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RAIN-SNOW BOUNDARIES ALONG MOUNTAINSIDES

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1. INTRODUCTION

A major issue in winter is the occurrence and type of precipitation over mountains. In general, the precipitation can be either rain or snow although mixtures are also common. Such mixtures include snow which has just melted a little (wet snow) as well as snow that has almost completed melting (slush). The region of mixed-precipitation is referred to as the rain-snow boundary.

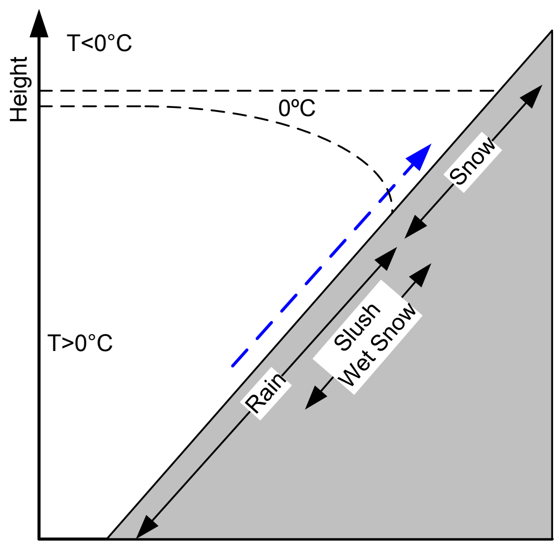

Figure 1: Schematic diagram of the thermodynamic environment associated with a rain-snow boundary along a mountainside. It shows the mountain (grey shading), the isothermal layer at 0ºC (dashed lines) with the lower isotherm bending towards the surface near the mountain. The associated precipitation types along the mountainside are also indicated. The dashed blue line shows the upslope winds.

The factors governing whether rain or snow will occur at the surface include whether the underlying surface is flat or sloped. Over flat terrain, Wexler et al. (1954) showed that rain can evolve into snow due to the cooling effects of melting on the atmosphere. The melting of snow also typically leads to an isothermal layer at 0ºC a few hundred meters deep. Over sloped terrain, this thermodynamic effect combined with orographic factors can cause the lower 0ºC isotherm to bend down towards the mountain surface (Figure 1). This can generate a major temperature difference (up to 7ºC) between the mountain surface and the flat terrain at a comparable height and a few tens of kilometers upstream (Marwitz, 1987). Lumb (1983a,b) showed that this processes is also enhanced by the cooling associated with the vertical ascent of air up the barrier.

It is not surprising that the determination of the precise location of the rain-snow boundary is very difficult given such considerations. Ralph et al. (2005) noted this in their summary of a recent workshop on winter precipitation issues for the United States. They pointed out five key issues to be addressed in winter storms. Several of these related to the transition region between rain and snow. In fact, the modeling sub-group at the workshop listed the physics of the transition region as the number one priority for improving models.

Given the importance of the phase of the precipitation formed on the surface weather conditions, a better understanding of the mechanisms influencing the rain-snow boundary needs to be achieved. In particular, the objective of this study is to better understand the transition of snow to rain (or vice versa) within the varying, and interacting, environmental conditions experienced over the mountainous terrain of, for instance, western North America. This will be accomplished with a systematic study using a numerical model.

The paper is divided as follows. Section 2 is the model description and the experimental design is given in Section 3. The evolution of the temperature fields and the surface precipitation rate with the effects of background vertical velocity is discussed in Section 4. Section 5 investigates the effects of various atmospheric conditions on the time to eliminate the melting layer and the precipitation types and their combination formed. The concluding remarks are given in Section 6.

2. MODEL DESCRIPTION

The new microphysics scheme developed to address this issue is based on the one developed by

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Milbrandt and Yau (2005a,b) with new precipitation categories added by Theriault et al. (2006). These new categories are wet snow and slush which are based on the degree of melting of the snowflakes. Wet snow is a partially melted particle in which the snowflake shape is still discernable. However, a slush particle is a partially melted snowflake composed mainly of liquid water and the snowflake shape is no longer discernable. Detailed melting of snowflake into wet snow, slush and rain has been improved in this scheme using a parameterization method based on a truncated gamma function developed by Szyrmer and Zawadzki (1999).

