The probability of precipitation as snow derived from daily air temperature for high elevation areas of Colorado, United States

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Abstract Precipitation phase affects the energy balance of the Earth's surface. Snow formation depends upon atmospheric conditions and is driven mainly by temperature. Dewpoint and air temperature thresholds at or near freezing temperatures have been used to determine precipitation phase in some climates, but may not adequately represent the same phase of precipitation in snowy and semi-arid regions, nor are relative humidity data available at many stations. The objective of this study is to describe relations between average air temperature and probability of snow for nine high elevation (>2000 m) meteorological stations across central Colorado, USA. Fifty years of data were analysed, generating snow probabilities from ratios of the number of days with snow and days with precipitation. These were compared to the average daily temperature during precipitation using 0.2°C intervals. Best-fit linear relations reveal higher probabilities of snowfall in the study areas at temperatures several degrees warmer than previously published curves.

Key words snowfall; precipitation; semi-arid climate

INTRODUCTION

The phase of precipitation is a function of the cloud conditions during formation and the atmospheric environment through which the precipitation falls. This is driven mainly by temperature. Snow crystals can form in clouds and melt during their fall to the ground, while in the presence of a temperature inversion, rain drops can freeze during their descent to the ground. The phase of precipitation is important to determine the energy balance at the Earth's surface, including the energy of the precipitation and the surface albedo derived from precipitation phase and the presence or absence of snowpack.

Traditionally climate and hydrologic models have used a 0°C threshold to distinguish between snow and rain. The 50% probability of snow as defined by Auer (1974), which is 2.2°C, was used as the threshold for the BATS land surface scheme snow sub-model, and yielded more appropriate snowpack characteristics than using a 0°C (Yang *et al.*, 1997). The Auer (1974) curve was derived from 1000 meteorological stations and thus represents average conditions. In the wetter climate of the California Sierra Nevada, the probability of snow curve (US Army Corps of Engineers, 1956) is closer to the 0°C threshold with a 50% probability of 1.35 degrees (see Fassnacht *et al.*, 2001; Fassnacht & Soulis, 2002). Even over short distances, the probability curves can be quite different, such as the 12-km between Arosa and Davos, Switzerland, as shown by Rohrer (1989). At Arosa, there were even marked seasonal differences (Rohrer, 1989).

To accommodate these climate-based differences, Marks *et al.* (2001) used a dewpoint temperature of 0°C as the threshold for rain *versus* snow. Recently, it was shown that over time and elevation, i.e. spatio-temporally, snowpack accumulation patterns were estimated equally well for an inter-continental climate in Idaho, USA, using the air, dewpoint, and dry-bulb temperature thresholds of 0°C (Marks *et al.*, 2013). However, many long-term meteorological stations only have records of daily precipitation, maximum and minimum temperature, without observations of snow or relative humidity. This makes the use/availability of such data difficult in certain regions and in the past. The temporal resolution of meteorological data may be too coarse to merit its use in estimating snowpack accumulation (Fassnacht, 2007); this can be due to a mismatch of model requirements or more importantly coarser resolution data do not represent processes correctly.

Snow can exist near the Earth's surface at warmer temperatures in a drier environment as compared to wet environments. For example, at 15:25 MST on 25 April 2011, snow was observed to fall on the west side of Colorado State University (CSU) in Fort Collins, Colorado. At the CSU weather station http://ccc.atmos.colostate.edu/~autowx, approx. 1-km away, the air temperature averaged +12°C (from 10-minute observations of +11.8 and +12.2°C), with a relative humidity of 46.8% (40 and 54%), yielding a dewpoint temperature of +0.86°C (–1.1 and 2.83°C). Considering this variability, we have examined the occurrence of snowfall at air temperatures warmer than zero degrees Celsius in snow dominated, continental environments, i.e. semi-arid regions. The objective of this paper is to determine a relation between air temperature and the probability of snow for high-elevation locations in a semi-arid climate such as Colorado, USA.

METHODOLOGY

Huntington *et al.* (2004) (and subsequently Knowles *et al.*, 2006, and Feng & Hu, 2007) used the daily observations of snowfall (code SNOW) from National Weather Service (NWS) Cooperative (COOP) stations. This is a record of fresh snow in the past 24 h, as the indication of solid phase precipitation and then used the daily precipitation amount (NWS COOP code PRCP) to determine the annual amount of precipitation as snow. Here we used the presence or absence of snowfall to identify the daily temperature during precipitation. Since only the daily maximum and minimum temperatures were recorded, these temperatures were averaged to estimate the mean daily temperature. The probability of snow was determined per 0.2°C temperature bin. The data were obtained from the GHCN (Global Historical Climatology Network) daily data time series for the 50 year period of record from 1961 to 2010 www.ncdc.noaa.gov.

