region of the Republic of Sakha, Russia. The observation site is operated by the Institute of Biological Problems in the Cryolithozone (Siberian Branch of the Russian Academy of Sciences – IBPC SB RAS). The mean annual precipitation in this area is 234 mm, and the mean annual air temperature is -8.4 °C, and the minimum monthly temperature is -38.1 °C in January and the maximum 19.8 °C in July (1986–2015).

The dominant species in the local forest is larch (*Larix cajanderi*), mixed with birch (*Betula pendula*) and willow (*Salix bebbiana*), with floor vegetation primarily composed of evergreen cowberry (*Vaccinium vitis-idaea*) mixed with several herbs (e.g., *Actaea erythrocarpa* and *Pyrola asarifolia*). The composition rate and height distribution of these species changed over the studied decade (from 1998 to 2014; Figs. 3.1 and 3.2). In 1998, the stand density of the larch trees was 848 trees ha^{-1}, the mean height was 18 m, and the wood volume was 221 m^3 ha^{-1} (based on allometric



(a) August, 2003 (b) August, 1997

(c) July,2007 (d) June, 2009

(e) July, 2014 (f) June, 2013

(g) June, 2013 (h) June, 2013

Fig. 3.1 Photograph of larch forest of SPA (**a**–**f**) and ELG (**g**–**h**)

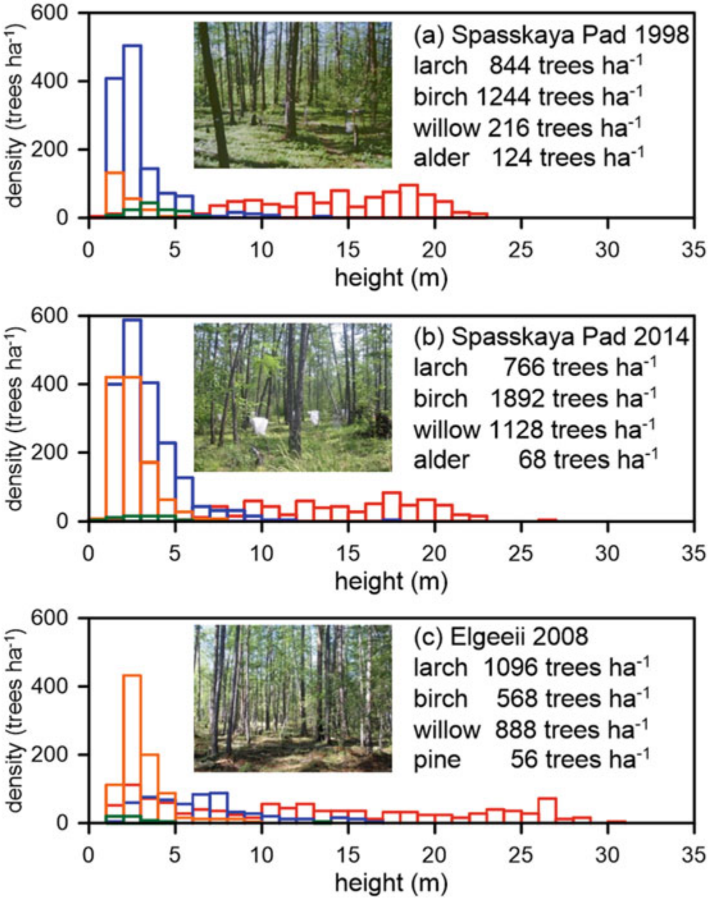


Fig. 3.2 Height class distribution and tree density for main tree species at Spasskaya Pad in 1998 (**a**), 2014 (**b**), and Elgeeii in 2008 (**c**). Red, blue, orange, and green colors indicate larch, birch, willow, and alder, respectively. Reduction of larch trees in Spasskaya Pad is due to fallen/felled dead trees

relationship of Schulze et al. (1995)). During the wet climate period of 2005–2008 (described below), the birch developed from 1244 trees ha^{-1} to 1892 trees ha^{-1}, and the willow trees developed from 216 trees ha^{-1} to 1128 trees ha^{-1} (Fig. 3.2). Other species, such as birch and pine (*Pinus sylvestris*), are clustered in 10–100 m scale patches around the larch forest observation site. Soils in the larch forest consist of an alluvial sandy loam classified as sod-pale solodic (Kononov et al. 2012) with a sandy loam texture. The upper layer has previously been reported to be sandy loam and the deeper layer to be silt loam (Lopez et al. 2007a) with vertical inversions in some places. The geographical features of an alluvial plain and the effect of cryoturbation (Sawada 2006) can produce these heterogeneous structures.

As a comparison to Spasskaya Pad, field observations were conducted at the Elgeeii Forest Station (60°01′ N 133°49′ E, 202 m a.s.l.) located on a terrace of the Aldan River (a tributary of the Lena River). Ust-Maya (60 km east of Elgeeii) has a mean annual precipitation of 302 mm and a mean annual air temperature of −8.5 °C (−39.4 °C in January and 18.8 °C in July, 1986–2015). The air temperature is similar to that in Yakutsk; however, the precipitation is 30% greater than that in Yakutsk. The species composition is similar to that of the Spasskaya Pad larch forest but with a more remarkably dominant development of larch trees. The stand densities of larch, birch, and willow are 1096, 568, and 888 trees ha^{-1}, respectively. The floor vegetation is primarily evergreen cowberry with shrubs such as dog rose and honeysuckle. Sod-pale soils with silt loam texture are found at Elgeeii. Traces of a former wildfire were detected in some locations within the forest.

Continuous observations have been conducted at these stations to obtain the energy balance, relating meteorological components such as air temperature, humidity, radiation, and wind and, inside the forest canopy, soil environmental components such as ground temperature and water content since 1998 at Spasskaya Pad and since 2009 at Elgeeii (Ohta et al. 2008; Iijima et al. 2014). Evapotranspiration has been observed at 32 m since 1998, at 3 m (inside the forest) since 2004 at Spasskaya Pad (Dolman et al. 2004; Ohta et al. 2008; Iida et al. 2009), and at 35 m since 2009 at Elgeeii (Kotani et al. 2014).

3.3 Evapotranspiration of the Larch Forest in Eastern Siberia

Figure 3.3 shows the climate and soil environment conditions in Spasskaya Pad since 1998, in which various climate conditions including dry and wet years were reported. In this chapter, characteristics of the forest evapotranspiration on primarily the Spasskaya Pad larch forest based on field observations over two decades are presented.

3.3.1 Seasonal Variation of the Forest Evapotranspiration

The energy balance of the larch forest showed seasonal variation reflecting the physical environment, such as solar radiation, air and ground temperature, soil water, and the plant phenology at Spasskaya Pad (Fig. 3.4; Ohta et al. 2001). Before snowmelt and the thaw of the frozen soils in spring, most of the net radiation is divided into the sensible heat flux, which increases following the net radiation. As snowmelt and the thaw of frozen soils commence, latent heat flux, which is evaporation from the ground surface because the trees do not have open leaves, gradually increases (Iida et al. 2009). The sensible heat flux is remarkably dominant compared

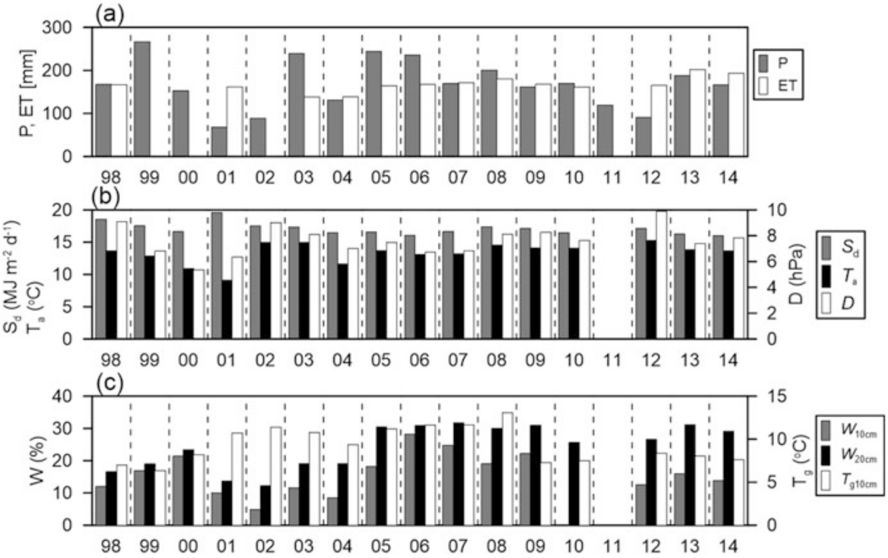
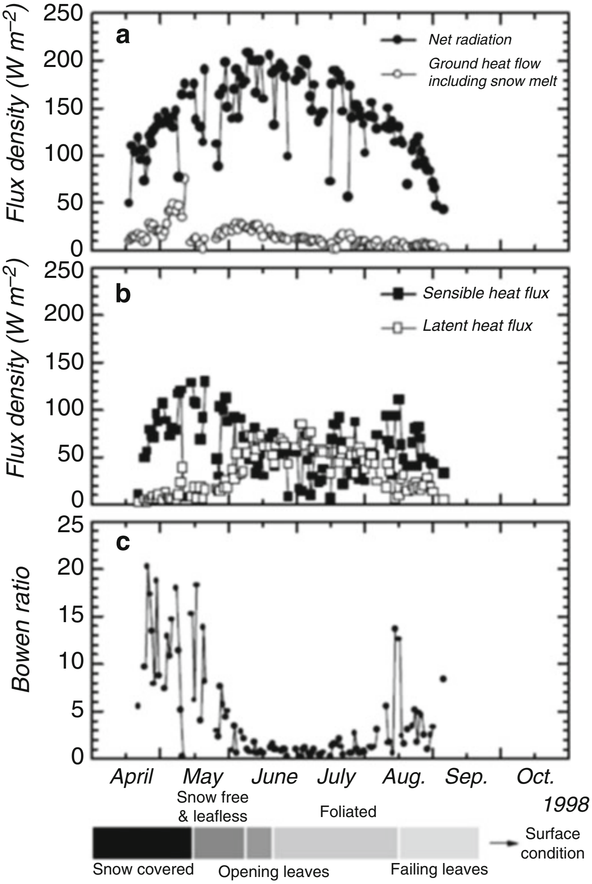


