THESIS

ALPINE WIND SPEED AND BLOWING SNOW TREND IDENTIFICATION AND ANALYSIS

Submitted by

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ABSTRACT

ALPINE WIND SPEED AND BLOWING SNOW TREND IDENTIFICATION AND ANALYSIS

The substantial quantity of climate change related analyses has resulted in increased research efforts concerning temporal wind speed trends. A change in wind speeds over time could have a widespread effect on snow transport and distribution in alpine regions. Since alpine meteorological stations are sparsely distributed, the intentions of this research were to explore North American Regional Reanalysis (NARR) to assess long-term trends of atmospheric conditions affecting snow transport with greater spatial coverage. NARR is a consistent, continuous and long-term dataset spanning the extent of North America at a spatial resolution of 32 km^2 grids. NARR data were compared to two alpine sites (Niwot Ridge, Colorado and Glacier Lakes Ecological Experiments Station, Wyoming) from 1989 to 2009. Multiple analyses were conducted to evaluate dataset agreement and temporal trends of alpine climatic conditions at the annual, seasonal and daily scales. The correlation of temperature, precipitation and wind speed between NARR and alpine *in situ* datasets showed temperature data as correlated, but wind and precipitation lacked agreement. NARR wind speed data were systematically lower when compared to observational data for both locations, but the frequency of wind events was captured. Thus, to more accurately assess blowing snow dynamics using NARR additional methods would be needed to relate the lower wind speed values to the extent of blowing snow.

Trend analyses of wind speed datasets for each temporal scale (annual, seasonal and daily) showed slight trends, minimal significance and trends were not significantly different between NARR and *in situ* data. The statistical similarities were observed for trends with opposite signatures and slopes and a result of weak trends. Additional blowing snow analyses were conducted using temperature, wind speed and precipitation to estimate probable blowing snow events. The low agreement between NARR and observational data for wind speed and precipitation parameters prohibited the use of NARR to assess blowing snow processes and expand spatial and temporal coverage.

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PREFACE

This research was designed to gain a greater understanding of wind speed and blowing snow trends in the Front Range of the Rocky Mountains. Two meteorological stations (Niwot Ridge, Colorado and Glacier Lakes Ecosystem Experimental Station, Wyoming) were compared to the corresponding North American Regional Reanalysis (NARR) grid cells. The *in situ* and NARR datasets were compared to see if the NARR dataset could be used to expand spatial and temporal coverage and improve our understanding of alpine meteorological processes. To compare *in situ* and North American regional Reanalysis data and understand temporal blowing snow trends many hypotheses were tested. Hypotheses included 1) temperature, precipitation and wind speed data are highly correlated between these datasets; 2) mean wind speeds show a significant change (increase or decrease) in temporal trends for annual, seasonal and daily data; 3) daily mean wind speeds show a change (increase or decrease) in variance over time; 4) wind speed trends are statistically similar between both datasets at each temporal increment; 5) there has been a change in wind speeds exceeding set threshold categories for blowing snow; and 6) the number and intensity of blowing snow days have changed over time and trends are statistically similar between datasets.

The thesis is organized into two chapters: a manuscript and a literature review. Chapter 1 is formatted as a manuscript for submission to a peer reviewed journal. The manuscript includes an introduction, research objectives, methods, results, discussion and a conclusion. Appendix A of this document is a literature review covering current wind trend research across the globe and pertinent snow transport research. Full details of the methodology and results can be found in the other appendices.

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CHAPTER 1: ALPINE WIND SPEED AND BLOWING SNOW TREND IDENTIFICATION AND ANALYSIS

Introduction

The distribution of snow in alpine regions has received a great deal of attention in recent years due to the importance of snow as a water resource. While snow as a water resource is valuable, snow and blowing snow present considerable hazards for transportation and backcountry safety. A better understanding of temporal wind speed trends affecting the spatial distribution of snow is important for accurate estimation of the amount of water equivalent stored within a snowpack. The amount of water derived from a melted snowpack is known as snow water equivalent (SWE). SWE is estimated using the depth and density per unit area of a snowpack. The estimation of SWE is difficult in complex terrain because of interactions among snow, wind and topography (Elder et al. 1991; Greene et al. 1999). Increasing the knowledge base of alpine wind speed and snow distribution trends is crucial because water from alpine areas is a key component in the hydrologic cycle and supports the water needs for 1/6th of the global population (Barnett et al. 2004). This research compared long-term trends in wind speeds affecting snow transport in the alpine between two different data types: 1) *in situ* meteorological stations, and 2) North American Regional Reanalysis (NARR), a gridded regional model output. NARR encompasses all of North America and is a consistent, long-term, high-resolution 3-dimentional atmospheric and land surface hydrologic dataset (Messinger et al. 2006). If *in situ* and NARR data correlate well then perhaps NARR can be used to increase spatial and temporal coverage so a better understanding of alpine meteorological processes can be achieved.

