MEASUREMENT AND SIMULATION OF THE ENERGY AND MASS BALANCE OF SNOW AT AN ALPINE VALLEY SITE

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Abstract:
This investigation is based on data collected during a comprehensive field campaign focussing on air pollution and noise aspects in the lower Inntal valley (Austria) during winter 2005/2006. In this context, the evolution of snow plays an important role too, e.g. with respect to the strength and persistence of inversions. This is of particular interest in view of the exceptional situation during winter 2005/2006, which was characterized by an almost unbroken snow cover all over the country.
A one-dimensional mass and energy balance model is successfully used to simulate the seasonal evolution of the snow pack and its interaction with the atmosphere and the underlying soil. Profiles of snow temperature and density, grain size, or liquid water content are predicted by numerically solving for the governing equations of the relevant processes. The model is driven by the basic meteorological parameters and validation of the simulation results is based on comparison with a set of independent measurement data.
The energy balance during the accumulation period was characterized by a net loss due to radiation and the prevalence of evaporation, which was offset by the positive contributions from turbulent sensible and conductive soil heat fluxes. During the melt period, the snow pack experienced enhanced energy input, which was mainly associated to the now positive radiation budget and the soil heat flux directed towards the surface. The initial ablation rates were significantly enhanced as soon as melt water and solar radiation approached the snow-soil interface.

Keywords: Alpine snow, energy and mass balance, snow modelling, SNTHERM, turbulent fluxes, air pollution

1. INTRODUCTION

The winter 2005/2006 was characterized by exceptionally low temperatures and a permanent snow cover which in the area of Schwaz built up to a depth of about 50 cm. A nearby climate station (Jenbach) recorded that mean winter temperature (DJF) was -2.8°C below the decadal average (1993-2002), while precipitation was 18 % above the long-term average. On the other hand, there was a number of long lasting high-pressure periods inducing weak winds, strong temperature inversions and correspondingly enhanced levels of air pollution.

2. MEASUREMENT DATA

We consider data that were collected by an automatic weather station during November 2005 to March 2006. The measurement site was located near the city of Schwaz on the bottom of the Inn valley (540 m asl.). Instrumentation was set up as an energy balance station measuring temperature, dew point temperature and wind speed at 2, 5 and 10m above ground as well as wind direction, air pressure, short- and long wave radiation components and soil temperatures at 1, 16 and 32cm below the grass ground surface. Moreover, the sensible heat flux was directly measured by an ultrasonic instrument mounted at a level of 5m above ground. Occasionally, snow surface temperature as well as depth and density of the snow pack were determined by hand measurements, too. The performance of all sensors was checked by laboratory and field intercomparison measurements before and after the field season. These efforts and post processing quality checks yielded a well documented and high quality data set. Major uncertainties concern the wind and radiation measurements suffering from episodic snow and rime accumulation. Such problems were identified by cross-correlation with data from other sites in the area, which provided a means to complement a five days gap due to failure in power supply, too.

3. MODEL SET UP

A one-dimensional mass and energy balance model (SNTHERM, Jordan 1991) is used to simulate the seasonal evolution of the snow pack and its interaction with the atmosphere and the underlying soil. The model is adaptable to a wide range of meteorological conditions including multiple freeze and thaw cycles.

Profiles of the basic snow physical parameters like temperature and density, grain size, or liquid water content are calculated by numerically solving for the governing equations of the processes determining heat, mass and momentum exchange.

The simulation is driven by half hourly values of the basic meteorological parameters including air temperature, relative humidity, wind speed, short wave incoming and reflected radiation as well as atmospheric long wave radiation and precipitation. Precipitation input is derived from measurements at a nearby climate station and local snow pit investigations. The model domain considers 10m of soil upon which the development of the seasonal snow cover is simulated. The input soil properties are derived from analysis of probes taken at 15cm below the surface. To further initialize the simulations, measured vertical profiles of snow (soil) temperature, density and grain size are prescribed. The specific set up also considers a temperature and wind dependent parameterization for fresh snow density (Jordan, 1991) and the turbulent heat fluxes are treated according to Andreas (1987) and Högstrom (1988), respectively. Validation and fine tuning of the simulation results is based on comparison with independent measurement data, as far as available.