Fig. 3.3 Variability of meteorology and soil conditions in warm season (May–September) from 1998 to 2014 at SPA larch forest. (**a**) Sum of precipitation P and evapotranspiration ET, (**b**) average of daily solar radiation S_d, air temperature T_a, and vapor pressure deficit D, and (**c**) average of soil water contents W at 10 and 20 cm depth, and soil temperature T_g at 10 cm depth

to the latent heat flux during this period, and the Bowen ratio, which is ratio of sensible heat flux to latent heat flux (H/LE), is approximately 5–20. When the larch trees and the other deciduous plants come into emergence and expand their leaves, the latent heat rapidly increases due to plant transpiration (Ohta et al. 2001; Dolman et al. 2004). The seasonal maximum of the latent heat flux appears in June–July, while the sensible heat flux decreases. During this period, the latent and sensible heat fluxes are nearly equal, or the sensible heat is slightly larger (the Bowen ratio is close to 1). In the latter half of the foliation period (August–September), the latent heat flux gradually decreases due to the browning and shedding of leaves and again the Bowen ratio increases beyond 1 (Ohta et al. 2001; Dolman et al. 2004). The rate of the latent heat decrease depends on the soil moisture at the time, which depends on the summer precipitation; after a summer with higher precipitation, the latent heat flux does not decrease rapidly and is maintained in the late summer. In a young larch forest in the same region, seasonal variations similar to the Spasskaya Pad larch forest were found; the seasonal maximum of the sensible heat flux preceded that of the latent heat flux and the Bowen ratio was close to 1 during the summer (Tanaka et al. 2008). Tanaka et al. (2008) also found that, during the summertime, the daily sensible heat flux responded to variations in the daily net radiation, while the latent heat flux (evapotranspiration) was relatively stable.

Seasonal variations in the energy balance over forests, particularly deciduous forests, strongly reflect plant phenologies, such as leaf emergence, expansion, and dormancy, as shown above. Therefore, interannual variations in the length of the

Fig. 3.4 Seasonal variation of (**a**) net radiation and ground heat flux including snowmelt, (**b**) sensible and latent heat flux, and (**c**) Bowen ratio at SPA larch forest. (Ohta et al 2001)



foliation period should affect the annual evapotranspiration. However, even though the date of the leaf emergence at the Spasskaya Pad larch forest varied by a maximum of 30 days, the evapotranspiration summed over the warm season (May–September) did not correlate to the length of the foliation period (Xue et al. 2012). The seasonal sum of the evapotranspiration depended on the evapotranspiration during the maximum leaf area period (middle of June–end of August), and the evapotranspiration during leaf expansion and shedding had little influence (Xue et al. 2012). The non-negligible contribution of the understory vegetation to the forest evapotranspiration, as described below (Sect. 3.3.2), makes it difficult to explain the whole-forest dynamics with only larch phenology.

As shown above, periods of the snow cover and plant phenology at the larch forest were major drivers of the seasonal variation in the energy balance. Phenological observation from 2013 to 2015 found that onset of snowmelt and leaf emergence was earlier, and leaf senescence at autumn was later (Sect. 10.4.3) compared to the late 1990s to early 2000s (Ohta et al. 2001). Typical seasonal sequence of the Bowen

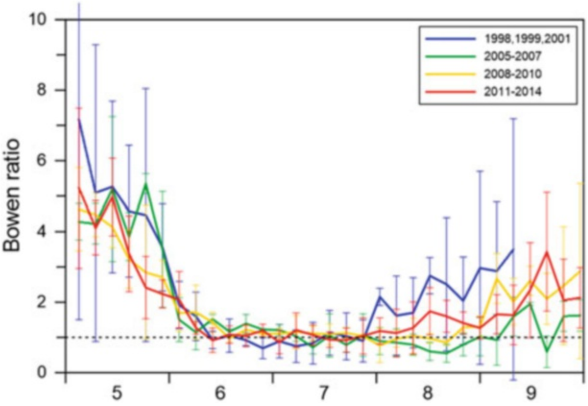


Fig. 3.5 Seasonal variation of 5 days average of the Bowen ratio at SPA larch forest. Only days without rainfall was averaged in 1998–2001 (excluding 2000), 2005–2007, 2008–2010, and 2011–2014. Error bars show standard deviations between years

ratio as described above (Ohta et al. 2001; Dolman et al. 2004) was modified following these changes (Fig. 3.5). Decrease of the Bowen ratio in spring started half month early. In contrast, the summer lowest values around 1 were kept until late August. This is particularly remarkable around 2005 through 2007 because of much soil water near the ground surface (see Sect. 3.6), which could support soil evaporation and transpiration of plants, and this effect was prolonged even after surface water disappeared probably because deeper soils were still wet (Fig. 3.3).

3.3.2 *Evapotranspiration from the Understory Vegetation*

In general, in boreal forests with sparse crown structures compared to temperate and tropical forests, the contribution to transpiration of the understory vegetation and the soil evaporation is large (Baldocchi et al. 2000). At Spasskaya Pad, the contribution of the understory vegetation to the forest evapotranspiration is approximately 50% during the foliation period, as revealed by several independent means. The transpiration of the larch trees, which was evaluated via sap flow measurements, was approximately 35% (Ohta et al. 2001) to 50–60% (Lopez et al. 2007a). Measurements of the water vapor flux based on the eddy covariance method at 3-m height inside the forest indicated that evapotranspiration from the underground vegetation including evaporation from the soil was equal to approximately 50% of the forest evapotranspiration (Iida et al. 2009, Fig. 3.6). Isotopic analyses of the water vapor sampled above the forest indicated that 80% of the forest evapotranspiration originated in plant transpiration under plant active conditions in the summer daytime (Ueta et al. 2014). The transpiration from evergreen cowberry on the floor, based on leaf chamber measurements, corresponded to 35–60% of the forest evapotranspiration (Miyahara et al. 2004); this is 40–65% of the sum contribution of transpiration by tree and soil evaporation. During the summer, the transpiration of the cowberry decreased just after emergence of the larch needles that means increased

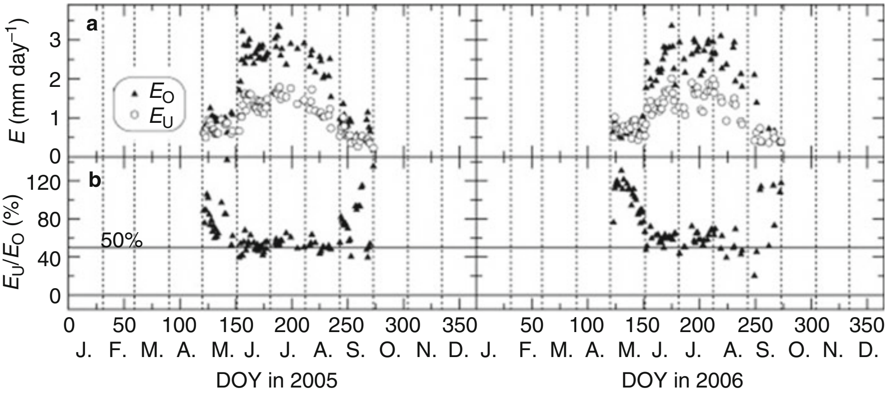


Fig. 3.6 Seasonal variation of daily evapotranspiration at SPA larch forest. (**a**) Total evapotranspiration of forest E_o and understory evapotranspiration E_u, and (**b**) ratio of E_u to E_o. (Iida et al. 2009)

transpiration by larch, likely indicating competition for the use of the soil water close to the ground surface (Miyahara et al. 2004), as well as reduced solar radiation reached into the forest floor (Iida et al. 2009).

The contribution of the understory vegetation including soil evaporation in the boreal forests in various regions ranges from 10% to 60% during the summer (lists are provided in Lindroth and Crill 2011; Iida et al. 2009). A relatively large contribution was found in the larch forests in eastern Siberia compared to the boreal forests in Canada and Scandinavia. The effective penetration of solar radiation through the sparse canopy and the larger atmospheric humidity deficit inside the forests due to the arid climate are likely the main reasons for this phenomenon (Iida et al. 2009).