To compare *in situ* and North American regional Reanalysis data and understand temporal blowing snow trends six hypotheses were tested. Hypotheses included 1) temperature, precipitation and wind speed data are highly correlated between these datasets; 2) mean wind speeds show a significant change (increase or decrease) in temporal trends for annual, seasonal and daily data; 3) daily mean wind speeds show a change (increase or decrease) in variance over time; 4) wind speed trends are statistically similar between both datasets at each temporal increment; 5) there has been a change in wind speeds exceeding set threshold categories for blowing snow; and 6) the number and intensity of blowing snow days have changed over time and trends are statistically similar between datasets.

Background

While many studies have focused on how wind transports and distributes snow across a landscape, few studies have analyzed long-term wind speed trends and the potential effects on snow distribution. Snow depth can spatially vary from a few centimeters to many meters and be caused by land-surface characteristics (Elder et al. 1991; Winstral et al. 2002; Liston et al. 2007) and stronger winter wind speeds (St. George and Wolfe 2010; Klink 2002). Alpine regions are likely more sensitive to long-term change and variability (Beniston 2006; IPCC 2007). A change in wind speed behavior when snow cover is present could have a widespread effect on the extent and amount of blowing snow.

Wind speed research conducted in China (1960-2006) and Switzerland (1983-2006) used observational data to analyze wind speed trends in mountainous regions (McVicar et al. 2010). Their results showed alpine wind speeds decreased at a faster rate when compared to low elevation sites. The decline in wind speeds was more prevalent during winter months for both China and Switzerland, but was not significant (McVicar et al. 2010). Their study showed the magnitude of decreasing wind speeds at alpine locations was -0.0138 and -0.0086 m s^{-1} a^{-1} (meters per second per year) for China and Switzerland, respectively. The mean wind speeds were not stated by McVicar et al. (2010) so the percentage or amount change relative to the mean could not be assessed. However, estimating from the figures provided, the overall mean for alpine wind speeds were approximately 2.5 m s^{-1} for China and 2.25 m s^{-1} for Switzerland, recorded at 10 m heights.

Low-elevation observational stations have shown significant evidence of declining wind speeds over the past 30-50 years in North America, Europe, Australia, Canada, Switzerland and China (McVicar et al. 2008, 2010; Pryor et al. 2009; Klink 1999; Tuller 2004; Roderick et al. 2007; Pirazzoli and Tomasin 2003; Jiang et al. 2010). The average magnitude of decline from these studies was -0.01 m s^{-1} a^{-1} and significance varied among the different locations and datasets. This decline was further confirmed by McVicar et al. (2011) where the average trend was -0.017 m s^{-1} a^{-1} from 148 wind speed studies.

Data

While results from wind speed analyses are seemingly consistent and widespread, many issues plague *in situ* stations that may create false trends or mask real trends, and ultimately lead to inaccurate wind speed and snow transport assessments. In order to look at long-term wind speed trends it is critical to reduce errors and inconsistencies from observational data. Unavoidably, all observational stations are subject to data continuity issues caused by variability among instrument type, height, location, collection methods and record length (Legates and Deliberty 1993). Alpine 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 proves difficult, in part because there are far fewer alpine stations.

Two alpine stations were identified in the Front Range of the Rocky Mountains with approximately 20 years of continuous temperature, wind speed and precipitation data. To sufficiently assess climate trends the temporal extent of 20 years may be too short, but was the best data available. Increased spatial coverage is also needed to comprehensively analyze alpine wind speed and blowing snow trends. In complex terrain, a dataset with finer spatial resolution is more attractive because it may capture the localized, convective meteorology, which is common in mountainous terrain. NARR was viewed as a solution because it is a dataset that maintains fine spatial resolution, has many improvements compared to other similar datasets, and is consistent (Messinger et al. 2006). The NARR dataset has been used to help answer questions concerning precipitation variability, identify patterns in weather and climate, represent extreme events, make regional assessments and forecast future climate scenarios. However, before NARR can be used to expand spatial coverage, we first must understand how well it captured atmospheric conditions influencing snow transport in alpine regions.

NARR data are derived from surface and upper air meteorological observations, which are organized into 32 km horizontal grids consisting of 45 vertical levels. Grid cell estimates of meteorological parameters are available every 3 hours from 1979 to present. Data output includes, but is not limited to, surface temperature, precipitation, humidity, radiation, wind, pressure, convective energy, snow depth, and albedo (NCEP 2009). NARR also assimilates observational data, and as a result, draws a closer relationship between NARR and observational variables (Messinger et al. 2006; Lin et al. 1999). Data consistency is improved because all datasets are assimilated into the same climate model for the entire extent of NARR data (NCEP 2009).

Temperature, humidity, pressure and wind speed are collected and assimilated into NARR from rawinsondes or weather balloons. Rawinsondes are launched twice daily from a network of sites and the data are evaluated to create a vertical profile of the atmosphere. These data are then organized and reanalyzed to provide a complete spatial replication of the atmosphere (Oort 1977). The North American rawinsonde network is comprised of approximately 120 launch sites, a majority of which have been consistently operated by the National Weather Service since the early 1950's (National Weather Service Forecast Office 2010).

