*International Conference "Water, Environment, Energy and Society" (WEES–2009)*
*New Delhi, 12–16 January 2009*

# Estimation of SWE and Surface Energy Balance for a Snow Cover in Pir-Panjal Range of N-W Himalaya

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**ABSTRACT:** Melting of seasonal snowpack in mountainous ranges of Indian Himalaya contributes significantly to the rivers flowing in the mountain valley. The melting of snow starts in late winter, i.e., from April onwards and produces substantial amount of melt water till the complete ablation of the snowpack.

An accurate estimation of Snow Water Equivalent (SWE) from a catchment/basin area of a river can be of great help for the planning of agriculture irrigation, hydroelectric power generation, flood control and water supply to various urban areas. Observation of snow cover evolution and total amount of seasonal snow available in the catchment area of a river is a challenging task particularly for the remote, inaccessible and ungauged basin areas. Snow and Avalanche Study Establishment (SASE) has developed a Snow Cover Simulation Model (SCSM) for the study of evolution of a snowpack. The SCSM comprises of various sub-modules and simulates snowpack properties in terms of measurable snow and meteorological parameters. The model can be used to estimate the snowpack depth, internal temperature profile, density profile and thickness of individual layers as the snowcover evolves through the season.

This paper presents the estimation of Snow Water Equivalent (SWE) and results of surface energy balance studies carried out at Dhundi observatory which lies in the Pir Panjal range of Indian Himalaya. The observatory can be considered a representative observatory of upper Beas catchment area. Snow and meteorological data, recorded at this location for winter year 2005–2006 were used as an input to simulate the snowpack properties by SCSM. Energy balance module of SCSM was used to calculate net energy at the snow surface.

## INTRODUCTION

Seasonal snow melt contributes substantially to rivers of north India every year during the ablation period which generally occurs from April to June. Indian Himalaya particularly the Pir Panjal range receives most of the precipitation in the form of snow in pre and mid winter and sometimes rain in the late winter due to the western disturbances between November and April each year. The seasonal snowpack grows in layered structure with each layer having distinct physical and mechanical characteristics. The snowpack gets stratified because of successive snow events throughout the winter season and each snow event is associated with unique set of meteorological parameters at the time of its occurrence. Snow pack continuously interacts with environment and exchanges energy with atmosphere above it and ground below. The energy exchange processes set up the temperature distribution within the snow pack which is responsible for metamorphic changes with time and over all evolution of snow cover on the ground. The net energy available at snow surface and the thermal state of snow pack controls the amount of snow melt discharge at the ground.

An accurate estimation of snow water equivalent from a catchment/basin area of a river can be of great help for the planning of agriculture irrigation, hydroelectric power generation, flood control and water supply to various urban areas. Estimation of total amount of seasonal snow available in the catchment area of a river is a challenging task particularly for the remote, inaccessible and ungauged basin areas. Snow and Avalanche Study Establishment (SASE) has developed a Snow Cover Simulation Model (SCSM) (Ganju *et al.*, 1994, A. Singh *et al.*, 2004) for the study of evolution of a mountain snow pack. The SCSM comprises of various sub-modules and simulates snowpack properties in terms of basic measurable snow and meteorological parameters. The information of snowpack available at an observatory can be used to assess the SWE by using various extrapolation technique and ground topography. The information can also be used for the ground validation of remotely sensed snow cover parameters.

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[1] Conference speaker

Operational use of a snow cover model began with a French model named CROCUS (Brun *et al.*, 1989) which was an energy and mass model, predicting the settlement, phase change, densification and temperature profiles and metamorphism. A model called SNTHERM (Jordon, 1991) was developed at CRREL mainly to predict the temperature within the snowpack and at the snow surface. Recently, CROCUS has been incorporate with a large scale meteorological model (SAFRAN) and an expert system for estimating snow pack stability for a verity of spatial and elevational zones (Durand *et al.*, 1999). The SCSM developed at SASE is an energy and mass balance model where snow cover is considered as uni-dimensional pack of layers lying on flat ground surface. The energy balance equation for each layer is expressed in a implicit finite-difference form. The thickness of each layer varies with time due to the different metamorphic processes continuously occurring inside the snow pack. The model simulates various physical properties like densification, energy exchange between atmosphere and snow cover, grain and bond growth and temperature profile. In this paper, we discuss the estimation SWE and net energy balance at snow surface at an observatory location in terms of easily measurable snow met parameters by using the model. The scheme can be extended to simulate the snow pack evolution in remote inaccessible areas by putting a network of automatic weather stations for measuring basic input parameters used in SCSM.