3.3.3 *Interception Evaporation*

Interception evaporation during rainfall and just after rainfall is also affected by characteristics of the forest environment such as an arid climate with large atmospheric humidity deficits and a large contribution by understory vegetation. The interception evaporation of the Spasskaya Pad larch forest was estimated to be 15% of the gross rainfall (Ohta et al. 2001). This value seems rather small compared to other boreal forests such as spruce forests in Sweden (26.6%, Bergkvist and Folkeson 1995), mixed forests of spruce and pine in Sweden (30%, Grelle et al. 1997), and spruce forests in Canada (23%, Price et al. 1997), likely due to the small interception storage capacity of the sparse canopy crown (Lindroth and Crill 2011). The energy source for interception evaporation during rainfall is the net radiation at the Spasskaya Pad larch forest in contrast to those at temperate and tropical forests, in which the sensible heat flux from the atmosphere is typically the main energy source (Toba and Ohta 2005).

3.3.4 Forest Water Balance

The daily evapotranspiration in the Spasskaya Pad larch forest was 2–3 mm day^{-1} at the seasonal maximum, which is comparable to other larch forests in eastern Siberia (Kelliher et al. 1997; Lopez et al. 2008; Kotani et al. 2014) and in northern Mongolia (Miyazaki et al. 2014). It is also similar to the evapotranspiration of the other boreal forests summarized in Eugester et al. (2000), Lindroth and Crill (2011), and Miyazaki et al. (2014). Evapotranspiration in the warm season (May–September) ranged between 138 mm and 180 mm during the period of 1998–2011 (Ohta et al. 2014), and this interannual variation was smaller than the variation in the annual precipitation (111–347 mm). The interannual variation of the one-dimensional water balance based on Eq. (3.1) from 1998 to 2006 is shown in Fig. 3.7 (Ohta et al. 2008). Despite the interannual difference in precipitation, that in evapotranspiration is rather stable, as stated above, and the change in the soil water storage and residual flux (runoff) responded to the precipitation. The remarkable increase in the soil water storage since 2005 was caused by both the precipitation and water inflow from outside the system (negative runoff), which indicates an expanding seasonal thaw depth of the permafrost (Ohta et al. 2008).

One possible reason for the relatively stable evapotranspiration in spite of the small amount of precipitation and its large interannual variability is the supply of water from thawed frozen ground and snowmelt. The frozen ground layer extends to the ground surface in the winter season, and thawing commences from the ground

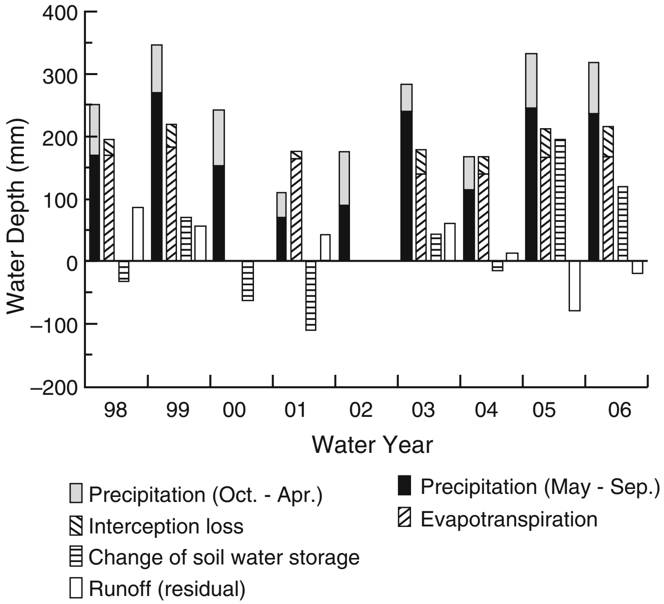


Fig. 3.7 Annual water balance in SPA larch forest. (Ohta et al. 2008)

surface just after the snow melts; the thaw water is stored in the active layer (the layer of the soil above the permafrost that thaws and freezes seasonally). Plants consume rainwater during wet summers and soil water from the deeper layers during dry summers (Chap. 6, Sugimoto et al. 2002). Furthermore, soil water in the active layer correlates better with the precipitation of the previous year rather than that of the current year indicating that soil water storage before freezing is carried over to the next year (Ohta et al. 2008). Soil water in the active layer increases in summers with more precipitation, and that water decreases gradually until frozen due to the stable evapotranspiration. Conversely, during summers with less precipitation, the shortage of soil water close to the ground surface results in reduced heat conductivity, suppressed thawing speed, and soil water being stored in shallower layers where the root depth is concentrated, resulting in maintaining the transpiration (Lopez et al. 2007a).

Snowmelt water is also essential to the soil water dynamics in the active layer. When little soil water was stored before soil freezing, there is little water supplied by the thawing frozen soil in the next summer; however, in such years, infiltration of the snowmelt water into the non-water/ice-saturated ground is effectively accelerated and supports plants taking water, particularly in periods of leaf emergence (Lopez et al. 2015). Conversely, ice-rich frozen soil prevents the infiltration of snowmelt water, and excess water can be discharged to the surrounding lower grassland depression, called an Alas (Sect. 3.5 and Chap. 8), and recharge thermokarst lake water (Lopez et al. 2015). The discharge water also transports salts from the forest to the Alas and plays a role in reducing salt accumulation in the forest soil (Lopez et al. 2007b; Herzschuh et al. 2013).

Interactions between the permafrost and forest ecosystem, in which the soil freezing–thawing process and the plant water use are connected, are an essential feature in addition to the interaction between the forest and atmosphere in terrestrial processes in eastern Siberia. With changing permafrost and forest conditions in the future, it is unknown whether the stable water cycle, particularly the evapotranspiration, which has considered to be a peculiarity of this region, will be maintained. Climate warming sensitivity experiments based on vegetation dynamic modeling indicate that a two-degree warming would result in the collapse of the interaction system between the permafrost–forest–atmosphere and a transition from a deciduous conifer (larch) forest to an evergreen conifer forest (Zhang et al. 2011). Other experiments indicate an increase in the larch productivity due to an increase in the precipitation and soil water (Sato et al. 2016). Furthermore, more local damage to forests and permafrost by ether forest fires or waterlogging (Sect. 3.6) could cause local modifications in the surface water and energy balance. Sensitivity experiments using nonhydrostatic atmospheric modeling to detect the influence of land cover changes in the Lena Basin on the regional water cycle revealed that changes in the evapotranspiration due to transitions from forests to grasslands or water areas are sensitive to the size of the water area (Yoshida et al. 2013). They also indicated an increase in the precipitation consistent with the evapotranspiration indicating a strong interaction between the forest and atmosphere (Yoshida et al. 2013).

3.4 Response of the Forest to Environmental Conditions

3.4.1 *Evapotranspiration*

Causes of variations in the forest evapotranspiration can be divided into plant physiological responses (stomata control) to control transpiration and the physical environment (atmosphere and radiation) deciding the atmospheric evaporation demand. Under a cool or cold climate with modest precipitation, boreal forests have restricted growth and photosynthesis capacities but survive by using water effectively via the regulation of stomatal closure (e.g., Baldocchi et al. 2000).

In the Central Yakutia middle taiga, stomatal control on larch transpiration is remarkable because the atmospheric humidity deficit is high during the hot and dry summers (Vygodskaya et al. 1997). Stand transpiration based on sap flow measurements of larch trees at the Spasskaya Pad station revealed a strong regulation due to the atmospheric humidity deficit (Kuwada et al. 2002, Lopez et al. 2007a). Even though the nitrogen density in the larch needle is small because there is less soil nitrogen available for the plant, larch trees adapt to the dry climate by increasing the leaf weight per unit area (Schulz et al. 1995; Popova et al. 2013). As another adaptation to the dry climate, the reduced sensitivity of the stomatal conductance to the atmospheric humidity deficit under high humidity deficits results in avoiding a drop in the conductance in the afternoons when the humidity deficit increases (Arneth et al. 1996). These physiological responses of individual larch trees to adapt to the dry climate support assimilating CO_2 efficiently during the short foliation period in this region (see also the photosynthesis of larch in Sect. 4.1).

Forest evapotranspiration is less sensitive to increases in the atmospheric humidity deficit compared to the CO_2 uptake of the forest ecosystem (Tanaka et al. 2000; Dolman et al. 2004). Reduced CO_2 uptake indicates closed stomata; therefore, at the same time, larch transpiration would be reduced. In actuality, decreased transpiration was observed during dry summers with reduced soil water (Lopez et al. 2007a). However, forest evapotranspiration includes both plant transpiration and soil evaporation and the enhanced evaporation owing to a high atmospheric humidity deficit compensates for the reduced transpiration (Schulze et al. 1999). In addition, the water supply from the active layer supports plant water uptake during dry summers, as noted above, and avoids fatal stress on water uptake by plants, while floor vegetation without deeper roots could be affected by water deficits in the surface soil. Such an efficient mechanism, supported by a stable water supply from thawing soil water as noted above, enables a relatively stable level of ET compared to the highly variable annual precipitation in this region (Ohta et al. 2008).

