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CONTRIBUTION OF SNOW PARAMETERS IN A SEMI-EMPIRICAL MODEL

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Abstract: Snow cover has an immense value as a natural resource of water used particularly for irrigation purposes. The amount of snow accumulated in a (mountain) watershed determines the runoff after the onset of melt during spring. Hence, the measurements of snow cover extent and snow characteristics (snow depth and snow water equivalent) in real time are very important. Conventional methods of data collection (for example, snow surveys or isolated stations using *in situ* sensors) are time consuming and spatially limited. Consequently, the resultant snow water equivalent measurements are enormously different from the actual snow water equivalent. At high elevation and in remote areas of the globe where very little *in situ* data exists, remote sensing is the only mean by which to observe the snow cover distribution. Microwave radiation penetrating through clouds and snow covered area could provide snow depth and snow water equivalent information about a snow pack. However, due to the coarse spatial resolution of the passive microwave sensors, in a single footprint, the presence of snow surface area along with forest fraction and water bodies contribute considerable signal variation. The principal objective of this study is to analyze the degree to which SSM/I brightness temperature can be affected by the snow parameters. The sensitivity analyses of the snow surface on the brightness temperature estimation with semi-empirical model using Special Sensor Microwave Imager (SSM/I) frequencies are investigated. In the sensitivity analysis the parameters of interest were snow density, snow salinity, snow wetness, snow grain size, snow temperature and snow depth.

Keywords: Microwave radiation penetration, microwave sensor, semi-empirical model, sensitivity analysis, snow parameters.

INTRODUCTION

In the distribution of snow cover the global influence and atmospheric effects cannot be considered independently [McKay and Gray 1981]. The snow pack growth resulted from precipitation, super-cooled rain droplets, and newly fallen snow reflect parent atmospheric conditions, consequently interact with electromagnetic waves in very different ways adding errors to the evaluation of snow water equivalent based on both the ground and satellite measurements. The research into snow cover physical structure has often been made without assessing the complication and considering the homogeneous stratification of snow pack [Mellor 1977, Lahgham 1981, Colbeck 1982].

The spatial inconsistency of snow cover is controlled, at macroscale by latitude, elevation and orographic conditions, at mesoscale by local wind flow patterns and at microscale by interaction between terrains surface roughness and potential transport conditions. Elevation is intricately linked with climatology, slope and aspect, and therefore produces suspect results for predicting snow growth discrepancy. Aspect is combined with the occurrence of snowfall, direction of flow of parent air masses, and energy and radiation transfer processes controlling ablation [McKay and Gray 1981]. Dry cold and loose snow is easily redistributed even in a gentle wind of speed ~ 10 km h^{-1}. Similarly, energy and moisture transfer modify the snow pack erodability, mass and condition. The albedo, that initially is related to snow depth, is the major control on radiation transfer to and from a snow pack. The decrease in albedo is observed with occurrence of free liquid water and contamination of the snow surface. In addition, the difference in albedo is also related with heat and mass transfer from atmosphere and ground. Albedo plays an important roll in the detection and monitoring of snow cover particularly at visible wavelength because of maximum reflectivity and minimum absorption properties of snow.

The influence of forest on snow accumulation depends on the type of tree, for example the snow accumulation in deciduous tree is greater than in pine or fir tree forest. In addition, the depth of snow is found to be greater in smaller opening forest (for example, 100 m x 200 m) than in larger opening (for example, 1000 m x 2000 m), strengthening the idea of radiating biomass and wind action [McKay and Gray 1981]. Hence the presence of vegetation in the form of forest can complicate the up-welling radiation during snow monitoring by satellite system. Furthermore, non-forested vegetation can reflect and emit signals and hence modify the scattering behavior of bulk signal.

