Temporal Trend Analyses of Alpine Data Using North American Regional Reanalysis and In Situ Data: Temperature, Wind Speed, Precipitation, and Derived Blowing Snow

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ABSTRACT

Across the globe, wind speed trends have shown a slight decline for in situ meteorological datasets. Yet few studies have assessed long-term wind speed trends for alpine regions or how such trends could influence snow transport and distribution. Alpine-region meteorological stations are sparsely distributed, and their records are short. To increase spatial and temporal coverage, use of modeled data is appealing, but the level of agreement between modeled and in situ data is unknown for alpine regions. Data agreement, temporal trends, and the potential effects on snow distribution were evaluated using two in situ sites in an alpine region [Niwot Ridge in Colorado and the Glacier Lakes Ecological Experiments Station (GLEES) in Wyoming] and the corresponding grid cells of the North American Regional Reanalysis (NARR). Temperature, precipitation, and wind speed variables were used to assess blowing-snow trends at annual, seasonal, and daily scales. The correlation between NARR and in situ datasets showed that temperature data were correlated but that wind speed and precipitation were not. NARR wind speed data were systematically lower when compared with in situ data, yet the frequency of wind events was captured. Overall, there were not many significant differences between NARR and in situ wind speed trends at annual, seasonal, and daily scales, aside from GLEES daily values. This finding held true even when trends presented opposite signatures and slopes, which was likely a result of low trend slopes. The lack of agreement between datasets prohibited the use of NARR to broaden analyses for blowing-snow dynamics in alpine regions.

1. Introduction

Long-term changes and the variability of wind speeds could have a widespread effect on snow transport and distribution. The distribution of snow has become increasingly important for water-resource estimates, especially in the mountainous regions of the western United States, where snowpack largely contributes to annual water resources (Blöschl et al. 1991a,b; Blöschl and Kirnbauer 1992; Elder et al. 1991; Hartman et al. 1999; Luce et al. 1999; Liston et al. 2008). In this study, an alpine region refers to high-elevation mountainous terrain that is near to or above tree line. Estimating snow in alpine regions has become increasingly important as climate-change projections indicate decreases in annual snowpack (Pachauri and Reisinger 2007). Measuring and modeling snowpack depths in alpine regions are complicated because the interactions among snow,

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wind, and complex topography create heterogeneous snow distributions and depths (Elder et al. 1991; Greene et al. 1999; Winstral et al. 2002; Liston et al. 2007).

Estimating snow distribution over complex terrain has been improved using wind parameters through deterministic and statistical models (Schmidt 1986; Pomeroy and Gray 1990; Liston and Sturm 1998; Greene et al. 1999; Lehning et al. 2000). Current knowledge of alpine wind speeds is derived from in situ meteorological-station datasets, which are limited by sparsely distributed stations and incomplete records. To fill these gaps, climate models have been used to provide greater spatial and temporal coverage. In many regions of the world, wind speed researchers have evaluated the correlation between modeled and in situ data (McVicar et al. 2011), although to date only a single study has assessed alpine wind speeds (McVicar et al. 2010). It is unknown how a change in wind speed trends could affect snow transport in an alpine region. This research directly compared in situ and modeled climate data for multiple meteorological parameters and temporal trends. The meteorological parameters include air temperature, precipitation, and wind speed. Temporal trends were assessed for mean wind speeds at the annual, seasonal, and daily time steps and for daily mean sample variance. Next, a simple model was developed using temperature, precipitation, and wind speed data to evaluate the frequency and intensity of blowing snow days (BSDs). BSD temporal trends were examined, and in situ and modeled data were compared.

2. Background

Research on blowing-snow dynamics is based in hydrology and climatology and has developed on the basis of results and concepts from a breadth of studies (Pomeroy and Gray 1990; Liston and Sturm 1998; Liston 2004; Liston et al. 2007; Sturm and Wagner 2010; Bernhardt et al. 2012). Although blowing snow is extensively studied in many locations where snow affects human life, much of the research has been focused on transportation (Schmidt 1986; Tabler 1994) because blowing snow affects roadways, commerce, and human well-being (Pomeroy 1991). Other hazards, such as avalanches, also contribute to snow and blowing-snow processes (Gubler 1980; Fohn 1980; Schmidt 1986; Greene et al. 1999; Lehning et al. 1999; Fierz et al. 2003).

In the most elementary case, if snow is present, wind is the first-order effect in determining whether blowing snow and snow redistribution will occur. During a precipitation event, snow can be redistributed by wind at any speed. The minimum wind speed that initiates snow transport is a threshold. There are a variety of environmental conditions that influence the threshold required to redistribute snow (Schmidt 1986; Pomeroy and Gray 1990; Kind 1990; Tabler 1994; Liston et al. 2007). Together, changes in temperature and wind speed behavior could have a significant impact on the extent and amount of blowing snow. Once snow is deposited on the ground, though, snow metamorphism leads to increased density, increased strength through bonding, and an overall decrease in mobility. The rate of metamorphism depends primarily on temperature. Thus, a higher threshold is required to transport snow once bonding has occurred.

Over the past 30–50 years, declining wind speeds have been observed at in situ stations in North America, Europe, Australia, Canada, Switzerland, and China (Klink 1999; Pirazzoli and Tomasin 2003; Tuller 2004; Roderick et al. 2007; McVicar et al. 2008, 2010; Pryor et al. 2009; Jiang et al. 2010). Averaged across these studies, the wind speed declined by $-0.01\ \mathrm{m\,s^{-1}\,yr^{-1}}$ and significance varied among the different locations and datasets. In a review of 148 wind speed studies, McVicar et al. (2011) further confirmed an average wind speed decline of $-0.017\ \mathrm{m\,s^{-1}\,yr^{-1}}$.

A study comparing alpine and low-elevation wind speed trends found that alpine wind speeds were decreasing at a faster rate in China (1960–2006) and Switzerland (1983–2006; McVicar et al. 2010). Their study showed that wind speeds declined by -0.0138 and $-0.0086\ \mathrm{m\,s^{-1}\,yr^{-1}}$ for China and Switzerland, respectively. McVicar et al. (2010) did not state the mean wind speeds, and therefore the amount of change relative to the mean could not be gauged. An estimation from the provided figures yielded that the overall mean alpine wind speed was approximately $2.5\ \mathrm{m\,s^{-1}}$ for China and $2.25\ \mathrm{m\,s^{-1}}$ for Switzerland. For both locations, the decrease in wind speeds was more prevalent during winter months but neither was significant (McVicar et al. 2010).

3. Objectives and data

While many studies have focused on low-elevation wind speed trends or how wind transports and distributes snow across a landscape, there is a lack of research analyzing long-term wind speed trends in alpine regions and the potential effects on snow distribution. To address this lack, we compared long-term air temperature, precipitation, and wind speed trends in an alpine region between two different data types: 1) in situ meteorological stations and 2) the North American Regional Reanalysis (NARR). In situ meteorological stations are sparse in alpine regions, whereas NARR encompasses all of North America and is a consistent, long-term, high-resolution, three-dimensional atmospheric, and land-surface hydrologic dataset (Mesinger et al. 2006).

A strong correlation between alpine in situ and NARR data will allow a spatial and temporal expansion that uses NARR to provide a broader perspective of blowing-snow processes in alpine regions.

The first objective of this research aimed to quantify the relationship between measured and modeled meteorological parameters for temporal trends in an alpine region. The second objective was to determine whether a significant trend in blowing snow has occurred over recent decades. To meet these objectives, five hypotheses were tested:

1) in situ data are *highly correlated* to NARR data for air temperature, precipitation, and wind speed,
2) annual, seasonal, and daily wind data present a *significant change in mean wind speeds* over time,
3) daily mean wind speeds show a significant change in *sample variance,*
4) *the frequency* of wind speeds within and above specific thresholds has significantly changed over time, and
5) the *frequency and intensity* of blowing-snow days have significantly changed over time.

a. In situ data

Alpine-region in situ stations may more accurately represent wind speed trends because of fewer anthropogenic changes (e.g., station relocation, urban development, and land-use/land-cover change). In addition, the stations are closer to the free atmosphere where winds are less affected by surface friction (Garratt 1994). Despite these advantages, finding long-term, accurate, and reliable datasets has proven to be difficult, in part because there are far fewer stations in alpine regions worldwide. Likewise, many issues confound in situ station data that may create false trends or mask real trends and ultimately lead to inaccurate wind speed and snow-transport assessments. It is unavoidable that all in situ stations are subject to data-continuity issues caused by variability in instrument type, height, location, collection methods, and record length (Legates and DeLiberty 1993). To look at long-term wind speed trends, it is critical to reduce errors and inconsistencies from observational data.

Criteria for site selection included a minimum of 20 years of continuous temperature, precipitation, and wind speed data; instrumentation situated within an alpine zone; and a location where minimal land-use/land-cover change has occurred. An extensive data search produced two viable sites within the eastern Rocky Mountains of Colorado and Wyoming. The meteorological stations that met these requirements were the Long Term Ecological Research station at Niwot Ridge, Colorado (see online at http://culter.colorado.edu/NWT/data/datmansearch.html; Losleben 2011a,b), and the Glacier Lakes Ecological Experiments Station, Wyoming (Korfmacher and Hultstrand 2009), referred to hereinafter as Niwot and GLEES, respectively. The temporal extent of 20 years for each of these two stations may be too short to sufficiently assess climate trends, but these two datasets represented the most continuous and best data available in this region.

Niwot and GLEES in situ precipitation data were from proximal Snowpack Telemetry (SNOTEL) sites, and wind speed data were from anemometers at the highest elevation in each region. Temperature data were available from the SNOTEL for both in situ site locations. For each location, the wind tower and SNOTEL stations are situated within the same NARR grid cell. Location information for the in situ sites and the NARR grid cells encompassing each meteorological station is provided in Fig. 1. All in situ stations are part of a network of meteorological stations and assure continuous and accurate data records. The in situ sites are visited on a near-weekly basis for datalogger downloads, instrument calibration, and maintenance, and both datasets are rigorously scrutinized through quality-control procedures (see online at http://culter.colorado.edu/NWT/data/datmansearch.html; Korfmacher and Hultstrand 2009). Also, if instrument malfunctions arise, data from a proximal in situ station are scaled accordingly and inserted into data gaps.

The instrumentation at the Niwot wind tower simultaneously collects temperature with a thermohydrograph and Brooklyn Thermometer Co. thermometer. Both instruments are at 2-m height, but only the wind speed data were used. The GLEES wind-tower temperature data are collected by a thermistor at 15-m height. Dataloggers are the same as the wind speed loggers at these sites, and no instrument changes were recorded.