4. VALIDATION OF RESULTS

Records of snow height and density, surface temperature and ground temperatures at three depths below the surface as well as directly measured turbulent heat fluxes are considered in this context. The latter are derived from eddy correlation measurements at 5m above ground and will be discussed later. Fig. 1a demonstrates that the model is well able to simulate the observed evolution of snow depth throughout the winter. Snow pit measurements reveal an excellent agreement in terms of snow density and water equivalent (e.g. 03 Jan 2006: 0.078m measured vs. 0.067m simulated). This indirectly proves a correct treatment of the processes related to snow metamorphism (new snow density, compaction, melt). The snow cover disappeared on 15 March 2006, which is well reproduced by the model, too. Moreover, the temperatures at the snow surface and at the snow-ground interface are particularly interesting parameters, which are sensitive indicators of a proper treatment of the thermal processes within snow and ground. Fig. 1a and Fig.1b prove a reasonable skill with this respect, too.

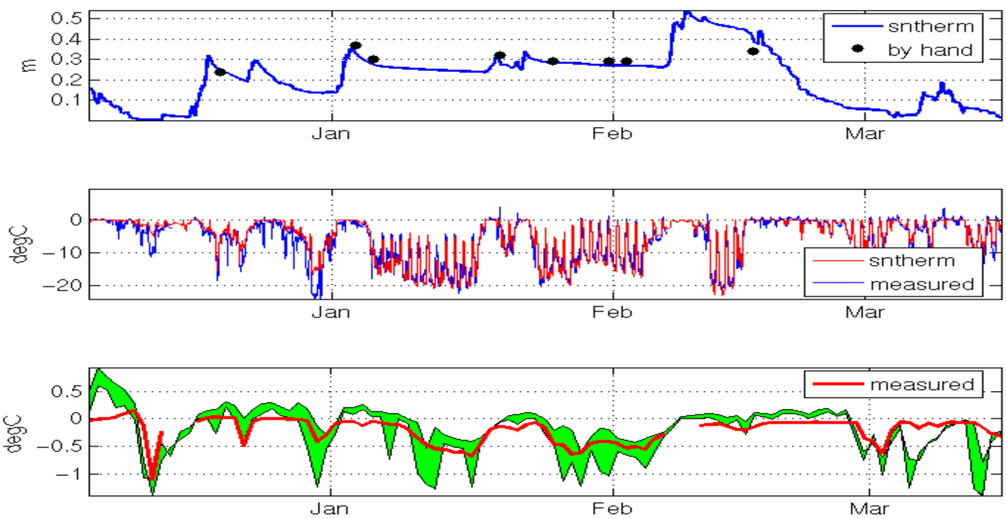

Figure 1: Comparison of measured and simulated snow depth (a), snow surface temperature (b) and temperature at the snow-ground interface (c). In response to the inherent uncertainties (exact positioning) the simulated ground temperature is indicated by two curves (brown) corresponding to ±5cm below /above the nominal depth of the soil thermometer (red).