Immediately after the snow is deposited on the ground the process of metamorphism starts. The metamorphism of snow grains in a snow pack is also linked to the change in crystal size distribution with respect to time [Wakahama 1965]. If the impurities are present in the snow pack the development rate is slowed down. At the time of snowfall the snow crystals can also smash into with other crystals to form multi-crystal shape [Mellor 1977]. Most snow packs are composed of complex layered characteristics that affect the bulk properties and physical structure and hence, modify the reflected or emitted electromagnetic signals from snow. These layers alter their features because of snow metamorphism, dense layers eliminated on the introduction of water in wet and dry snow. The ice layers, in wet snow vanish due to melting along intergranular veins and are replaced with depth hoar in dry snow due to temperature gradient [Langham 1975]. The layers created by atmospheric and melt-freeze processes have high densities and low permeability, and act as barrier to vapor and liquid flow. Although, all these processes are identifiable, the accurate nature of interaction between layers and un-layered snow is still unclear. The attenuation of electromagnetic radiation by different types of layers is very significant in the application of remote sensing.

Another important quantity in the retrieval of snow pack parameters is the amount of free liquid water content present in snow pack. If the temperature of falling snow is near the melting point of ice, the resultant build up snow is characterized as wet snow. The presence of water in liquid form depends on the absolute temperature. The amount of water in a snow pack is of particular interest for modelers and hydrological purposes. This is a problem to estimate snow water equivalent even directly from ground measurements hence, researcher uses snow depth, snow density, and areal extent of snow to estimate the snow water equivalent. The exact amount of water in a snow pack is the most useful quantitative parameter for modeling. Both wet and dry snow has dissimilar electromagnetic response depending on presence of liquid water and snow characteristics.

The retrieval of snow pack parameters (for example, snow depth and snow water equivalent) depends on temporal and spatial scales. Butt [2002], and Butt and Kelly [2002] have shown in their studies the effect of percentage of water area and forest stem volume on the prediction of brightness temperature values. Hence, airborne/satellite remote sensing are the potential solutions for the retrieval of data at large scales. However, the choice of data retrieval highly depends on the nature of application. The electromagnetic energy, at different wavelengths, has variable interaction with various snow covers (fresh, old, dry, wet etc.). Since the first satellite method for areal monitoring of snow with visible and infrared range, the utility of multi-spectral high-resolution images has been considered by Nolin and Dozier [1993]. The potential for using microwave observation of snow packs was first recognized by Meier [1972]. Microwave radiation offer more quantitative information of snow pack. The evaluation of snow cover parameters is an ongoing topic of research, particularly in the area of microwave remote sensing. In satellite remote sensing, for the retrieval of snow pack parameters the scale of the snow cover inconsistency and the physical change in snow pack characteristics must be considered. One of the most advanced passive microwave sensor is Special Sensor Microwave Imager (SSM/I). At 3 dB beam width the spatial resolution of SSM/I at its highest frequency range is 14 km by 16 km whilst at lowest frequency the resolution is 45 km by 70 km. Passive microwave remote sensing of snow cover is limited to large scale continental and high alpine snow cover monitoring [Chang *et al*. 1987, Grody 1991, Hallikainen and Jolma 1992].

ELECTROMAGNETIC BEHAVIOUR OF SNOW

The incident passive microwave radiation on snow surface is affected by absorption and scattering processes. The geometric (snow crystal diameter and shape and snow density) and dielectric characteristics control these two mechanisms. Due to the simplicity Maxwell's equations, have mostly been given preference on radiation transfer theory to characterize physical properties of wet and dry snow covers [Tiuri 1984, Foster *et al*. 1984, Stogryn 1986]. The Rayleigh theory (when particle size is very much smaller than the electromagnetic wavelength) and Mie theory (when the particle size is greater than the incident wavelength) are used to calculate the scattering and absorption coefficients. These coefficients are model parameters, used as input to the models in the radiative transfer equation, and determine the power loss due to scattering and absorption respectively. The extinction coefficient that is the sum of absorption and scattering coefficients is given as:

$$\kappa_e = \kappa_a + \kappa_s \,. \tag{1}$$

where κ_a = absorption coefficient, κ_s = scattering coefficient, and κ_e = extinction coefficient.