To more comprehensively assess ground-level precipitation data from the contiguous U.S. (CONUS) were assimilated into NARR from various sources: National Climatic Data Center (NCDC) cooperative stations, and Hourly Precipitation Data (HPD) (Shafran et al. 2004). Over 11,000 station observations create a 1/8˚ grid in the U.S. (Shafran et al. 2004). In Canada and Mexico, where gauge stations are limited, a 1˚ gridded precipitation dataset exists (Shafran et al. 2004). The assimilation of these data also affords more realistic precipitation events and totals.

While NARR functionally reduces data inconsistencies arising from instrument disparities at individual weather stations, it is still affected by limitations of sparse and temporally inconsistent meteorological observations. Regions with sparsely distributed gauges (deserts, mountains, rangelands, and remote, unpopulated areas) and a limited number of rawinsonde launch sites have resulted in the misrepresentation of large or diverse areas (Hiemstra et al. 2006; Businger et al. 2001). Weaknesses were confirmed in Canada, where the number of precipitation gauges and rawinsonde launches were few (Messinger et al. 2006). Limitations were also observed in areas of complex terrain and caused by a larger frequency of cumulus convective events and localized meteorological dynamics (Kistler et al. 2001). Since NARR is largely based on rawinsonde data at, and above, mountain top level, NARR data may be well suited for expanding and improving information about alpine weather and climate. However, there appears to be few previous studies utilizing NARR data to investigate alpine wind patterns, blowing snow processes and changes over time.

Study Area

The comparisons between *in situ* meteorological station and NARR data were conducted to understand how comparable NARR data were to observed alpine conditions. This analysis allowed us to determine if NARR data could be used to reconstruct alpine atmospheric conditions and expand spatial coverage. Criteria for site selection included: a minimum of 20 years of consistent surface weather data, instrumentation situated above 3000 meters and a location where minimal land use-land cover change has occurred (Figure 1). The Long Term Ecological Research (LTER) station at Niwot Ridge, Colorado, referred to as Niwot, and Glacier Lakes Ecological Experiments Station (GLEES), Wyoming meteorological stations met these requirements. The NARR grid cells encompassing each meteorological station are identified (Figure 2).

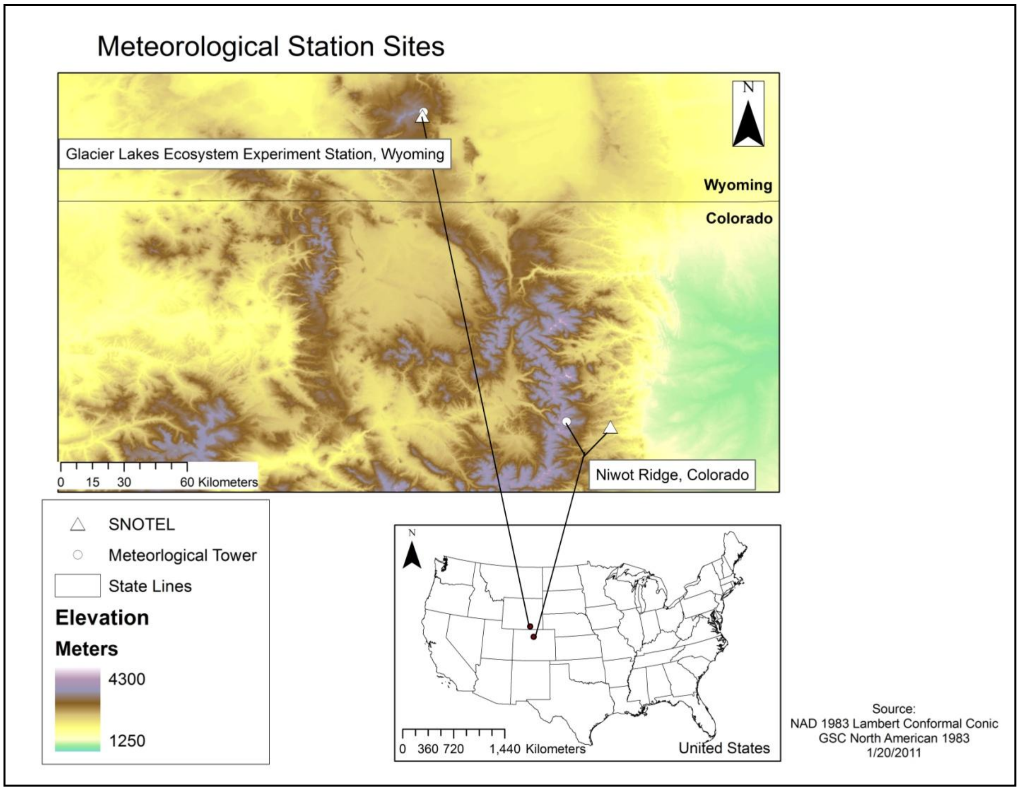

Figure 1: Location of meteorological stations in Colorado and Wyoming.