By contrast, the influence of soil water in the active layer on forest evapotranspiration at Spasskaya Pad was unclear compared to those of the atmospheric condition, such as the atmospheric humidity deficit and solar radiation in diurnal and seasonal scale variations (Yoshida et al. 2010). The relatively stable supply of thaw water is one of the main reasons for this. Correlations between the forest evapotranspiration and the soil water content (0–50 cm) appeared on time scales longer than 2 months, and stronger correlations were found on longer time scales, such as interannual scales (Yoshida et al. 2010). Evapotranspiration at larch forests with deeper active layers (3 m maximum) in northern Mongolia also depends on summer soil water and precipitation (Miyazaki et al. 2014). The influence of soil water on evapotranspiration was not found in black spruce forests in shallower active layers, in which volumetric soil water content was maintained at as high as 40–80%, in Interior Alaska (Iwata et al. 2012).

Environmental control factors including the atmospheric humidity deficit and the soil water content on the forest evapotranspiration at Spasskaya Pad were also variables that could explain the differences in forest evapotranspiration compared to other regions. Comparing the characteristics of the water and energy exchanges at five sites of evergreen, deciduous, and mixed forests, including the Spasskaya Pad larch forest, in three different climate zones, Matsumoto et al. (2008a) revealed that the spatial difference was not due to the atmospheric demand and that the land surface regulation makes a difference in evapotranspiration. The primary reasons for the low levels of evapotranspiration at the Spasskaya Pad forest were the reduced transpiration due to the high atmospheric humidity deficit and the small leaf area of the conifer needles (Matsumoto et al. 2008a).

3.4.2 Conductance

Forest evapotranspiration is driven by atmospheric conditions and controlled by plant and soil conditions. Surface conductance, which indicates efficiency in canopy-scale evapotranspiration with regard to physical environmental variability, is generally smaller in boreal forests than in temperate and tropical forests (Baldocchi et al. 2000; Hall et al. 2004). The surface conductance of larch and pine forests in eastern Siberia is smaller than that of other climate forests, and this difference can be explained by the leaf area index (LAI) difference (Matsumoto et al. 2008b; Khatun et al. 2011). The decoupling factor, which is derived from the Penman–Monteith formula and presents the contribution of radiation and aerodynamic drivers on the evapotranspiration (McNaughton and Jarvis 1983), represents the importance of surface conductance on forest evapotranspiration in Spasskaya Pad larch forests (Iida et al. 2009). This feature indicates that the atmospheric demand of evaporation strongly covariates with evapotranspiration and is common in boreal forests, which generally have large roughness (Khatun et al. 2011).

The daily mean surface conductance of the larch forest at Spasskaya Pad decreased when the atmospheric humidity deficit increased (Ohta et al. 2001; Dolman et al. 2004). Otherwise, the yearly mean surface conductance was well correlated with the soil water content (Yoshida et al. 2010; Xue et al. 2012). The interannual variation in the evapotranspiration normalized by the potential evaporation, which, similar to the surface conductance, represents the land surface control of the evapotranspiration, was also explained by the soil water content (Ohta et al. 2008). A strong correlation between the soil water and the surface conductance was found on a yearly scale, and this correlation decreased in the daily or seasonal scale variations (Yoshida et al. 2010). To focus on the contribution to transpiration by the upper canopy primarily consisting of larch leaves, the difference between the forest evapotranspiration and the floor evapotranspiration was considered to be the larch layer, and the surface conductance (canopy conductance) of this larch layer was then calculated (Xue et al. 2014). The conductance under the standard condition (an assumed vapor pressure deficit of 1 kPa and saturated solar radiation) at the Spasskaya Pad larch forest was larger than that at other boreal forests (Xue et al. 2014). This is evidence of the reduced surface conductance due to the increase in the atmospheric humidity deficit, similar to the response of the stomatal conductance at the leaf scale discussed above.

Observations of the Spasskaya Pad larch forest with datasets of other climate and forest types were used for parameterization for biogeochemical models. Matsumoto et al. (2008b) compared the responses of the surface conductance to environmental factors in five forest sites in Siberia and Japan. They presented a function of the LAI to explain the inter-site differences in the maximum surface conductance and applied this function to a Jarvis-type conductance model (Fig. 3.8, Matsumoto et al. 2008b). They also showed that their model was optimized for each site and that the bundle of all sites did not differ in precision when estimating the surface conductance (Matsumoto et al. 2008b). These results suggest that the surface conductance of the various mature forests had the same maximum value and response properties, that is, the spatial differences of the environmental responses of forest evapotranspiration depend on the ambient environment rather than the type of forest.

Forest structures such as canopy roughness and tree density also influence the heat and water vapor transport. Such aerodynamic parameters, e.g., surface roughness length and zero plane displacement, which are usually normalized by the canopy height, can be parameterized with the LAI or be assumed constant (Dolman et al. 2003). Boreal forests with large ratios of height to diameter for trees and small ratios of leaf area to stem area, however, are not always applicable to the functions used to evaluate temperate and tropical forests. Nakai et al. (2008) compared these aerodynamic parameters for five forests with various tree densities and height distributions from Siberia and Japan and explained the differences between them using the tree density. They showed a seasonal variation in the aerodynamic parameters following the LAI and found that larch forests with small leaf area varied less compared to other forests. However, an evaluation of these parameters is important for energy and water vapor transport in the larch forest, in which the aerodynamic driver dominates the evapotranspiration.

3.5 Spatial Variability in Eastern Siberia

In the Central Yakutia, precipitation increases toward the south owing to the influence of the surrounding mountains (Yoshida et al. 2012), and forests with high productivity are distributed in the south (Troeva et al. 2010). In the southern

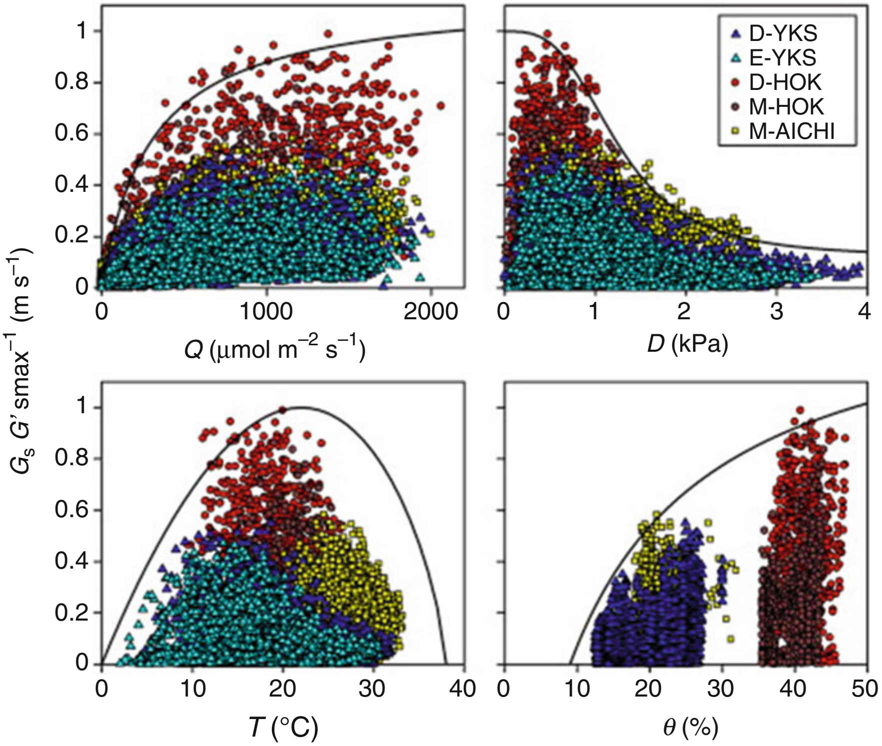


Fig. 3.8 Relation between surface conductance normalized by maximum surface conductance and environmental variables (photosynthesis active radiation *Q*, atmospheric water vapor deficit *D*, air temperature *T*, and volumetric soil water content *θ*). D-YKS is deciduous (larch) forest in SPA; E-YKA is evergreen (pine) forest in SPA; D-HOK and M-HOK are deciduous and deciduous-evergreen mixed forests in Hokkaido, Japan; and M-AICHI is deciduous-evergreen mixed forest in Aichi, Japan. (Matsumoto et al 2008b)

forest, Elgeeii, more precipitation, soil water, and larger carbon assimilation are found compared to the larch forest in Spasskaya Pad (Chap. 4); however, the difference in the forest evapotranspiration is surprisingly small (Kotani et al. 2014). One possible reason could be the underestimation of the interception evaporation at Elgeeii, where the leaf area is larger than Spasskaya Pad. Soils at Elgeeii consist of finer grain sizes than those at Spasskaya Pad and had higher water retention but lower permeability, which restricted water movement and plant water uptake. At Spasskaya Pad, soil water close to the ground surface decreased without precipitation inputs due to active evapotranspiration from the floor vegetation and soil, whereas soil water in the 20-cm layer was relatively stable likely due to rapid percolation from the upper layers and supply from the deeper layer owing to the vertical gradient of the water potential (Sugimoto et al. 2003). Furthermore, large contributions of soil evaporation and floor plant transpiration could achieve total evapotranspiration comparable to the Elgeeii forest. Different ways of control due to different soil and forest structures work on forest evapotranspiration. Under the evaporation demand determined by the atmosphere, which is similar at both sites, forest evapotranspiration is usually optimized to the meteorological conditions in the region. This effect could be one of the reasons for the small variability in the annual evapotranspiration (e.g., Ohta et al. 2008).