The above equation is used to calculate absorption and scattering coefficients. The absorption coefficient is a function of permitivity and loss factor terms in the dielectric constant and varies with frequency. In dry snow pack volume scattering that is related to the penetration depth (the distance over which 63% of power is reduced) is dominant whilst, in wet snow surface scattering is important in addition to volume scattering. Thus the scattering of microwave radiation often results from an inhomogeneous medium and depends on, the individual snow grains, the vertical density variation within the pack, and horizontal and vertical inhomogeneities of snow density by wind action. In addition, scattering is divided into random scattering medium and discrete medium [Chang *et al*. 1976].

SNOW MODEL

The emission behavior of snow is such that it consists of emission from snow surface and underlying soil. Thus, to model the realistic microwave emission of snow the soil emission contribution also needs to be considered. The brightness temperature model presented by Pulliainen *et al*. [1999] for a homogeneous snow layer with a total thickness of, *d*, is:

$$T_B\left(d^-,\theta\right) = T_B\left(0^+,\theta\right)e^{-(\kappa_e - q\kappa_s)\sec\theta d} + \frac{\kappa_a T_s}{\kappa_e - q\kappa_s}\left(1 - e^{-(\kappa_e - q\kappa_s)\sec\theta d}\right) \tag{2}$$

where $T_B\left(0^+,\theta\right)e^{-(\kappa_e - q\kappa_s)\sec\theta d}$ = brightness temperature contribution of soil, $\frac{\kappa_a T_s}{\kappa_e - q\kappa_s}\left(1 - e^{-(\kappa_e - q\kappa_s)\sec\theta d}\right)$ = emission contribution of homogeneous snow layer.

Butt [2001] has used the above model (Eq. 2) to predict the snow depth and snow water equivalent in UK. The first term in Eq. 2 represents the brightness temperature contribution originating below the snow layer and attenuated by the snow. The second term is the brightness temperature contribution of the homogeneous snow layer. The only empirical term used in the Eq. 2 is a parameter, *q*, which appears when considering the forward scattered incoherent intensity using the method given in Ishimaru [1978]. By using the snow pack brightness temperature and propagation measurements under controlled conditions conducted in Finland and Switzerland in 1980's [Hallikainen *et al*. 1987, Matzler 1987], Pulliainen *et al*. [1999] showed that the value of q = 0.96 for all frequencies. The other terms in Eq. 2 are given as:

T_s = snow physical temperature, κ_a = absorption coefficient,
κ_e = extinction coefficient, κ_s = scattering coefficient,
$\boldsymbol{\theta}$ = angle of incidence.

The snow extinction, absorption and scattering coefficients (Eq. 2) are modeled using the relations given in Hallikainen *et al*. [1987]. Since dry snow is a heterogeneous mixture of air and ice, the dielectric constant of dry snow (independent of temperature and frequency in the microwave range) depends on its density, ρ_s, dielectric constant of air and ice. The dielectric constants of air and ice are constant thus the dielectric constant of dry snow is a function of its density only. Its value varies between 1.0 for pure air and 3.2 for pure ice [Cumming 1952, Stiles and Ulaby 1980]. Several researchers have demonstrated the dependencies of the dielectric constant of snow solely on the snow density by presenting various models, for example, Cumming [1952], Hallikainen [1978], Hofer and Matzler [1980], Stiles and Ulaby [1980], Ulaby and Stiles [1980], Nyfors [1983], Ulaby *et al*. [1986]. These models assume that there is no grain size effect in the determination of the dielectric constant of snow [Hallikainen *et al*. 1987]. The imaginary part of the dielectric constant of dry snow (ε'' = 0.001) is much smaller than its real part (ε' = 1.55), particularly at higher frequencies, and can be neglected. However, the real part of dielectric constant of dry snow itself has a value, which is much smaller than that of most of the natural media (for example, for dry soil ε' = 2.7, for wet soil ε' = 25) [Hallikainen and Jolma 1986, Matzler 1996]. Matzler [1987] produced an expression to calculate the real part of the dielectric constant of dry snow and its results agree well with measured data. The model is of the form:

$$\varepsilon'_{ds} = 1 + \frac{1.60\rho_{ds}}{1 - 0.35\rho_{ds}} \qquad (3)$$

where ρ_{ds} = density of dry snow.

