# Discrimination of Solid from Liquid Precipitation over Northern Eurasia Using Surface Atmospheric Conditions

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**Abstract**

Daily synoptic observations were examined to determine the critical air temperatures and dew points that separate solid versus liquid precipitation for fall and spring seasons at 547 stations over northern Eurasia. We found that critical air temperatures are highly geographically dependent, ranging from -1.0 to 2.5°C, with the majority of stations over European Russia ranging from 0.5 to 1.0°C and those over south central Siberia ranging from 1.5-2.5°C. Fall season has a 0.5°-1.0°C lower value than the spring at 42% stations. Relative humidity, elevation, station's air pressure, and climate regime were found to have varying degrees of influences on the distribution of critical air temperature, although the relationships are very complex and cannot be formulated into a simple rule that can be applied universally.

Although the critical dew point temperatures have a spread of -1.5 to 1.5°C, 92% of stations have critical values of 0.5-1.0 °C. The critical dew point is less dependent on environmental factors and seasons. A combination of three critical dew points and three air temperatures are developed for each station for spring and fall separately that has improved snow event predictability when dew point is in the range of -0.5-1.5°C and improved rainfall event predictability when dew point is higher than or equal to 0°C based on statistics of all 537 stations. Results suggest that application of site-specific critical values of air temperature and dew point to discriminate between solid and liquid precipitation is needed to improve snow and hydrological modeling at local and regional scales.

## 1. Introduction

Precipitation is the most important water resource for the land surface. In high-latitude/elevation regions, solid precipitation consists of a very significant portion of total precipitation amount and its accumulation has a profound influence on surface energy budgets, hydrological cycles, permafrost condition, surface air temperature, atmospheric circulation, etc. At middle and high latitudes where most precipitation starts in solid form, the type of precipitation that reaches the ground is determined by the atmospheric condition through which the snowflakes fall. The most common method to separate solid versus liquid precipitation involves surface air temperature, which is the most easily obtained measurement.

In 1974, Auer studied 1,000 US Service A Teletype surface weather observations to identify surface air conditions associated with snow and rain respectively. He concluded that when the air temperature is 2.2°C, the probability of rain and snow are 50% each, and that 95% probability for snow occurs at 1.1°C and for rain at 5.6°C. He also stated that rain was virtually never recorded when the air temperature was below 0°C and that snow was never observed when temperature exceeded 6.1°C. A recent study by Dai (2008) using global synoptic observations, estimated that the half point of snow versus rain over the global land surface is 1.2°C and over the oceans is 1.9°C and the range of transition is very wide (-2 to 4°C over low and moderately low land). Both studies combined all available station records to derive a single set of critical temperatures that can be applied to all localities over a large study region and over the ocean for all years.

In reality, the atmospheric condition that separates solid versus liquid can vary greatly from one place to another. For example, a study in Japan suggested that critical temperature differences are up to 3°C between different locations (Montoyama, 1990). Rohrer (1989) found that change in the measurement site resulted in significant change of the mean and the spread of the transition range of air temperature. This may explain the large differences (about 1.0°C) in the critical air temperature of the half point (50% of snow and rain) revealed in the studies of Auer (1974) over U.S. and Dai (2008) over the global land area and oceans. The Kienzle (2008) study of 15 stations across southwestern Alberta, Canada, revealed a large spread of half point temperature, ranging from 1.2°C to 4.5°C of daily mean. Kienzle (2008) used daily mean temperature, which may increase the range of the difference compared to higher temporal resolution measurements other studies used (Rohrer 1989). Yang et al (1997)'s modeling study at five stations over Siberia found that by lowering critical temperature to 0°C from 2.2°C improved the snow accumulation calculation significantly, suggesting a possibly lower critical temperature in Siberia.

In addition to air temperature, other variables that can influence precipitation types include humidity, due to its evaporating role in cooling (Matsuo et al 1981; Montoyama 1990), air density/pressure that affects the falling speed of each snow flake (Stull, 2000; US Army Corps of Engineers, 1956), salt content in droplets that reduce freezing point (Dai, 2008), elevation that affects the thickness of the air layer through which a snow flake travels, topography that influences direct solar heating of the ground, etc. Most of these factors are not dominant ones, but do influence critical air temperature values to varying extents and with varying degrees of complexity.

The near-surface vertical temperature profile is also critical to precipitation type. The strong inversion layer found in the Arctic may make it possible for rain to occur even at a very low surface air temperature (Serreze et al 1992; Bradley et al 1992). In the Swiss Alps, Rohrer (1989) found that rain occurred with a surface air temperature of -5.8°C due to the presence of a strong inversion and high elevation. Kienzle's Alberta, Canada study (2008) found a strong seasonal oscillation in critical temperature with a maximum in winter and minimum in summer. Insignificant differences in seasonality of critical temperature were found in the study of Dai (2008) in which the entire global land areas were combined without discriminating between regional differences.

The large diversity in critical air temperatures on the transition of snow to rain found in different regions, and uncertainty about the potential significance of dew point temperature present a need for more comprehensive studies over a large geographical region with very fine spatial resolution. Northern Eurasia is ideal due to its high frequency in snow events, the sheer size of the subarctic landmass, good quality of historical synoptic observations, and the significant role of Eurasian snow cover to the global climate system (Cohen and Entekhabi 1999).

We investigate critical surface air temperature and dew point for individual stations across Northern Eurasia for spring (Mar-June; to include some snow events in June in northern regions) and fall (Sept-Nov) seasons. Dew point temperature is directly related to atmospheric humidity, the second-most significant factor in determining precipitation type (Matsuo et al 1981) and it may have a more consistent critical value for mountain stations (Mark and Winstra, 2007). The winter season is excluded from this study due to the fact that liquid precipitation events are mostly limited to European Russia; the rest of the region is predominantly solid precipitation during winter (Ye et al., 2008). Similarly, summer season is excluded from this study due to its small sample size: the average last snowfall date for the coldest stations is June 9 (Ye, 2003). The critical value is defined as the half point in precipitation state (50% solid, 50% liquid). This half point value is the most important number for estimating annual snow accumulation based on sensitivity tests in Canada (Kienzle, 2008). In addition, most precipitation is a single event of either solid or liquid (Dai, 2008) rather than a mixture of both in different proportions depending on air temperatures, an assumption made in many climate models.. Detailed station-by-station information is important for small-scale regional hydrological models to better understand local snow accumulation and hydrological processes. This will reveal the geographical and seasonal differences in atmospheric conditions that determine precipitation type. Finally, the potential changes of the ratio of snow to total precipitation will be examined to better understand potential changes in frequencies of precipitation forms under a warming climate (Ye 2008).

## 2. Data and Methodology

The data set used is the Global Synoptic Climatology Network, C: The former USSR, available from the National Climatic Data Center (NCDC, 2005). It is the compilation of in-situ hourly meteorological observations for the former USSR. Although some stations go back as early as 1871, there were only 3 daily observations before 1936 and 4 daily observations from 1936 to 1965 based on mean astronomic times, and 8 daily observations since January 1966 based on local standard times. There were also many inconsistencies in observation times among stations before 1966. This data set includes 2095 stations. However, only 757 stations have continued observation through January 2001 due to significant drops in station operation from 1990 to 1993. For this study we chose the time period from 1966-2000 due to more consistent observational practices. Among these 757 stations, 547 stations are retained for this study, having record lengths ranging from 27-35 years.

The synoptic observation records include sea level pressure, station pressure, air temperature, vapor pressure, relative humidity, wind speed, wind direction, cloud cover and type, and weather condition. The weather condition has codes to indicate many varieties of precipitation types. In this study, we focus only on liquid and solid precipitation. Liquid precipitation includes drizzle, rain, shower, freezing rain and freezing drizzle, and thunderstorm with liquid products; solid precipitation includes snow, snow shower, ice pellets, snow grain, and diamond dust. These groupings are the same as those used in an earlier study examining changes in precipitation types (Ye, 2008). The very small number of mixed precipitation events is excluded in analyses. There is a potential problem with weather code “0”, which supposedly indicates no weather; there is the possibility that missing values in weather code are also labeled as”0” (NCDC, 2005). Since it is very hard to distinguish missing weather observations from no weather condition, we use the air temperature observation as a safe guard. If the air temperature value is labeled as missing and the weather code is ‘0”, we assume that the accompanying weather code “0” is a missing value at that observation time. Because these observations were made manually, if the person was not able to make it to the station to do a reading of air temperature, it is most likely that he or she would not have been able to record the weather condition either.