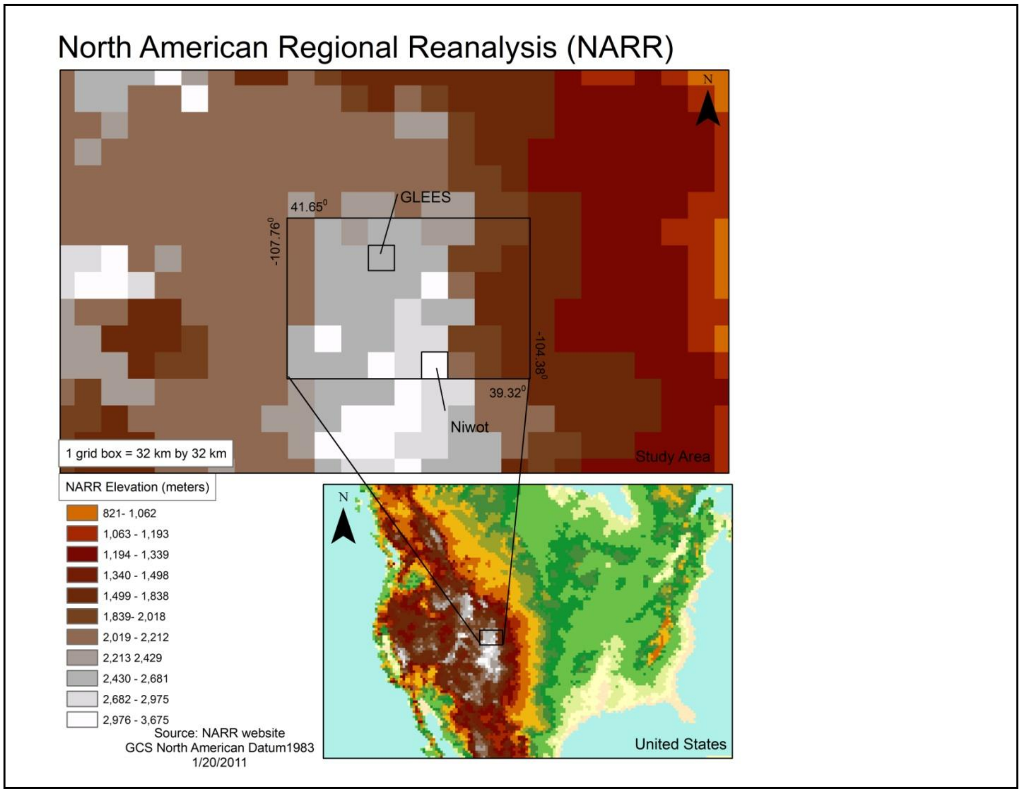

Figure 2: North American Regional Reanalysis grid identification.

The meteorological parameters analyzed were temperature, precipitation and wind speed. *In situ* wind and temperature data were acquired from research facilities at Niwot (LTER 2009) and GLEES (Korfmacher and Hultstrand 2009). Precipitation data were harvested from proximal Snowpack Telemetry (SNOTEL) stations for both locations so that instrumentation and quality control procedures were consistent. SNOTEL stations collect climate and snowpack related data to better forecast water resources within the western mountains of the U.S and Alaska (NRCS 2010). SNOTEL sites are typically located away from ridges or wind dominated areas to maximize collection accuracy. Tables 1 and 2 delineate the parameter details for both *in situ* stations (Table 1) and NARR (Table 2) datasets. For each location, NARR data were set to the same time frame as the *in situ* dataset.

Table 1: *In situ* station details for meteorological parameters, location and dataset extent.

Station	Meteorological parameter	Name	Latitude	Longitude	Elevation	Tower height	Years
Niwot	Wind speed Temperature	Niwot - D-1 station	40.05944	-105.6166	3743 m	9 m	1989 - 2008
	Precipitation	Niwot SNOTEL	40.03583	-105.4291	3018 m	2.5 m	
GLEES	Wind speed Temperature	GLEES	41.38400	-106.2280	3300 m	15 m	1989-2009
	Precipitation	Brooklyn Lakes SNOTEL	41.36670	-106.2330	3115 m	2.5 m	

Table 2: NARR grid cell locations, meteorological parameter details and dataset extents. The latitude and longitude coordinates are the center points of the grid cells.

NARR	Meteorological parameters	Grid coordinates	Latitude	Longitude	Elevation	Height	Years
Niwot	Wind speed Temperature Precipitation	178, 109	40.087	-105.688	2976	10 m 10 m 10 m	1979-2009
GLEES	Wind speed Temperature Precipitation	176, 113	41.247	-106.429	2681	10 m 10 m 10 m	1979-2009

Methods

Data preparation

To quantify trends at different temporal scales, annual, seasonal and daily means were analyzed. Data for the Niwot *in situ* site spanned from 1989 to 2008 and GLEES data spanned a similar extent from 1989 to 2009. The NARR data, although of longer extent, were reduced to match the respective *in situ* record. Daily means (0000 – 2400 MST) were organized into hydrologic years (October 1st to September 30th). Annual means were calculated from all daily means per year and seasonal means were derived from appropriate daily means for each year. Seasons were defined as September, October, and November (fall); December, January and February (winter); March, April, and May (spring) and June, July and August (summer). NARR daily precipitation totals can be estimated at miniscule amounts (e.g. 0.00034 mm), which is an artifact of the model. To remedy these arbitrary precipitation values when NARR daily means were below 0.2 mm the value was changed to zero. This value was chosen because it was the threshold that minimized data that were likely an artifact of the NARR model.