On the other hand, the imaginary part of the dielectric constant of dry snow, which is much smaller than its real part, is treated with a formula modified by Hallikainen *et al*. [1987] and is based on the Polder-van Santen mixing model given as:

$$\frac{\varepsilon''_{ds}}{\varepsilon''_i} = 3\nu_i \frac{(\varepsilon'_{ds})^2 (2\varepsilon'_{ds} + 1)}{(\varepsilon'_i + 2\varepsilon'_{ds})\left[\varepsilon'_i + 2(\varepsilon'_{ds})^2\right]} \qquad (4)$$

where ε'_{ds} = real part of dielectric constant of dry snow, ε'_i = real part of dielectric constant of ice, ε''_i = imaginary part of dielectric constant of ice, ν_i =volume fraction of ice in dry snow given as:

$$\nu_i = \frac{\rho_{ds}}{\rho_i} \tag{5}$$

where ρ_i = density of ice.

The influence of ice on the microwave spectrum is very weak and its dielectric constant can be identified by $\varepsilon_i = 3.17 \pm 0.03$ [Ray 1972, Vant *et al*. 1974, Glen and Paren 1975, Blue 1980]. Matzler [1987], however, formulated the empirical relations for the determination of the real and imaginary part of the dielectric constant of ice given as:

$$\varepsilon_i' = 3.1884 + 0.91 \cdot 10^{-3}\left(T - 273K\right) \tag{6}$$

and $$\varepsilon_i'' = \frac{A}{f} + Bf^{C} \tag{7}$$

where T = temperature of snow, f = frequency and A, B and C = empirical constants that depend on the temperature and purity of ice.

The penetration depth of passive microwave radiation in dry snow is of the order of a centimeter to several meters, depending on the wavelength of the incident wave [Hallikainen 1989]. The radiation is attenuated due to the extinction (absorption and diffusion) process when passing through the snow surface. Bohren and Barkstrom [1974] studied the extinction process and showed that diffusion is more important than absorption. The low emissivity values of winter snow at higher frequencies are the result of volume scattering of the microwave radiation within the snow pack. However, high polarization differences at the intermediate frequencies are due to the layered structure of winter snow type [Ulaby *et al*. 1986]. This is an important property of dry snow during snow monitoring by microwave satellite remote sensing.

SENSITIVITY ANALYSIS

In the sensitivity analyses of snow surface, the snow-input parameters were varied one by one. The snow salinity was varied from 0 to 0.18 promiles with an increment of 0.02 promiles, snow temperature was varied from 0° to -9° C at an increment of -1° C, snow density was varied from 0.03 to 0.3 g cm^{-3} with an increment of 0.03 g cm^{-3}, snow layer thickness was varied from 0 to 0.5 m at an increment of 0.05 m, snow moisture was varied from 0 to 0.18% at an increment of 0.02%, and snow grain size was varied from 0.6 to 1.5 mm with an increment of 0.1 mm. The results of the sensitivity analyses for snow parameters are shown in Figs. 1-6. The gradient of plot lines in Figs. 1 and 2 is very small. Hence, the snow salinity (Fig. 1) and snow temperature (Fig. 2) are regarded as the insensitive parameters. Fig. 3 shows that snow density, particularly at 19 and 37 GHz frequencies where the gradient of the plot line is very small, has very little effect on the model predicted brightness temperature values. However, the gradient of plot lines in Figs. 4-6 is very large.

Hence, snow layer thickness (Fig. 4), snow moisture (Fig. 5) and snow grain size (Fig. 6) are regarded as the sensitive parameters.