2.1 *Overview of the Microphysics Scheme*

The new scheme is a combination of a double moment and single moment depending on the hydrometeor category. It is double-moment for snow, freezing rain, rain, cloud droplets, wet snow and the slush category is assumed to be single moment. A schematic of the size distribution of the semi-melted particles, wet snow and slush as well as rain is shown in Figure 2.

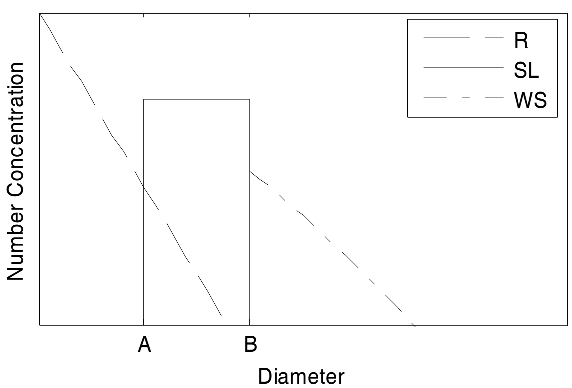

Figure 2: Schematic of the size distribution in liquid water equivalent of rain (R), slush (SL) and wet snow (WS). A is the minimum diameter of slush (d_{0sl}). B is the maximum diameter of slush (d_{msl}) and the minimum diameter of wet snow (d_{0ws}).

The double-moment scheme predicts the number concentration (0th moment) and the mass mixing ratio (3rd moment for spherical hydrometeor category and 2nd moment for non-spherical ones) based on the size distribution

$$N_x(D_x) = N_{0x}\exp(-\lambda_x D_x) \quad \text{for } D_x \geq d_{ox} \qquad (1)$$

where D_x is the hydrometeor diameter, N_{0x} is the initial number concentration, λ_x is the slope parameter and d_{0x} is the minimum diameter of the distribution (d_{0x} = 0 for $x \in$ R,CL and d_{0x} = 0 for $x \in$ WS). The minimum diameter is associated with the largest wet snowflake that could exist within the given environmental conditions (Section 2.3). For example, the wet snow size distribution is truncated by the diameter d_{0ws} shown in Figure 2. The parameters N_{0x} and λ_x can vary and are diagnosed using the mass mixing ratio Q_x and the number concentration N_x. It is explained in detail in Milbrandt and Yau (2005a,b).

Because slush particles are formed within very narrow atmospheric conditions (Theriault et al. 2006), they are assumed to be single-moment (only 3rd moment of the size distribution is predicted). Their size distribution is assumed by a rectangle

$$N_{sl}(D_{sl}) = N_{0sl} \quad \text{for } d_{0sl} \leq D_{sl} \leq d_{msl} \qquad (2)$$

where d_{0sl} and d_{msl} are the minimum and maximum diameter of the distribution (Section 2.3). The parameter N_{0sl} can vary and is diagnosed by the total mass mixing ratio of slush. A schematic of the slush size distribution is shown in Figure 2.

The sedimentation and characteristics of each hydrometeor are largely described in Milbrandt and Yau (2005a,b). However, snowflakes are assumed to have a non-spherical shape (Mitra et al., 1990). Also, slush falls at a terminal velocity between that of snowflakes and raindrops. Its value is based on the terminal velocity varying the liquid fraction and the diameter of the melting snow defined in Szyrmer and Zawadzki (1999).

2.2 *Threshold Liquid Fraction within Snowflakes*

The melting stages of snowflakes have been described by Fujiyoshi (1986). There are six stages; the snowflake shape is still discernable up to stage 5. At that point, the snowflake shape collapses and it is defined as a slush particle until it is completely melted into a raindrop.

A sharp increase in the melting snowflake terminal velocity has been observed at a liquid fraction of 70% (Mitra et al., 1990). This observation suggests that the wet snowflake collapses into slush particle at that liquid fraction. Therefore, snow falling within the melting layer melts into wet snow (f_L<70%), wet snow melts into slush (f_L<100%) and slush melts completely into rain (f_L=100%).