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.

To further 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. In each of these models, we assumed the error to be normally distributed, however not necessarily independent. The analysis of daily time series data required a more complex analysis due to autocorrelation of the daily values. An exploratory analysis indicated that an autocorrelation regression model (AR (1)) would be adequate to model the residual dependence in the daily mean time series data for each of the three data types (Ott and Longnecker 2001).

Wind speeds were also analyzed at set thresholds to observe the frequency of winds influencing snow transport. A threshold is the minimum wind speed required to initiate or sustain snow transport (Schmidt 1986; Pomeroy and Grey 1990). Wind speeds 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). When winds reach speeds greater than 14 m s^{-1} and snow particles are not fully bonded, the amount of blowing snow increases (Li and Pomeroy 1997). Thus, thresholds were categorized as < 5, 5-14 and >14 m s^{-1}.

To assess the frequency and intensity of blowing snow, precipitation, wind speed and temperature were used to index a day where blowing snow was probable defined as blowing snow day (BSD). A BSD was established when temperatures were 0 degrees Celsius or below, wind speeds were in either 5-14 m s^{-1} or >14 m s^{-1} category and when precipitation was present. Since blowing snow could occur on days when precipitation was not present, the subsequent four days were also included but only if temperature and wind speed specifications were met.

The same method was used to analyze wind speed threshold frequency distributions and BSDs by applying a binary response to each daily data point. A value of 1 was assigned when criteria were met for each category, otherwise a 0 was assigned and then each category was summed. To compare the count data for the different categories, odds ratios were computed and inferences were performed using the Gaussian approximation to the log-odds ratio.

Results

NARR and in situ temperature, precipitation and wind speed correlation

Results from NARR and *in situ* temperature data proved to be highly correlated. The r^2 values for temperature were 0.84 at Niwot (1989-2008) and 0.85 for GLEES 1989-2009). *In situ* stations recorded slightly colder temperatures compared to NARR, where the average degree difference was 1˚ C at Niwot and 4˚C at GLEES. Although temperatures were highly correlated, temporal trends differed between NARR and *in* situ data for the Niwot site. Temperatures have significantly increased at the Niwot *in situ* station of 1.5˚ C per decade (p=0.02). However, NARR data did not portray similar significance. The point estimate showed an increasing trend of 0.04˚ C per decade, but was not significant (p=0.87) indicating the NARR temperature trend was not significantly different than zero. No significant temperature trends were observed at GLEES.

Precipitation and wind speed data ranged in agreement. The correlation between *in* situ and NARR precipitation data proved highly uncorrelated with r^2 value of 0.001 and 0.186 for Niwot and GLEES, respectively.

Wind speed correlation values for Niwot and GLEES were fairly similar but not significant with r^2 value of 0.36 and 0.38 for Niwot and GLEES, respectively. Both *in situ* meteorological stations showed higher wind speeds compared to NARR.

Temporal trend analyses for wind speed

Long-term wind speed trend analyses were conducted for annual, seasonal and daily means. No significant annual trends were present for the meteorological stations or NARR sites.

Niwot seasonal trends for both *in situ* and NARR were not significant. The hypothesis $\beta_1 = 0$ (i.e., no trend) was tested and if this trend was not zero, the alternative hypothesis was accepted if p-value ≤ 0.1 level. Although slight, GLEES NARR data had a positive significant trend during the winter season of 0.0402 m s^{-1} a^{-1} (p=0.06). However, no trend was observed for the GLEES *in situ* station for the winter season (Figure 3b). The differences in means between NARR and *in situ* winter mean data are apparent for both sites in Figure 3, but more pronounced for Niwot.

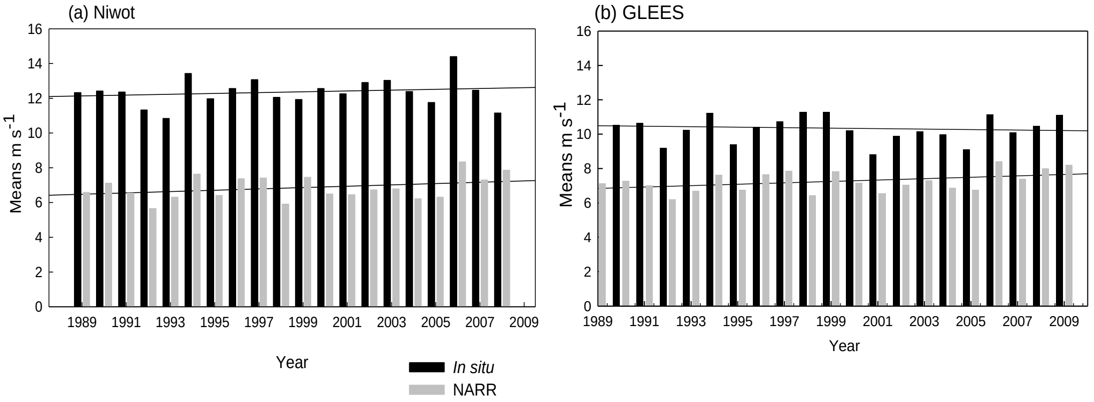

Figure 3: Seasonal wind speed means for December, January, and February (winter); (a) Niwot and (b) GLEES. The GLEES NARR seasonal winter trend is significantly ($p < 0.1$) increasing at by 0.04 m s^{-1} per year.