Since the original data set does not include dew point temperature, which is also an important variable that closely corresponds to precipitation type based on our earlier exploratory research with a different data set, the dew point temperature is derived from air temperature and relative humidity based on the Magnus formula:

$$Td=cr/(b-r) \quad (1)$$

$$r=\ln(RH/100)+bT/(c+T) \quad (2)$$

where T is air temperature in Celsius, RH is relative humidity in percentage, b=17.67, c=243.5°C (Bolton, 1980). Ironically, the original NCDC data description document indicates that many of the relative humidity and vapor pressure measurements were converted from dew point temperature that has a precision of a whole degree, thus there could be some range of error in the accuracy of 3% and 4mbrespectively (NCDC, 2005). The conversion back to dew point generates decimals; thus a small range of possible errors in the dew point conversion is expected.

Each liquid and solid event is counted according to each half degree interval from -3.5°C to 3.5°C for both air temperature and dew point at each station. The frequency distribution for rain and snow is constructed respectively across this temperature range as illustrated in Figure 1a. As air temperature increases, snow frequency decreases while rain frequency increases. The crossing point where snow frequency drops below 50% and rain frequency rises above

50%, the critical air temperature (CT) for the snow-to-rain transition is thus determined. In a similar way, the critical dew point is also estimated for each station (Figure 1b).

The mean values of relative humidity, air pressure, dew point, and air temperature at each station are derived from all observations during the study period. If more than 10% of observations are missing, that variable is considered as missing for the month, and thus missing for the season. However, if the desired quantity is the climatology value for a station, regardless of the time or year, the mean value is derived from all available observations.

## 3. Results

### 3.1 Critical Air Temperatures

The critical air temperature (CT) for all fall (Sept-Nov) and spring (Mar -Jun) months ranges from -1.0°C (only at one station) to 2.5°C with 85% of all the stations having an observed CT of 1.0°C (285 stations) and 1.5°C (180 stations). The distribution of CT is shown in Figure 2. The salient features are the lower CTs over European Russia, the highest CTs over southern Central Siberia near Lake Baikal, and the moderate CTs in eastern Siberia. Central Siberia is where the elevation starts to rise associated with the high topography of Central Asia. To examine if elevation is a factor for increased CT, the scatter plot of CT versus station's elevation is shown in Figure 3. No stations at sea level have CTs higher than 1.5°C, but the highest elevation is not associated with the highest CT. In other words, the very high elevation stations can have very low CTs and the highest CTs occur in the midrange of elevation around 400-500 meters (Figure 3). This indicates that elevation is not the only determinant of CT although the correlation coefficient between elevation and CT is 0.3142, significant at a 99% confidence level (for the sample size of 547 stations). This complex relationship between critical temperatures and elevation was consistent with the findings by Kienzle (2008) in Alberta, Canada and by Feiccabrino and Lundberg (2008) in Sweden. Thus, we cannot just use one simple rule to adjust the CT with varying elevations even at nearby stations.

The location of these high CT stations is mostly in a climate regime of Dwc (Dry, cold) compared to Dfs (Dfb,Dfc,Dfd, fairly humid, cold) over the rest of the study region based on Köppen's classification. To examine the impact of relative humidity on CT, the scatter plot of CTs and relative humidity are shown in Figure 4. In general, the higher CTs are found at stations with lower relative humidity and lower CT stations are associated with higher relative humidity. This is consistent with other studies that suggest snow is more likely to occur at higher air temperature conditions when the air is dry (Matsuo, 1981; Montoyama, 1990). The correlation coefficient between the two is -0.4087 (sample size of 547 stations), statistically significant at the 99% level and above.

The combined effects of elevation and relative humidity on CT are shown in Figure 5. Stations with low CTs are located at low elevations and have higher relative humidity while high CTs are found at stations with lower relative humidity and higher elevations. However, the overall separation is not strong.

To further understand how atmospheric conditions alone might impact CT, the data are separated into spring (March to May) and fall (September to November) seasons and the CT for each season is calculated independently. Any difference in CT is dependent on the atmospheric condition since the geographical features are the same for each station. The map of CT difference between fall and spring (fall CT-spring CT) shows that 231 stations have a 0.5 to 1°C lower CT in the fall, 285 stations have no difference and only 31 stations show that the fall has a higher CT than that of spring (Figure 6). There is no distinct geographical pattern in the difference of CT between the two seasons, except that large positive numbers (a very small percentage of stations) are mostly found along the southeastern coastal and island stations.

An example of a shift in CT between fall and spring is shown at Figure 7, at a randomly selected station in European Russia (Hanty-Mansij at 61.0N, 69.0E). The potential contributors to the CT difference may be the station's relative humidity and air pressure. Differences in CT between fall and spring are plotted against differences in relative humidity and air pressure in Figure 8. Fall season has a higher relative humidity and higher air pressures at most stations. As a result, fall tends to have a lower CT compared to that of spring. Higher relative humidity tends to reduce critical temperature while high air pressure associated with high air density decreases the falling speed of snowflakes and provides more time for melting thus reducing critical temperature. The eastern coastal stations that have higher fall CTs tend to have lower relative humidity in fall (shown in red and orange stars).

**3.2 Critical Dew Point Temperatures**

The critical dew point temperature (CTd) ranges from -1.5 °C to 1.0°C, with 396 stations having 0.5°C and 108 stations having 1.0°C (accounting for 92.1% of all stations; see Figure 9). There is no distinct geographical distribution pattern of critical dew point temperature, suggesting that the critical values of dew point are less sensitive to local geographical features. Furthermore, differences in critical dew point between fall and spring is much less clear: 373

stations show no difference, 75 stations show fall has slightly lower and 99 stations show fall has slightly higher critical temperature (0.5-1.0°C). Also, critical dew point seems to be insensitive to relative humidity and elevation. Stations with lower CTd appear more likely to have higher station pressure, but there are many exceptions with no clear relationship. This indicates that dew point temperature may be a better variable to use in separating solid from liquid precipitation because it seems to be less sensitive to environmental factors. Mark and Winstral (2007) in their study to identify the air temperature and dew point when snow changed to rain during major storm events over the Owyhee Mountains of Idaho (1488-1868m elevation) pointed out this consistency in critical dew point temperature.

**3.3 Combination of Critical Air Temperatures and Dew Points**

The plot of solid and liquid precipitation against corresponding temperature and dew point at a range of -3.5°C to 3.5°C is shown at a randomly selected station (Ulan-Ude at 51.8N, 107.43E; Figure 10). The combination of critical temperature and dew point do a better job of separating solid from liquid precipitation than using just temperature or dew point alone. The most clear results are: solid precipitation is dominant when air temperature is lower than or equal to CT and dew point is lower than or equal to CTd (lower left section); liquid precipitation is dominant when air temperature is higher than CT and dew point is higher than CTd (upper right section). There are still some mixes of both precipitation types at other combinations of temperature and dew point (upper left section and lower right section). Although the number of events falling into these combinations are not as large as those clearly defined for snow and rain events (especially the upper left section), there seems to be a pattern. For example, when the dew point is lower than CTd (lower right section of Figure 10), solid precipitation is more likely when air temperature is low; when the dew point is higher than CTd (upper left section) liquid precipitation is more likely when temperature is high (Figure 10).