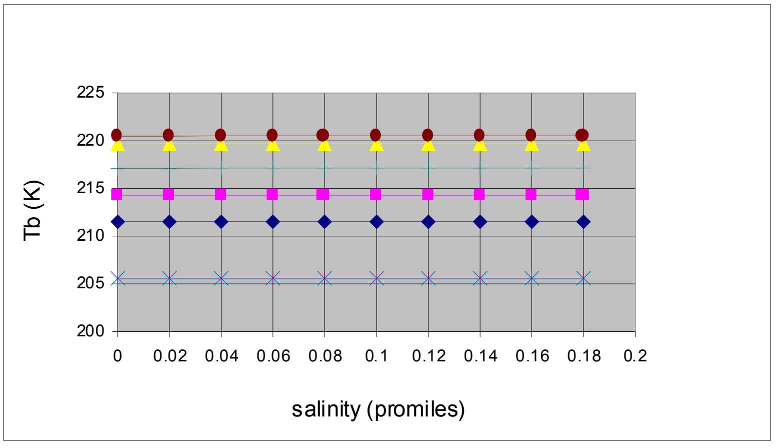

Fig. 1: Sensitivity analyses of snow salinity.

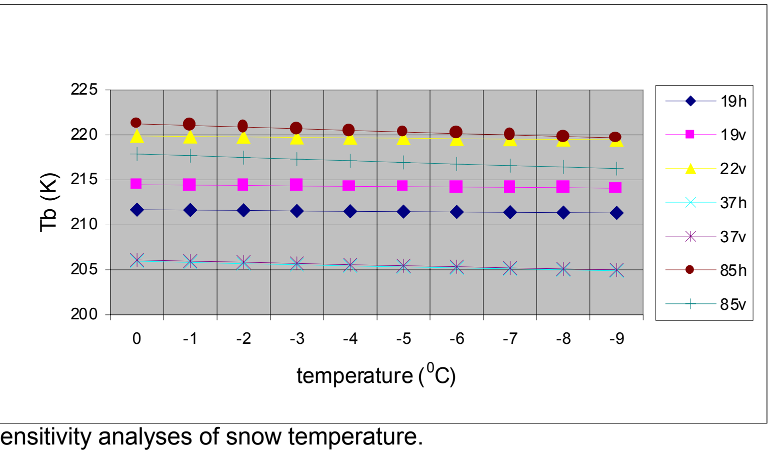

Fig. 2: Sensitivity analyses of snow temperature.

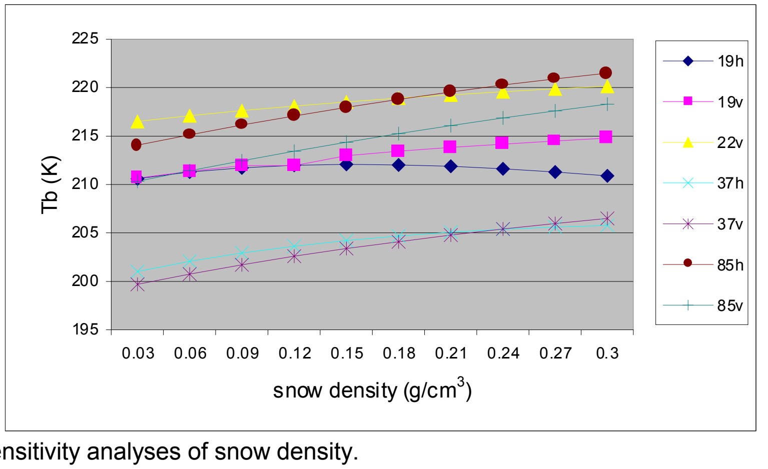

Fig. 3: Sensitivity analyses of snow density.

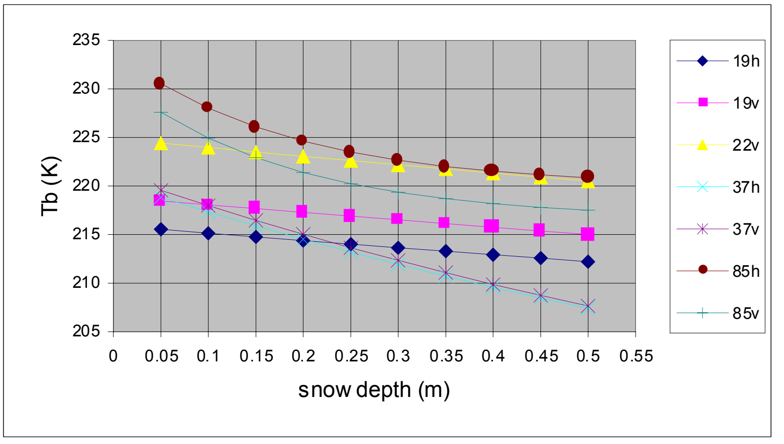

Fig. 4: Sensitivity analyses of snow layer thickness.