The temperature datasets from the wind tower and SNOWTEL were compared with one another and NARR, and the dataset that was most correlated with NARR was identified and used for analyses. The temperature and precipitation data were harvested from SNOTEL stations. SNOTEL stations collect climate and snow data to forecast water resources within the western mountains of the United States and Alaska, and all maintain consistent instrumentation and data-quality-control procedures (NRCS 2010). SNOTEL sites are typically located in forest gaps and are away from ridges or wind-dominated areas to maximize collection consistency and minimize access issues. Snow-weight and snow-depth measurements are taken at both of the SNOTEL sites with snow-pillow 50- and 100-in. (1 in. $\approx$ 2.54 cm) Honeywell International, Inc., Sensotec transducers, which

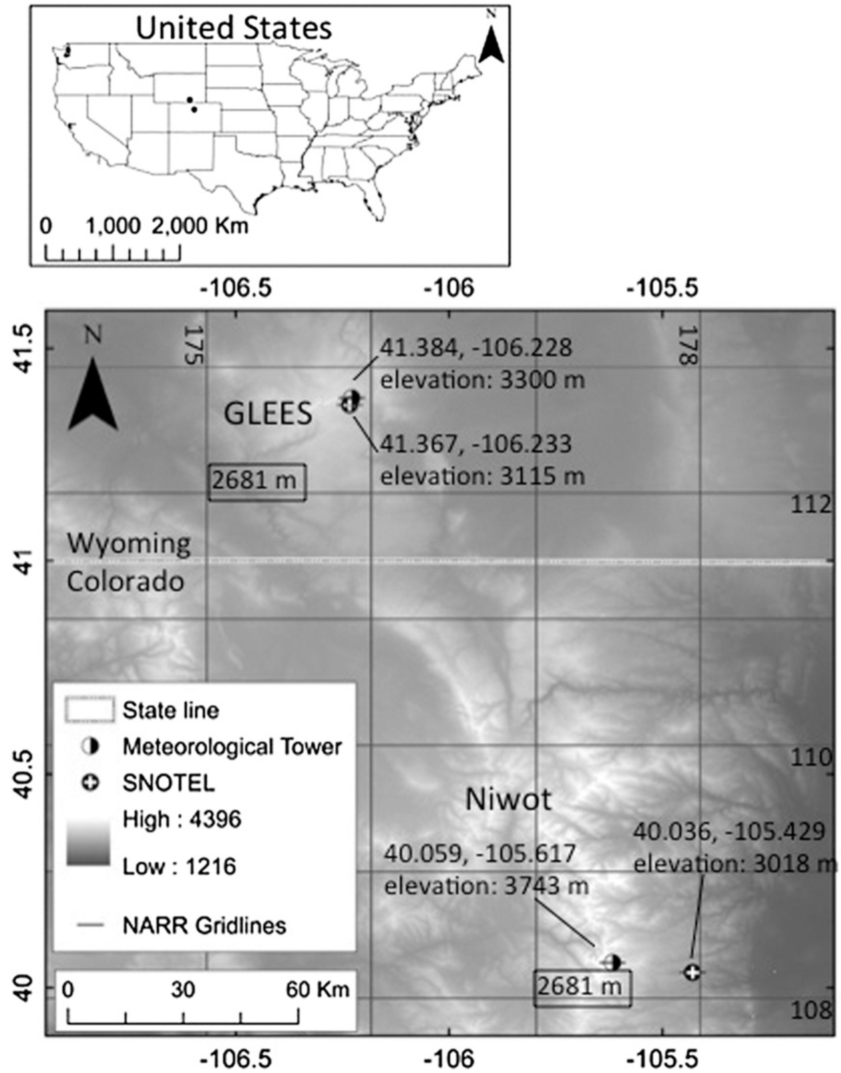

FIG. 1. Meteorological and SNOTEL in situ stations for Niwot and GLEES. Each in situ site has latitude, longitude, and elevation information listed. The gray gridlines represent NARR cells, and the elevation of the grid cell containing the in situ station is in a box in the bottom corner of each cell.

are at the ground level. The 50- and 100-in. sensors were used for different time periods at the Niwot and GLEES sites. The difference between the instruments is in their total capacity and does not influence instrument sensitivity or accuracy. Data are recorded instantaneously and output as hourly and daily averages. The SNOTEL site at Niwot is at location C-1, and GLEES is located at Brooklyn Lake. The temperature gauges at SNOTEL sites are extended-range temperature sensors at a height of 2.5 m. The temperature sensors were upgraded at Niwot in 2005 and at GLEES in 2006; no data discrepancies were observed.

At Niwot the wind speed gauge is a three-cup, AC-generating anemometer (R. M. Young Co. Model 05103-5) at a height of 9 m. The anemometer was replaced with the same model in 1997, and no data discrepancies were observed. The GLEES anemometer is a Met One Instruments, Inc., three-cup anemometer at a height of 15 m. There is no indication of instrument changes in the metadata. Campbell Scientific, Inc., dataloggers were used at both locations to record subminute, hourly, and daily means for wind speed, and the loggers have been updated over the years without any observed inconsistencies.

Elevation differences exist between the in situ stations and NARR grid cells. The elevation of the Niwot NARR cell is 2976 m, the wind tower is at 3743 m, and the SNOTEL site is at 3018 m. Likewise, the GLEES

NARR cell is at 2681 m, the wind tower is at 3300 m, and the SNOTEL site is at 3115 m. Using an NARR grid cell that has an elevation that is more similar to each in situ station was considered, but selecting an NARR grid cell for elevation alone would not produce results that clearly identify how the NARR and in situ datasets compare. If an NARR cell was selected solely on elevation characteristics, many other landscape characteristics of the in situ location (slope, aspect, wind forcing, microclimate, topographical complexity, land cover, etc.) would be negated and the higher correlation coefficients of the meteorological parameters would likely be by chance. Likewise, conducting elevation matching for larger extents is not reasonable and defeats the purpose of reanalysis modeling.

b. NARR

To expand beyond these stations, increased spatial coverage is needed to comprehensively analyze alpine-region wind speed and blowing-snow trends. Spatial coverage is commonly expanded with modeled data, which are organized into a gridded extent and range in spatial and temporal resolution. In complex terrain a finer spatial resolution is more attractive because more detail is maintained. NARR was viewed as the most ideal dataset because it spans the period of interest, it has relatively fine spatial resolution, it includes many improvements relative to similar datasets, and the data are spatially and temporally consistent (Mesinger et al. 2006).

Climate models, such as NARR, incorporate meteorological-station datasets to simulate the dynamics among the ocean, atmosphere, and land surface. NARR elevation and topography are derived from U.S. Geological Survey 30″ global elevation data. Each grid cell is assigned a mean elevation and land-cover type when 50% or more of the area is covered by a land-cover type (Mesinger 1996). NARR meteorological data are derived from surface and upper-air observations, which are then organized into 32-km horizontal grids consisting of 45 vertical levels. Temperature, humidity, pressure, and wind speed are collected and assimilated into NARR from rawinsondes. The North American rawinsonde network comprises approximately 120 launch sites, the majority of which have been consistently operated by the National Weather Service since the early 1950s (see online at http://www.erh.noaa.gov/rah/virtualtour/collecting.met.data.radiosonde.php). These data are then organized and reanalyzed to provide a complete spatial replication of the atmosphere (Oort 1977). The vertical level of the data used in this research was the 10-m height. Gridcell estimates of meteorological parameters are available every 3 h from 1979 to the present.

Comprehensive assessment of ground-level precipitation was completed using data from the contiguous United States and assimilated into NARR from various sources: National Climatic Data Center cooperative stations and the Hourly Precipitation Data product (Shafran et al. 2004). Over 11 000 station observations were used to create a 1/8° grid in the United States (Shafran et al. 2004). In Canada and Mexico, where gauge stations are limited, a 1° gridded precipitation dataset was created (Shafran et al. 2004). The assimilation of these data affords more realistic precipitation events and totals.

NARR functionally reduces data inconsistencies arising from instrument disparities at individual weather stations, but it is still affected by limitations of sparse and temporally inconsistent meteorological observations. In regions with sparsely distributed gauges (deserts, mountains, rangelands, and remote, unpopulated areas) and a limited number of rawinsonde launch sites, misrepresentation of large or diverse areas has resulted (Hiemstra et al. 2006; Businger et al. 2001). Weaknesses were confirmed in Canada, where the numbers of precipitation gauges and rawinsonde launches are few (Mesinger et al. 2006). Limitations were also observed in areas of complex terrain because of a larger frequency of cumulus convective events and localized meteorological dynamics (Kistler et al. 2001). Because NARR data are largely based on rawinsonde data at and above mountaintop level, the data may be well suited to expand and improve upon information about weather and climate in alpine regions. However, there are no previous studies, to the authors' knowledge, that utilize NARR data to investigate alpine-region wind patterns, blowing-snow processes, and changes therein over time.

NARR data outputs include, but are not limited to, surface temperature, precipitation, humidity, radiation, wind, pressure, convective energy, snow depth, and albedo (NOAA/ESRL Physical Sciences Division 2009). NARR also assimilates observational data and, as a result, draws a closer relationship between NARR and observational variables (Lin et al. 1999; Mesinger et al. 2006). Data consistency is improved because all datasets are assimilated into the same climate model for the entire extent of NARR data (NOAA/ESRL Physical Sciences Division 2009). The NARR dataset has been used to help to answer questions concerning precipitation variability (Sun and Barros 2010; Gan et al. 2011), to identify patterns in weather and climate (Li et al. 2010; Radic and Clarke 2011), to represent extreme events, to make regional assessments, and to forecast future climate scenarios (Mesinger et al. 2006). Before NARR can be used to expand spatial coverage, we first must understand how well it captured the atmospheric conditions that influence snow transport in alpine regions.

4. Methods

a. Data preparation

Annual, seasonal, and daily means were analyzed to quantify trends at different temporal scales. Data for the Niwot in situ site spanned from 1989 through 2008, and GLEES data were 1 yr longer, from 1989 through 2009. Here, the goal was to use the longest datasets available for each site, and, because the two locations are not compared, matching temporal extents was not necessary. The NARR data were temporally reduced to match the respective in situ records. Daily means (0000–0000 next day mountain standard time) were organized into hydrologic years (1 October–30 September). Annual and seasonal means were calculated from daily means per year and per season, respectively. Seasons were defined as autumn (September–November), winter (December–February), spring (March–May), and summer (June–August). NARR daily precipitation estimates can be minimal (e.g., 0.000 34 mm), which is an artifact of the model formulation. When NARR daily means were below 0.2 mm, the value was changed to zero to account for these minor and potentially erroneous precipitation values. The 0.2-mm value is chosen because it is a reasonable assumption.

Wind speeds were analyzed at set thresholds to observe the frequency of wind speed thresholds that influence snow transport. A threshold is the minimum wind speed required to initiate or sustain snow transport (Schmidt 1986; Pomeroy and Gray 1990). Wind speeds of greater than 5 m s^{-1} are sufficient to transport unbonded snow. Wind speeds below this threshold likely cause minimal or no snow transport (Li and Pomeroy 1997). The amount of blowing snow increases when snow particles are not fully bonded and winds speeds are greater than 14 m s^{-1} (Li and Pomeroy 1997). Thus, thresholds were categorized as <5, 5–14, and >14 m s^{-1}.