5. RESULTS ON THE MASS AND ENERGY BALANCE

The development of the snow pack during the winter may be divided into an accumulation and ablation period (lasting from 04 Dec 2005-16 Feb 2006 and 17 Feb 2006-15 Mar 2006), respectively. In comparison to the accumulation period, the ablation period was characterized by significantly higher air temperatures, lower humidity and higher wind speeds (Tab.1). The model results indicate that these characteristics result in correspondingly enhanced sensible heat fluxes (providing energy to the surface), which are mostly balanced by the also stronger heat losses due to evaporation (withdrawing energy from the surface) on the other hand. Thus there is no significant difference in the net turbulent fluxes (sensible plus latent) during the accumulation and ablation period. On average however, the snow pack experiences a net gain of energy to due to sensible and latent heat fluxes (+0.8Wm^{-2}), calculated by the model using input data measured at 2m above ground. However, there is a striking signal concerning net radiation, which is negative during the accumulation period (-6.9Wm^{-2}) and positive during the ablation period (+11.0Wm^{-2}). The latter constitutes an important source of energy that is available for melt of the snow pack during spring. Interestingly, the model results indicate a strong energy input at the lower boundary of the snow pack, too. This is due to heat conduction from the underlying soil, which is induced by correspondingly shaped temperature profiles. The available measurements reveal that the average soil temperature was +0.7C at a depth of 32 cm as compared to a temperature of -0.2 °C at the snow-ground interface (Fig. 1). There is a slightly smaller contribution during the ablation period, which is due to the seasonal course of the annual heat wave within the ground.

Table 1: The basic meteorological parameters and modelled energy balance components during the whole measurement period (05 Dec 2005–15Mar 2006, 4849 half hourly values). A positive sign of the fluxes denotes a gain of energy to the snow pack.

	WHOLE PRIOD	ACCUMULATION PERIOD	ABLATION PERIOD
MEASURED			
air temperature [°C]	-3.5	-4.5	-0.6
rel. humidity [%]	85	87	78
wind speed [ms^{-1}]	1.8	1.5	2.6
albedo	0.76	0.78	0.69
SIMULATED			
net radiation [Wm^{-2}]	-2.1	-6.9	11.0
sensible heat flux 0-2m [Wm^{-2}]	5.3	3.8	9.4
latent heat flux 0-2m [Wm^{-2}]	-4.5	-2.8	-9.4
soil heat flux [Wm^{-2}]	13.0	13.3	12.3
residual [Wm^{-2}]	11.7	7.4	23.3

The snow cover built up to a maximum height of 0.54m with an average density of 258kgm^{-3}, yielding a water equivalent of 0.13m we. The simulations nicely demonstrate the isolating effect of snow on the underlying ground (Fig. 2a). Several warm spells induced enhanced settling of the snow pack or episodic melt events inducing higher liquid water contents down to about 0.4m below the ground surface (Fig. 1b). The ablation period was characterized by an isothermal snow pack with average melt rates of 3.5cmd^{-1}.

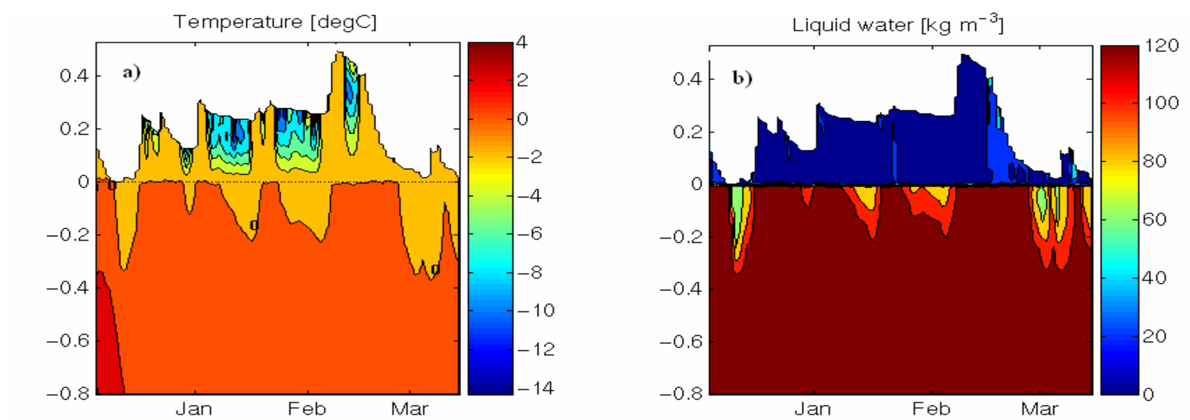

Figure 2: Time-depth evolution of snow and ground temperature (a) and liquid water content (b). Depth is given in meters, zero denoting the snow-soil interface, respectively.