To further improve the classification of solid versus liquid precipitation based on these two sections where both could occur, a secondary critical dew point and air temperature can be derived by using similar methods but with a set of limited range of dew point and air temperature specific for each of these two sections respectively. For the upper left section of air temperature < or =CT and dew point >CTd, the secondary critical dew point is the cross point where solid precipitation frequency falls below 50% and liquid precipitation frequency rises above 50% in all events that fall into these conditions. In the case of station Ulan-Ude, the secondary CTd (CTd-upper) is 0.5°C in the fall (Figure 10). A similar method determines that secondary CTd for the lower right section (CTd-lower) of air temperature >CT and dew point < or = CTd is -2.0°C in the fall. After the secondary CTd is determined, the rest of precipitation events that fall either above (upper left section) or below (lower right section) are used to determine that secondary CT. Then the secondary critical air temperature from those events that occur at dew point >CTd-upper and air temperature < or = CT is derived (called CT-upper; 1°C for this station in the fall). Similarly, secondary CT for the lower right section of dew point < or = secondary CTd and air temperature > CT (CT-lower) is 3.5°C in the fall. Now, the solid versus liquid precipitation separation is improved with the combination of three CTs and three CTds for each station for spring and fall season separately. In summary, for solid precipitation to occur, there are three combinations of air temperature (T) and dew point (Td) conditions: (1)

T<= TC and Td <=CTd-upper; (2) T< =CT-upper; (3) T< = CT-lower and Td < = CTd-lower. The other conditions will result in liquid precipitation.

When there are not enough sample sizes, especially for the upper left or lower right section, the secondary CTs and/or CTds may have the same value as the primary CT or CTd and therefore do not contribute to improve the predictability of the precipitation form. After careful examination of the three CTs and three CTds, we found very few cases of CT-upper and CT-lower equal to primary CT for both spring and fall (0- 2%), and the similar situation for CTd-Lower (less than 1%). But for CTd-upper, 168 (31%) stations in spring and 226 (41%) stations in fall have the same value as the primary CTd. This suggests that there is no need for the secondary dew point to help separate snow from rain for the upper left section only.

The results of classified snow and rain events by using various critical CTs and CTDs are compared with those observed at all stations. the snow and rain events (black line) and those classified snow and rain events based on the primary CT only (red line), primary CTd only (blue line), and the combination of 3 CTs and 3 CTds (green line) are plotted in Figure 11a and Figure 11b for fall and spring respectively. These figures are based on each 0.5°C increment of dew point temperature for all months studied and all stations. The combination of 3 CTs and CTds correctly predicts 100% of all snow events when the dew point is equal to or below -0.5°C, as does primary CT-only prediction, but the primary CTd-only prediction missed some events (Figure 11a). When dew point temperature is higher than -0.5°C and lower than 1.5°C, the combination of 3 CTs and 3CTds has similar predictability as those using Ctd only. When dew point falls above 1.5°C, the primary CTd-only is the best predictor of snow events. Thus, it seems the combination of using CTs and CTds improves prediction for solid precipitation events most effectively when dew point is higher than -0.5°C and lower than 1.5°C.

For predicting rain events, using the combination of CTs and CTds improves rain prediction when the dew point temperature is above 0C. When the dew point is below that, CTd alone predicts inlt slightly better, but temperature alone missed many rainfall events (Figure 11b). For dew points higher than 0°C, using the CT alone or the combination of CTs and CTds correctly predicted 100% of rain events, but not when the CTd was the sole predictor. In general, the combination of CTs and CTds improves the prediction for rain events.

**3.4 Future Projection**

The geographical distribution of dew point and ratio of snow to total precipitation events averaged from the spring and fall seasons are shown in Figure 12. The mean dew point among these 547 stations ranges from -17.2°C to 10°C decreasing towards northern and inland areas (Figure 12a). A similar distribution pattern of ratio of snow over precipitation events is found, ranging from 2% to 95% averaged from both spring and fall (Figure 12b).

The ratio of snow events to total precipitation events at each station is plotted against the station's mean dew point temperature in Figure 13. It clearly shows that ratio of snow events to total precipitation events decreases with increasing dew point in a linear relationship. A simple regression analyses with ratio as the dependent variable and dew point as the independent variable found the ratio decreases -3.2 per degree of dew point increase. The correlation coefficient between the two is -0.9182, statistically significant at 0.01 or above (N=547). The ratio of 50% snow over total precipitation event corresponds to a mean dew point temperature of about -2.6°C. This is observable in Figure 2 where geographical regions of 50% ratio line seems to roughly corresponding to those of the -2°C dew point line.

The projected changes in snow versus total precipitation events will be across the board reduction of about 3.2% for each dew point temperature increases. Climate models predicted a 4-6°C increase in air temperature by 2090-99 over the study region (Trenberth et al. 2007). It is a reasonable assumption that the dew point temperature would increase a little more than air temperature given that if the relative humidity stays constant (Trenberth et al. 2007). To be conservative, we assume due point temperature increases at similar magnitude if the dew point depression stays relatively constant. Using an estimated increase of dew point temperature by 4°C, the ratio of snow to total precipitation events would decreases by more than 12% in all locales in the study region.

**4. Conclusions**

This study uses historical synoptic observations to define critical thresholds of air temperature and dew point that separate solid versus liquid precipitation over northern Eurasia. A total of 547 stations over the period of 1966 through 2000 are evaluated. Results show that critical air temperature that separates solid versus liquid precipitation is geographically and seasonally dependent and influenced by elevation, relative humidity, and station air pressure. Over European Russia, the CTs are around 0.5°C-1.0°C lower than the rest. The highest CTs of 2.0°C-2.5°C are found over south central Siberia.

Critical dew point temperature, however, is less dependent on geographical features and atmospheric conditions, although it occasionally varies with locality, and thus it is a more representative variable for precipitation phase overall. About 92% of the stations located in northern Eurasia have critical dew point temperatures of 0.5-1.0C (defined as the frequency midpoint of solid versus liquid precipitation). Considering the lack of accuracy in dew point records (rounded to the nearest whole number) and the need to derive dew point values for this research, our results are quite encouraging.

To further improve the predictability of solid versus liquid precipitation we recommend using the combinations of three critical air temperatures and three dew point temperatures specifically derived for each station. The most significant improvement for event prediction achieved using this combination occurred when dew point is higher than –0.5°C and lower than 1.5°C. When dew point is lower than or equal to -0.5°C, the use of CT alone is adequate and when the dew point is 2.5°C or above, CTd alone can be applied.. For rain events, the combination of critical CT and CTd improves rainfall prediction when dew point is higher than or equal to 0°C. Otherwise, dew point alone can be used. . The combinations of three CTs and three CTds are included in the appendix for use in model simulations of snow accumulation in cold regions.

The ratio of snow events to total precipitation events decreases at a rate of -3.3% for each degree of dew point increase over the region of study. Using the projection of possible 4°C dew point temperature increase, the ratio of snow events to total precipitation events would decrease by more than 12% across the study region in spring and fall.

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Figure Captions:

Figure 1. Frequency distribution of solid (stars) and liquid (squares) corresponding to each half degree increments in a. air temperature; b. dew point temperature for a randomly selected station (Hanty-Mansil; 61.0N, 69.0E). Horizontal line is the 50% frequency.

Figure 2. Critical air temperature distribution map for all 547 stations and all days in March-June, and Sept-Nov.

Figure 3. Critical air temperatures plotted against stations' elevations

Figure 4. Critical air temperature plotted against stations' relative humidity

Figure 5. Critical air temperature in relationship with relative humidity and elevation. Red stars=2.5°C; Orange stars=2.0°C;Yellow stars=2°C;Green triangles=1.5°C;Light blue triangles=1°C;Blue triangles=0.5°C;Purple triangles=-0.5°C or lower.

Figure 6. Differences of critical air temperatures between fall (Sept-nov) and spring (Mar-May) (fall-spring)

Figure 7. Frequency distribution of solid (solid lines) and liquid (dashed lines) precipitation for all (solid lines) and spring (dashed line) in corresponding to each 0.5C increment in air temperature. Horizontal line is the 50% frequency.