Daily wind speed values were categorized into seasons to best assess trends. The daily trend analyses showed no changes over time for the Niwot *in situ* station. Winter daily means for both NARR datasets indicated a positive trend for Niwot at 0.0368 m s^{-1} a^{-1} (p=0.01) and GLEES at 0.0388 m s^{-1} a^{-1} (p=0.05). The GLEES meteorological station had a negative trend for summer daily means at -0.0349 m s^{-1} a^{-1} (p=0.01). Again, higher wind speeds for the *in situ* data were captured. For a visual representation all daily wind speed means for the extent of the data are shown in Figure 4.

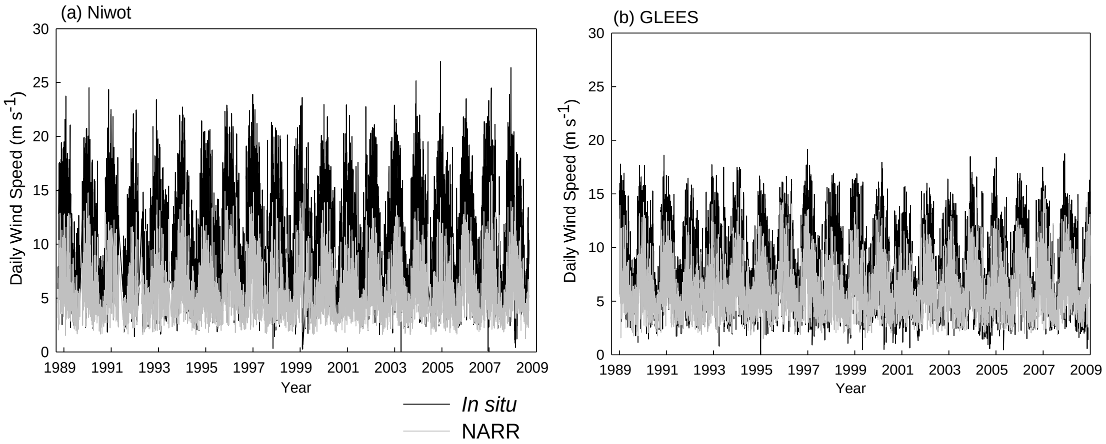

Figure 4: ***In situ*** **station and NARR daily mean wind speeds, (a) Niwot, and (b) GLEES. To display the seasonal variance all daily means are presented, with winter months as the peaks and summer months as the valleys.**

Overall, both locations exhibited very few significant trends for annual, seasonal and daily means and trends were rarely consistent between *in situ* and NARR. Detailed results are listed in Table 3. The statistical comparison of trend variance and correlation between *in situ* and NARR showed all trends as statistically similar. Meaning similarities were consistent among all trends even when the trends had opposite signatures or differing degrees of significance.

Table 3: Results from annual, seasonal and daily mean wind speeds are presented. In addition, a mean was derived from the entire wind speed dataset for each site so the amount of change could be conceptualized. Trend values are meters per second per year m s^{-1} a^{-1}. Significance codes: 0.01 ‘*’; 0.05 ‘+’; <0.1 ‘^ ’. Seasonal divisions are fall (September, October, November); winter (December, January, February); spring (March, April, May); and summer (June, July, August).

Dataset	**Annual trend in m s^{-1} a^{-1}**	**Season**	**Overall mean**	**Seasonal trends in m s^{-1} a^{-1}**	**Daily trends in m s^{-1} a^{-1}**
Niwot *in situ*	0.0058	Fall	10.39	0.0032	-0.0010
		winter	12.35	0.0238	0.0191
1989-2008 mean in m s^{-1}	9.617	spring	9.324	0.0274	0.0085
		summer	6.218	-0.0132	-0.0167
Niwot NARR	0.0078	fall	5.515	-0.0071	-0.0153
		winter	6.836	0.0265	0.0368^
1989-2008 mean in m s^{-1}	5.465	spring	5.559	0.0123	0.0153
		summer	3.977	-0.0035	-0.0136
GLEES *in situ*	-0.0203	fall	7.885	-0.0212	-0.0421
		winter	10.35	-0.0085	-0.0041
1989-2009 mean in m s^{-1}	7.838	spring	7.930	-0.0196	-0.0268
		summer	5.269	-0.0304^	-0.0349 *
GLEES NARR	0.0148	fall	6.091	-0.0032	-0.0029
		winter	7.248	0.0402 ^	0.0388 +
1989-2009 mean in m s^{-1}	5.958	spring	5.961	0.0219	0.0189
		summer	4.558	0.0005	-0.0085

Sample variance temporal trends for daily mean wind speeds

Daily mean wind speeds were also tested for temporal trends in the variance. A preliminary analysis was conducted in which the sample variance of daily mean wind speeds 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. The hypothesis that $\beta_1 = 0$ (i.e., no trend) was tested, and all tests failed to reject this null hypothesis at the p-value ≤ 0.1 level. As these preliminary results provided evidence that significant trends are not present, no additional analyses were performed.