The wind speed data were paired with precipitation and temperature data to produce a simple blowing-snow-day (BSD) model that estimates the most likely conditions for snow transport. A BSD was established when temperatures were 0°C or below, a precipitation event occurred, and wind speeds were indexed as either 5–14 or >14 m s^{-1}. Air temperatures at or below 0°C typically result in solid precipitation, and, as the precipitation nears the ground, the ground-level temperatures are most indicative of the precipitation phase: solid, mixed (snow and rain), or rain. Although solid precipitation can occur at temperatures up to 3°C at the ground level, snow is most commonly and reliably observed at or below 0°C (L'hôte et al. 2009). Also, as temperatures approach or exceed 0°C, metamorphism rates rapidly increase, and the resultant bonding decreases the likelihood of transport. To assess accurately the precipitation phase at the in situ sites, temperature and precipitation gauges were at the same SNOTEL locations, whereas NARR data were modeled at the same height. Blowing snow can also occur in the absence of a precipitation event because the surface of the snowpack could have unbonded snow from a previous event. Thus, the four days subsequent to a precipitation event were also included as BSDs, but only if temperature and wind speed specifications were met. The BSD index allowed us to assess statistically the frequency and intensity of probable snow transport events. Snowpack depth and snow surface conditions were not incorporated into the analysis because of the heterogeneity of such data across a landscape.

b. Statistical procedures

Multiple analyses were conducted to evaluate data correlation and temporal trends of alpine climatic conditions for NARR and in situ datasets. The degree of correlation between in situ and NARR data was assessed for each of the three response variables: temperature, precipitation, and wind speed using daily data.

To better understand wind speed patterns and trends, additional analyses were conducted. The first test consisted of fitting a linear regression model to annual, seasonal, and daily mean time series data. We tested the significance of the estimated trends and compared the trends between in situ and NARR data. The hypothesis $\beta_1 = 0$ (i.e., no trend) was tested, and if this trend was not zero then the alternative hypothesis was accepted if the significance p value ≤ 0.1 level. For each of these models we assumed that the error was normally distributed with a mean of 0 and a standard deviation of 1. Because of nonnegligible correlation in the daily data, we assumed a first-order autocorrelation regression model [AR(1)] error structure for the daily data. The daily data required a different statistical analysis than did monthly and annual data because of the autocorrelation of daily values. Here, AR (1) is adequate to model the residual dependence of the daily means for the three meteorological parameters (Ott and Longnecker 2001).

The wind speed threshold categories 5–14 and >14 m s^{-1} were used, without combining them, to analyze the role of intensity in the frequency of BSDs by applying a binary response to each daily data point. A value of 1 was assigned when criteria were met for each BSD category; otherwise, a 0 was assigned. Then each wind speed category was counted. To compare the count data for the different wind speed categories, odds ratios

TABLE 1. Summary of whether the hypothesis tested is accepted (A) or rejected (R; ''R all'' indicates reject for annual and all four seasons, and N/A indicates not applicable). Hypotheses a–e correspond to sections 5a–5e of the text. For each location the right column is for the in situ data and the left column is for the NARR data.

Hypothesis	Analysis	Niwot		GLEES	
a. *In situ data are highly correlated with NARR data* for air temperature, precipitation, and wind speed	Temperature	A		A	
	Precipitation	R		R	
	Wind speed	R		R	
b. Annual, seasonal, and daily wind data present a *significant change in mean wind speeds* over time	Annual	R	R	R	R
	Seasonal	Autumn: R	Autumn: R	Autumn: R	Autumn: R
		Winter: R	Winter: R	Winter: R	Winter: A
		Spring: R	Spring: R	Spring: R	Spring: R
		Summer: R	Summer: R	Summer: A	Summer: R
	Daily	Autumn: R	Autumn: R	Autumn: R	Autumn: R
		Winter: R	Winter: A	Winter: R	Winter: A
		Spring: R	Spring: R	Spring: R	Spring: R
		Summer: R	Summer: R	Summer: A	Summer: R
c. Daily mean wind speeds show a *significant change in sample variance trends* over time	Autumn	R	R	R	R
	Winter	A	R	R	R
	Spring	A	R	R	R
	Summer	R	R	R	R
d. *The frequency of wind speeds* within and above specific thresholds *has significantly changed* over time	$<5\ \mathrm{m\ s^{-1}}$	R all	R all	R all	R all
	$5–14\ \mathrm{m\ s^{-1}}$	Annual: R	Annual: R	Annual: R	Annual: R
		Autumn: R	Autumn: R	Autumn: R	Autumn: R
		Winter: R	Winter: R	Winter: A	Winter: R
		Spring: R	Spring: R	Spring: R	Spring: R
		Summer: R	Summer: R	Summer: R	Summer: R
	$>14\ \mathrm{m\ s^{-1}}$	Annual: R	Annual: A	Annual: A	Annual: R
		Autumn: R	Autumn: N/A	Autumn: A	Autumn: N/A
		Winter: R	Winter: N/A	Winter: A	Winter: N/A
		Spring: A	Spring: N/A	Spring: R	Spring: N/A
		Summer: N/A	Summer: N/A	Summer: N/A	Summer: N/A
e. The *frequency and intensity of blowing-snow days have significantly changed* over time	$5–14\ \mathrm{m\ s^{-1}}$	Annual: R	Annual: R	Annual: R	Annual: A
		Autumn: R	Autumn: R	Autumn: R	Autumn: A
		Winter: A	Winter: A	Winter: A	Winter: A
		Spring: R	Spring: R	Spring: R	Spring: R
	$>14\ \mathrm{m\ s^{-1}}$	Annual: R	Annual: R	Annual: A	Annual: R
		Autumn: R	Autumn: R	Autumn: R	Autumn: N/A
		Winter: R	Winter: R	Winter: A	Winter: N/A
		Spring: R	Spring: R	Spring: R	Spring: N/A

were computed and inferences were performed using the Gaussian approximation to the log-odds ratio.

The statistical comparison of in situ and NARR trend variance and correlation was significant if values exceeded the ± 1.96 bounds. When significance values were within the ± 1.96 bounds, statistic similarities were observed even if the trends were opposite in signature or maintained different degrees of significance.

5. Results

The numerous analyses warranted a table to present clearly each hypothesis and to state whether it is accepted or rejected (Table 1). To accept a hypothesis means that we accept the alternative hypothesis or fail to reject the null hypothesis because a significant trend or correlation of data was present. To reject indicates that the hypothesis was not supported by trends that were significantly different from zero.

a. In situ data are highly correlated with NARR data for air temperature, precipitation, and wind speed

Temperature data proved to be highly correlated between in situ and NARR. Values of the square of the correlation coefficient r^2 for daily temperatures were 0.92 between the Niwot NARR and SNOTEL data and 0.87 between the GLEES NARR and SNOTEL data. The in situ correlation between NARR and the wind-tower in situ temperature data was $r^2 = 0.84$ for Niwot and $r^2 = 0.85$ for GLEES. The correlation coefficients for the two in situ (SNOTEL and wind tower) sites were $r^2 = 0.79$ at Niwot and $r^2 = 0.75$ at GLEES. Here, higher correlation values were observed between both in situ sites and NARR than between each other. The temporal trends between the two in situ sites were statistically similar.

For the remainder of the analyses, the temperature data are from the SNOTEL sites because correlation values were the highest. Both in situ stations recorded lower temperatures in comparison with NARR, where the average degree difference was 0.6° ± 0.8°C at Niwot and 4° ± 1°C at GLEES. Although temperature data were more highly correlated for mean annual temperatures, the temporal trends were statistically different between NARR and in situ data for GLEES and Niwot. The Niwot in situ average annual temperature has significantly increased at a rate of 1.3°C $(10\,\mathrm{yr})^{-1}$ (p value < 0.001). Niwot NARR temperature data showed an increasing trend of 0.04°C $(10\,\mathrm{yr})^{-1}$ and were not significant, with a p value = 0.87. Similarly, GLEES in situ data showed that the average annual temperature has increased by 2.2°C $(10\,\mathrm{yr})^{-1}$ (p value < 0.0001). No significant temperature trends were observed for the GLEES NARR data, but the temperature has increased by 0.03°C $(10\,\mathrm{yr})^{-1}$ (p value = 0.90).

By season, Niwot in situ temperature trends all significantly increased over time, and all had a p value that was lower than 0.01. In contrast, NARR seasonal data decreased slightly for all seasons except for summer, and none of the trends were significant. GLEES in situ seasonal temperature trends also showed significant temperature increases, with all p values being lower than 0.001. GLEES NARR temperature trends slightly decreased for autumn and spring and increased for winter and summer; only the summer temperatures were significant at p value = 0.05. All temporal temperature trends, for both sites, were significantly different from one another.

Precipitation and wind speed data ranged in their levels of agreement. Daily in situ and NARR precipitation data proved to be highly uncorrelated, with r^2 values of 0.001 and 0.186 for Niwot and GLEES, respectively. Wind speed correlation values for Niwot and GLEES were fairly similar, with r^2 values of 0.36 and 0.38, respectively. Both in situ meteorological stations had systematically higher wind speeds in comparison with NARR.

b. *Annual, seasonal, and daily wind data present a* significant change in mean wind speeds *over time*

Long-term wind speed trend analyses were conducted for annual and seasonal means (Fig. 2). Significant trends were absent for Niwot in situ and NARR data. In situ data for winter had mean wind speeds that were higher than those for NARR for both sites; this situation was more pronounced for Niwot. The average difference in winter means between in situ and NARR data was 5.52 and 3.01 $\mathrm{m\,s^{-1}}$ for Niwot and GLEES, respectively. The summer wind speed trends for the GLEES in situ station showed a negative trend of $-0.03\,\mathrm{m\,s^{-1}\,yr^{-1}}$ (p value = 0.1). GLEES NARR data had a significant positive trend during the winter season of $0.04\,\mathrm{m\,s^{-1}\,yr^{-1}}$ (p value = 0.1). The statistical comparison of in situ and NARR for temporal trends showed trend variance and correlation for all data to be statistically similar.

The differences between data types for daily mean wind speeds are presented in Figs. 3a and 3b. Both locations exhibited very few significant temporal trends for daily means (Figs. 3c,d). For Niwot, the daily mean trend analyses showed no changes over time for any season except NARR-data winters. NARR winter daily means indicated a positive trend at Niwot of $0.04\,\mathrm{m\,s^{-1}\,yr^{-1}}$ (p value = 0.01) and at GLEES of $0.03\,\mathrm{m\,s^{-1}\,yr^{-1}}$ (p value = 0.05). GLEES in situ summer daily means had a negative trend of $-0.04\,\mathrm{m\,s^{-1}\,yr^{-1}}$ (p value = 0.01). Daily trend variance and correlation between in situ and NARR showed trends to be statistically similar for Niwot daily data, but for GLEES all trends were significantly different.

c. *Daily mean wind speeds show a* significant change in sample variance trends *over time*

Daily mean wind speeds were tested for variance over time (Figs. 3c,d). The daily mean wind speed sample variance was found for each season within each year, and then a linear regression was fit. The sample variances were treated as data, not accounting for the uncertainty in the estimates. These preliminary results provided evidence that significant trends are not present, and therefore no additional analyses were performed.