2.3 *Threshold Diameters*

The diameter of the largest completely melted snowflake is computed using the melting equation for snow in Milbrandt and Yau (2005b). That diameter, d_{0sl}, is the minimum diameter of the slush distribution. Using an equation relating the liquid fraction and the diameter in Szyrmer and Zawadzki (1999), the maximum diameter of the slush distribution (d_{msl}) is obtained. The maximum slush diameter is also associated with the minimum size of the wet snow size distribution (d_{0ws}) when wet snow exists. However, when wet snow is completely melted into slush, the maximum slush diameter stays constant as it falls through the melting layer because slush is no longer being formed but the minimum diameter keeps increasing. The slush is completely melted into rain when the minimum diameter is the same size as the maximum diameter.

2.4 *Microphysical Processes*

The microphysical processes used in this scheme are melting, sublimation, deposition, evaporation, condensation as well as collisions between wet snow, rain and cloud droplets as well as slush interactions with rain and cloud droplets. All the processes associated with phase changes are changing the atmospheric conditions such as the temperature and the degree of saturation of the atmosphere. For instance, melting of snow cools the atmosphere whereas condensation forming cloud droplets warms it.

The melting rate is one of the most important microphysical processes within the rain-snow boundary along mountain sides. When snowflakes fall through a melting layer, they undergo partial melting. First, they partially melt into slush particles when their liquid fraction is ≥ 70% and slush particles completely melt into raindrops. A fraction of the melted liquid water will be changed into slush (rain) and the other fraction will stay in the wet snow distribution (slush). The mass of wet snow transferred to the slush category within one time step is the difference between the mass of wet snow with the minimum diameter d_{0ws}, $M_{ws}(d_{0ws})$, and the mass of wet snow with the increased cutoff diameter by Δd_{0ws} during the time step. Thus, the mass of slush is increased by

$$\Delta M_{sl} = M_{ws}(d_{0ws}) - M_{ws}(d_{0ws} + \Delta d_{0ws}) \quad (3)$$

The total concentration is computed similarly as well as the mass of slush changed into rain and the number of slush particles changed into rain.

3. EXPERIMENTAL DESIGN

The numerical experiments use a one dimensional kinematic cloud model used in Theriault and Stewart (2007) coupled with the microphysics scheme described in Section 2. The model is initialized by the temperature profile depicted into Figure 3. It is composed of a melting layer 1 km deep above the ground. The surface temperature is 5ºC and it decreases with height.

Along mountainsides, upslope wind is associated with cooling of the environment and the opposite is true for downslope wind. This study focuses on the upslope winds and, thus constant ascending air is assumed.

A schematic diagram is shown Figure 1 but in more detailed in Figure 3. Several maximum values of vertical air velocity (w_{max}), 5 cm/s, 10 cm/s, 15 cm/s and 20 cm/s are used to investigate the relative effects of adiabatic cooling and temperature variation due to the phase changes. These values of the vertical velocity are comparable to observed vertical velocity along mountainsides (Marwitz et al. 1983).

The impact on the precipitation type evolution is also investigated by varying precipitation rates and degrees of saturation of the atmosphere. The initial precipitation rates studied are 1 mm/h, 2 mm/h, 5 mm/h and 10 mm/h and the relative humidities studied are 80%, 85%, 90%, 95% and 100%.

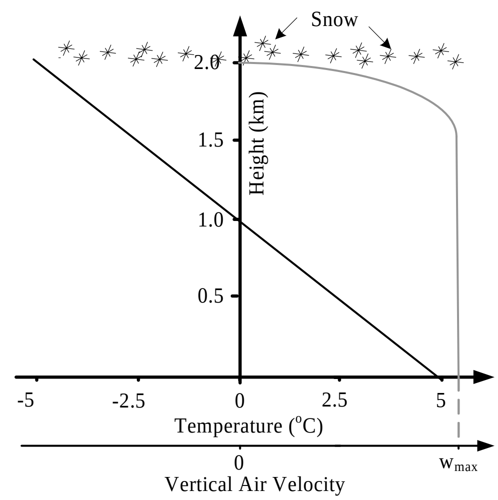

Figure 3: The vertical temperature (black line) and vertical motion (grey line) profiles assumed in this study. Snow continuously falls from 2 km above the ground. The grey line is the vertical air velocity profile (w_{max}).