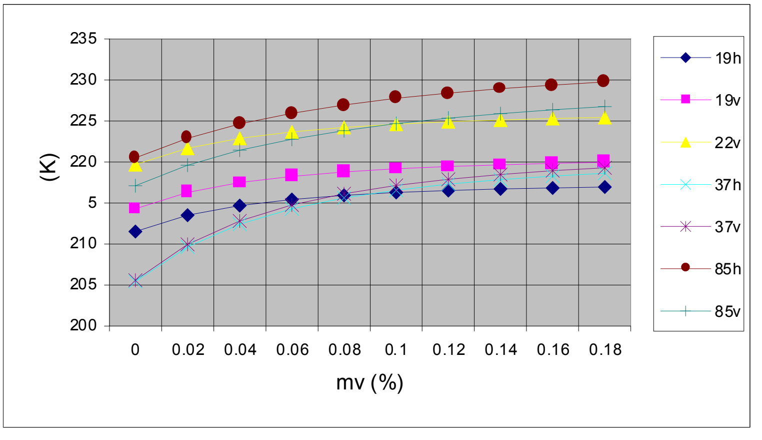

Fig. 5: Sensitivity analyses of snow moisture.

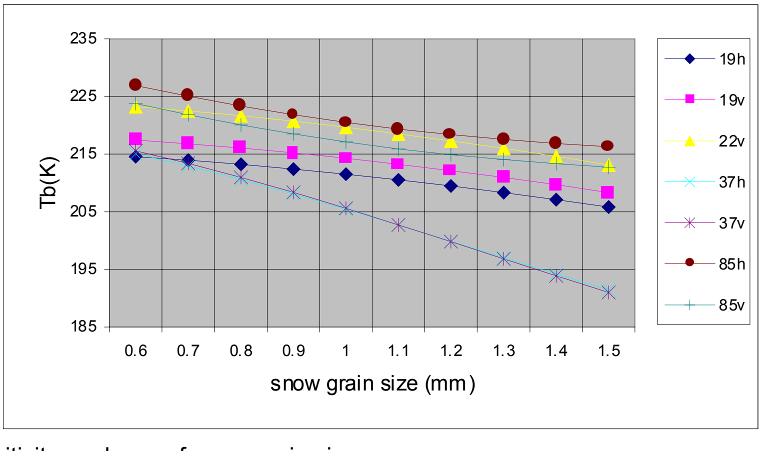

Fig. 6: Sensitivity analyses of snow grain size.

CONCLUSIONS

The emission of microwave radiation sensed by a satellite sensor depends on the receiving system parameters (frequency, angle and polarization) and on the surface space and time-dependent physical properties. All earth objects either reflect and/or emit electromagnetic radiation. The strength and spectral distribution of the electromagnetic radiation received by the satellite sensor system are modified to some extent through scattering by atmospheric parameters. The complex dielectric constant of a material ($\varepsilon = \varepsilon^{/} + \varepsilon^{//}$) describes its response to an incident electromagnetic wave. If the medium is a snow surface, it is regarded as half-space (soils) overlaid by a mixture of ice particles and air; or ice particles, liquid water and air. The emission behavior of snow depends on the thickness of the snow layer and the physical structure of the snow. In retrieving snow cover parameters, the emission behavior of the underlying soil, the reflected sky radiation and the radiation emitted by the snow pack must be considered [Hiltbrunner and Matzler 1997]. The sensitivity analyses of snow pack parameters show that the snow salinity and snow temperature are insensitive parameters whilst snow density has very little effect particularly at 19 and 37 GHz frequencies. However, snow layer thickness, snow moisture and snow grain size are regarded as the sensitive parameters.

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