## OBSERVATION SITE AND DATA ACQUISITION

The Dhundi, observation site (lat: 32° 21′ 20″, long: 77°07′ 41″, 3050 m msl), located in Pir Panjal of N-W Himalaya, is surrounded from three sides with high mountains partially covered with vegetation. The tree line extends up to approximately 3500 m.

The snow pack generally starts building up from the month of November and maximum mean standing snow was recorded in the month of March. The average weather conditions of this site are discussed by Singh & Ganju (2006). The mean of maximum temperature remained always above zero. The snow pack in this region can be considered relatively warm and deep, a feature of maritime snow climate.

For the present study, snow and meteorological parameters used to drive the SCSM model were collected by an automatic data collection instrument called Snow Pack Modeller (SPM). The SPM collects snow met data including air temperature, relative humidity, wind speed, incoming solar radiation, reflected solar radiation, total snow height and snow surface temperature. It also consists of snow and soil temperature profilers to measure the temperature distribution at specific points within the snow pack and soil. All parameters except snow level are logged at an average interval of 15 minutes and snow level is measured hourly by SPM. Other parameters like fresh snow amount and fresh snow density required for initializing the model were used from STORM DATA collected during snow storm in at three hourly intervals and the same was interpolated for hourly input values. The hourly fresh snow amount was also derived directly from snow depth data of SPM. These snow met data averaged for one hour interval were used as an input to solve the equations used to model the physical processes of snow pack.