STUDY STATIONS

Nine stations were selected for various high elevation locations across central Colorado, USA (Table 1 and Fig. 1). All the stations are at higher elevations (above 2000 m) and as such all were considered as snow climates with cool summers according to the Köppen-Geiger climate classification (code *Dfc*: Snow, Fully Humid, Cool Summer) except Alamosa, which had a cold semi-arid climate (code *Bsk*: Arid, Steppe, Cold Arid) (Kottek *et al.*, 2006).

Table 1 Summary of the study stations, including location and annual average climate: total precipitation, days with precipitation, days with trace events, annual snowfall totals as a cumulative depth of fresh snow, days with snowfall, average maximum temperature, and average minimum temperature.

Station Name	Lat. (N)	Long. (W)	Elev. (m)	Zip code	Total precip. (mm)	Days with precip.	Days with trace events	Snowfall amount [mm]	Days with snow	Max. temp. (°C)	Min. temp. (°C)
Alamosa	37.50	105.89	2307	81101	192	112	45	832	43	15.2	–4.65
Aspen	39.18	106.86	2458	81611	616	133	4	4426	76	13.1	–2.21
Climax	39.38	106.19	3440	80429	599	172	16	6961	122	6.18	–7.32
Hartsel	38.99	105.89	2730	80449	266	88	13	1214	35	11.8	–7.45
Leadville	39.25	106.29	3110	80461	350	166	46	3637	101	9.74	–6.33
Steamboat Springs	40.49	106.83	2064	80487	418	132	47	427	65	13.1	–4.96
Telluride	37.94	107.82	2676	81435	589	138	13	4513	63	13.4	–4.52
Vail	39.65	106.40	2491	81657	599	136	14	5005	82	11.0	–4.32
Walden	40.73	106.28	2471	80480	289	103	10	1557	55	11.6	–5.72

Alamosa, Hartsel, and Walden are all semi-arid locations with annual precipitation less than 300 mm (Table 1), yet these are not at the lowest elevation but located within high elevation plateaus (San Luis Valley, South Park and North Park). These locations are surrounded on all sides by mountains that are 1500–2000 m higher. Leadville averages 350 mm of precipitation per year but the surrounding mountains are 1000 m higher. The other five stations are in more snowy areas closer to the mountains; Steamboat Springs is at the base of the Park Range. Steamboat Springs, Leadville and Alamosa each had on average 1.5 months of trace events, while the other six stations had 2 weeks or less. The number of days with snow increased, as did the days with precipitation; Hartsel had 35 snow days on average of its total 88 days with precipitation (38%) while Climax had 122 snow days from its 172 precipitation days (71%). The latter station was the highest elevation station.