Larch forests in the southern mountain area with discontinuous permafrost also showed similar seasonal variations in the energy balance, in which the Bowen rate consistently decreased with the emergence of larch needles and increased following larch shedding (Kubota et al. 2004). The latent heat flux before leaf emergence was larger than that in the Spasskaya Pad larch forest because the net radiation on the floor did not conduct into the ground due to the insulating effect of the moss layer, and the majority of the net radiation on the floor was distributed as sensible and latent heat fluxes (Kubota et al. 2004; Suzuki et al. 2007). Evaporation before leaf emergence was equal to 22% of the total forest evapotranspiration from April to October and made a large contribution to the annual water and energy balance of the forest (Suzuki et al. 2007).

The pine forest at the Spasskaya Pad station (2 km from the larch site) presented a small difference in its seasonal variation due to its evergreen species. The onset of evapotranspiration in the pine forest was earlier than that in the larch forest because the pine trees started transpiration just after snowmelt (Hamada et al. 2004). Gradual increases in the evapotranspiration and remarkable reductions in the sensible heat flux in midsummer were not observed. Therefore, distinct seasonal variations in the Bowen ratio similar to those in the larch forest were not found (Hamada et al. 2004). Seasonal variations similar to those of the Spasskaya Pad pine forest were observed in the same species of pine forest in Central Siberia (Yenisei River), where both the sensible heat flux and the latent heat flux followed the net radiation (Tchebakova et al. 2002). In the Central Siberia pine forest, however, the latent heat flux did not decrease with the net radiation and sensible heat flux during the late summer; therefore, the seasonal minimum of the Bowen ratio appeared in the late summer (Tchebakova et al. 2002).

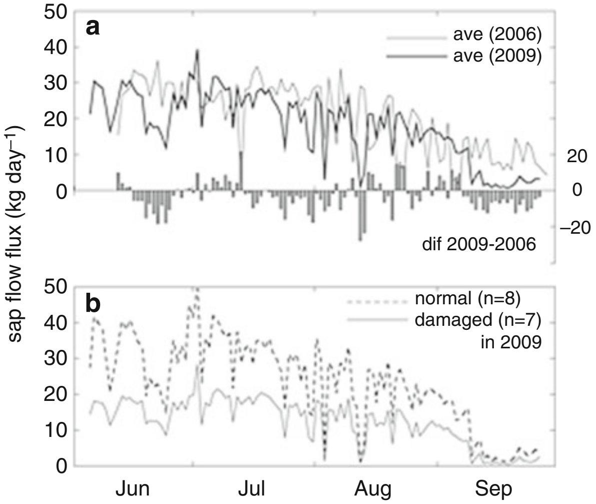
In the Central Yakutia Taiga region, grasslands and lakes formed in the thermokarst depression were found sporadically in the forest (Chap. 8). There are lakes in center of the grasslands, which are lowlands relative to the surrounding forests, and soil water decreases from the vicinity of the lake to the surrounding forest. Such Alas landscapes cover approximately 20% of the Lena lowland (Lopez et al. 2008), and the surface energy and water balance in these grasslands should be considered when evaluating the regional energy and water balance. Seasonal variations in the surface heat balance of the grassland and adjacent forests are contrasting. The grasslands are flooded or nearly saturated by water after the snowmelt at the end of April, and then gradually the water area diminishes and grasses begin to grow by the beginning of June (Yabuki et al. 2004). Following grass expansion, there is a rapid increase in the latent heat flux that exceeds the sensible heat flux, and the Bowen ratio is close to 0.1 until the grass is cut. Even though the net radiation of the grassland is smaller than that of the forest, its remarkably small Bowen ratio results in the latent heat flux at the grassland being similar or at least half of that in the forest. At the same time, the sensible heat flux in the grassland is 1/2–1/3 of that in the forest, which means the atmosphere is heated less by the grassland than by the forest (Yabuki et al. 2004). At other Alas grasslands, evapotranspiration from the grassland is 10% smaller than that of adjacent forests, and its variability depends on the lake area (Lopez et al. 2008). Larger yearly variation was found in the grassland evapotranspiration due to the larger yearly variation in the depth of the active layer and the associated soil water and plant biomass (Lopez et al. 2008). Lastly, the evaporation from lakes located at the centers of the grasslands reached twice the grassland evapotranspiration (Ishii et al. 2001). Lake area varies each year and therefore could have a large influence on the energy and water balances in Alas ecosystems.

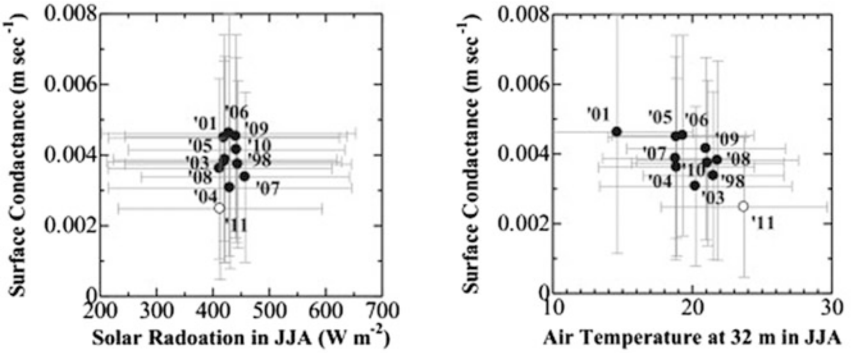
3.6 Response of Larch Forests to Wetting Climates

Over the two decades of observations, knowledge of forest evapotranspiration without remarkable disturbance in the Central Yakutia middle taiga region has been collected. Long-term observations also provide unexpected environmental variations on longer time scales. Large precipitation before winter and snow accumulation during the period of 2004–2008 caused an increase in the soil water coincident with an increase in the ground temperature and active layer thickness around Yakutsk (Iijima et al. 2010). In particular, unusually high soil water during the period of 2006–2007 in comparison to the past 100 years was detected using tree-ring stable isotope chronology (Tei et al. 2013, Chap. 7). In the following summer of 2007, damage to larch trees in areas with elevated soil water, where the degree of saturation increased and the gas diffusivity decreased, was apparent in the form of yellowing and browning leaves (Iwasaki et al. 2010). A decline in tree transpiration as estimated from sap flow measurements was also detected for trees located over a locally moistened and deepened active layer due to micro-topography (Fig. 3.9, Iijima et al. 2014, Chap. 8).

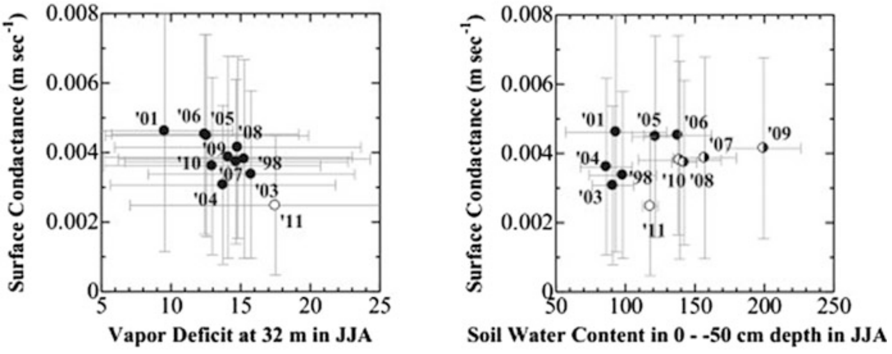
During this period, forest evapotranspiration increased in 2005 and 2006 in response to the high soil water but decreased in 2007 in spite of plentiful soil water (Ohta et al. 2014). By contrast, evapotranspiration from the understory vegetation increased. During the years of continuous wet soil conditions, some of the larch trees and other plants in this forest ecosystem changed; there was an invasion of water-tolerant grass species and growth of young trees (Fig. 3.2). However, yearly mean surface conductance, which had a strong positive correlation to the soil water before the larch damage (Sect. 3.4.2), decreased as expected from the previous correlation (Fig. 3.10, Ohta et al. 2014). By contrast, the surface conductance of the understory vegetation was relatively stable. The aerodynamic conductance of the understory evapotranspiration increased likely due to sufficient soil water leading to the growth of understory vegetation and the simultaneous partial decline in the larch crown altering the environment inside the forest by increasing the light and enhancing the turbulent mixing. The decline in the larch

Fig. 3.9 Daily sap flow flux of larch trees in SPA larch forest. (**a**) Comparison of year 2006 and 2009 with difference in 2 years, and (**b**) comparison of normal and damaged larch in 2009. (Iijima et al. 2014)





a) Solar radiation at 32 m b) Air temperature at 32 m



c) Vapor pressure deficit at 32.0 m d) Soil water content in 0 – 50 cm

Fig. 3.10 Relation between surface conductance and (**a**) solar radiation, (**b**) air temperature, (**c**) vapor pressure deficit, and (**d**) soil water content in SPA larch forest. Each plot indicates average in summertime (June–August) from 1998 to 2011 (Ohta et al. 2014) contribution was compensated for by the understory growth, resulting in a relatively stable whole-forest exchange rate, at least during this study period. Interactions between larches and understory vegetation could support the resilience of this forest ecosystem and the water cycle under environmental variability.