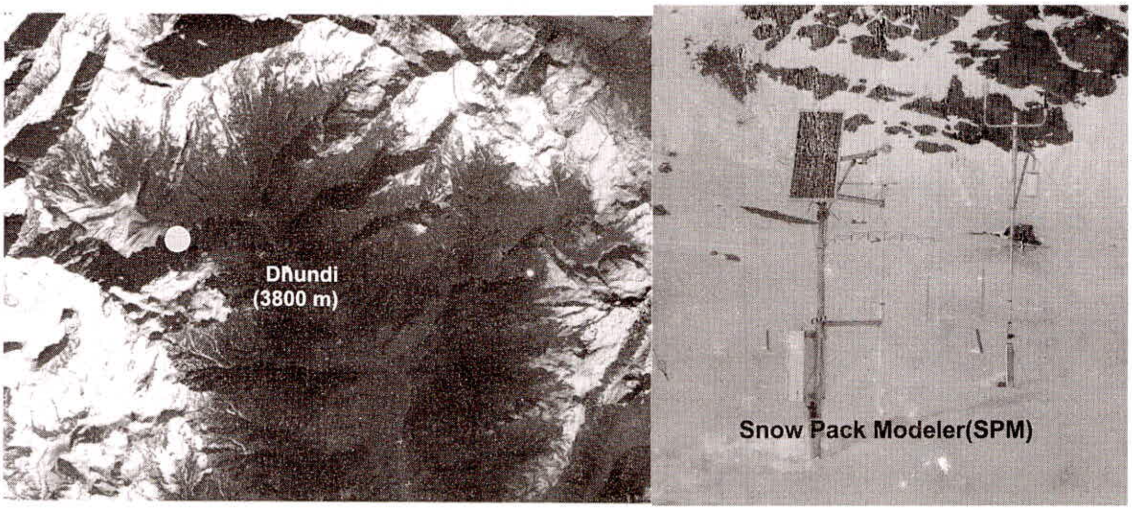

**Fig. 1:** Observation site Dhundi (lat: 32° 21′ 20″, long: 77°07′41″, 3050 m msl) and Snow Pack Modeler (SPM)

The meteorological conditions used to run the model from 1st January to 19th April 06 are shown in Figure 2. Daily mean air temperature and daily mean surface temperature are shown in panel (A). The daily mean air temperature varied between –3.2°C to 9.6°C with a mean value of 3.2°C. The minimum daily snow surface temperature –5.7°C was recorded on 21st Jan. 06 and snow surface first time attained 0°C on 21st Jan. 07, after that it fluctuated between –1.6°C and 0°C. Snowpack became completely isothermal after 24th March 06. The mean snow surface temperature for complete observation period is –1.0°C. The average wind speed recorded at the observatory was 1.2 m/s with a maximum value 2.23 m/s on 30th Mar. 07 (panel B). The mean atmospheric pressure fluctuated between 716.26 mb to 727.78 mb with a mean of 721.51 mb for complete observational period (panel B). The average relative humidity was 53.55% and it fluctuated between 16.34% for clear days to 98.90% for bad weather/snowfall days (panel C). The observatory experienced all type of weather condition including clear, partly cloudy, overcast and snow fall days during the study period. The insolation at observatory varied greatly with weather conditions, mainly on the cloudiness of the sky. Mean insolation at the observatory was 347.11 W/m$^2$ with mean cloudiness 4.8 octa for complete observation period (panel D & E). The maximum insolation 719.27 W/m$^2$ was received at the station on 5th April 06.