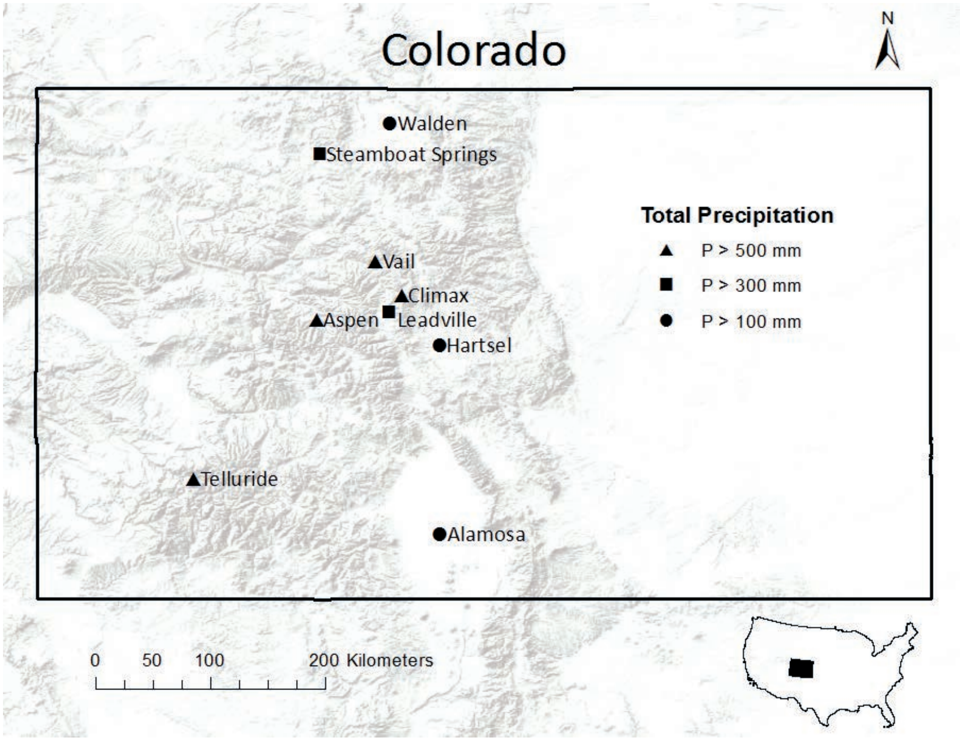

Fig. 1 Map of the state of Colorado illustrating the nine study stations and their annual precipitation rate.

RESULTS AND DISCUSSION

The probability of snow was plotted as a function of the daily average air temperature for the nine study stations in Colorado using the 0.2°C intervals (Fig. 2). For many stations, the probability of snow at near surface air temperatures colder than 0°C was 100% and 0% at temperatures warmer than 10°C. The warmest temperature with 100% snow was 3°C with the coldest 100% probability of rain occurring at 8°C. Each of these are approx. 2°C warmer than the Auer (1974) function. The probability of snow at air temperatures warmer than 10°C is small, i.e. this was observed for few stations, while the probability of rain at air temperatures colder than freezing is as low as 60%. The variability between 100% and 0% was approx. 3°C (Fig. 2).

The Steamboat Springs, Walden and Hartsel stations presented most of the coldest temperatures with rain. Steamboat Springs had a number of rain events at cold temperatures, with 17 rain observations at temperatures colder than –20°C. Many of the cold rain events were trace events; Steamboat Springs averaged 47 trace days per year over the entire period with an average of 61 days with trace events in the first 20 years (1961–1980). Since it was unclear if this decrease is real or due to a change in observation protocol or observer, the trace events were removed from this station for the computation of the probability of snow. When the trace events were included, the probability of snow was about 80% for all temperatures colder than freezing; it approached 95% when they were excluded.

The relations between air temperature and probability of snow could be approximated by linear functions between 100% and 0% snow (Fig. 3), except at the Steamboat Springs station. For

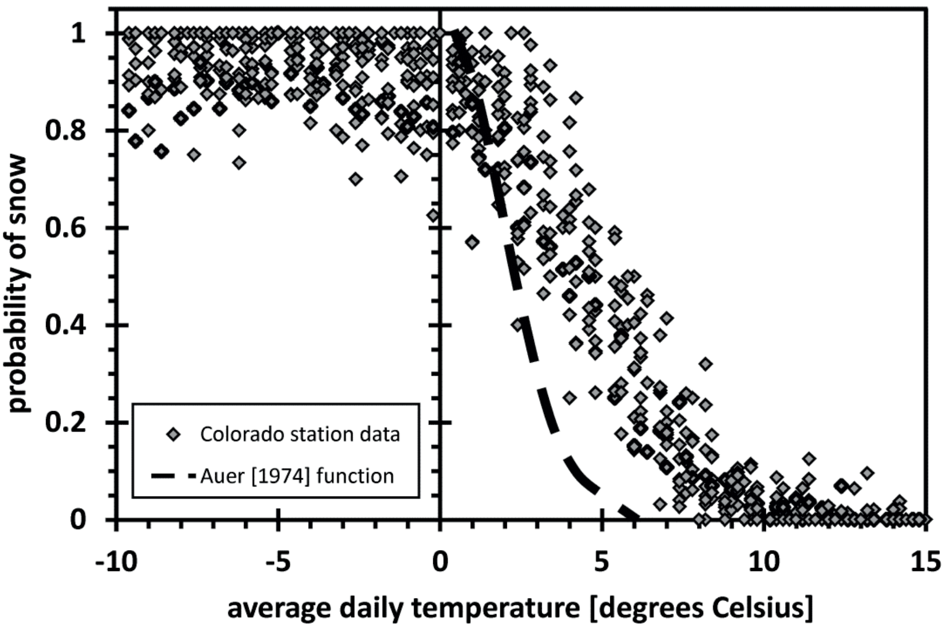

Fig. 2 The probability of snow as a function of the daily average air temperature for the nine study stations in Colorado. The average air temperature is the mean of the maximum and minimum. The temperatures were divided into 0.2°C intervals. The probability of snow was a ratio of the number of days with snow determined when snowfall was also recorded (from Huntington *et al.*, 2004) as a fraction of the total number of days with precipitation. The Auer (1974) curve is included for comparison. Data were obtained from the National Climatic Data Center www.ncdc.noaa.gov.

