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# Solar radiation transmittance of a boreal balsam fir canopy: Spatiotemporal variability and impacts on growing season hydrology

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ABSTRACT

Forest canopies act as permeable barriers between the atmosphere and the ground, reflecting and absorbing solar radiation. In the boreal forest, the large number of gaps and heterogeneities further complicates these processes. Several studies have adequately measured and modeled the transmittance of solar radiation through forest canopies in western North America and Scandinavia, but few have addressed those of Eastern North America. Furthermore, most of these studies have assessed the effects of solar radiation transmittance on snowpack energetics, but few have focused on the hydrological impacts during the growing season. This paper addresses this knowledge gap with precise measurements of sub-canopy solar radiation in a juvenile balsam fir forest located in the Montmorency Forest, Quebec, Canada. Twenty (20) sub-canopy stations were deployed in a 200 m by 150 m gridded box around a flux tower measuring above canopy radiation and eddy covariance fluxes during late summer and early fall 2016. Results show that the heterogeneous forest has substantial spatial variability of transmittance, with site-specific seasonal averages ranging between 0.07 and 0.69. Canopy gaps of size relative to tree height ($H$) between $0.1H$ and $H$ had a temporal influence on solar radiation transmittance in canopy gaps at the sub-daily scale, but do not influence seasonal trends. This is attributed to very frequent cloudiness at the site, which renders the solar radiation mostly diffuse. As a result, a Beer-Lambert extinction law proved adequate at modeling site-specific or spatially averaged transmittance on a seasonal basis. We complement the observations by modeling canopy and soil moisture balances at 20 sites using the Canadian Land Surface Scheme (CLASS). The modeling results exhibit the following trend: a thicker (thinner) vegetation leads to more (less) evapotranspiration, because there is more (less) evaporation of intercepted precipitation and more (less) transpiration, but less (more) ground evaporation. During drier periods, the latter leads to wetter soil conditions for the thicker vegetation. These modeling results of sensitivity to vegetation density, while informative, still need to be confirmed with observations.

## 1. Introduction

Forest canopies have intricate relationships with incoming solar radiation $K$ and precipitation $P$, acting as a permeable barrier between the atmosphere and the ground. Canopies reflect a proportion of the solar radiation back to the atmosphere, while the rest is either absorbed or transmitted to the ground. The absorbed radiative energy flux activates photosynthesis (Sellers, 1985; Berbigier and Bonnefond, 1995), transpiration (Sellers, 1985; Berbigier and Bonnefond, 1995; Pieruschka et al., 2010) and changes in canopy temperatures that in turn create substantial turbulent transport (Bourque and Arp, 1994; Kellomäki and Wang, 1999) and longwave radiation emissions (Sicart et al., 2004; Pomeroy et al., 2009), along with other processes. Canopies also intercept a fraction of the precipitation before it may reach the ground (Hedstrom and Pomeroy, 1998; Huber and Iroumé, 2001; Storck et al., 2002), part of which is returned to the atmosphere by evaporation (Lundberg et al., 1997; Lundberg and Halldin, 2001; Lundberg and Koivusalo, 2003; Pypker et al., 2005; Toba and Ohta,

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2005) or sublimation (Pomeroy et al., 1998; Parviainen et al., 2000; Essery et al., 2003; Gelfan et al., 2004; Montesi et al., 2004). These water fluxes are also linked to the absorbed solar radiation and resulting canopy temperatures (Asdak et al., 1998; Klaassen et al., 1998; Toba and Ohta, 2005; Molotch et al., 2007). The transmitted fraction of solar radiation plays a crucial role in near-ground plant regeneration processes (Aubin et al., 2000; Montgomery and Chazdon, 2002; Ricard et al., 2003; Balandier et al., 2006), soil temperature dynamics (Breshears et al., 1998; Ritter et al., 2005), and snow energetic (Hardy et al., 2004; Talbot et al., 2006; Tribbeck et al., 2006; Ellis and Pomeroy, 2007; Musselman et al., 2012a,b; Gouttevin et al., 2015).

In the conifer forests of the circumpolar boreal biome, these barrier effects are magnified by the constant influence of a dominant evergreen vegetation. Compared to deciduous species, albedo is lower all year long (Wang, 2005), implying that much of the available energy is absorbed. The needleleaf canopy interception of solar radiation (Reid et al., 2014) and precipitation (Storck et al., 2002) is also higher than that of deciduous species in winter. The boreal forest is characterized by numerous gaps (Kneeshaw and Bergeron, 1998) and large-scale heterogeneities, including those created by anthropogenic disturbances (Gauthier et al., 2015). These gaps directly affect large-scale precipitation interception (Koivusalo and Kokkonen, 2002) and solar radiation (Hardy et al., 2004; Lawler and Link, 2011; Musselman et al., 2015), net radiation (Seyednasrollah et al., 2013), and turbulent exchanges (Wharton et al., 2017) with impacts on the land surface energy and water balance. As this biome contains 30% of the world's forests (Brandt et al., 2013) and sequesters 20% of the global forest carbon (Pan et al., 2011), a proper assessment of the partitioning of non-reflected solar radiation is crucial to the modelling of the thermal energy balance of the land surface.