Waterlogging in the soil affects various plant physiological responses such as metabolism, carbon assimilation, transpiration, and nitrogen cycles via the lowered oxygen concentration around the roots (Drew 1997; Bacon 2004). In particular, coniferous species have difficulty managing under insufficient oxygen conditions due to their limited ability to transport oxygen (Kozlowski 1984). Several experimental studies have been conducted to reveal the effects of excessive soil water in various parts of the forest ecosystem at the Spasskaya Pad station. Irrigation experiments, in which twice the natural precipitation was supplied resulting in excess water, did not change the larch transpiration and water storage at root depth indicating infiltration into deeper layers or horizontal drainage (Lopez et al. 2010). Under a water controling experiment, the response of larch seedlings to excess water did not appear in the current year, while root development and the gas exchange rate of needles were reduced in the following year (Takenaka et al. 2016a). A more remarkable reduction appeared in the case of exposure to drought conditions in the year prior to the excess water experiment (Takenaka et al. 2016a). Mature larch trees that experienced drought soil in the previous year suppressed root development and vice versa (Takenaka et al. 2016b). These results indicate the longer than yearly scale memory of previous environmental stresses experienced by individual trees.

While knowledge concerning various responses of individual trees to wet conditions (e.g., Kozlowski 1997; Kreuzwieser and Gessler 2010) has been accumulated, studies on the forest ecosystem scale are relatively rare. Most such studies have investigated riparian forests or maritime forests (e.g., Crawfold et al. 2003). Even though studies on boreal forests are limited, it is noteworthy that the wetting situation of forests in permafrost regions, e.g., the vegetation transition from forest to wetland progressing with permafrost degradation, was reported in sporadic and discontinuous permafrost regions of Canada and Alaska. Forest fragmentation due to thawing permafrost and expanding wetlands was observed, as well as the reduced water uptake and leaf area of black spruce trees located on forest edges in boreal peatland in the Northern Territories in Canada (Baltzler et al. 2014). The transition from birch to spruce occurred with thermokarst succession in boreal wetlands in Interior Alaska (Lara et al. 2016). These vegetation transitions could likely change the forest evapotranspiration and water cycles. Because forests located on wetlands are a common ecosystem in Scandinavia and West Siberia, the variability of rain and snowfall as well as the air temperature has caused prolonged flooding periods (Wang et al. 2013) and root pathogens (Pavlov 2015).

The processes of changes in forest components caused by excess soil water differ from those resulting from disturbances such as forest fires or lodgings, which have been intensively investigated. While there have been many studies focusing on drought stress, the response of forest evapotranspiration to too wet conditions is yet not sufficiently understood. Knowledge of energy and water cycles in grassland–forest ecosystems, as shown above, will help predict water cycle changes in the case of a transition from forest to grassland in this region. At the same time, grasslands act as buffer for excess water from surrounding forests (Lopez et al. 2010) and, therefore, considering energy and water cycles at a landscape scale will be beneficial to our understanding of regional water cycles.

3.7 Concluding Remarks

Two decades of field observations and a comparison to other climate regions has resulted in various knowledge concerning the forest water cycle, where the forest ecosystem is adapted to a continental climate with low precipitation and a hot and dry summer and foliation periods as short as a few months. Concerning larch forest evapotranspiration, which is the primary focus of this chapter, there are many important features including stomata regulation against atmospheric humidity deficits, the contribution of evapotranspiration from floor and understory vegetation, and the relatively stable evapotranspiration compared to soil water and precipitation. These features occur due to the underlying permafrost and in part the complementary support of the thermokarst grassland and forest via water flow.

Climate change in eastern Siberia in the future will likely bring both drying and wetting terrestrial conditions. Either way, changes in the forest energy and water cycles are possible via the responses of the forest and will feedback into the atmospheric processes. Changes in the water cycle also will affect the forest ecosystem via material transport including salt accumulation. Continuous monitoring of water and biogeochemical cycles (Chaps. 4 and 5) combined with the water and energy cycles is necessary to understand the terrestrial processes and predict the fate of the forests in this region.

References

Arneth A, Kelliher FM, Bauer G, Hollinger DY, Byers JN, Hunt JE, Mcseveny TM, Ziegler W, Vygodskaya NN, Milukova I, Sogachov A, Varlagin A, Schulze ED (1996) Environmental regulation of xylem sap flow and total conductance of Larix gmelinii trees in eastern Siberia. Tree Physiol 16:247–255. https://doi.org/10.1093/treephys/16.1-2.247

Bacon MA (2004) Water use efficiency in plant biology. Blackwell, London

Baldocchi D, Kelliher FM, Black TA, Jarvis P (2000) Climate and vegetation controls on boreal zone energy exchange. Glob Chang Biol 6:69–83. https://doi.org/10.1046/j.1365-2486.2000.06014.x

Baltzler J, Veness T, Chasmer LE, Sniderhan AE, Quinton WL (2014) Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. Glob Chang Biol 20:824–834. https://doi.org/10.1111/gcb.12349

Bergkvit and Folkeson (1995) The influence of tree species on acid deposition, proton budgets and element fluxes in South Swedish forest ecosystems. Ecol Bull 44:90–99

Boike J, Grau T, Heim B, Günther F, Langer M, Muster S, Gouttevin I, Lange S (2016) Satellite-derived changes in the permafrost landscape of central Yakutia, 2000–2011: wetting, drying, and fires. Glob Planet Chang 139:116–127. https://doi.org/10.1016/j.gloplacha.2016.01.001

Bulygina ON, Groisman PY, Razuvaev VN, Korshunova NN (2011) Changes in snow cover characteristics over Northern Eurasia since 1966. Environ Res Lett 6:045204. https://doi.org/10.1088/1748-9326/6/4/045204

Crawford RMM, Jeffree CE, Rees WG (2003) Paludification and forest retreat in Northern Oceanic environments. Ann Bot 91:213–226. https://doi.org/10.1093/aob/mcf185

Dolman AJ, Moors EJ, Grunwald T, Berbigier P, Bernhofer C (2003) Factors controlling forest atmosphere exchange of water, energy, and carbon. In: Valentini R (ed) Fluxes of carbon, water, and energy of European forests, Ecological Studies, vol 63. Springer, Berlin, pp 207–223

Dolman AJ, Maximov TC, Moors J, Maximov AP, Elbers JA, Kononov AV, Waterloo MJ, van der Molen MK (2004) Net ecosystem exchange of carbon dioxide and water of far eastern Siberian Larch (Larix cajanderii) on permafrost. Biogeosciences 1:133–146. https://doi.org/10.5194/bg-1-133-2004

Drew MC (1997) Oxygen deficiency and root metabolism: injury and acclimation under hypoxia and anoxia. Annu Rev Plant Physiol Plant Mol Biol 4:223–250. https://doi.org/10.1146/annurev.arplant.48.1.223

Eugster W, Rouse WR, Pielke SA Sr, McFadden JP, Baldocchi DD, Kittel TGF, Vaganov E, Chambers S (2000) Land-atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate. Glob Chang Biol 6:84–115. https://doi.org/10.1046/j.1365-2486.2000.06015.x

Fedrov AN, Gavrilief PP, Konstantinov PY, Hiyama T, Iijiima Y, Iwahana G (2014) Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia. Ecohydrology 7:188–196. https://doi.org/10.1002/eco.1378

Grelle A, Lundberg A, Lindroth A, Morén S, Cienciala E (1997) Evaporation components of a boreal forest: variations during the growing season. J Hydrol 197:70–87. https://doi.org/10.1016/S0022-1694(96)03267-2

Groisman PY, Gutman G (2013) Regional environmental changes in Siberia and their global consequences. Springer, Berlin

Groisman PY, Soja AJ (2009) Ongoing climatic change in Northern Eurasia: justification for expedient research. Environ Res Lett 4:045002. https://doi.org/10.1088/1748-9326/4/4/045002

Hall FG, Betts AK, Frolking S, Brown R, Chen JM, Chen W, Halldin S, Lettenmaier DP, Schafer J (2004) The boreal climate. In: Kabat P (ed) Vegetation, water, humans and the climate: a new perspective on an interactive system. Springer, Berlin, pp 93–114

Hamada S, Ohta T, Hiyama T, Kuwada T, Takahashi A, Maximov TC (2004) Hydrometeorological behaviour of pine and larch forests in eastern Siberia. Hydrol Process 18:23–39. https://doi.org/10.1002/hyp.1308

Herzschuh U, Pestryakova LA, Savelieva LA, Heinecke L, Böhmer T, Biskaborn BK, Andreev A, Ramisch A, Shinneman ALC, Birks HJB (2013) Siberian larch forests and the ion content of thaw lakes form a geochemically functional entity. Nat Commun 4:2408. https://doi.org/10.1038/ncomms3408

Iida S, Ohta T, Matsumoto K, Nakai T, Kuwada T, Kononov AV, Maximov TC, van der Molen MK, Dolman AJ, Tanaka H, Yabuki H (2009) Evapotranspiration from understory vegetation in an eastern Siberian boreal larch forest. Agric For Meteorol 149:1129–1139. https://doi.org/10.1016/j.agrformet.2009.02.003