The sample variance was plotted for Niwot and GLEES for the winter and spring seasons to show the temporal trends in daily mean wind speed variance (Fig. 4). Niwot in situ data show an increasing trend in the sample variance for winter ($0.33\,\mathrm{m\,s^{-1}\,yr^{-1}}$) and spring ($0.16\,\mathrm{m\,s^{-1}\,yr^{-1}}$) with p values = 0.10. No significant trends were present for Niwot NARR or for either of the GLEES datasets. The statistical comparison between in situ and NARR data for variance and correlation showed that all trends were statistically similar.

d. The frequency of wind speeds *within and above specific thresholds* has significantly changed *over time*

Annual and seasonal wind speed means were categorized into three thresholds: <5, 5–14, and $>14\,\mathrm{m\,s^{-1}}$. The threshold categories were chosen because each

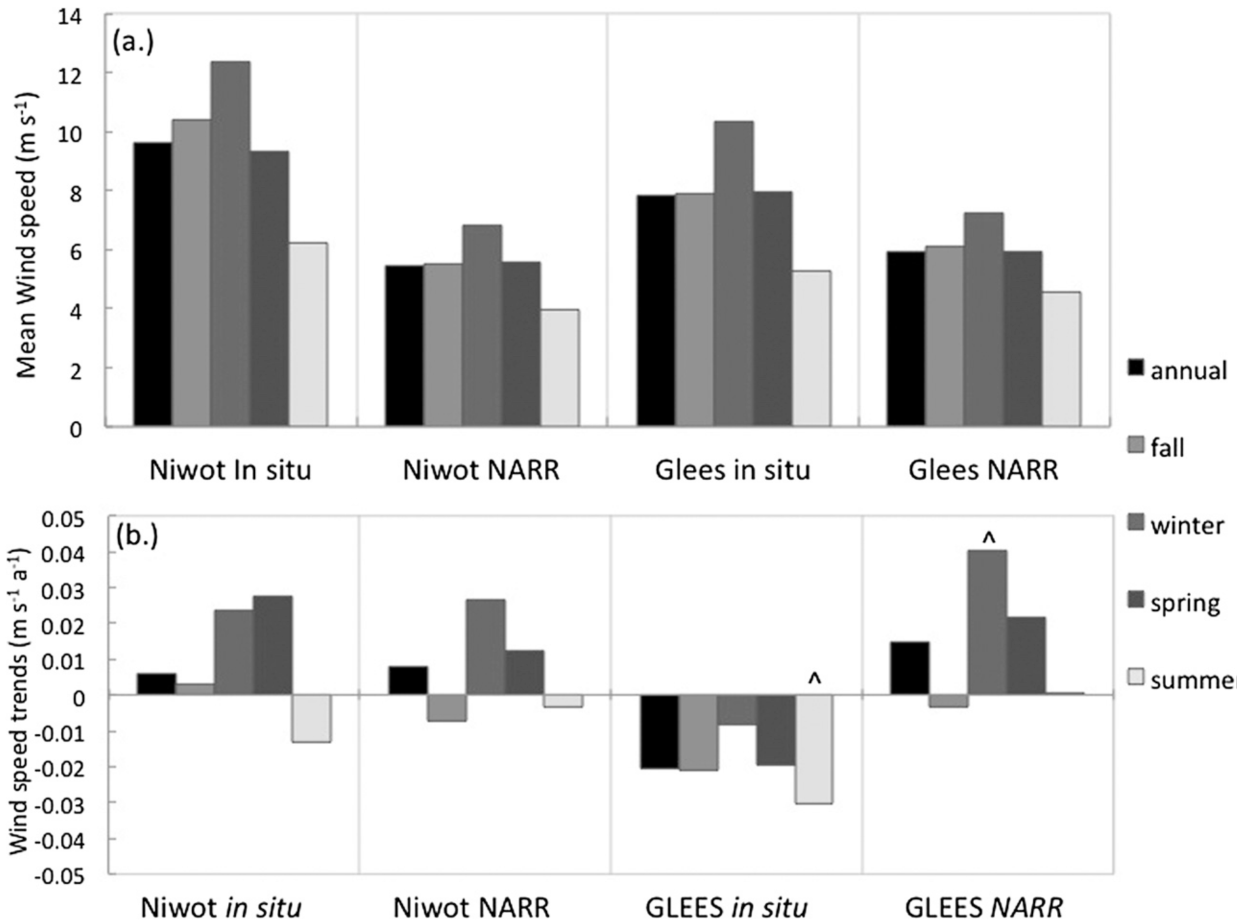

FIG. 2. Annual and seasonal (a) mean wind speed (m s^{-1}), and (b) mean wind speed trends (m s^{-1} yr^{-1}). The significance for wind speed trends at a p value of <0.1 is indicated by the caret symbol. The seasonal divisions are autumn (September–November), winter (December–February), spring (March–May), and summer (June–August).

threshold influences snow transport to a different extent. To assess potential snow transport events, a binary response for wind speeds was established as a percent of occurrence per time step for each threshold category. The percentage of wind speeds occurring in each threshold category for the winter season is shown in Fig. 5. Overall, annual and seasonal wind speeds in each threshold category changed minimally over time (Fig. 6). The only trend observed was for Niwot NARR annual wind speeds of >14 m s^{-1}, and it increased by 0.02% yr^{-1} (p value = 0.1). All annual threshold trends were statistically similar between the Niwot in situ and NARR data. The GLEES annual in situ wind speeds >14 m s^{-1} demonstrated a negative trend at a rate of −0.19% yr^{-1} (p value = 0.05). This trend was significantly different than the GLEES NARR annual data trend (0.01% yr^{-1}). The other annual thresholds had statistically similar trends.

When NARR winds were divided into seasons, there were too few positive responses for wind speeds of >14 m s^{-1} to be analyzed accurately, establishing that wind speeds of >14 m s^{-1} were not accurately captured by NARR. Summer data were also excluded from analyses because wind speeds that were stronger than 14 m s^{-1} and blowing-snow conditions rarely occur for these locations during the summer. Overall though, more significant trends were observed at the seasonal time step. Niwot in situ spring wind speeds of >14 m s^{-1} experienced a 0.32% yr^{-1} increase (p value = 0.1). Niwot data for winter wind speed thresholds at 5–14 m s^{-1} were opposite in signature and significantly different, with a decrease of −0.45% yr^{-1} for in situ data and an increase of 0.36% yr^{-1} for NARR data. The GLEES in situ winter 5–14 m s^{-1} threshold increased by 0.49% yr^{-1} (p value = 0.05), and the >14 m s^{-1} threshold decreased in the autumn and winter by −0.26% and −0.56% yr^{-1} (p value = 0.05), respectively. GLEES NARR did not experience any significant trends, nor were there significant differences observed for GLEES seasonal wind speed threshold trends.

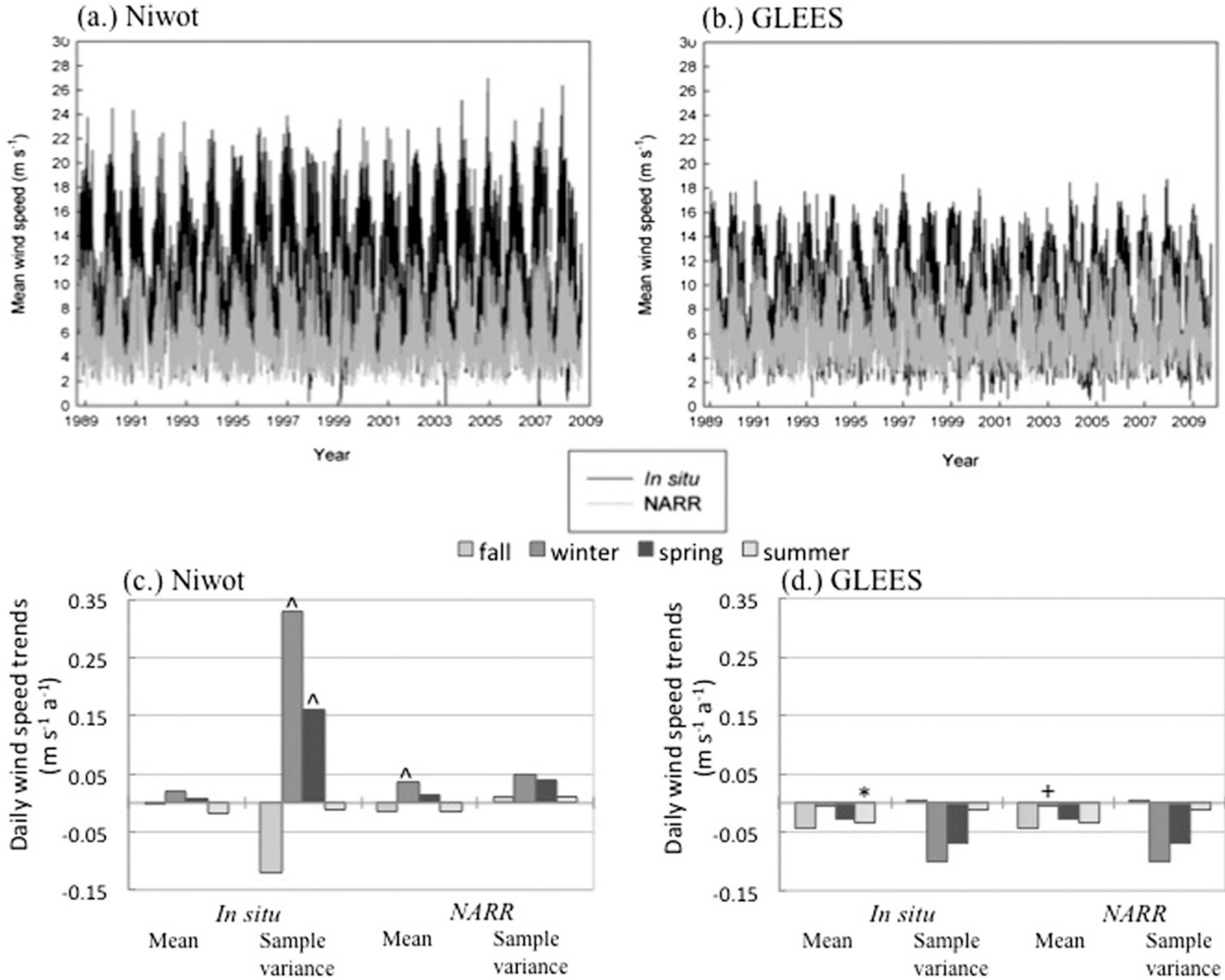

FIG. 3. Daily mean wind speeds for (a) Niwot and (b) GLEES in situ and NARR data for the entire temporal extent ($m\,s^{-1}$) Here, the winter months show as peaks and the summer months show as valleys. (c) Niwot and (d) GLEES daily mean and sample variance wind speed trends per season ($m\,s^{-1}\,yr^{-1}$). Significance *p* value of 0.01 is shown by an asterisk, a plus sign denotes $p = 0.05$, and carets show $p < 0.1$. The seasonal divisions are as in Fig. 2.

e. *The* frequency and intensity of blowing-snow days have significantly changed *over time*

The percent change per year for BSDs at annual and seasonal time steps was assessed for wind speed categories 5–14 and $>14\,m\,s^{-1}$ (Fig. 7). Niwot in situ data and NARR data for BSD trends were not significant for either annual or seasonal temporal scales, except for in situ winter BSDs. The Niwot in situ winter BSDs for 5–14 and $>14\,m\,s^{-1}$ presented positive trends of 0.67% and 0.75% yr^{-1}, respectively, and both were significant at *p* value = 0.05. All trends for Niwot were statistically similar between data types for all time steps and thresholds.