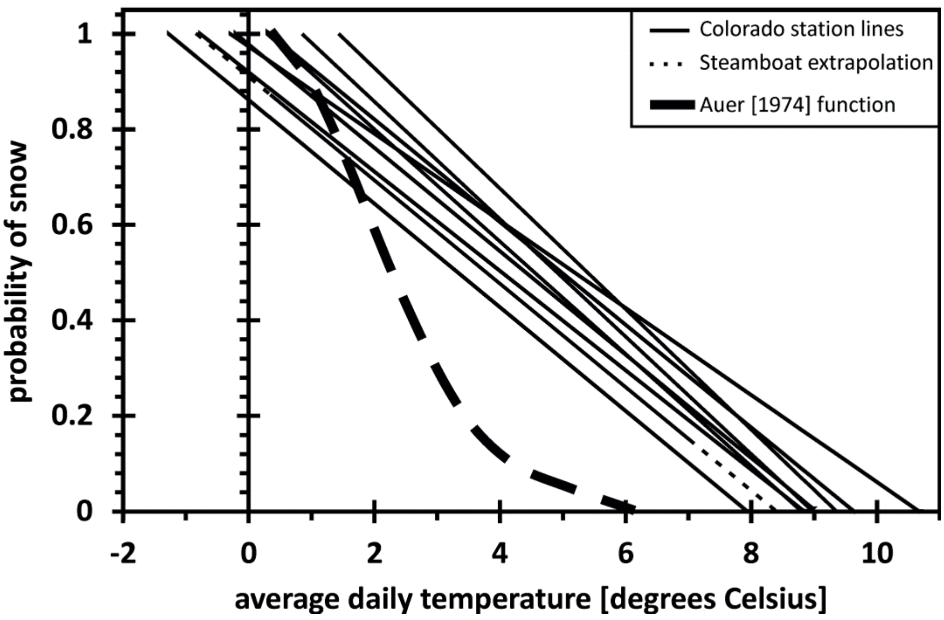

Fig. 3 The best fit lines for the nine study stations relating probability of snow as a function of daily average air temperature. The line is considered extrapolated for the Steamboat Springs station since the snow probabilities greater than 0.9 and less than 0.15 were nonlinear. The Auer (1974) curve is included for comparison. Data were obtained from the National Climatic Data Center www.ncdc.noaa.gov.

this station the slope of the relation was less at probabilities greater than 90% (T < 0.5°C) and less than 15% (T > 7°C) and as such was considered extrapolated and illustrated as dashed lines (Fig. 3). The slopes of the lines are similar, averaging a decrease in probability of snow of 11% per degree Celsius (Table 2). Aspen had the lowest change (9.1%°C) while Leadville had the greatest change (12.6%/°C) (Fig. 3). The slope of the Auer (1974) function between 90% and 20% probability of snow was a decrease of about 30%/°C. Outside these probabilities the Auer curve showed why Fassnacht & Soulis (2002) fitted a sixth order polynomial in their work.

The y-intercept of the lines varied between 0.86 and 1.18, yielding a lower limit of the lines of about –1.3 to 1.4°C. The average lower limit (probability of snow is 100%) was 0°C with an average upper limit of approx. 9°C (probability of snow is 0%), with a range from 7.9 to 10.7°C (Table 2). The Auer curve had limits of 0.45 and 5.97°C; it was an average of 1000 stations and hence does not reflect the aridity of the Colorado stations presented herein. The California Sierra Nevada function fitted by Fassnacht & Soulis (2002) showed colder temperatures for the same probability of snow, as is expected for a wetter environment.

In this paper, the daily average air temperature was computed as the mean of the maximum and minimum temperatures. This may not always be valid. As such we fitted lines to the probability of snow as a function of the daily minimum and maximum air temperature. For the Walden station, the slope of the probability relation with the maximum temperature was about ½ (5.7% decrease in probability per °C) of the average temperature (Fig. 4). The slope using the minimum temperature was about ¾ (7.9% decrease in probability per °C). These lines did not fit the data as well as average temperature. However, the relations for the other stations were all similar to the Walden station shown in Fig. 4).