Iijima Y, Fedorov AN, Park H, Suzuki K, Yabuki H, Maximov TC, Ohata T (2010) Abrupt increase in soil temperature following increased precipitation in a permafrost region, central Lena river basin, Russia. Permafr Periglac Process 21(1):30–41. https://doi.org/10.1002/ppp.662

Iijima Y, Ohta T, Kotani A, Fedrov AN, Kodama Y, Maximov TC (2014) Sap flow changes in relation to permafrost degradation under increasing precipitation in an eastern Siberian larch forest. Ecohydrology 7:177–187. https://doi.org/10.1002/eco.1366

Ishii Y, Yabuki H, Nomura M, Kobayashi N, Tanaka H, Tanaka H, Desyatkin RV (2001) Water and energy flux observation an alas lake in central Yakutia, eastern Siberia. In: Proceedings 5th International study conference on GEWEX in Asia and GAME (GAME Publ. 31), pp 117–120

Iwasaki H, Saito H, Kuwao K, Maximov TC, Hasegawa S (2010) Forest decline caused by high soil water conditions in a permafrost region. Hydrol Earth Syst Sci 14:301–307. https://doi.org/10.5194/hess-14-301-2010

Iwata H, Harazono Y, Ueyama M (2012) The role of permafrost in water exchange of a black spruce forest in Interior Alaska. Agric For Meteorol 161:107–115. https://doi.org/10.1016/j.agrformet.2012.03.017

Kelliher FM, Hollinger DY, Schulze ED, Vygodskaya NN, Byers JN, Hunt JE, McSeveny TM, Milukova I, Sogatchev A, Varlargin A, Ziegler W, Arneth A, Bauer G (1997) Evaporation from an eastern Siberian larch forest. Agric For Meteorol 85:135–147. https://doi.org/10.1016/S0168-1923(96)02424-0

Khatun R, Ohta T, Kotani A, Asanuma J, Gamo M, Han S, Hirano T, Nakai Y, Saigusa N, Takagi K, Wang H, Yoshifuji N (2011) Spatial variations in evapotranspiration over East Asian forest sites. I. Evapotraspiration and decoupling coefficient. Hydrol Res Lett 5:83–87. https://doi.org/10.3178/hrl.5.83

Kononov AV, Maximov TC, Maximov AP, Petrov RE (2012) Annual soil carbon dioxide fluxes in larch forests of central and south-east Yakutia. In: Proceedings 5th international workshop on C/H2O/energy balance and climate over boreal and arctic regions with special emphasis on eastern Eurasia, pp 39–43

Kotani A, Kononov AV, Ohta T, Maximov TC (2014) Temporal variations in the linkage between the net ecosystem exchange of water vapour and CO_2 over boreal forests in eastern Siberia. Ecohydrology 7:209–225. https://doi.org/10.1002/eco.1449

Kozlowski TT (1984) Flooding and plant growth. Academic, Orlando

Kozlowski TT (1997) Responses of woody plants to flooding and salinity. Tree Physiol 17:490. https://doi.org/10.1093/treephys/17.7.490

Kreuzwieser J, Gessler A (2010) Global climate change and tree nutrition: influence of water availability. Tree Physiol 30:1221–1234. https://doi.org/10.1093/treephys/tpq055

Kubota J, Suzuki K, Yamazaki Y, Ohata T, Vuglinsky V (2004) Water and energy budget in the Southern mountainous region of Eastern Siberia. In: Proceedings 6th international study conference on GEWEX in Asia and GAME (GAME CD-ROM Publ. 11), T1JK28Jul04102130

Kuwada T, Kotake T, Takeuchi S, Maximov TC, Yoshikawa K (2002) Relationships among water dynamics, soil moisture and vapor pressure deficit in a Larix gmelinii stand, eastern boreal Siberia. J Japn For Soc 84:246–254. in Japanese with English abstract

Lara MJ, Genet H, Mcguire AD, Euskirchen ES, Zhang Y, Brown DRN, Jorgenson MT, Romanovsky V, Breen A, Bolton WR (2016) Thermokarst rates intensify due to climate change and forest fragmentation in an Alaskan boreal forest lowland. Glob Chang Biol 22:816–829. https://doi.org/10.1111/gcb.13124

Lindroth A, Crill P (2011) Hydrology and biogeochemistry of Boreal forest. In: Forest hydrology and biogeochemistry: synthesis of pas research and future directions, Ecological studies 216. https://doi.org/10.1007/978-94-007-1363-5_14

Lopez CML, Saito H, Kobayashi K, Shirota T, Iwahana G, Maximov TC, Fukuda M (2007a) Interannual environmental-soil thawing rate variation and its control on transpiration from Larix cajanderi, Central Yakutia, Eastern Siberia. J Hydrol 338:251–260. https://doi.org/10.1016/j.jhydrol.2007.02.039

Lopez CML, Brouchkov A, Nakayama H, Takakai F, Fedorov AN, Fukuda M (2007b) Epigenetic salinization and water movement in the active layer of Central Yakutia, Eastern Siberia. Hydrol Process 21:103–109. https://doi.org/10.1002/hyp.6224

Lopez CML, Gerasimov E, Machimura T, Takakai F, Iwahana G, Fedorov AN, Fukuda M (2008) Comparison of carbon and water vapor exchange of forest and grassland in permafrost regions, Central Yakutia. Russia Agric For Meteorol 148:1968–1977. https://doi.org/10.1016/j.agrformet.2008.09.013

Lopez CML, Shirota T, Iwahana G, Koide T, Maximov TC, Fukuda M, Saito H (2010) Effect of increased rainfall on water dynamics of larch (Larix cajanderi) forest in permafrost regions, Russia: an irrigation experiment. J For Res 15:365–373. https://doi.org/10.1007/s10310-010-0196-7

Lopez CML, Takakai F, Iwahana G, Fedorov AN, Iijima Y, Hatano R, Fukuda M (2015) Snowmelt and the hydrological interaction of forest–grassland ecosystems in Central Yakutia, eastern Siberia. Hydrol Process 29:3074–3083. https://doi.org/10.1002/hyp.10424

Matsumoto K, Ohta T, Nakai T, Kuwada T, Daikoku K, Iida S, Yabuki H, Kononov AN, van der Molen MK, Kodama Y, Maximov TC, Dolman AJ, Hattori S (2008a) Energy consumption and evapotranspiration at several boreal and temperate forests in the Far East. Agric For Meteorol 148: 1978–1989. https://doi.org/10.1016/j.agrformet.2008.09.008

Matsumoto K, Ohta T, Nakai T, Kuwada T, Daikoku K, Iida S, Yabuki H, Kononov AN, van der Molen MK, Kodama Y, Maximov TC, Dolman AJ, Hattori S (2008b) Responses of surface conductance to forest environments in the Far East. Agric For Meteorol 148: 1926–1940. https://doi.org/10.1016/j.agrformet.2008.09.009

McNaughton KG, Jarvis PG (1983) Predicting effects of vegetation changes on transpiration and evaporation. In: Kozlowski TT (ed) Water deficits and plant growth, vol 7. Academic, New York, pp 1–47

Miyahara M, Takenaka C, Kuwada T, Ohta T, Maximov TC (2004) How much does cowberry transpiration contribute to evapotranspiration in larch forest? In: Proceedings international semi-open workshop “C/H2O/energy balance and climate over Boreal regions with special emphasis on Eastern Eurasia”, pp 99–102

Miyazaki S, Ishikawa M, Baatarbileg N, Damdinsuren S, Ariuntuya A, Jambaljav Y (2014) Interannual and seasonal variations in energy and carbon exchanges over the larch forests on the permafrost in northeastern Mongolia. Pol Sci 8:166–182. https://doi.org/10.1016/j.polar.2013.12.004

Muskett RR, Romanovsky VE (2009) Groundwater storage changes in arctic permafrost watersheds from GRACE and in situ measurements. Environ Res Lett 4:045009. https://doi.org/10.1088/1748-9326/4/4/045009

Nakai T, Sumida A, Daikoku K, Matsumoto K, van der Molen MK, Kodama Y, Kononov AV, Maximov TC, Dolman AJ, Yabuki H, Hara T, Ohta T (2008) Parameterisation of aerodynamic roughness over boreal, cool- and warm-temperate forests. Agric For Meteorol 148:1916–1925. https://doi.org/10.1016/j.agrformet.2008.03.009

Ohta T, Hiyama T, Tanaka H, Kuwada T, Maximov TC, Ohata T, Fukushima Y (2001) Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia. Hydrol Process 15:1459–1476. https://doi.org/10.1002/hyp.219

Ohta T, Maximov TC, Dolman AJ, Nakai T, van der Molen MK, Kononov AV, Maximov AP, Hiyama T, Iijima Y, Moors EJ, Tanaka H, Toba T, Yabuki H (2008) Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006). Agric For Meteorol 148:1941–1953. https://doi.org/10.1016/j.agrformet.2008.04.012

Ohta T, Kotani A, Iijima Y, Maximov TC, Ito S, Hanamura M, Kononov AV, Maximov AP (2014) Effects of waterlogging on water and carbon dioxide fluxes and environmental variables in a Siberian larch forest, 1998–2011. Agric For Meteorol 188:64–75. https://doi.org/10.1016/j.agrformet.2013.12.012