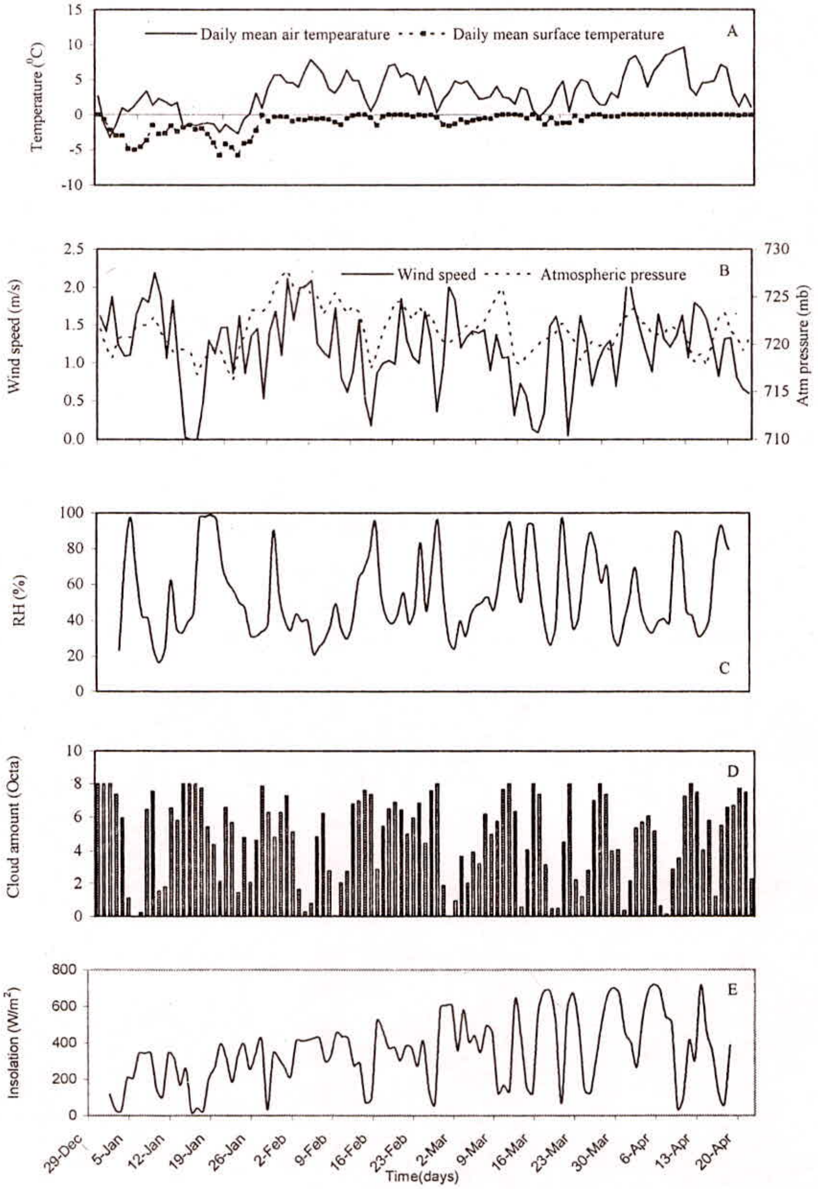

**Fig. 2:** Time series variation of air temperature, snow surface temperature, wind speed, wind direction, relative humidity, cloud amount, and insolation at Dhundi observatory (1 January–19 April 2007)

**Table1:** Snow-Meteorological Parameters for Model Input

| *S. No.* | *Parameter* | *Measuring Time Interval (average)* | *Measuring Instrument* |
|---|---|---|---|
| 1. | Fresh snow amount | Hourly/3 hourly | Snow stake/Snow depth sensor |
| 2. | Fresh snow density | 3 hourly | Density meter |
| 3. | Incoming Radiation | 15 min | Pyranometer, Type 8104 (PPHIOLIPP SCHENK GmbH Wien & Co KG, Austria) |
| 4. | Outgoing Radiation | 15 min | Pyranometer, Type 8104 (PPHIOLIPP SCHENK GmbH Wien & Co KG, Austria |
| 5. | Air temperature | 15 min | Temperature sensor |
| 6. | Snow surface temperature | 15 min | Temperature sensor (Everest Interscience Inc, AZ) |
| 7. | Relative Humidity | 15 min | Humidity sensor |
| 8. | Wind speed | 15 min | MTX Italia |
| 9. | Atmospheric pressure | 15 min | Vaisala, USA |
| 10. | Cloud Amount | hourly | Manual |
| 11. | Cloud type | hourly | Manual |

## RESULTS

### Snow Water Equivalent (SWE)

Dhundi observatory received a total of 14 snow storms between 1 January–19 April 2006. Figure 3 shows comparison between simulated snow depth with measured snow depth. Snow depth at field station was measured manually twice daily (SMD 11 data) and automatically on hourly basis by using ultrasonic snow depth sensor. The trend curve of predicted snow depth and measured snow depth are in good agreement with correlation coefficient between the two is 0.85 for complete observation period (Figure 3). The model was also able to broadly capture melt period in late winter with small underestimation. The large disparity was observed during the second snow storm which was a major storm occurred during 15–18 January 06 with total cumulative fresh snowfall of 371 cm. The settlement rate predicted by the model was relatively high during the occurrence of the storm than the observed settlement rate which created the difference between observed and predicted snow height. The mean square error for complete season was 17 cm.

Snow-pit statrigraphy data was used for the comparison between modeled and observed density profiles. Six number of snow pit analysis were carried out during whole observation period from 1 January–19 April 06. Figure 4 shows a linear regression between observed and simulated densities. Correlation coefficient between observed and modeled density is 0.85 with MSE 0.11 gm/cc.