For this study, we assume snow continuously falling from 2 km above the ground. When snow falls through the air column the precipitation changes phase and it interacts with the environment by varying the temperature and the relative humidity. The model is run until the melting layer is completely eliminated and temperatures everywhere are ≤0ºC. The impact on background vertical air velocity and the latent heat of cooling and warming due to phase changes on the temperature fields are compared. This is assuming a vertical air velocity of 10 cm/s and a snowfall rate of 2 mm/h falling within a saturated with respect to water environment. Also, the duration of the evolution needed to completely eliminate the melting layer as well as the duration of each precipitation type and their combinations are then compared for the various precipitation rates, degrees of saturation and vertical velocity values.

4. EFFECTS OF PHASE CHANGES AND BACKGROUND VERTICAL AIR VELOCITY ON THE TEMPERATURE FIELDS

The precipitation types formed when falling through a vertical air column are very dependent on the temperature profile and the degree of saturation of the atmosphere. In this study, the temperature profile is altered by both phase changes and the effects of upslope wind. The upslope wind alters the temperature profile by vertical temperature advection and by adiabatic cooling of the air.

The effects of background vertical air velocity and the latent heat release from phase changes are shown in Figure 4. It was assumed that snow falls from above the melting layer at a rate of 2 mm/h within a saturated environment with respect to water. The vertical air velocity is assumed to be 10 cm/s. At levels above 1 km, temperature changes are observed and they are only due to the cooling by the prescribed vertical motion. Thus, only the temperature evolution with time in the lower part of the domain (< 1 km) is shown.

The temperature fields evolve differently within the melting layer (< 1 km) depending on the microphysical processes occurring within melting layer. Figure 4a compares the temperature evolution with only the effects of background vertical motion and the both effects of cooling by melting and the background vertical air motion. First, the time to eliminate the melting layer into a layer of temperatures <0ºC are comparable in both cases. During the first 25 min, the cooling within the melting layer is only due to the background vertical air motion. However, when snow starts to penetrate at the top of the melting layer, the isotherms starts to evolve differently. The effects of cooling due to melting occurs at lower altitudes and correlates with the presence of wet snow and slush deeper within the melting layer. In general, the effects of melting generate colder temperatures than with only the effects of background vertical motion and this implies advection of colder temperature increases. This explains the difference in temperature with and without the effects of melting at elevation above 1 km.

The effects of vertical air motion generate cloud droplets by producing supersaturated environment from adiabatic cooling. The production of cloud droplets by condensation increases the temperature profile. The effects of condensation on the temperature field evolution are compared to the effects on the temperature due to all the microphysics in Figure 4b. The time evolution of the melting layer into a layer of temperatures <0ºC with the effects of condensation only and with all the microphysics is 240 min. However, this is twice as long and without any temperature changes due to the microphysical processes or with only melting of snow and slush (Figure 4a). Thus, the effects of warming by condensation have an impact on the evolution of the rain-snow boundary.

The temporal evolution of the isotherms due to condensation only is compared with the effects of all the microphysical processes. In both cases, the time to cool the temperature below 0ºC is comparable. However, the one considering all the microphysical processes is slightly faster due to the additional cooling by the melting of snow and slush. This additional cooling term also produces the difference in the temperature profile evolution that is evident near the top of the melting layer.

In general, the temperature profile evolves into vertical isotherms and this is mainly due to the effects of vertical temperature advection. The constant vertical air velocity brings the warm air from lower elevation upwards.

