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Snow surface energy and mass balance in a warm temperate climate mountain

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SUMMARY

In warm temperate mountain regions where water is often scarce vapor losses from the snow-surface can substantially limit snowmelt. Therefore, understanding the key snow dynamic processes that affect water availability in these mountains is essential. We studied the snowpack energy and mass balance in Mt. Hermon, Israel using a comprehensive field campaign during 2010/11. We analyzed the snowpack energy and mass balance during the winter of 2010/11 in a Deep Snow Patch (DSP), and in the Bulan valley experiment area (BVEA), where both windswept locations and lee-side (deep snowpack) locations were examined. We applied for this analysis an energy and mass balance snow model that was forced by input from two meteorological stations. The calibration of the model for the DSP and BVEA was based on surveyed snow water equivalent data, and melting cycles that were measured with time-lapse cameras, respectively. Using a step function to describe wind speed over the DSP we showed that the turbulent fluxes were influenced by changes in snowpack height. The turbulent fluxes were found as the dominant energy fluxes at the snow-surface. During winter, vapor losses varied between 46% and 82% of the total ablation. Consequently, latent heat flux consumed much of the available energy at the snow-surface, greatly limiting melting rate to 1 mm day^{-1}. During spring, vapor flux was positive which enhanced condensation, resulting in an average melting flux of 86 mm day^{-1}. The spatial variation in the vapor flux at the BVEA due to terrain orientation yield variation in space of the available water at the bottom of the snowpack.

1. Introduction

Most of our knowledge about the energy and mass balance of snow-surface comes from cold areas. However in mountain ranges located in the warmer areas like the warm temperate climate (Kottek et al., 2006) snow can be a significant component in the hydrology cycle (Aouad-Rizk et al., 2005; Herrero et al., 2009; Schulz and de Jong, 2004). Examples of such mountains can be found in the Sierra Nevada, Spain (Herrero et al., 2009); the Atlas mountain, Morocco (Schulz and de Jong, 2004); the Salt and Verde Basins, Arizona (Hawkins and Ellis, 2007); the White Mountains (Crete), Greece (Kourgialas et al., 2008); and the Olympus and Pieria Mountains, Greece (Karpouzos et al., 2011), Mt. Lebanon (Aouad-Rizk et al., 2005) and Mt. Hermon, which is divided between Israel, Lebanon and Syria (Samuels et al., 2010).

Although snow can be found in many warm temperate regions only few studies investigate the energy of mass balance in this environment. These studies suggest that in warmer climate regions the turbulent fluxes (i.e. the latent and sensible heat fluxes) are the dominant components of the snowpack's energy and mass budget (Hawkins and Ellis, 2007; Herrero et al., 2009; Schulz and de Jong, 2004). During the winter a relatively large portion of the energy is consumed by latent heat fluxes at the snow–atmosphere interface (Herrero et al., 2009). This implies that, snow ablation is dominated by evaporation and sublimation processes and snow melt processes are greatly inhibited. Herrero et al. (2009) estimated vapor losses from the snow surface to be over 40% of total ablation in the Sierra Nevada, Spain. Schulz and de Jong (2004) reported similar results for the high elevations (>3000 m) of the Atlas Mountains, Morocco. However, they showed that in the lower elevations the melt processes had a larger role in the ablation of the snow pack. These examples indicate that the snow surface

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turbulent energy fluxes are central for understanding snow ablation dynamic in warmer climate regions.

In cold climate regions, the turbulent fluxes are affected by changes in the snow cover extent. As snow cover becomes patchy local advection often supplies additional heat at the snow surface (Liston, 1995; Marsh and Pomeroy, 1996; Mott et al., 2011). However, when a stable boundary layer develops over the patchy snowpack the sensible heat flux is inhibited (Mott et al., 2013). The development of the patchy snow cover found in mountainous terrain is in locations where wind interacts with the local topography (Mott et al., 2011; Pohl and Marsh, 2006). Decrease in wind speed at local topographic depression enhances accumulation but reduces turbulent fluxes, therefore location of deep snowpacks have lower melting rates (Mott et al., 2011). In cold environment, changes in the turbulent fluxes because of terrain modification of the wind field were found significant even in relatively gently sloped topography (Pohl and Marsh, 2006).

Fujita et al. (2010) showed that in Hamaguriyuki, northern Japan Alps (cold environment), the turbulent fluxes in a snow patch were controlled by 'self-regulating' mechanism. In deep snowpack conditions (i.e. high snow-surface elevation), the snow surface is exposed to a relatively strong wind that strengthen the turbulent fluxes; while in shallower snow conditions (i.e. low snow surface elevation) because of sheltering by the surrounding terrain the snow surface experience lower wind and weaker turbulent fluxes.