Figure 8. Difference of CT between fall and spring in relationship with that of stations' relative humidity and air pressure. Orange stars=2.0°C;Yellow stars=2°C;Green

triangles=1.5°C;Light blue triangles=1°C;Blue triangles=0.5°C;Purple triangles=-0.5°C or lower.

Figure 9. Critical dew point temperature distribution map for all 547 stations and all days in March-June and September-November.

Figure 10. Solid (star) and liquid (triangle) precipitation corresponding to air temperature and dew point when it occurred at a randomly selected station (Ulan-Ude 51.8N, 107.43E). Horizontal solid line is the critical dew point (CTd) and vertical solid line is the critical air temperature (CT). Horizontal dashed lines are secondary CTds and vertical dashed line are secondary CTs.

Figure 11. Observed and predicated precipitation events arranged according to each half degree increment of dew point for all stations and all solid or liquid events. Black line is all solid (or liquid) observed precipitation events; red line is predicted based on CT only; blue line is predicated based on CTd only; green line is predicated based on combination of three CTs and three CTds.

Figure 12. Geographical distribution of a. mean dew point temperature and b. ratio of snow events to total precipitation events for both spring and fall season combined.

Figure 13. Scatter plot of each station's ratio of snow events to total precipitation events against the dew point temperature. The thick line is the simple linear regression line represents the computed rate of change.

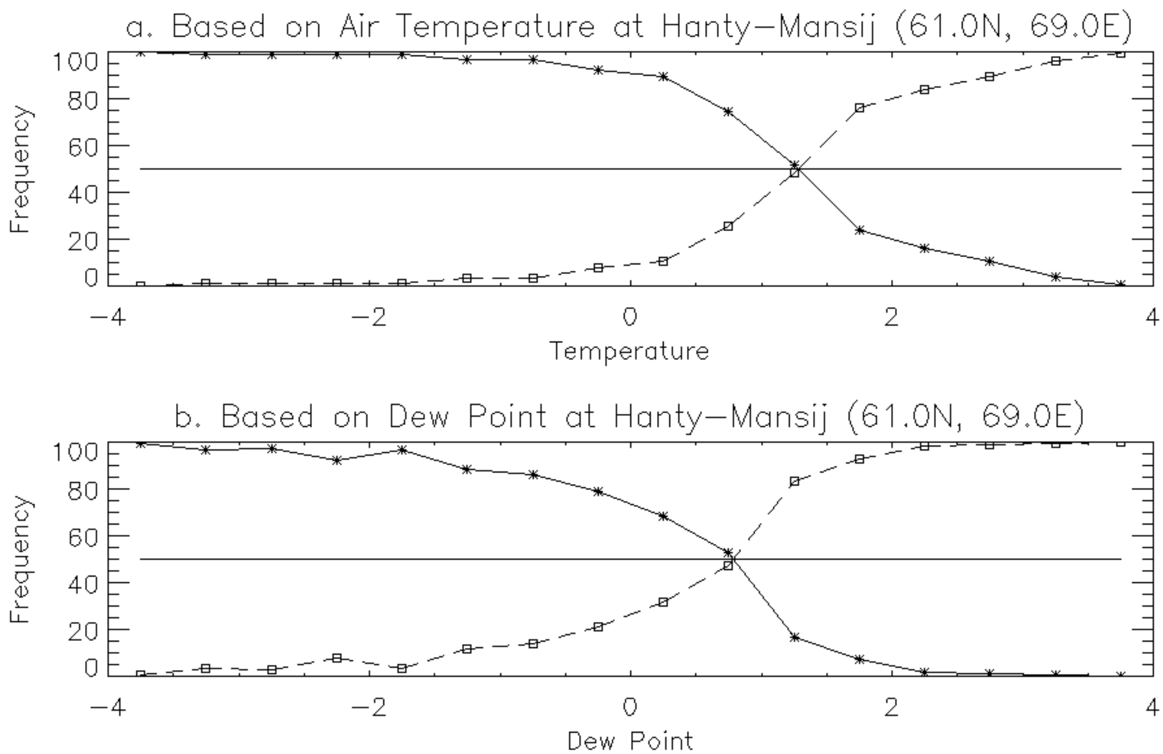


Figure 1. Frequency distribution of solid (stars) and liquid (squares) corresponding to each half degree increments in a. air temperature; b. dew point temperature for a randomly selected station (Hanty-Mansil; 61.0N, 69.0E). Horizontal line is the 50% frequency.

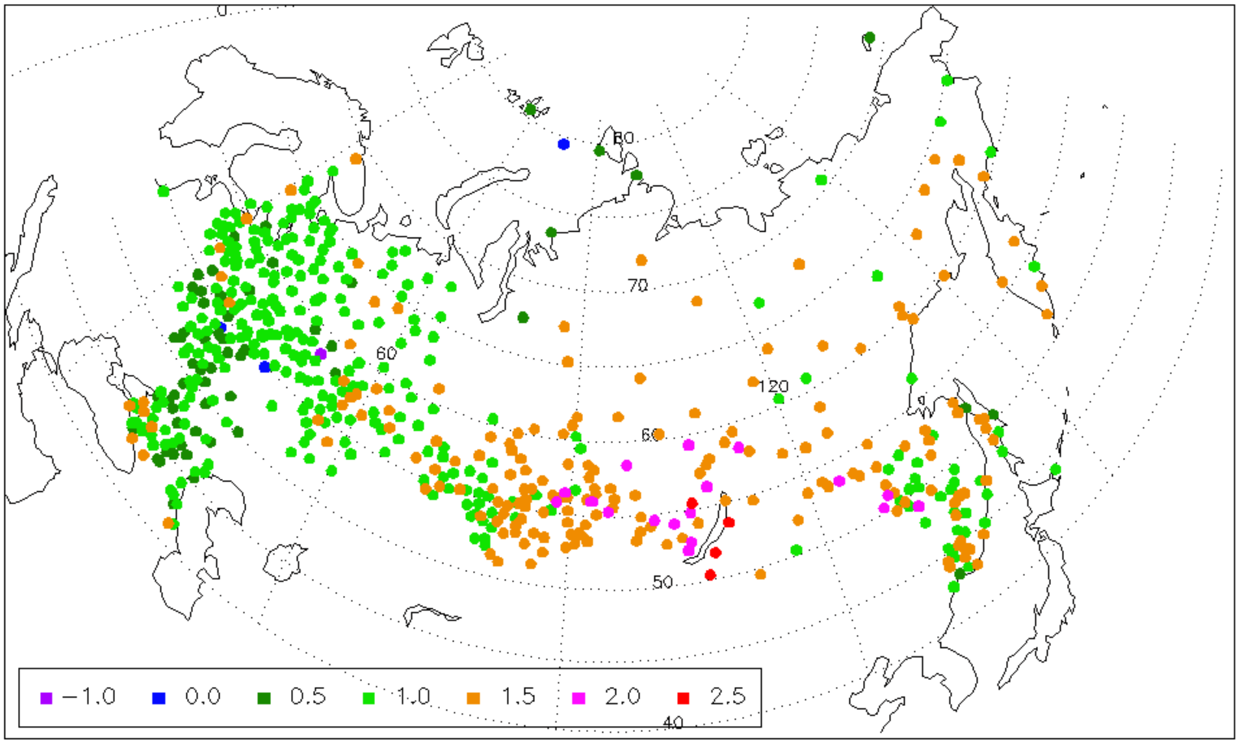


Figure 2. Critical air temperature distribution map for all 547 stations and all days in March-June, and Sept-Nov.