Pavlov IN (2015) Biotic and abiotic factors as caused of coniferous forests dieback in Siberia and Far East. Contemp Probl Ecol 8:440–456. https://doi.org/10.1134/S1995425515040125

Popova AS, Tokuchi N, Ohte N, Ueda MU, Osaka L, Maximov TC, Sugimoto A (2013) Nitrogen availability in the taiga forest ecosystem of northeastern Siberia. Soil Sci Plant Nutr 59:427–441. https://doi.org/10.1080/00380768.2013.772495

Price AG, Dunham K, Carleton T, Band L (1997) Variability of water fluxes through the black spruce (Picea mariana) canopy and feather moss (Pleurozium schreberi) carpet in the boreal forest of Northern Manitoba. J Hydrol 196:310–323. https://doi.org/10.1016/S0022-1694(96)03233-7

Sato H, Kobayashi H, Iwahana G, Ohta T (2016) Endurance of larch forest ecosystems in eastern Siberia under warming trends. Ecol Evol 6:5690–5704. https://doi.org/10.1002/ece3.2285

Sawada Y (2006) Preliminary results of the micro-topographical change and its effects on the active layer in boreal forest near Yakutsk, Eastern Siberia. In: Hatano R, Guggerberger G (eds) Symptom of environmental change in Siberian Permafrost region. Hokkaido University Press, Sapporo, pp 207–212

Schulz ED, Lloyd J, Kelliher FM, Wirth C, Rebmann C, Lühker B, Mund M, Knohl A, Milyukova IM, Schulze W, Ziegler W, Varlagin AB, Sogachev AF, Valentini R, Dore S, Grigoriev S, Kolle O, Panfyorov MI, Tchebakova N, Vygodskaya NN (1999) Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink –a synthesis. Glob Chang Biol 5:703–722. https://doi.org/10.1046/j.1365-2486.1999.00266.x

Schulze ED, Schulze W, Kelliher FM, Vygodskaya NN, Ziegler W, Kobak KI, Arneth A, Kustesova WA, Sogatchev A, Issajev A, Bauer G, Hollinger DY (1995) Above-ground biomass and nitrogen nutrition in a chronosequence of pristine Dahurian Larix stands in eastern Siberia. Can J For Res 25:943–960. https://doi.org/10.1139/x95-103

Schulze ED, Vygodskaya NN, Tchebakova NM, Czimszik CI, Kozlov DN, Lloyd J, Mollicone D, Parfenova E, Sidorov KN, Varlagin AV, Wirth C (2002) The Eurosiberian transect: an introduction to the experimental region. Tellus 54B:421–428. https://doi.org/10.1034/j.1600-0889.2002.01342.x

Shiklomanov AI, Lammers RB (2009) Record Russian river discharge in 2007 and the limits of analysis. Environ Res Lett 4:045015. https://doi.org/10.1088/1748-9326/4/4/045015

Sugimoto A, Yanagisawa N, Naito D, Fujita N, Maximov TC (2002) Importance of permafrost as a source of water for plants in east Siberian taiga. Ecol Res 17:493–503. https://doi.org/10.1046/j.1440-1703.2002.00506.x

Sugimoto A, Naito D, Yanagisawa N, Ichiyanagi K, Kurita N, Kubota J, Kotake T, Ohata T, Maximov TC, Fedorov AN (2003) Characteristics of soil moisture in permafrost observed in East Siberian taiga with stable isotopes of water. Hydrol Process 17:1073–1092. https://doi.org/10.1002/hyp.1180

Suzuki K, Kubota J, Yabuki H, Ohata T, Vuglinsky V (2007) Moss beneath a leafless larch canopy: influence on water and energy balances in the southern mountainous taiga of eastern Siberia. Hydrol Process 21:1982–1991. https://doi.org/10.1002/hyp.6709

Takenaka C, Miyahara M, Ohta T, Maximov TC (2016a) Effects of two-year variation in soil moisture condition on the development of Larch root system in Eastern Siberia. Am J Clim Chang 5:157–166. https://doi.org/10.4236/ajcc.2016.52015

Takenaka C, Miyahara M, Ohta T, Maximov TC (2016b) Response of larch root development to annual changes of water conditions in eastern Siberia. Pol Sci 10:160–166. https://doi.org/10.1016/j.polar.2016.04.012

Tanaka H, Ohta T, Hiyama T, Maximov TC (2000) Seasonal variation of photosynthesis and transpiration properties of a boreal deciduous forest: analysis using a single layer canopy model. J Japn For Soc 82:259–267. in Japanese with English abstract

Tanaka H, Hiyama T, Kobayashi N, Yabuki H, Ishii Y, Desyatkin RV, Maximov TC, Ohta T (2008) Energy balance and its closure over a young larch forest in eastern Siberia. Agric For Meteorol 148:1954–1967. https://doi.org/10.1016/j.agrformet.2008.05.006

Tchebakova NM, Kolle O, Zolotoukhine D, Arneth A, Styles JM, Vygodskaya NN, Schulze ED, Shibistva O, Lloyd J (2002) Inter-annual and seasonal variations of energy and water vapor fluxes above a Pinus sylvestris forest in the Siberian middle taiga. Tellus B 54:537–551. https://doi.org/10.1034/j.1600-0889.2002.01337.x

Tei S, Sugimoto A, Yonenobu H, Yamazaki T, Maximov TC (2013) Reconstruction of soil moisture for the past 100 years in eastern Siberia by using δ13C of larch tree rings. J Geophys Res G: Biogeosci 118:1256–1265. https://doi.org/10.1002/jgrg.20110

Toba T, Ohta T (2005) An observational study of the factors that influence interception loss in boreal and temperate forests. J Hydrol 313:208–220. https://doi.org/10.1016/j.jhydrol.2005.03.003

Troeva EI, Isaev AP, Cherosov MM, Karpov NS (2010) The far North: plant biodiversity and ecology of Yakutia. Springer, Dordrecht

Ueta A, Sugimoto A, Iijima Y, Yabuki H, Trofim TC (2014) Contribution of transpiration to the atmospheric moisture in eastern Siberia estimated with isotopic composition of water vapour. Ecohydrology 7:197–208. https://doi.org/10.1002/eco.1403

Velicogna I, Tong J, Zhang T, Kimball JS (2012) Increasing subsurface water storage in discontinuous permafrost areas of the Lena River basin, Eurasia, detected from GRACE. Geophys Res Lett 39:L09403. https://doi.org/10.1029/2012GL051623

Vygodskaya NN, Milyukova I, Varlagin A, Tatarinov F, Sogachev A, Kobak KI, Desyatkin R, Bauer G, Hollinger DY, Kelliher FM, Schulze ED (1997) Leaf conductance and CO_2 assimilation of Larix gmelinii growing in an eastern Siberian boreal forest. Tree Physiol 17:607–615. https://doi.org/10.1093/treephys/17.10.607

Wang AF, Roitto M, Lehto T, Zwiazek JJ, Calvo-Polanco M, Repo T (2013) Waterlogging under simulated late-winter conditions had little impact on the physiology and growth of Norway spruce seedlings. Ann For Sci 70:781–790. https://doi.org/10.1007/s13595-013-0325-5

Xue B, Komatsu H, Kumagai T, Kotani A, Otsuki K, Ohta T (2012) Interannual variation of evapotranspiration in an eastern Siberian larch forest. Hydrol Process. https://doi.org/10.1002/hyp.9195

Xue B, Li Z, Yin X, Zhang T, Iida S, Otsuki K, Ohta T, Guo Q (2014) Canopy conductance in a two-storey Siberian boreal larch forest, Russia. Hydrol Process 29:1017–1026. https://doi.org/10.1002/hyp.10213

Yabuki H, Ishii Y, Ohata T (2004) Comparison of water and heat balance on grassland and forest in Central Yakutia, East Siberia. In: Proceedings 6th international study Conference on GEWEX in Asia and GAME (GAME CD-ROM Publ. 11), T1HY30Jul04115511

Yoshida M, Ohta T, Kotani A, Maximov TC (2010) Environmental factors controlling forest evapotranspiration and surface conductance on a multi-temporal scale in growing seasons of a Siberian larch forest. J Hydrol 395:180–189. https://doi.org/10.1016/j.jhydrol.2010.10.023

Yoshida R, Sawada M, Yamazaki T (2012) Roles of Eastern Siberian mountain ranges in precipitation – Verkhoyansk, Dzhugdzhur and Stanovoy mountain ranges. SOLA 7:145–148. https://doi.org/10.2151/sola.2011–037

Yoshida R, Sawada M, Yamazaki T, Ohta T, Hiyama T (2013) Influence of land cover change on regional water cycles in eastern Siberia. J Appl Meteorol Climatol 52:484–497. https://doi.org/10.1175/JAMC-D-12-043.1

Zhang N, Yasunari T, Ohta T (2011) Dynamics of the larch taiga-permafrost coupled system in Siberia under climate change. Environ Res Lett 6:024003. https://doi.org/10.1088/1748-9326/6/2/024003

Zhang X, He J, Zhang J, Polyakov I, Gerdes R, Inoue J, Wu P (2012) Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. Nat Clim Chang 3:47–51. https://doi.org/10.1038/NCLIMATE1631