Table 2 Description of the linear best-fit equations for the probability of snow as a function of daily average air temperature.

Station	Alamosa	Aspen	Climax	Hartsel	Leadville	Steamboat	Telluride	Vail	Walden
Slope (/°C)	–0.123	–0.0912	–0.118	–0.109	–0.126	–0.108	–0.108	–0.108	–0.104
y–intercept (°C)	1.104	0.973	1.035	0.862	1.181	0.910	0.978	1.036	0.920
lower limit (°C)	0.85	–0.29	0.30	–1.27	1.43	–0.84	–0.21	0.33	–0.77
upper limit (°C)	8.98	10.67	8.80	7.94	9.35	8.41	9.04	9.64	8.84

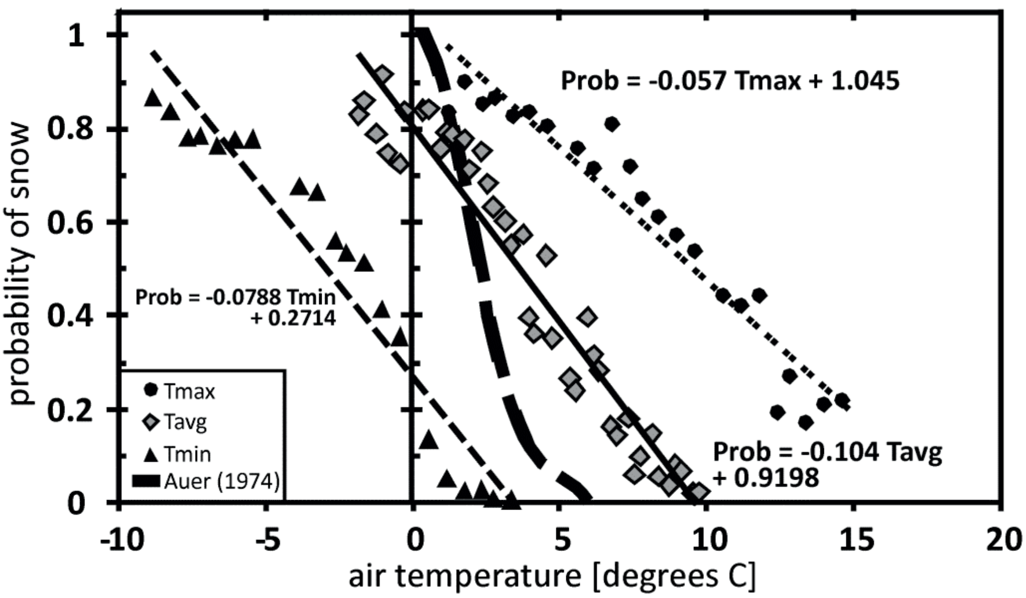

Fig. 4 The probability of snow as a function of daily maximum, average, and minimum air temperature for Walden Colorado. The relations illustrated are the best-fit linear equations. The Auer (1974) curve is included for comparison. Data were obtained from the National Climatic Data Center www.ncdc.noaa.gov.

CONCLUDING REMARKS

More advanced methods are being developed to use additional meteorological data to define the threshold conditions between rain and snow, i.e. the phase of precipitation. For example, Marks *et al.* (2013) compared the use of a dewpoint and dry-bulb threshold temperature for phase discrimination. Various papers have estimated the probability of snow as a function of air temperature (see Fassnacht & Soulis, 2002; Marks *et al.*, 2013). However, these have all been in environments that are not continental, i.e. not semi-arid, such as Colorado. There are numerous regions of the world that do not receive much precipitation, but are cold and most of the precipitation is snowfall, e.g. polar regions. These areas have been shown to be among the most sensitive to climate change, and as such can or will experience a shift in the amount of precipitation as snow. This paper presents a new set of relations to estimate the probability of snow for higher elevation regions that are semi-arid.

Acknowledgements The authors wish to acknowledge the financial support of the National Science Foundation Dynamics of Coupled Natural and Human Systems (CNH) Program (award BCS-1011801 entitled “Does Community-Based Rangeland Ecosystem Management Increase Coupled Systems' Resilience to Climate Change in Mongolia?”) and the National Aeronautic and Space Administration Terrestrial Hydrology Program (award NNX11AQ66G entitled “Improved Characterization of Snow Depth in Complex Terrain Using Satellite Lidar Altimetry”).

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