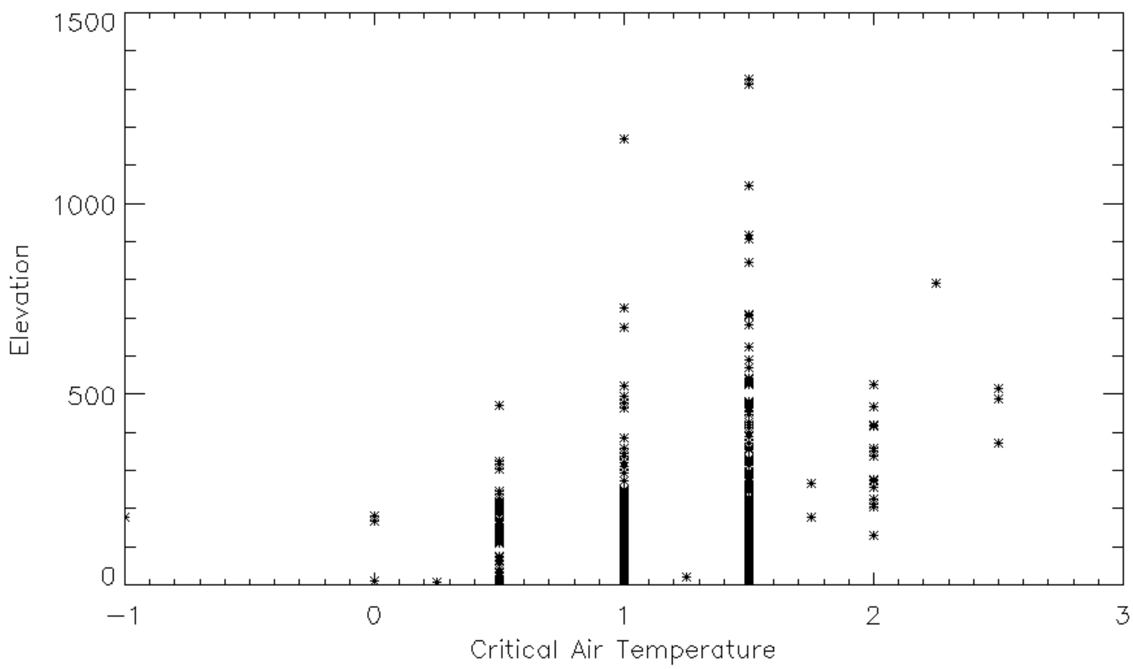


Figure 3. Critical air temperatures plotted against stations' elevations

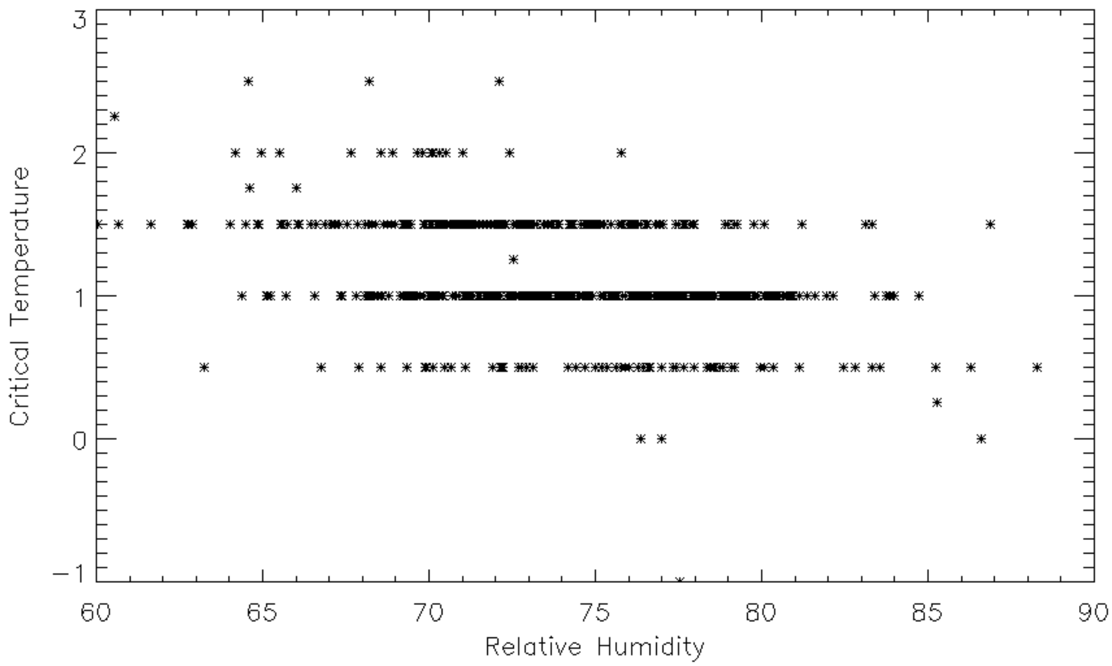


Figure 4. Critical air temperature plotted against stations' relative humidity

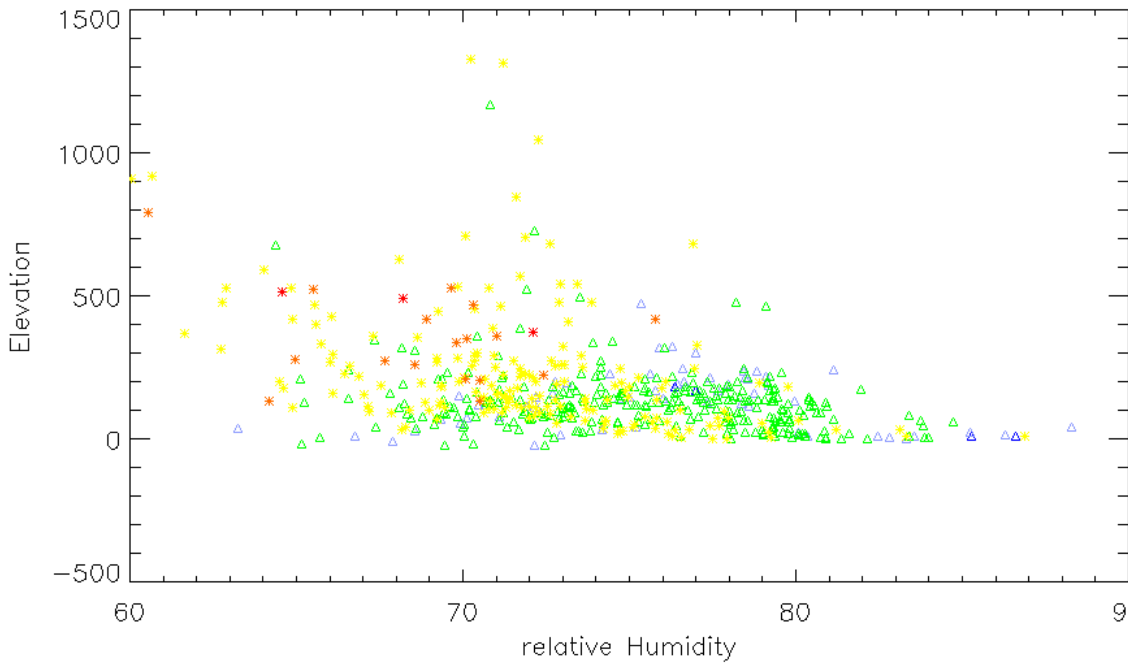


Figure 5. Critical air temperature in relationship with relative humidity and elevation. Red stars=2.5°C; Orange stars=2.0°C;Yellow stars=2°C;Green triangles=1.5°C;Light blue triangles=1°C;Blue triangles=0.5°C;Purple triangles=-0.5°C or lower.