GLEES had multiple significant trends for BSDs. On an annual basis, GLEES in situ BSD data showed a negative trend of $-0.15\%\,yr^{-1}$ when winds were greater than $14\,m\,s^{-1}$ (*p* value = 0.05). GLEES NARR BSDs showed an increase of 0.69% yr^{-1} for wind speeds 5–14 $m\,s^{-1}$. GLEES annual BSD data showed that trends were significantly different between data types for both threshold categories. Seasonal results showed GLEES in situ autumn BSD threshold categories with negative trends, but the only significant trend was for the threshold $>14\,m\,s^{-1}$, with a decline of $-0.16\%\,yr^{-1}$ (*p* value = 0.1). Winter in situ BSDs had a positive trend of 0.77% yr^{-1} (*p* value = 0.001) for 5–14 $m\,s^{-1}$ wind speeds and a negative trend of 0.36% yr^{-1} (*p* value = 0.05) for wind speeds of $>14\,m\,s^{-1}$. GLEES in situ spring BSDs also decreased for 5–14 $m\,s^{-1}$ wind speeds at a rate of $-0.60\%\,yr^{-1}$ (*p* value = 0.05). GLEES NARR BSDs showed increasing trends for all seasons. The GLEES

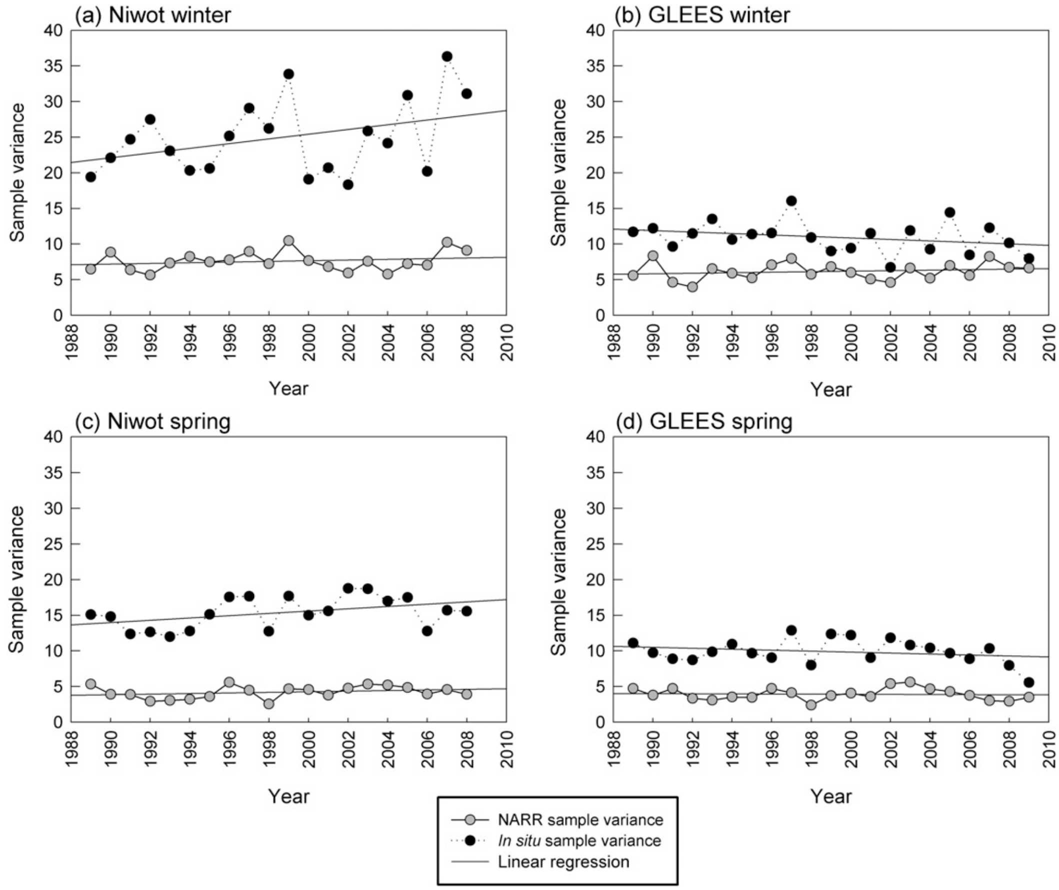

FIG. 4. Daily mean wind speed sample variances plotted per year with a linear regression trend line for (a) Niwot winter, (b) GLEES winter, (c) Niwot spring, and (d) GLEES spring. Niwot in situ data show a significant positive trend (p value = 0.1) for winter and spring sample variances.

NARR data for 5–14 $m s^{-1}$ wind speeds increased at a rate of 0.52% yr^{-1} (p value = 0.01) for autumn and 1.94% yr^{-1} (p value = 0.001) for winter. All seasonal temporal trends were significantly different between GLEES in situ and NARR data.

The occurrence of daily BSD wind speeds for in situ and NARR data is shown in Fig. 8. The frequency of BSD wind speeds of >14 $m s^{-1}$ is more numerous for both in situ stations.

6. Discussion

Different meteorological parameters have different variability and temporal continuity characteristics, and, as a result, the observation accuracy of each parameter varies. For example, temperature data, even when accounting for diurnal effects, lack dramatic oscillations (Hiemstra et al. 2006) due to boundary layer mixing. Thus, temperature data are more accurately recorded and tend to have higher correlation among datasets when compared with other meteorological parameters. This effect was present in this study and in a similar study by Hiemstra et al. (2006), who found that temperature r^2 values ranged from 0.64 to 0.99 between the National Oceanic and Atmospheric Administration Local Analysis and Prediction System (LAPS) gridded data and 107 in situ station datasets. Similar to NARR, LAPS assimilates multiple observational meteorological datasets to create a three-dimensional model of atmospheric processes. The Hiemstra et al. (2006) study compared temperature, precipitation, relative humidity, and wind data for two years in the northern high plains region of the United States. They found that the average temperature difference between the datasets was <2°C. Results from this study were comparable and showed that Niwot in situ temperatures were 1°C warmer than NARR temperatures and that GLEES in situ data were 4°C warmer than NARR data.

Among all of the data analyzed, temperature trends achieved the most significant p values and steepest trends over time for all in situ data (wind tower and SNOTEL), but such trends were not modeled by

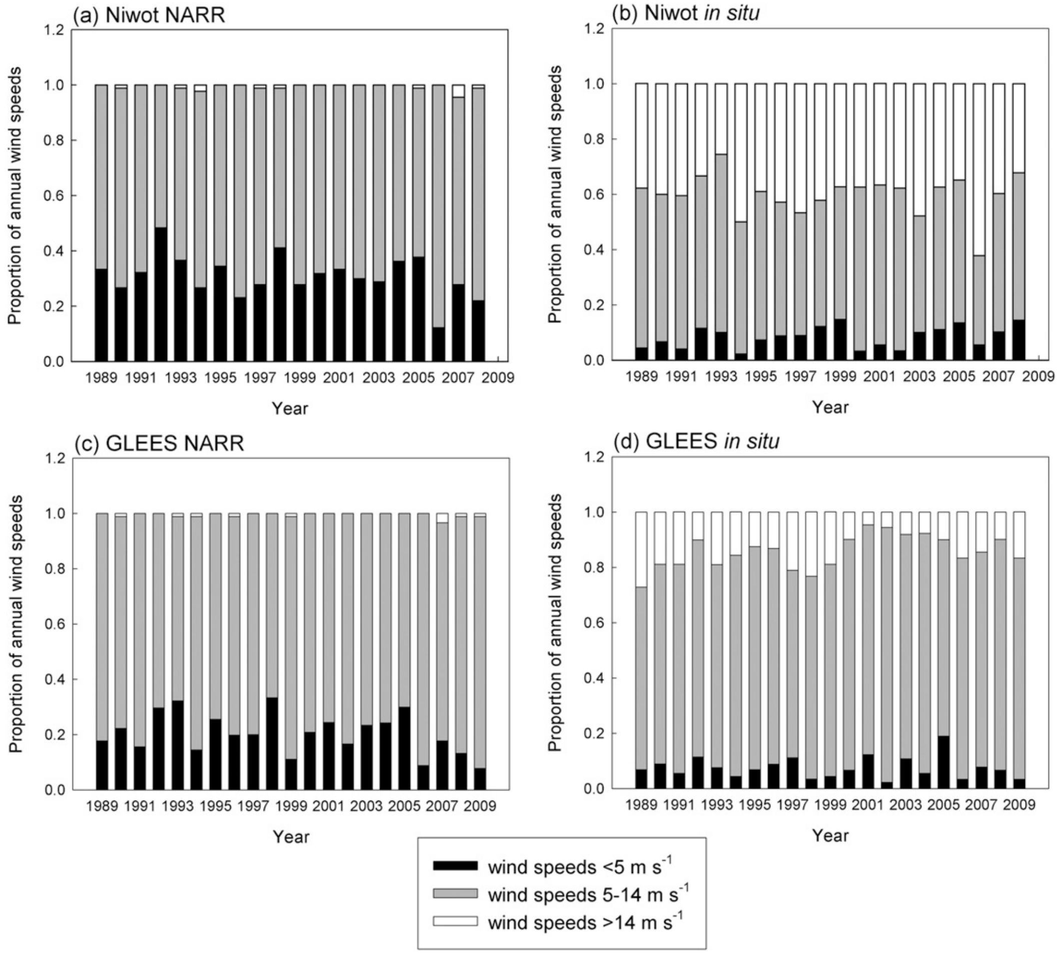

FIG. 5. The proportion of wind speeds per threshold category during the winter season (December–February) for (a) Niwot NARR, (b) Niwot in situ, (c) GLEES NARR, and (d) GLEES in situ data.