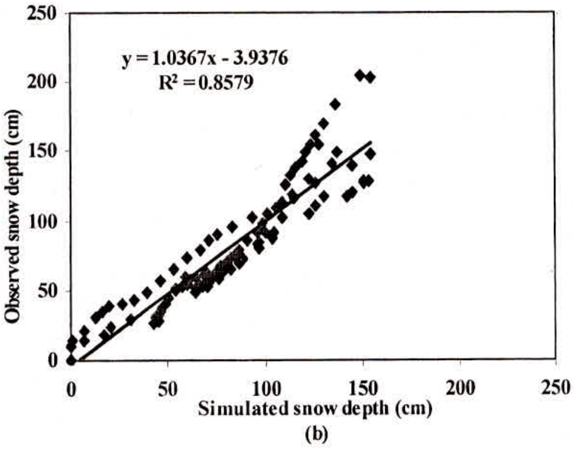

**Fig. 3:** Comparison of daily observed and simulated snow depth at Dhundi observatory for year 2005–06

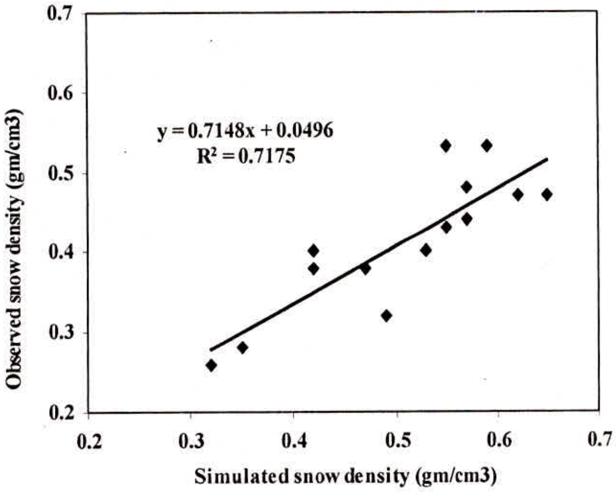

**Fig. 4:** Comparison of observed and simulated snow density at Dhundi observatory for year 2005–06

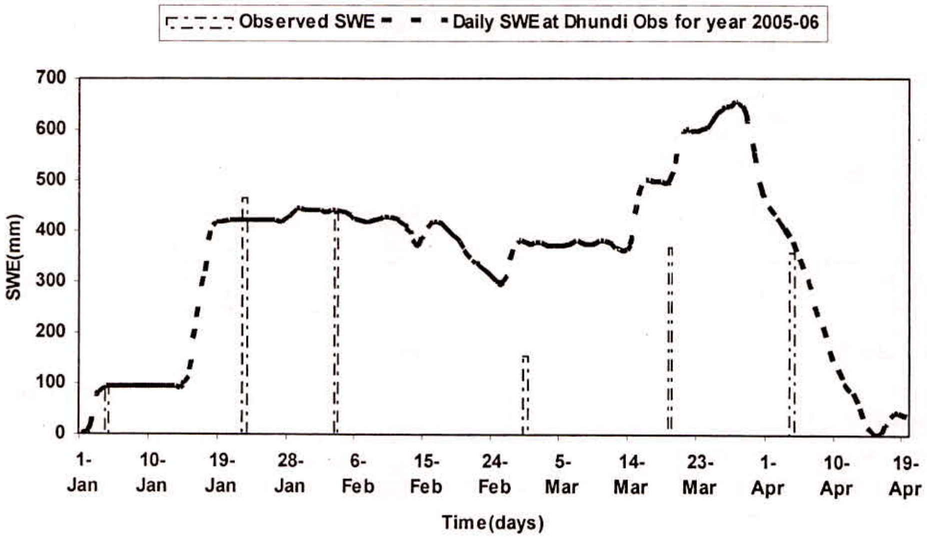

**Fig. 5:** Comparison of observed SWE (during pit analysis) and simulated SWE at Dhundi observatory for year 2005–06

Measured SWE was calculated from the measured snow depth and density at the observatory location. The model derived SWE was computed from simulated snow depth and corresponding snow density by the SCSM. The measured SWE was available for limited number of days (pit analysis days) for comparison. The estimated SWE was available for complete season from model output. Figure 5 shows comparison of estimated SWE with measured SWE. The estimated SWE is over all in good agreement with the measured one except on 28 February 06. The major deviation on 28 February 06 may have occurred due to erosion of snow from snow pit location at the observatory.