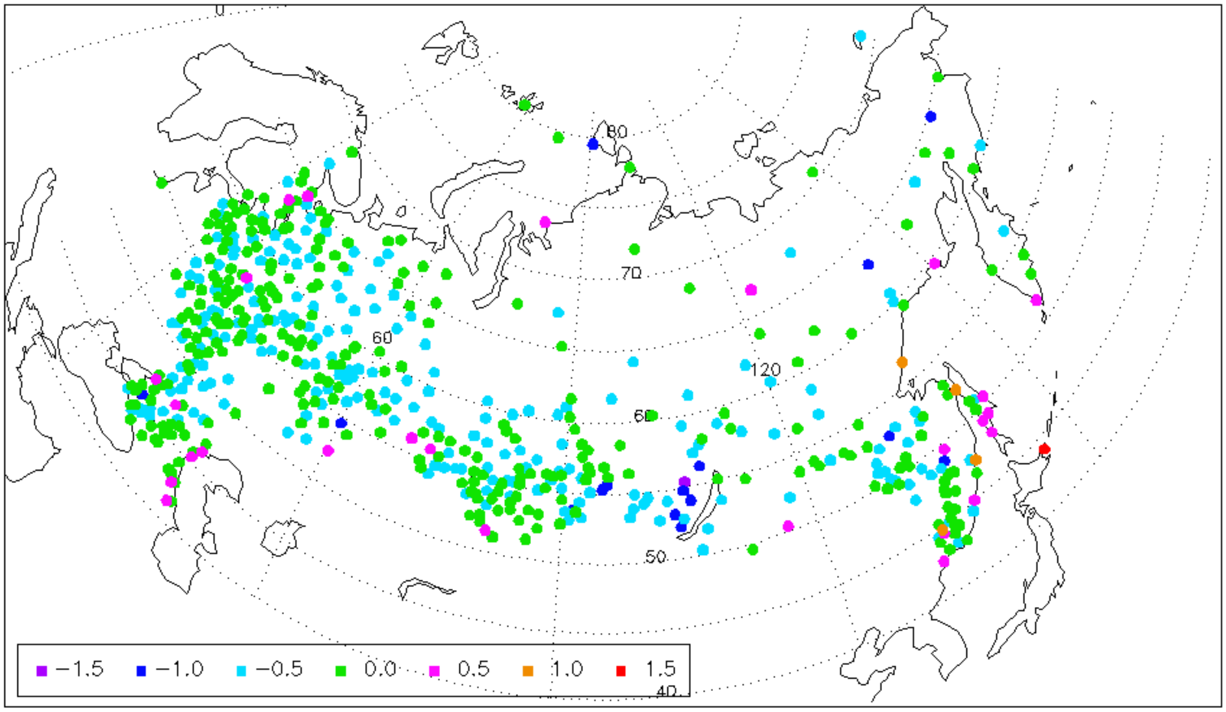


Figure 6. Differences of critical air temperatures between fall (Sept-nov) and spring (Mar-May) (fall-spring)

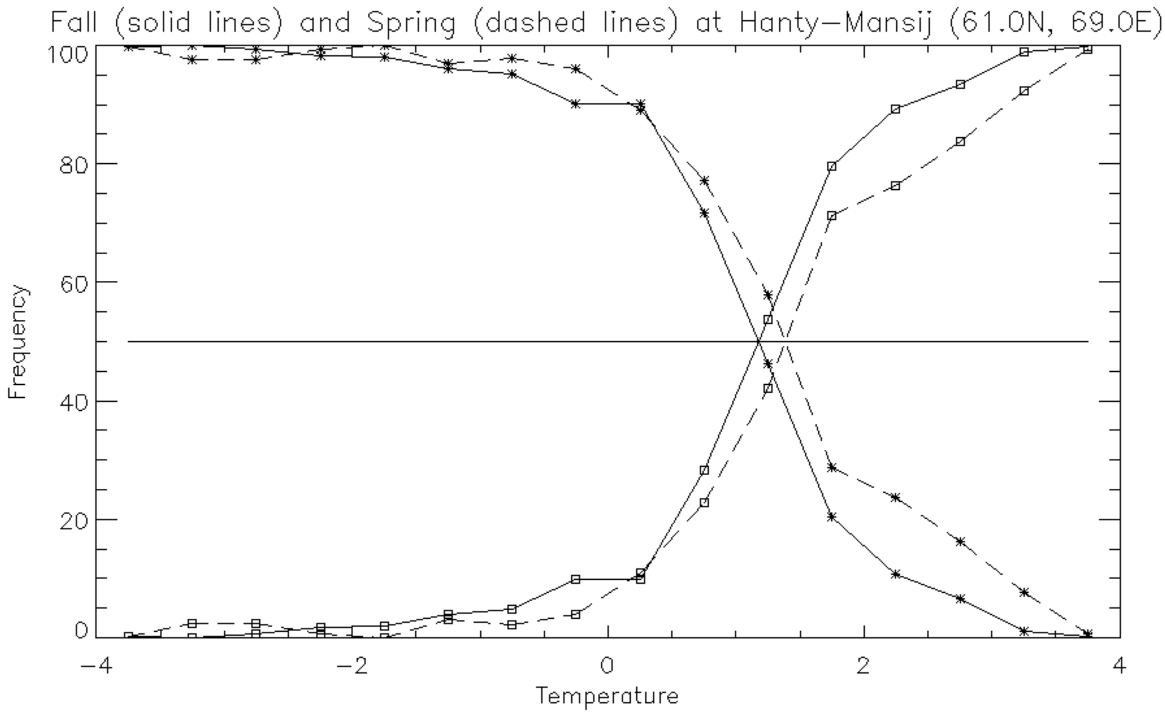


Figure 7. Frequency distribution of solid (solid lines) and liquid (dashed lines) precipitation for all (solid lines) and spring (dashed line) in corresponding to each 0.5C increment in air temperature. Horizontal line is the 50% frequency.

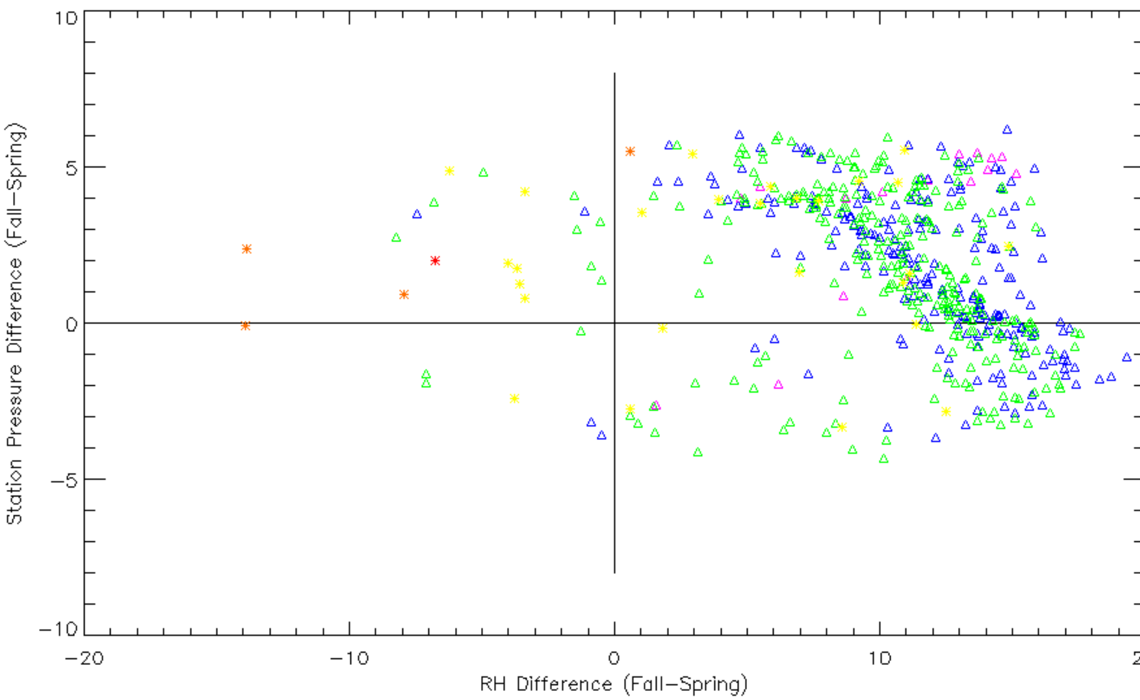


Figure 8. Difference of CT between fall and spring in relationship with that of stations' relative humidity and air pressure. Orange stars=2.0°C;Yellow stars=2°C;Green