A comparison of measured and modelled energy balance components allows judging some inherent uncertainties (Tab. 2). Thus, the model overestimates net radiation by about 5Wm^{-2}. Primarily, this is related to simulated long-wave emitted radiation (surface temperature), because the other components are measured and serve as input into the model. Fig. 1b indicates that the inherent problem is most pronounced at the beginning and end of the simulation period when there was a shallow snow cover. In this context however, some inherent measurement problems (rime, window heating effects) must be taken into account as well.

Table 2: Comparison of measured and simulated values of net radiation and turbulent heat fluxes. Averaging is based on the availability of surface temperature measurements (4583 cases) and direct turbulence measurements (2226 cases), respectively. Units are in Wm^{-2}.

	simulated	**measured** (instrument)
Net radiation	**-2.5**	**-7.6** (Kipp&Zonen, all components separately)
Sensible heat flux 0-2 m	**2.9**	**2.7** (USA-1 at 5m)
Sensible heat flux 0-5 m	**2.0**	**2.7** (USA-1 at 5m)
Sensible heat flux 0-10 m	**1.9**	**2.7** (USA-1 at 5m)

The turbulent heat flux was directly measured using a turbulence instrument (USA-1, METEK), which is interesting to compare with the simulated values. We do not know in what extent these measurements may be considered as a solid reference, which is frequently done on the other hand. For instance, rime effects might have degraded the quality of these data. On the other hand, the simulation of the turbulent heat flux is based on a bulk transfer parameterisation considering air temperature and wind speed measured at 2m above ground and simulated surface values of these parameters (Jordan, 1991). Moreover, the approach is based on the Monin-Obukhov frame work, whose validity is questionable with very stable atmospheric conditions and specific roughness effects occuring above snow and ice surfaces (Obleitner, 2000). In this context, however, state of the art modifications addressing snow specific issues related to roughness lengths, stability functions and intermittent turbulence have been considered in the simulation (Andreas, 1987; Högstrom, 1988).

The turbulence measurements were available during the accumulation period only. Selecting on these cases, Tab. 2 indicates a good coincidence between simulated and measured values (2.9 vs.2.7 Wm^{-2}). This is remarkable in view of the above mentioned issues and an inherent methodical problem, which may be argued in the context of potential flux divergences or intermittent turbulence phenomena. Under such conditions a straightforward comparison of very local measurements at a level of 5m above ground with simulations based on mean gradients within the near surface 2 meters may not be feasible. We touch this issue by model sensitivity studies using additional profile data measured at 5 and 10m above ground. Tab. 2 reveals that the average values are fairly stable with this respect indicating that flux divergences play a minor role only. Moreover, this gives some confidence in the overall performance of the turbulent flux calculations. On the other hand, inspection of the results in higher resolution (e.g. half hourly values) indicates some problems related to unstable stratification, which is pending for further investigation.

6. CONCLUSIONS

Proper input and verification data provided, snow modelling proves to be a valuable tool for the evaluation of the mass and energy balance of snow and the underlying ground. Moreover, enhanced insight into the associated processes can be achieved. Model sensitivity studies demonstrated further capabilities to investigate specific micrometeorological issues related to the calculation of sensible heat fluxes under stable atmospheric conditions. Moreover, the results provide a basis for in depth investigation on internal snow processes and their impact on the formation of temperature inversions and associated air pollution issues, respectively.

Acknowledgements: *This work is based on data that have been collected within the ALPNAP project, which is funded by the EU-"Interreg III B Alpine Space" program, the Tyrolean Government and Innsbruck University.*

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