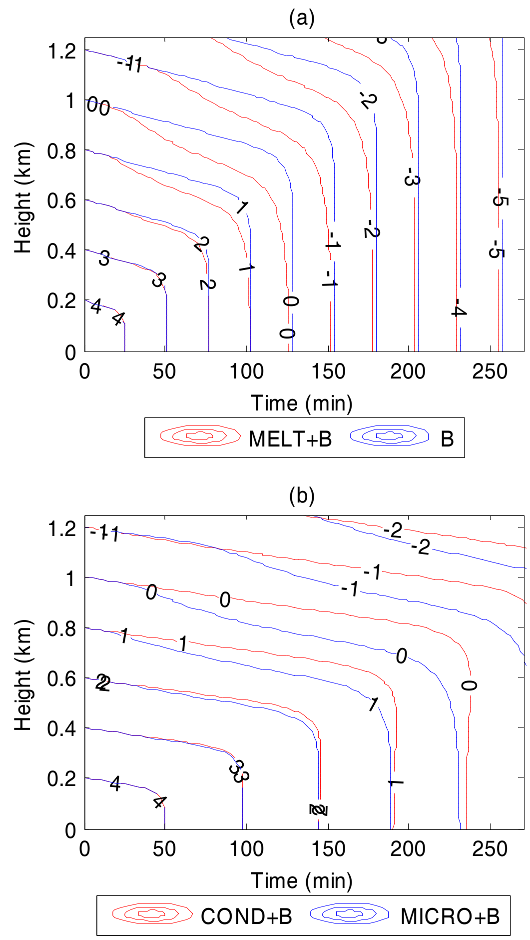

Figure 4: Temperature fields varying with time assuming precipitation falling at 2 mm/h within saturated environment and assuming background vertical air velocity of 10 cm/s. (a) Comparison with no effects of phase changes (B) and only melting (MELT +B). (b) Comparison with only the effects of condensation (COND+B) and all the microphysics (MICRO+B).

5. EVOLUTION OF THE RAIN-SNOW BOUNDARY WITHIN VARIOUS ATMOSPHERIC CONDITIONS

The evolution of rain into snow along mountainsides depends on many atmospheric factors such as, for instance, the strength of the vertical air velocity, the precipitation rate and the relative humidity. The impact of these factors is investigated in this Section.

5.1 *Time to Eliminate the Melting Layer*

Depending on the atmospheric conditions, the melting layer completely evolves into a layer of temperature <0ºC. Figure 5 shows the relation between the time to eliminate the melting layer varying the relative humidity of the environment, the vertical air velocity and the initial precipitation rate. Many precipitation types, such as rain, slush and wet snow, are produced during the elimination of the melting layer and only snow reaches the surface, when the melting layer is completely eliminated. That is the reason why the time to eliminate the melting layer is important.

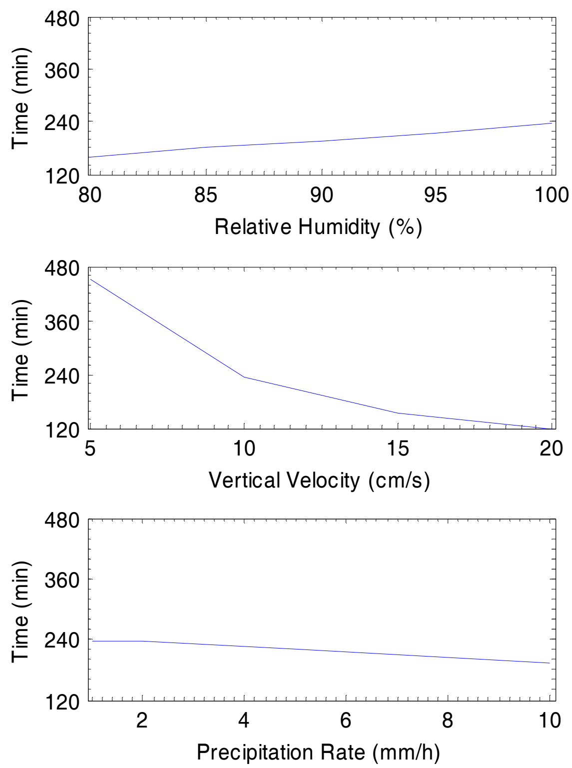

Figure 5: The time to completely eliminate the melting layer varying with (a) the degree of saturation of the environment (b) the strength of the upslope wind and (c) the values of initial precipitation rate aloft.