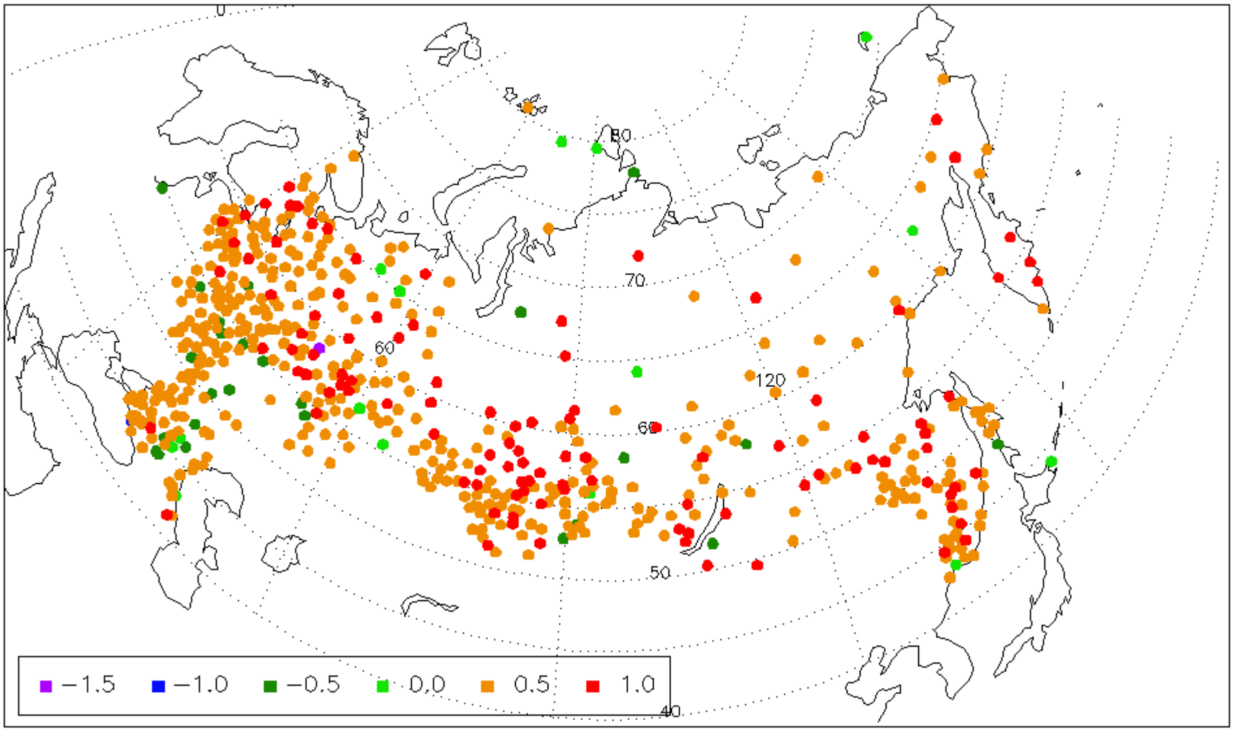


Figure 9. Critical dew point temperature distribution map for all 547 stations and all days in March-June and September-November.

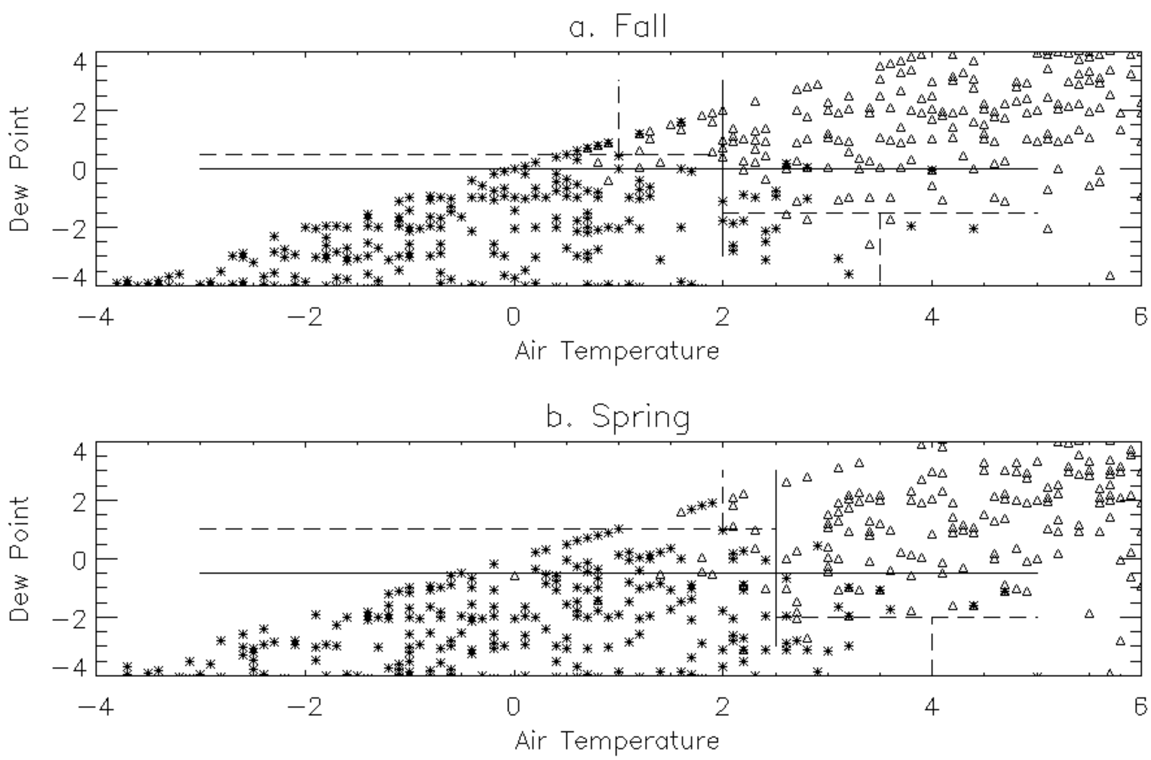


Figure 10. Solid (star) and liquid (triangle) precipitation corresponding to air temperature and dew point when it occurred at a randomly selected station (Ulan-Ude 51.8N, 107.43E). Horizontal solid line is the critical dew point (CTd) and vertical solid line is the critical air temperature (CT). Horizontal dashed lines are secondary CTds and vertical dashed line are secondary CTs.