The sample variance plots for Niwot and GLEES for the winter and spring seasons are shown in Figure 5. These seasons were chosen because the trends show the lowest p-values, which were less than p-value = 0.1 level. Niwot *in situ* data shows a significant increasing trend in the sample variance for winter 0.33 m s^{-1} a^{-1} and spring 0.16 m s^{-1} a^{-1} with p-value = 0.1 and

0.06, respectively. No significant trends were present for Niwot NARR or either GLEES datasets. The full results can be reviewed in Table 4.

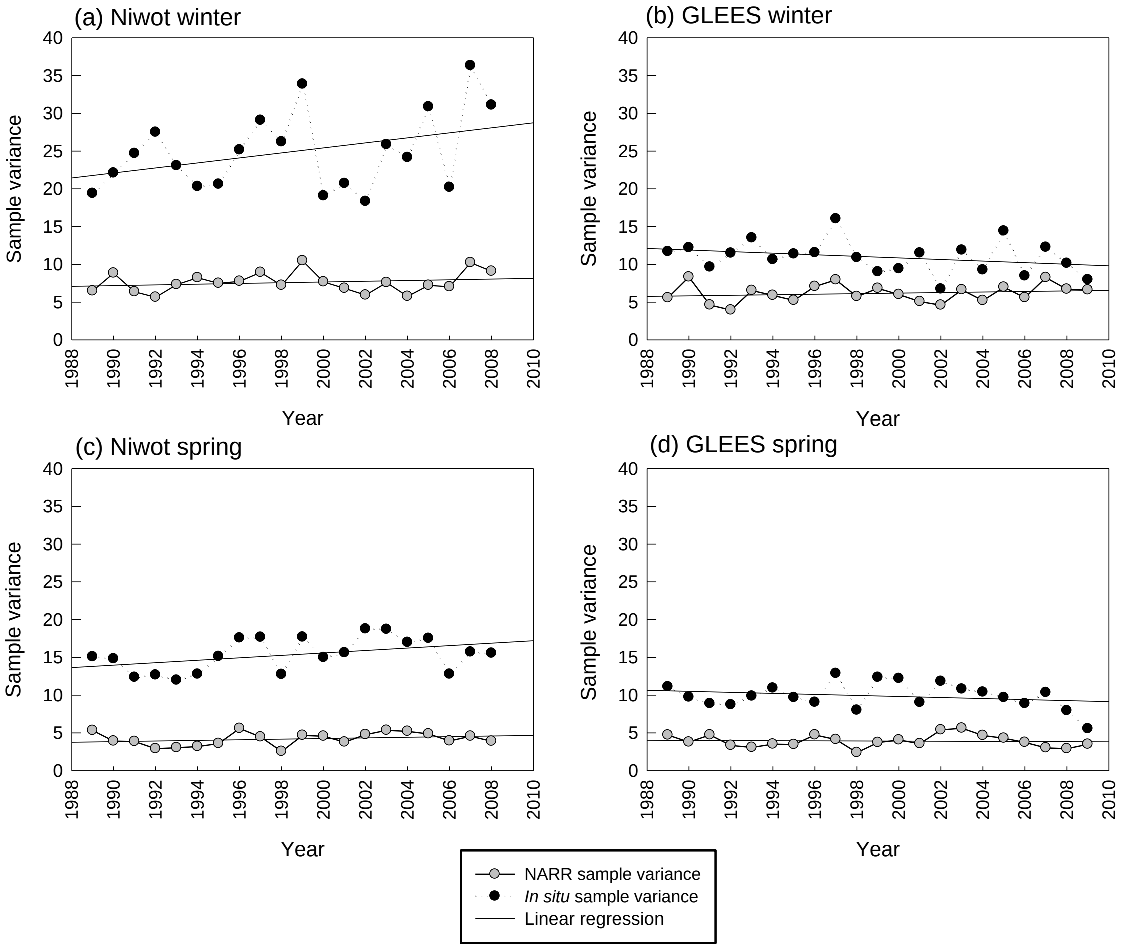

Figure 5: Sample variances plotted for daily mean wind speeds with linear regression trend line for (a) Niwot winter, (b) GLEES winter, (c) Niwot spring, and (d) GLEES spring.

Table 4: Sample variance results for daily mean wind speed for each Niwot and GLEES sites datasets. The slope of the trend in the sample variances are displayed in meters per second per year (m s^{-1} a^{-1}) Significance codes for p-values: <0.1 '^ '. Seasonal divisions are fall (September, October, November); winter (December, January, February); spring (March, April, May); and summer (June, July, August).