Figure 5a shows that the effects of relative humidity on the time to eliminate the melting layer. The lower relative humidity is associated with the faster evolution of the melting layer (160 min) compared to a saturated environment (235 min). The sub-saturated environment produced fewer cloud droplets by condensation, in turn, less warming of the environment. In contrast, the melting rate is reduced when snowflakes fall within a sub-saturated environment compared to a saturated environment because less cooling of the air will occur. However, snowflakes and rain will sublimate and evaporate, respectively, and this will cool the environment and increase the relative humidity of the air. Therefore, the time to eliminate the melting layer increases with increasing relative humidity of the environment.

The time to eliminate the melting layer with the effects of vertical air velocity decreases with increasing background vertical air motion (Figure 5b). There is a time difference of 330 min between the weakest and the strongest strength of ascending air and this is mainly due to the difference in adiabatic cooling due to the vertical air motion prescribed.

The initial precipitation rate also has an impact on the time to eliminate the melting layer (Figure 5c). However, this effect is less important than the relative humidity and the vertical air velocity. The time difference between a precipitation rate of 1 mm/h and 10 mm/h is 40 min and it is due to the greater amount of cooling from the melting of wet snow and slush.

Overall, the environmental conditions have an important impact on the time to eliminate the melting layer. This has a direct effect on the precipitation types reaching the surface.

5.2 *Surface Precipitation Type Evolution*

The variation of the duration of rain, slush, wet snow and snow falling within various environmental conditions is shown in Figure 6. The control run is assuming a vertical air velocity of 10 cm/s with an initial precipitation rate of 2 mm/h falling within a saturated environment. The sensitivity tests on relative humidity, vertical air velocity and precipitation rate are carried out by varying only one of these parameters and keeping the others constant. It shows that the duration of the transition from rain to snow decreases significantly with increasing background vertical air velocity, increasing initial precipitation rate aloft and increasing relative humidity. Therefore, the duration of the transition region correlates with the time to eliminate the melting layer discussed in Section 5.1.

In general, four combinations of precipitation types are observed during the time evolution: only rain, rain mixed with slush, a mixture of rain, slush and wet snow and wet snow only. However, a few cases produce other combinations of precipitation or have not produced one of these combinations.

First, the combination of slush and wet snow was produced in a few cases at the end of the evolution of the rain-snow boundary. For instance, for the background ascending air of 5 cm/s, when relative humidity is lower than 90% as well as with the precipitation rate of 1 mm/h, 5 mm/h and 10 mm/h. However, it only occurs during a short period of time and it is produced within very narrow atmospheric conditions.

Second, no rain only is observed with a relative humidity of 80%. The time evolution starts directly with a mixture of rain and slush. This is due to the dry environmental conditions, allowing the snow to sublimate until the wet bulb temperature is >0ºC. At that wet bulb temperature, melting of snowflakes starts to occur. At the same time, the temperature profile is also cooled by the ascending air within the column. Thus, it produced atmospheric conditions favorable for only partially melted snowflakes.