NARR. The slight temperature differences among the data types are likely explained by the differences in elevation and instrument (modeled) heights. Even though temperature differences are slight and correlation coefficients are high, the cause of statistical differences between temporal trends is not clear. A potential explanation for the discrepancies between data types could be the differences between point and gridded data. Point data record location-specific data and the extreme temperatures therein, whereas NARR data are smoothed over a larger extent (32 km). Because the SNOTEL in situ temperature station was at a lower elevation, it experienced less-extreme temperatures when compared with the wind-tower temperature station. Thus, the temperature correlation coefficients were better between the SNOTEL data and NARR.

Precipitation data-collection methods have long been plagued with accuracy issues for both observed and modeled data. All in situ precipitation gauges are affected by wind, wetting, evaporation, and inaccurate trace-precipitation collection (Guirguis and Avissar 2008). In situ precipitation data collection has shown more inconsistencies when temperatures drop below 0°C and precipitation is in the form of snow than when precipitation is collected as rain. Also, when wind speeds are $6\,\mathrm{m\,s^{-1}}$ or greater, precipitation collection is even more problematic because zero gauge catch becomes more frequent (Sugiura et al. 2006). Groisman and Legates (1994) showed that gauges during the winter recorded 20% less precipitation and that the undercatch was up to 75% less for individual storms.

For NARR, many issues inhibit the production of accurate precipitation data. First, the spatial distribution of assimilated observational points may result in a misrepresentation of dynamic meteorological processes because the spatial distribution is irregular, is sparse (Hiemstra et al. 2006), and linearly decreases northward from 20° to 50°N (Mesinger et al. 2006). Another issue

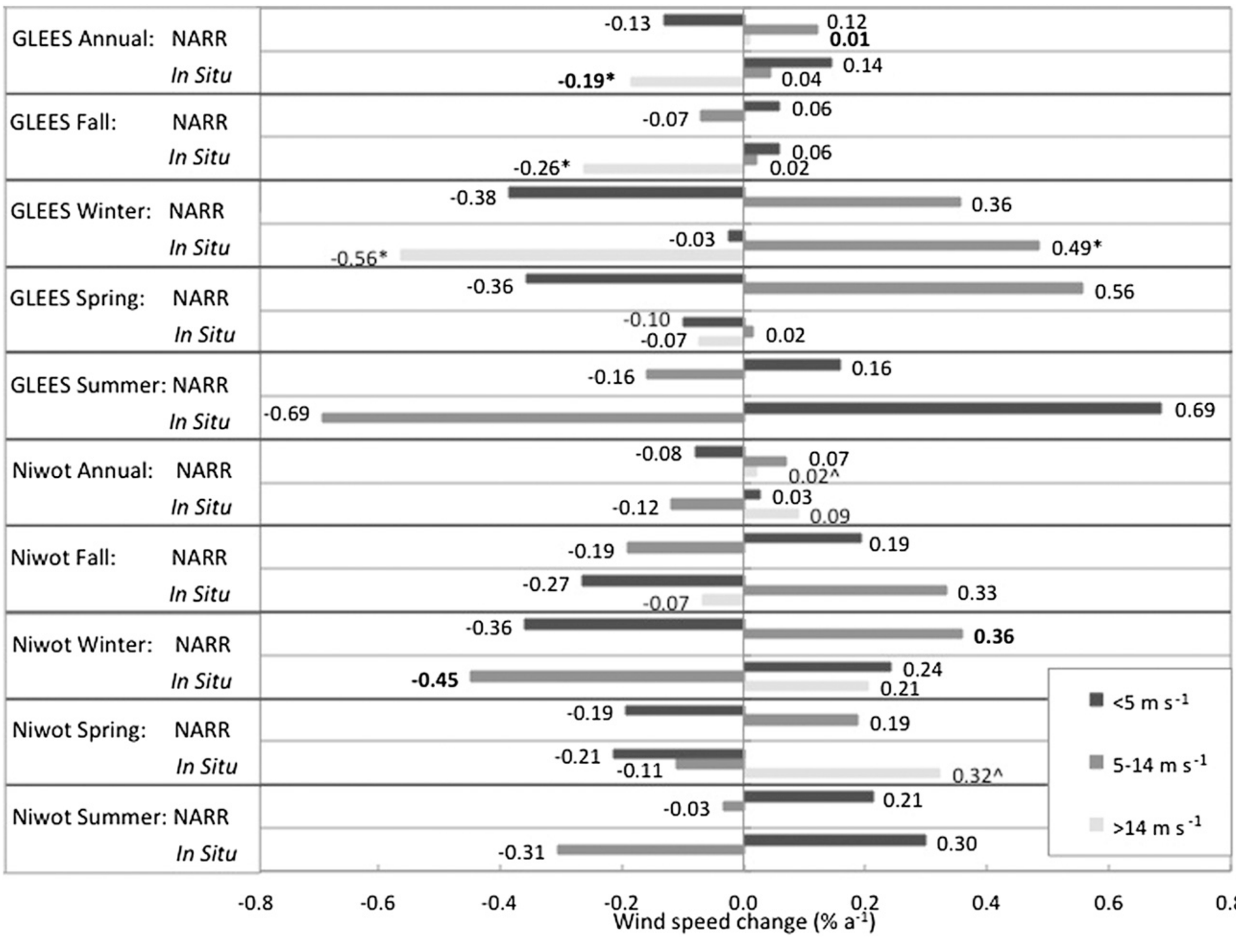

FIG. 6. Annual and seasonal data for each threshold category stated as wind speed change per year (% yr^{-1}) for the Niwot and GLEES datasets. NARR wind speeds $> 14\,m\,s^{-1}$ were not included because of the minimal number of days accounted for. Boldface values represent statistically different trends between in situ and NARR. Significance p value of 0.01 is shown by an asterisk, and carets show $p < 0.1$. The seasonal divisions are as in Fig. 2.

for NARR precipitation data is the magnitude of daily precipitation totals. NARR regularly outputs miniscule precipitation amounts [e.g., 0.000 04 mm $(3\,h)^{-1}$] instead of less frequent and more realistic higher precipitation totals.

Precipitation correlation disparities were likely a combination of observational errors, complications associated with measuring precipitation falling as snow, NARR model limitations, and sensor and modeled height differences. Aside from potential accuracy errors from in situ and NARR precipitation collection, NARR data were noticeably different in the timing and total accumulation of many of the precipitation events when compared with in situ events. For example, the largest precipitation totals recorded during a multiday event were rarely on the same day. Also, if precipitation totals were the only issue, it is likely that correlation between the datasets would have been better. Thus, manipulating in situ and NARR precipitation totals to account for undercatch or minuscule totals would not necessarily improve correlation between datasets but would likely introduce additional uncertainty.

The lower correlation values for wind speed may be at least partially explained by the differences in topographical characteristics between in situ station locations and NARR grid cells. The in situ stations record wind speeds at a specific point in a landscape. NARR smooths terrain and applies an average elevation to each grid cell, in effect minimizing the complexities of large-scale flows and localized weather events (Whiteman 2000). Besides topographical complexities, elevation differences further confound the wind speed differences. As elevation increases, wind speeds generally increase because of reduced surface friction and lower air density. Both in situ stations are at a higher elevation than

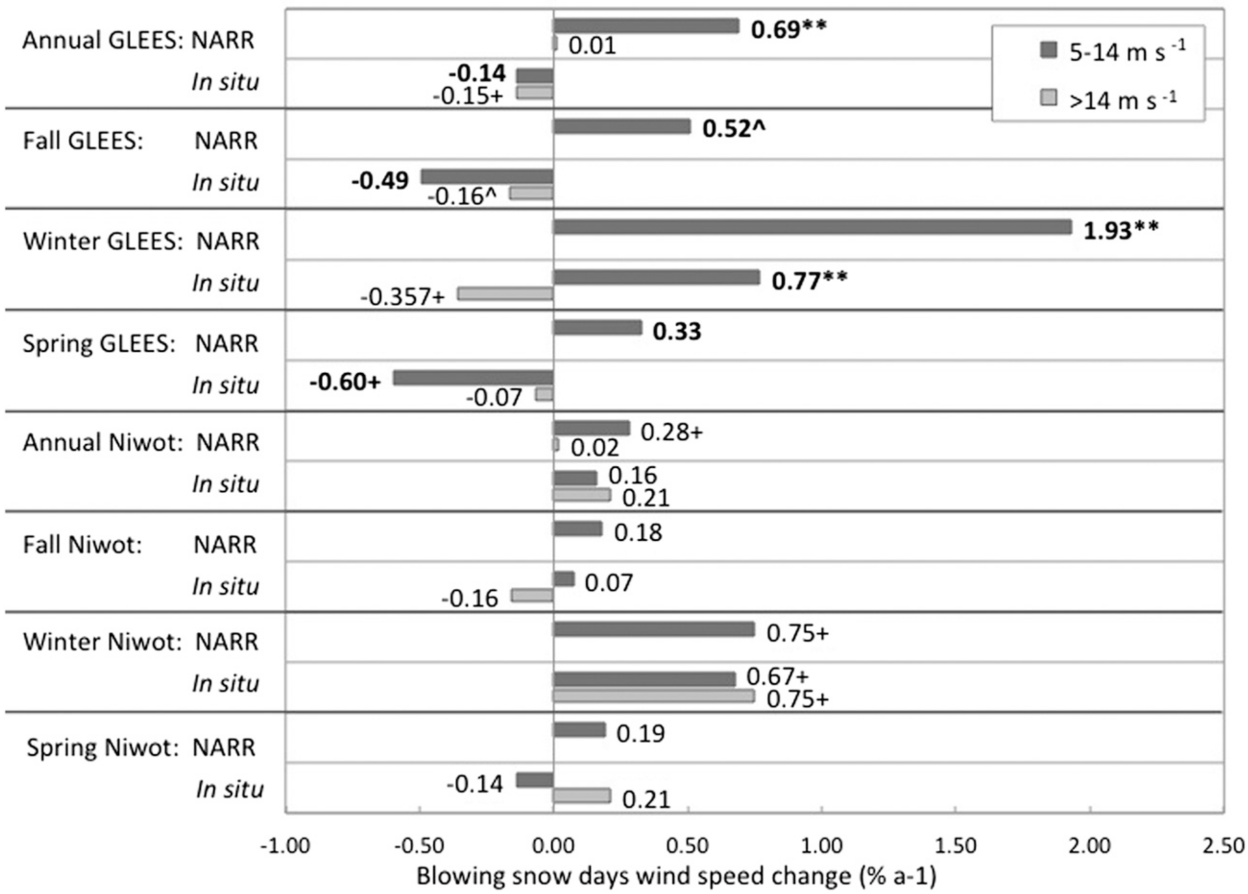

FIG. 7. Blowing-snow-day trends in percentage of change per year (% yr^{-1}) for wind speed threshold categories 5–14 or >14 $m s^{-1}$. NARR wind speeds > 14 $m s^{-1}$ and summer data were not included because of the minimal number of days on which BSD conditions occur. Boldface values represent statistically different trends between data types. Significance p value of 0.001 is shown by a double asterisk, a plus sign denotes $p = 0.05$, and carets show $p < 0.1$.

the NARR grid cell; the difference is 767 m at Niwot and 619 m at GLEES. The difference in elevation likely contributes to the higher wind speeds observed at the in situ sites. Scaling NARR wind speed data to an elevation equal to in situ sites may improve wind speed correlation coefficients, but such exercises would be specific to local topography and may not solve the problem on a wider scale. The overall goal of this research was to directly compare the two data types without introducing additional uncertainty by manipulating either dataset.