This study focuses on canopy transmittance of solar radiation, defined as:

$$\tau = \frac{K_u}{K_a} \tag{1}$$

where $K_u$ [W m$^{-2}$] is the under-canopy solar radiation and $K_a$ [W m$^{-2}$] is the above-canopy solar radiation. In the literature, $\tau$ has been identified as a necessary parameter of models focusing on larger-scale processes such as land surface schemes (*e.g.* Verseghy et al. (1993)) or hydrological models (*e.g.* Wigmosta et al. (1994), Gouttevin et al. (2015)). Even if some more detailed estimation methods of $\tau$ are available (*e.g.* Zhao and Qualls (2005), Mottus and Sulev (2006)), their computational needs render them impractical, leading to the common use of simpler options. Indeed, the most familiar formulation used to estimate $\tau$ is an adapted version of Beer-Lambert law for homogeneous medium (Monsi and Saeki, 1953), as follows:

$$\tau = \exp(-\kappa \mathrm{LAI}) \tag{2}$$

where $\kappa$ [–] is an extinction coefficient usually dependent on solar elevation and leaf angle distribution and LAI [m$^2$ m$^{-2}$] is the leaf area index of the canopy. The general definition of LAI is “the total one-sided area of leaf tissue per unit ground surface area” (Watson, 1947; Breda, 2003). This definition only includes the leaf portion of the canopy, excluding branches, trunks and other obstacles blocking radiation. For this reason, most studies and models use plant area index (PAI) in Eq. (2) to characterize the canopy-solar radiation interaction (Hardy et al., 2004; Musselman et al., 2012a; Reid et al., 2014).

The simplicity of the Beer-Lambert model makes it popular, but researchers must exercise caution at smaller spatiotemporal scales. $\tau$ is known to vary as a function of solar elevation, cloud cover, and canopy architecture (Hardy et al., 2004; Musselman et al., 2012b). Considering that the latter is largely discontinuous in boreal forests, most studies note that the Beer-Lambert formulation falls outside its range of applicability at the sub-daily timescale (Reifsnyder et al., 1971; Li et al., 1995; Ni et al., 1997; Nijssen and Lettenmaier, 1999; Yang et al., 2001). Some more recent models attempt to account for the precise spatiotemporal variation of the canopy elements interfering with solar radiation, with great success (Musselman et al., 2012a, 2013; Reid et al., 2014). Their methods still need to be evaluated in a diversity of environments.

Of the aforementioned studies on solar radiation transmittance, few compare modeling results with direct and precise observations under boreal or montane conifer canopies (Ni et al., 1997; Hardy et al., 2004; Ellis and Pomeroy, 2007; Musselman et al., 2012a,b, 2015; Reid et al., 2014). They are located in various environments of western North America and Scandinavia, but not in eastern North American forests, which host a different type of vegetation. Additionally, all of them focused on the influence of $\tau$ on snowpack energy accumulation and melt, a topic of tremendous relevance for the hydrology of boreal regions. Even if snowmelt is often the largest source of recharge of aquifers and surface water in the circumpolar boreal biome, the snow-free period still drives the global carbon and water cycles. Nevertheless, to our knowledge there have not been any studies aimed at quantifying the influence of $\tau$ on snow-free hydrology; that is during the growing season up to early fall when photosynthesis starts to decline.

This study characterizes the transmittance of solar radiation through a sparse juvenile balsam fir canopy typical of the southern boreal regions of eastern Canada. We are specifically interested in: (i) quantifying the spatiotemporal variability of solar radiation transmittance, and (ii) assessing the impacts of that variability on the growing season hydrology of the forest. The results are based on a three-month field campaign measuring solar radiation transmittance at 20 locations, complemented by land surface modeling.

## 2. Materials

This study was conducted in the Montmorency Forest (47°17′18″N; 71°10′05.4″W), located 80 km north of Quebec City, Canada, in the Laurentian Mountains. The field site lies within a 1.2-km$^2$ experimental watershed, part of the “Bassin Expérimental du Ruisseau des Eaux-Volées” (BEREV) (Lavigne, 2007; Tremblay et al., 2008, 2009; Noël et al., 2014). The BEREV has a mean altitude of 750 m above mean sea level (AMSL) with hills reaching 1000 m AMSL. The vicinity of the experimental setup is on a 12° slope facing northeast. The vegetation of the watershed is mostly composed of balsam fir (*Abies balsamea* (L.) Mill) mixed with white birch (*Betula papyrifera* Marsh) and white spruce (*Picea glauca* (Moench) Voss) (Lavigne, 2007; Tremblay et al., 2008, 2009). These trees reach heights between 4-8 m around the experimental setup and are classified as “juvenile”, a result of natural regeneration following the logging of 85% of the trees in 1993. The region is dominated by a continental climate with a short and cool growing season and significant precipitation all year round. A mean annual temperature of 0.5 °C and a mean annual precipitation of 1583 mm (40% as snow) was observed over the period of 1981–2010 by Environment and Climate Change Canada (Station “Foret Montmorency”, available at: http://climat.meteo.gc.ca/historical_data/search_historic_data_f.html).

### 2.1. Irradiance and complementary measurements

A 15-m flux tower has been in operation since the autumn of 2015 to measure surface energy budget components and other relevant meteorological variables in the watershed (see Fig. 1). Above-canopy shortwave (solar) and longwave, downward and upward radiation components are measured with two net radiometers (CNR4, Kipp and Zonen, The Netherlands) installed at 15 and 10 m above the surface. Above-canopy radiation was also measured at a complementary flux tower located 1.28 km to the southeast. These devices are equipped with a ventilating and heating unit (CNF4, Kipp and Zonen, The Netherlands) to minimize measurement errors following dew deposition.

Since no measurements of the diffuse fraction of solar radiation $f_d$