In this study we extend the work of Fujita et al. (2010) to a warm temperate climate mountain. We hypothesized that the 'self-regulating' mechanism plays an important role in the snow ablation of a large snow patch in Mt. Hermon. The snow pack at the high elevation (>1900 m) of this warm temperate mountain, consists of seasonal snow patches that at their peak often exceed 10 m deep and their seasonal evolution greatly alter the local relief (Shmida, 1977; Shmida and Sinai, 1980). Specifically, the objectives of this study are: (1) assessing the changes of the turbulent fluxes in the energy and mass balance of a large snow patch due to changes in its structure with time; and (2) identifying the key processes of snow dynamic that control water availability in warm temperate mountains.

2. Study site

Mt. Hermon is a high Mediterranean mountain which is partly covered with snow during winter and spring time. The mountain is located at 35°50′E, 33°25′N (Fig. 1) with a total area of 1250 km^2 and its summit (located in Syria) is at elevation of 2814 m (Gilad and Bonne, 1990). It is a narrow isolated anticline which consists mainly of thick (>2000 m) Jurassic limestone, with developed karstic formations divided by faults and semi-impermeable layers (Gilad, 1980).

During the winter, average air surface temperature at the upper meteorological station (2100 m; Fig. 1c) ranges from -0.8 to -1.6 °C, and February is usually the coldest month. Prevailing wind speed during winter storms is between 19 and 25 m s^{-1}, and can reach up to 39 m s^{-1}. Precipitation at the lower meteorological station (1640 m; Fig. 1c) is estimated as >1300 mm $year^{-1}$ where most occur from November to April. Relative Humidity (RH) during the winter is commonly about 60–70%. Spring and autumn months exhibit episodes of southern weather system dominated by warm dry wind during which RH occasionally drops below 10% (Kessler, 1980).

The Spatial distribution of Snow Water Equivalent (SWE) in the high elevation (>1900 m) on Mt. Hermon was described in details by Shmida (1977) and Shmida and Sinai (1980). It is characterized by long narrow strips of deep snow patches (usually over 10 m deep) next to areas with shallow snowpack. The deep snow patches are located in sheltered areas mostly on the eastern slopes. They are progressively built with each new snow fall event and reach their maximum size by the end of winter. These seasonal deep snow patches may last until the end of July. The areas with shallow snow accumulation are located on the windswept side, mostly on western slopes, where snow accumulates only up to the height of the rock and vegetation cover. Snow on the windswept areas ablates very fast even during the winter (Shmida, 1977; Shmida and Sinai, 1980).

The main research site is located in a small closed basin (karst doline) at elevation of 2065 m, where a seasonal deep snow patch develops (herein it will be referred to as DSP; Fig. 1c). The DSP is located above the southern slopes of a karstic depression known as the Bulan valley experimental area (BVEA; Fig. 1c) where four other nearby locations (i.e. Fig. 2 points 'a'–'d') were also used to asses snow dynamics in different topographic properties.

3. Methods

3.1. Field measurements

An extensive snow survey campaigns were conducted from December 2010 till June 2011. The field measurements included data from two meteorological stations, snow surveys at the DSP, monitoring of the snow spatial extent at the BVEA and a continuous monitoring of melt flux under the DSP using lysimeters. Table 1 provides a summary of the instruments used for the field campaign and includes locations, recording time resolution, sensors' range and accuracy, and sensors' manufacturer and model.

The upper meteorological station (Fig. 1c; 33°18.499N, 35°47.135E) located 500 m northwest of the DSP at elevation of 2082 m and it is operational since November 2006. The lower station (Fig. 1c; 35°76.960E and 33°31.181N) is located at elevation of 1640 m and is operational since January 2009. Both stations are equipped with sensors for wind speed, precipitation, air temperature, air RH and atmospheric pressure. The upper station measures solar radiation while the lower station measures incoming long-wave radiation (Table 1). In winter 2010/11, a heated rain gauge (tipping bucket 15,188, Lambrecht, Goettingen, Germany) was added to the lower station. The stations have been operated and maintained by the Yigal Allon Kinneret Limnological Laboratory. It was not possible to avoid use data from both station because of technical difficulties that are associated with meteorological measurements in cold windy environments. For example in the case of precipitation it is clear that the upper station values were incorrect. The wind at this height and location is often so strong that it is almost impossible to measure precipitation. The precipitation data that we could collect at this station were correct in timing, but the amount was $\sim$50% from the true value. The other difficulties are described in more detailed in Sade (2014).

Snow surveys to characterize the DSP properties included mapping of the DSP surface with differential Global Positioning System (dGPS) and measuring snow density and temperature profiles. The dGPS measurements were conducted with a rapid static method (Ashtech, 1998). In this method, one receiver (Base) is left stationary at a known point, were the other (Rover) is moved around. The simultaneously recorded data at the Base and the Rover receivers were post processed using Trimble Total Control 2.7 (Trimble Navigation Ltd., Ohio USA), to compute accurate surveyed position. We measured the DSP at intervals of about 2 m on the relatively flat areas and gentle slopes. At the vicinity of the ridge-cornice (the sharp terrain breaks), we used 0.2 m intervals. The accuracy of the measurements after the post processing was at least 5 cm