From the two stations assessed in this study, NARR underestimates wind speed values in complex terrain, and if similar results are widespread then model alterations may prove to be necessary. Uncorrelated wind speeds between modeled and in situ data are not limited to NARR; Hiemstra et al. (2006) found similar and slight correlation coefficients between in situ and LAPS data for wind speed. In their study, the r^2 values ranged from 0.01 to 0.85 and the agreement declined with increasing elevation. In a historically windy location off the coast of Greenland, where complex topography is not an issue, Moore et al. (2008) found that NARR underestimated high winds. The inability of NARR to capture the intensity of wind speeds, especially high winds, limits the usefulness of NARR to analyze wind speed climates and blowing-snow trends in an alpine region.

The comparison of in situ and NARR temporal trends exhibited that most trends were not significantly different; meaning the slope and the sign (positive or negative) of the trends were statistically similar, even when both sign and slope were opposite. Trend results were due to low slope angles and suggest that only slight long-term trends exist. Another viable explanation pertains to the length of the dataset; different trends may be present when different temporal extents are analyzed. Alpine wind speeds in Switzerland showed trends that were sensitive to the temporal extent, with an increasing trend of 0.0067 $m s^{-1} yr^{-1}$ between 1960 and 2006 and

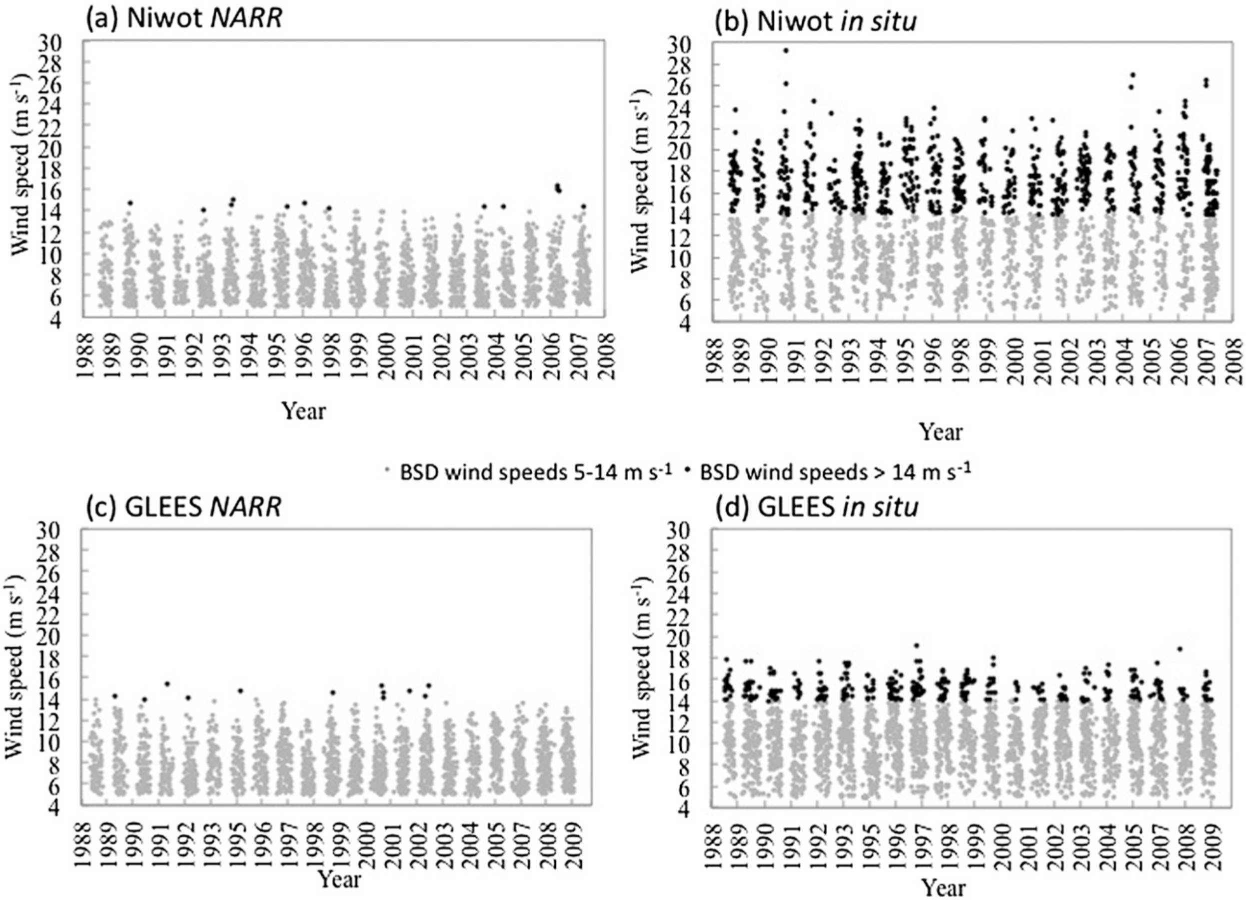

FIG. 8. Comparison of the daily mean wind speed intensity for BSDs between NARR and in situ data for wind speed threshold categories 5–14 (gray dots) or >14 (black dots) $m\,s^{-1}$: (a) Niwot NARR, (b) Niwot in situ, (c) GLEES NARR, and (d) GLEES in situ.

a decreasing trend of $-0.086\,m\,s^{-1}\,yr^{-1}$ between 1983 and 2006 (McVicar et al. 2010). The Niwot and GLEES temporal extent was similar to the latter Switzerland trends in that they are all slight trends over time and are not significant. Annual mean wind speed trends were observed at Niwot with a value of $0.006\,m\,s^{-1}\,yr^{-1}$ and at GLEES with a value of $-0.02\,m\,s^{-1}\,yr^{-1}$. It is possible that a few windy or relatively calm years or a different temporal scale would yield different results.

The investigation of 20 years of wind speed data at annual, seasonal, and daily temporal scales showed a minimal number of significant trends. Overall, the results presented here are similar to wind speed trend analyses in other regions of the globe (McVicar et al. 2011). The lack of trends led us to test changes in the daily wind speed sample variance over time. A change in the number of high wind speeds balanced by a change in low wind speeds could neutralize mean wind speed over time and potentially explain the minimal number of significant trends observed. Although a majority of the data showed no change in sample variance, there was a slight increase in sample variance for Niwot in situ winter and spring daily mean wind speed data. A change in variance could influence blowing-snow processes. Niwot in situ winters showed an increase in wind speed sample variance, yet at GLEES the sample variance did not change over time.

The results from BSD analyses showed trends to be statistically similar between NARR and in situ data. These results are misleading, because BSDs are dependent on precipitation, temperature, and wind speed data being highly correlated between datasets, and the lack of such largely affects trend comparisons for BSDs. Although the overall detection of BSDs between the datasets for Niwot and GLEES was similar, the wind speeds captured by NARR were lacking in the frequency (count) and intensity (wind speed) of wind speeds of $>14\,m\,s^{-1}$. Both sites experienced an increase in the frequency and intensity of winter BSDs in the 5–$14\,m\,s^{-1}$ category. The division of wind speeds into threshold categories highlights how NARR and in situ datasets differ. This lack would likely minimize the degree of blowing snow in an alpine environment, and higher wind speeds are critical when estimating the extent of blowing snow in alpine regions.

The warming trends could influence the number of BSDs accounted for, but, despite fewer 0°C days, BSD trends were increasing for some time steps. At both locations, NARR should model colder temperatures than in situ data because the model is higher in height and thus should identify more precipitation events at 0°C and BSDs. However, the opposite was true; in situ sites recorded colder temperatures and more BSDs, and this result remained even with significant warming trends. Because the NARR does not model similar temperature trends, modeled climate-change predictions in alpine regions may be inaccurate.

The lack of correlation for precipitation and wind speed data causes the BSD trend results to be unreliable. As a result, winter alpine meteorological processes were different between NARR and in situ data, and this limitation strained the use of NARR for a more broad-scale analysis of temporal trends. Identifying the limitations of NARR in alpine regions establishes a baseline for understanding how NARR is restricted and what types of improvements could be made so that NARR can continue to provide a dynamically consistent dataset for broad-scale analyses.

7. Conclusions

To assess alpine meteorological processes and blowing-snow trends over the last 20 years, NARR data were used to expand data from in situ meteorological stations in space and time. The lack of correlation between in situ and NARR data for alpine meteorological processes led to limitations in assessing long-term regional wind speed and blowing-snow trends across the eastern Rocky Mountains. The lack of agreement between different meteorological parameters showed that blowing-snow processes might be better assessed by observational datasets.

The slight and varied significance for temporal trends from all datasets leads to calls for additional analyses of alpine data to understand whether similar long-term trends are local or widespread. Likewise, datasets with shorter temporal extents could be analyzed to see whether different trends exist or whether the longer datasets more accurately represent long-term trends. Another avenue for additional research would be to increase the temporal resolution used in the blowing-snow model. For example, hourly data could be used instead of daily data to assess conditions suitable for blowing snow, or additional meteorological parameters, such as snow accumulation or relative humidity, could be incorporated into the model.

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REFERENCES

Bernhardt, M., K. Schulz, G. E. Liston, and G. Zängl, 2012: The influence of lateral snow redistribution processes on snow melt and sublimation in alpine regions. *J. Hydrol.,* **424–425,** 196–206.

Blöschl, G., and R. Kirnbauer, 1992: An analysis of snow cover patterns in a small alpine catchment. *Hydrol. Processes,* **6,** 99–109.

——, ——, and D. Gutknecht, 1991a: Distributed snowmelt simulations in an Alpine catchment: 1. Model evaluation on the basis of snow cover patterns. *Water Resour. Res.,* **27,** 3171–3179.

——, D. Gutknecht, and R. Kirnbauer, 1991b: Distributed snowmelt simulations in an Alpine catchment: 2. Parameter study and model predictions. *Water Resour. Res.,* **27,** 3181–3188.

Businger, S., M. E. Adams, S. E. Koch, and M. L. Kaplan, 2001: Extraction of geopotential height and temperature structure from profiler and rawinsonde winds. *Mon. Wea. Rev.,* **129,** 1729–1739.

Elder, K., J. Dozier, and J. Michaelsen, 1991: Snow accumulation and distribution in an alpine watershed. *Water Resour. Res.,* **27,** 1541–1552.

Fierz, C., P. Riber, E. E. Adams, A. R. Curran, P. M. B. Fohn, M. Lehning, C. Pluss, and J. R. Garratt, 2003: Evaluation of snow-surface energy balance models in alpine terrain. *J. Hydrol.,* **282,** 76–94.