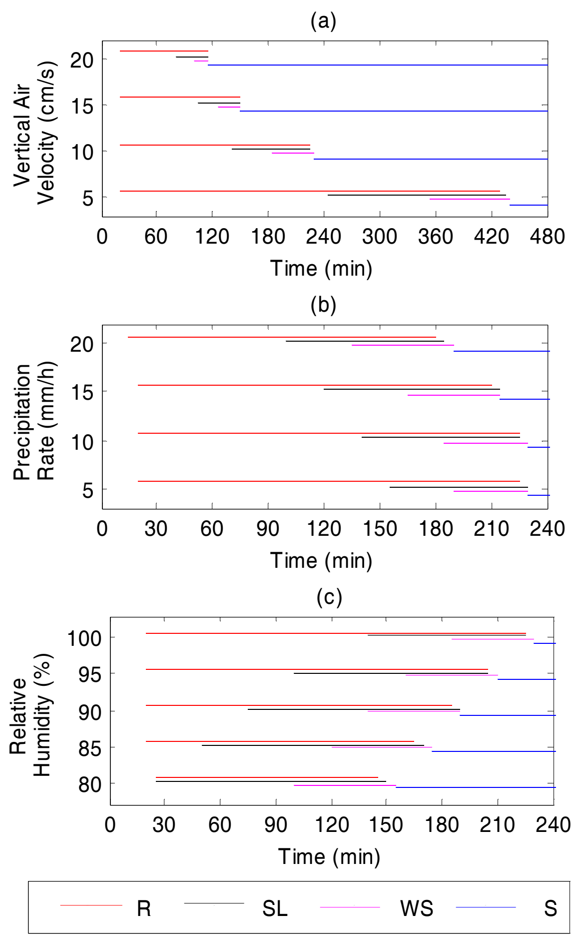

Figure 6: The surface precipitation varying with time. (a) Varying the upslope wind speed. An initial snowfall rate is 2 mm/h and assuming saturated atmospheric conditions. (b) Varying the initial precipitation rates aloft. A vertical air velocity value of 10 cm/s is assumed ascending within saturated atmospheric conditions. (c) Varying the degree of saturation of the environment. The initial snowfall rate aloft is assumed at 2 mm/h falling with the effects of background vertical air velocity of 10 cm/s. The precipitation types are rain (R), slush (SL), wet snow (WS) and snow (S).

Third, only wet snow was produced for a short period of time in many cases. For instance, when the vertical motion is 10 cm/s (which also correspond to a relative humidity of 100% and a precipitation rate of 2 mm/h), when the relative humidity is 95 %, and when the vertical motion is 20 cm/s.

5. CONCLUDING REMARKS

A systematic study of the precipitation formed in the vicinity of the rain-snow boundary along mountainside has been carried out. The effects of the upslope wind along the mountainside, temperature and humidity profile as well as the snowfall rate aloft have been investigated. A one-dimensional kinematic cloud model (Theriault and Stewart, 2007) coupled with a microphysics scheme including wet snow and slush is used to address this issue. The model is initialized by a typical temperature profile varying from 5ºC at the surface to -5ºC at 2 km above the surface.

The effects of latent heat of warming due to cloud droplets formation are increasing the time to eliminate the melting layer into a layer of temperature <0ºC by a factor of two compared to only the effects of background vertical air velocity. It shows also that the effects of melting varying the temperature fields in the top of the melting layer whereas condensation is more important near the surface.

We showed that the evolution of the melting layer into temperature ≤0ºC is faster within a background vertical air velocity. For example, it takes nearly four times as long to produce such a temperature profile with a vertical motion of 5 cm/s than when falling within a vertical motion of 20 cm/s. Also, the greater background vertical motion generates more adiabatic cooling for leading to different evolution of precipitation types and their combinations.

The other factors studied such as the degree of saturation of the environment and the initial snowfall rate also play an important role on the duration of each precipitation types and their combination as well as their duration. For instance, the time needed to eliminate the melting layer varies by only 40 min between the minimum and the maximum precipitation rate assumed. This difference in time is much shorter than the one produced between the minimum and maximum values of vertical air velocity.

This study demonstrates that the evolution of single precipitation types and their combination can vary depending on the atmospheric conditions such as the precipitation rate aloft, the degree of saturation and the upslope winds. For instance, most cases produce a precipitation type evolution of: rain only, rain mixed with slush; rain mixed with slush and wet snow and wet snow. A few cases also produced mixture of slush and wet snow for a short period of time. However, this precipitation combination is only produced within very narrow atmospheric conditions.

Finally, it was demonstrated that the evolution of the rain-snow boundary along mountainside can evolve between various single types of precipitation and various mixtures of precipitation. The correct prediction of winter precipitation types therefore requires not only a detailed simulation of the evolution of precipitation particles but it also requires the careful simulation of the relative humidity, precipitation rate and, most important, the vertical air velocity.

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