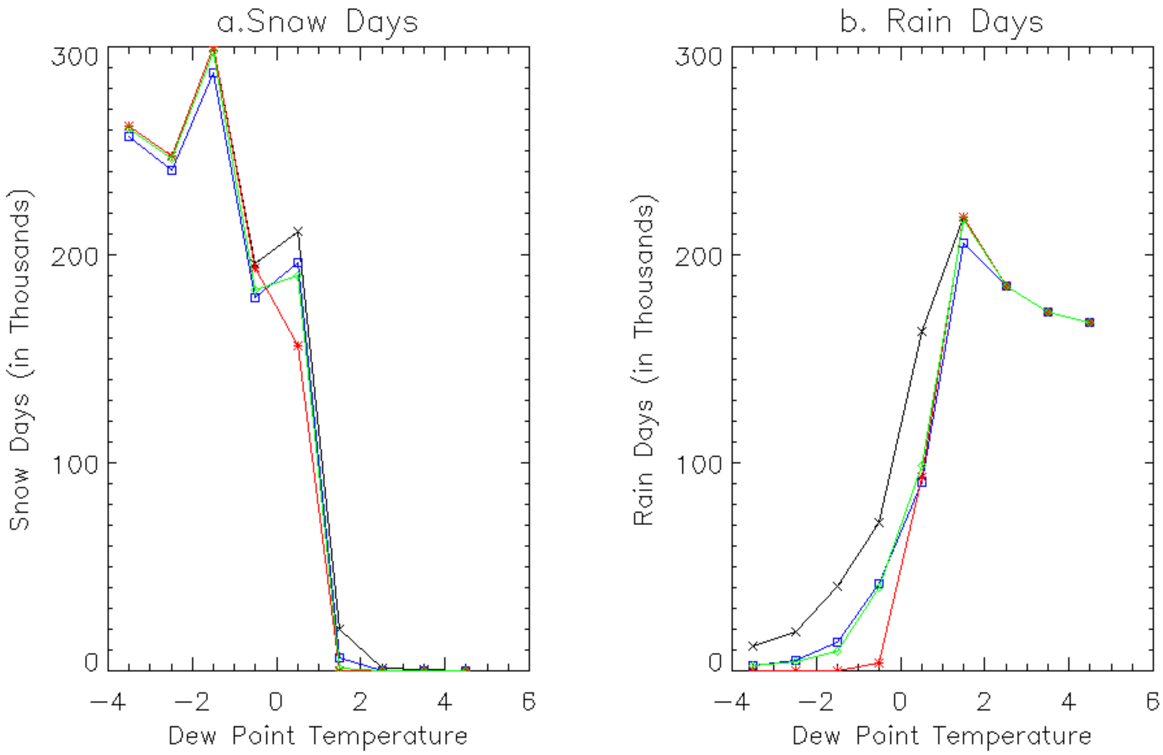


Figure 11. Observed and predicated precipitation events arranged according to each half degree increment of dew point for all stations and all solid or liquid events. Black line is all solid (or liquid) observed precipitation events; red line is predicted based on CT only; blue line is predicated based on CTd only; green line is predicated based on combination of three CTs and three CTds.

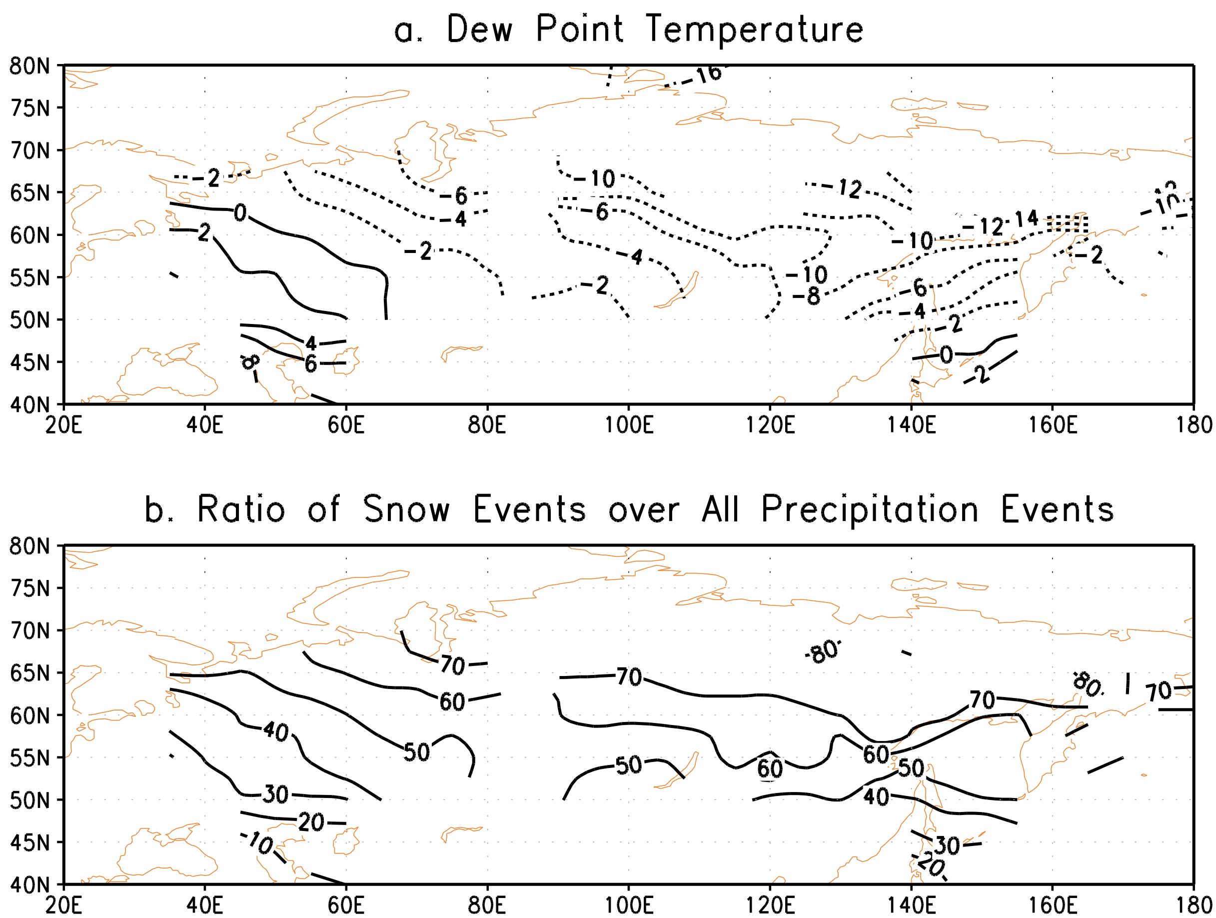


Figure 12. Geographical distribution of a. mean dew point temperature and b. ratio of snow events to total precipitation events for both spring and fall season combined.

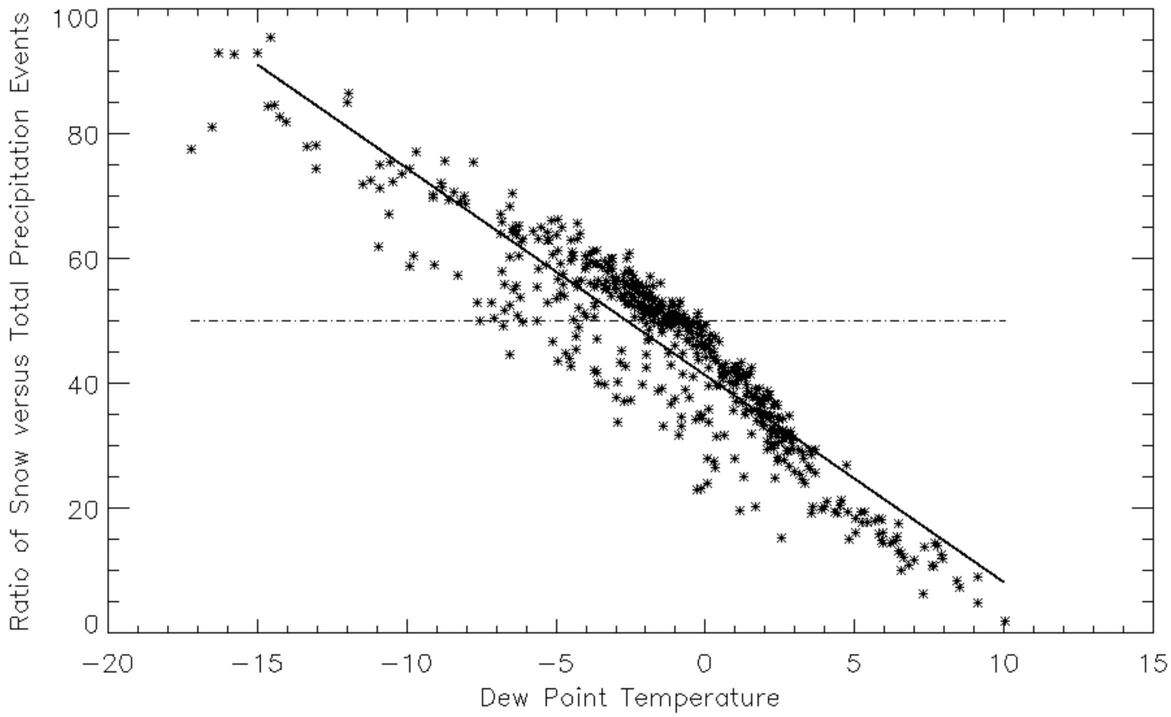


Figure 13. Scatter plot of each station's ratio of snow events to total precipitation events against the dew point temperature. The thick line is the simple linear regression line represents the computed rate of change.