Fohn, P. M. B., 1980: Snow transport over mountain crests. *J. Glaciol.,* **26,** 469–480.

Gan, T. Y., R. Barry, and A. Gobena, 2011: Changes in North American snow packs for 1979-2004 detected from the snow water equivalent data of SMMR and SSM/I passive microwave and related climatic factors. *Cold Regions Hydrology in a Changing Climate,* D. Yang, P. Marsh, and A. Gelfin, Eds., IAHS Publ. 346, Int. Association of Hydrological Sciences, 79–85.

Garratt, J. R., 1994: Review: The atmospheric boundary layer. *Earth Sci. Rev.,* **37,** 89–134.

Greene, E. M., G. E. Liston, and R. A. Pielke, 1999: Simulation of above treeline snowdrift formation using a numerical snow-transport model. *Cold Reg. Sci. Technol.,* **30,** 135–144.

Groisman, P. Ya., and D. R. Legates, 1994: The accuracy of United States precipitation. *Bull. Amer. Meteor. Soc.,* **75,** 215–227.

Gubler, H., 1980: Simultaneous measurements of stability indexes and characteristic parameters describing the snow cover and the weather in fracture-zones of avalanches. *J. Glaciol.,* **26,** 65–74.

Guirguis, K. J., and R. Avissar, 2008: A precipitation climatology and dataset intercomparison for the western United States. *J. Hydrometeor.,* **9,** 825–841.

Hartman, M. D., J. S. Baron, R. B. Lammers, D. W. Cline, L. E. Band, G. L. Liston, and C. Tague, 1999: Simulations of snow distribution and hydrology in a mountain basin. *Water Resour. Res.,* **35,** 1587–1603.

Hiemstra, C. A., G. E. Liston, R. A. Pielke Sr., D. L. Birkenheuer, and S. C. Albers, 2006: Comparing Local Analysis and Prediction System (LAPS) assimilations with independent observations. *Wea. Forecasting,* **21,** 1024–1040.

Jiang, Y., Y. Luo, Z. C. Zhao, and S. W. Tao, 2010: Changes in wind speed over China during 1956-2004. *Theor. Appl. Climatol.,* **99,** 421–430.

Kind, R. J., 1990: Mechanics of Aeolian transport of snow and sand. *J. Wind Eng. Ind. Aerodyn.,* **36,** 855–866.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

Klink, K., 1999: Climatological mean and interannual variance of United States surface wind speed, direction and velocity. *Int. J. Climatol.,* **19,** 471–488.

Korfmacher, J. L., and D. M. Hultstrand, cited 2009: Glacier Lakes Ecosystem Experiments Site (GLEES) hourly meteorology tower data: 1989-2005. U.S. Dept. of Agriculture Forest Service Rocky Mountain Research Station. [Available online at http://www.fs.usda.gov/rds/archive/Product/RDS-2006-0003/.]

Legates, D. R., and T. L. DeLiberty, 1993: Precipitation measurement biases in the United States. *J. Amer. Water Resour. Assoc.,* **29,** 855–861.

Lehning, M., P. Bartelt, B. Brown, T. Russi, U. Stockli, and M. Zimmerli, 1999: Model calculations for avalanche warning based upon a new network of weather and snow stations. *Cold Reg. Sci. Technol.,* **30,** 145–157.

——, J. Doorschot, and P. Bartelt, 2000: A snowdrift index based on SNOWPACK model calculations. *Ann. Glaciol.,* **31,** 382–386.

L'hôte, Y., P. Chevallier, A. Courdrain, Y. Lejeune, and P. Etchevers, 2009: Relationship between precipitation phase and air temperature: Comparison between Bolivian Andes and the Swiss Alps. *Hydrol. Sci. J.,* **50,** 989–997.

Li, L., and J. W. Pomeroy, 1997: Estimates of threshold wind speeds for snow transport using meteorological data. *J. Appl. Meteor. Climatol.,* **36,** 205–213.

Li, X., S. Zhong, X. Bain, and W. Heilman, 2010: Climate and climate variability of the wind power resources in the Great Lakes region of the United States. *J. Geophys. Res.,* **115,** D18107, doi:10.1029/2009JD013415.

Lin, Y., K. E. Mitchell, E. Rogers, M. E. Baldwin, and G. J. DiMego, 1999: Test assimilations of the real-time, multi-sensor hourly precipitation analysis into the NCEP Eta Model. Preprints, *Eighth Conf. on Mesoscale Meteorology,* Boulder, CO, Amer. Meteor. Soc., 341–344.

Liston, G. E., 2004: Representing subgrid snow cover heterogeneities in regional and global models. *J. Climate,* **17,** 1381–1397.

——, and M. Sturm, 1998: A snow-transport model for complex terrain. *J. Glaciol.,* **44,** 498–516.

——, R. B. Haehnel, M. Sturm, C. A. Hiemstra, S. Berezovskaya, and R. D. Tabler, 2007: Instruments and methods simulating complex snow distributions in windy environments using SnowTran-3D. *J. Glaciol.,* **53,** 241–256.

——, C. A. Hiemstra, K. Elder, and D. W. Cline, 2008: Mesocell study area snow distributions for the Cold Land Processes Experiment (CLPX). *J. Hydrometeor.,* **9,** 957–976.

Losleben, M., cited 2011a: D-1 (3743 m) climate station: CR23X data. Long Term Ecological Research Network. [Available online at http://tropical.lternet.edu/knb/metacat/knb-lter-nwt.402.6/lter.]

——, cited 2011b: D-1 (3743 m) climate station: DP211 data. Long Term Ecological Research Network. [Available online at http://tropical.lternet.edu/knb/metacat/knb-lter-nwt.72.5/lter.]

Luce, C. H., D. G. Tarboton, and K. R. Cooley, 1999: Subgrid parameterization of snow distribution for an energy and mass balance snow cover model. *Hydrol. Processes,* **13,** 1921–1933.

McVicar, T. R., T. G. Van Niel, L. T. Li, M. L. Roderick, D. P. Rayner, L. Ricciardull, and R. J. Donohue, 2008: Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophys. Res. Lett.,* **35,** L20403, doi:10.1029/2008GL035627.

——, ——, M. L. Roderick, L. T. Li, X. G. Mo, N. E. Zimmermann, and D. R. Schmatz, 2010: Observational evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations: 1960–2006. *Geophys. Res. Lett.,* **37,** L06402, doi:10.1029/2009GL042255.

——, and Coauthors, 2011: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *J. Hydrol.,* **416–417,** 182–205.

Mesinger, F., 1996: Improvements in quantitative precipitation forecasts with the Eta regional model at the National Centers for Environmental Prediction: The 48-km upgrade. *Bull. Amer. Meteor. Soc.,* **77,** 2637–2649.

——, and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.,* **87,** 343–360.

Moore, G. W. K., R. S. Pickart, and I. A. Renfrew, 2008: Buoy observations from the windiest location in the world ocean Cape Farewell, Greenland. *Geophys. Res. Lett.,* **35,** L18802, doi:10.1029/2008GL034845.

NOAA/ESRL Physical Sciences Division, cited 2009: NCEP North American Regional Reanalysis: NARR. [Available online at http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html.]

NRCS, cited 2010: SNOTEL and snow survey & water supply forecasting. U.S. Dept. of Agriculture Natural Resources Conservation Service brochure. [Available online at http://www.wcc.nrcs.usda.gov/snotel/SNOTEL-brochure.pdf.]

Oort, A. H., 1977: Adequacy of the rawinsonde network for global circulation studies tested through numerical model output. *Mon. Wea. Rev.,* **106,** 174–195.

Ott, R. L., and M. Longnecker, 2001: *An Introduction to Statistical Methods and Data Analysis.* 5th ed. Duxbury Thomson Learning, 1152 pp.

Pachauri, R. K., and A. Reisinger, Eds., 2007: *Climate Change 2007: Synthesis Report.* Cambridge University Press, 104 pp. [Available online at http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.]

Pirazzoli, P. A., and A. Tomasin, 2003: Recent near-surface wind changes in the central Mediterranean and Adriatic areas. *Int. J. Climatol.,* **23,** 963–973.

Pomeroy, J. W., 1991: Transport and sublimation of snow in a wind-scoured alpine terrain. *Snow, Hydrology and Forests in High Alpine Areas,* H. Bergmann et al., Eds., Vol. 205, International Association of Hydrological Sciences Publ. 205, 131–140.

——, and D. M. Gray, 1990: Saltation of snow. *Water Resour. Res.,* **26,** 1583–1594.

Pryor, S. C., and Coauthors, 2009: Wind speed trends over the contiguous United States. *J. Geophys. Res.,* **114,** D14105, doi:10.1029/2008JD011416.

Radic, V., and G. K. C. Clarke, 2011: Evaluation of IPCC models' performance in simulating late-twentieth-century climatologies and weather patterns over North America. *J. Climate,* **24,** 5257–5274.

Roderick, M. L., L. D. Rotstayn, G. D. Farquhar, and M. T. Hobbins, 2007: On the attribution of changing pan evaporation. *Geophys. Res. Lett.,* **34,** L17403, doi:10.1029/2007GL031166.

Schmidt, R. A., 1986: Transport rate of drifting snow and the mean wind speed profile. *Bound.-Layer Meteor.,* **34,** 213–241.

Shafran, P., J. Woollen, W. Ebisuzaki, W. Shi, Y. Fan, R. Grumbine, and M. Fennessy, 2004: Observational data used for assimilation in the NCEP North American Regional Reanalysis. Preprints, *14th Conf. on Applied Climatology,* Seattle, WA, Amer. Meteor. Soc., 1.4. [Available online at https://ams.confex.com/ams/pdfpapers/71689.pdf.]

Sturm, M., and A. M. Wagner, 2010: Using repeated patterns in snow distribution modeling: An Arctic example. *Water Resour. Res.,* **46,** W12549, doi:10.1029/2010WR009434.

Sugiura, K., T. Ohata, and D. Q. Yang, 2006: Catch characteristics of precipitation gauges in high-latitude regions with high winds. *J. Hydrometeor.,* **7,** 984–994.

Sun, X. M., and A. P. Barros, 2010: An evaluation of the statistics of rainfall extremes in rain gauge observations, and satellite-based and reanalysis products using universal multifractals. *J. Hydrometeor.,* **11,** 388–404.

Tabler, R. D., 1994. Design guidelines for the control of blowing and drifting snow. National Research Council Strategic Highway Research Program Rep. SHRP-H-381, 364 pp. [Available online at http://onlinepubs.trb.org/onlinepubs/shrp/SHRP-H-381.pdf.]

Tuller, S., 2004: Measured wind speed trends on the west coast of Canada. *Int. J. Climatol.,* **24,** 1359–1374.

Whiteman, C. D., 2000: *Mountain Meteorology: Fundamentals and Applications.* Oxford University Press, 355 pp.

Winstral, A., K. Elder, and R. E. Davis, 2002: Spatial snow modeling of wind-redistributed snow using terrain-based parameters. *J. Hydrometeor.,* **3,** 524–538.