## Surface Energy Balance

The daily mean surface energy balance components for entire study period are illustrated in Figure 6. Net short wave flux varied between 0 W/m$^2$ to 435 W/m$^2$ with an average value of 113 W/m$^2$ for complete observation period (Panel A). Net SW at Dhundi station increases as season progresses from month of December to April, firstly, following the seasonal trends of radiation in northern hemisphere and secondly, as melting period approached the snow albedo decreased and reduced the amount of reflected radiation. Variation of net LW flux at the snow surface is shown in panel (B). It was observed that the LW wave flux varied between –12 W/m$^2$ to –58 W/m$^2$ with a mean value –29 W/m$^2$. The fluctuations in LW were associated with snow surface and sky conditions prevailed at the station during measurement. Latent and sensible heat fluxes are shown in panel (C) and panel (D) of Figure 6 respectively. Latent heat at Dhundi observatory varied between –5 and 0.3 W/m$^2$ and sensible heat varied between –4 and 6 W/m$^2$ throughout the observation period. The mean latent heat flux and mean sensible heat flux were of almost same magnitude i.e. 1.4 W/m$^2$ with opposite direction for the complete study period.

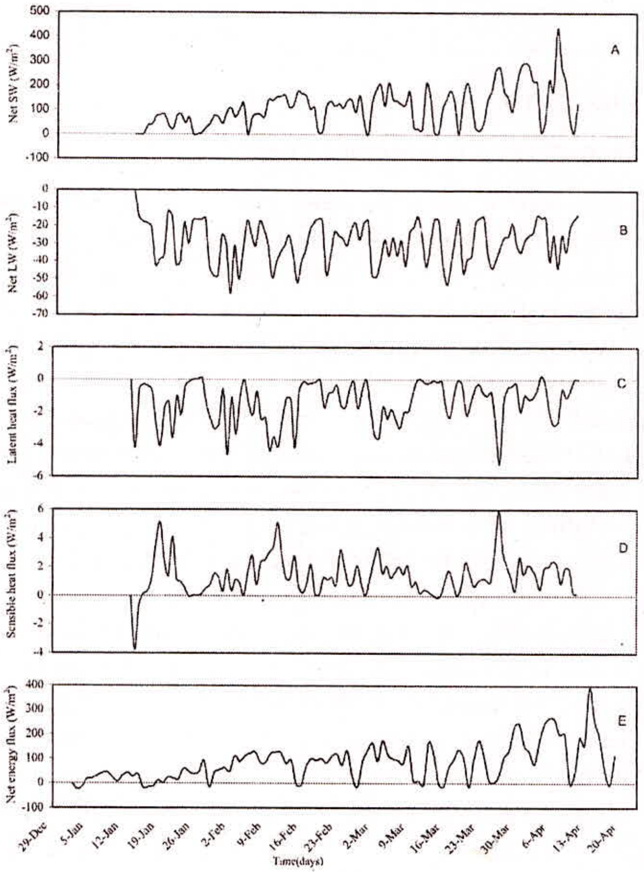

**Fig. 6:** Time series variation of Net short wave, Net long wave, Latent heat flux, Sensible heat flux and Net energy flux at Dhundi observatory (1 January–19 April 2007)

Net energy balance i.e., the algebraic sum of all the three components of energy budget is shown in panel (E). Net energy at snow surface varied between –23 W/m$^2$ to 391 W/m$^2$ with a mean value 84 W/m$^2$ for observation period. Maximum net energy, 391 W/m$^2$ was recorded in late winter on 13 April 2006.

## CONCLUSIONS

Snow water equivalent presented in this study was estimated by using an operational snow cover model. This model estimates various physical processes in terms of meteorological and snow parameters. Validation of estimated snow depth, snow density and SWE was carried out by using routine daily observations and weekly snow stratigraphy made at observatory during winter season. The measured SWE was available for comparison for few days when stratigraphy was conducted. Energy budget at surface was calculated by using energy balance module of the snow cover model. The energy balance components were calculated by using combinations of direct measurement and various algorithms. The measurement analysis presented here can be utilized for distributed snow pack evolution, SWE investigation and runoff modeling in the upper Beas catchment area by inclusion of topographical information.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical help provided by Sh. Rajeev Kumar STA 'C' and Sh. Sandeep Patel STA 'B' for data collection at field research station. This work was supported by the Defence Research Development Organization (Project No. RD – PI-2004/SAS-35).

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