Dataset	**Season**	**Sample variance trends in m s^{-1} a^{-1}**	**p-value**
Niwot *in situ*	Fall	-0.12	0.35
	Winter	0.33	0.10^
	Spring	0.16	0.06^
	Summer	-0.01	0.92
Niwot NARR	Fall	0.01	0.85
	Winter	0.05	0.37
	Spring	0.04	0.23
	Summer	0.01	0.65
GLEES *in situ*	Fall	0.004	0.83
	Winter	-0.10	0.19
	Spring	-0.07	0.28
	Summer	-0.01	0.83
GLEES NARR	Fall	-0.01	0.89
	Winter	0.04	0.41
	Spring	-0.01	0.78
	Summer	0.001	0.97

Frequency of wind speeds exceeding thresholds

The frequency of wind speeds exceeding set thresholds differed between *in situ* and NARR datasets. There were no significant annual trends observed at Niwot for either dataset or for GLEES NARR data. The GLEES meteorological station data demonstrated a negative annual trend for winds >14 m s^{-1} at -0.131% per year (p=0.05).

The percentage of wind speeds occurring in each threshold category are displayed in Figure 6 for the winter season. When NARR winds were divided seasonally there were too few positive responses for wind speeds >14 m s^{-1} to accurately be analyzed, which indicates that the high winds were not accurately captured by NARR. GLEES station data showed opposing significant trends for winter at different thresholds. Specifically, a decreasing trend was observed for winds > 14 m s^{-1} and an increasing trend for 5-14 m s^{-1}, at a similar rate of -0.562% and

0.486% per year (p=0.05), respectively. The summer season for both *in situ* and NARR data rarely experience winds stronger than 14 m s^{-1}, so summer data were excluded from analyses.

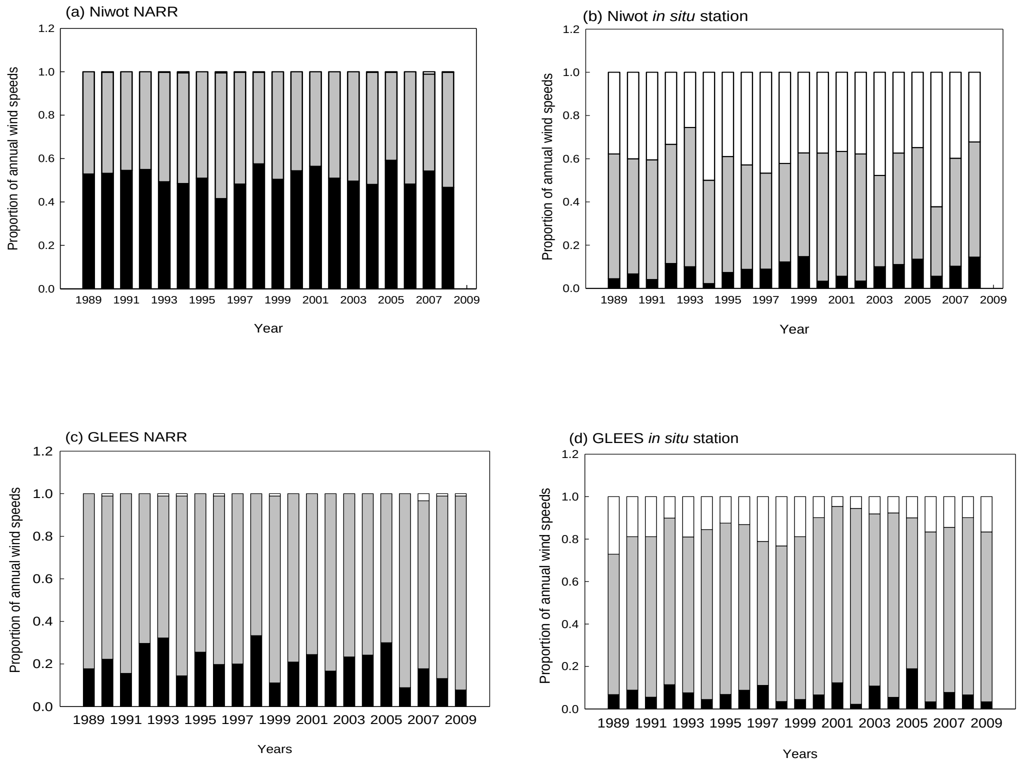

Figure 6: Wind speeds exceeding set thresholds during winter (December, January and February) displayed as a proportion of annual wind speeds per winter season; (a) Niwot NARR, (b) Niwot *in situ* station, (c) GLEES NARR, and (d) GLEES *in situ* station.

The variance was tested using three threshold categories, which influence snow transport. Overall, the binary responses of wind speeds in each category changed minimally over time. Table 4 shows the percentage of days per year that have changed for each threshold category. The i*n situ* and NARR data showed trends as similar for all categories except for annual GLEES wind speeds >14 m s^{-1} and Niwot winter wind speeds 5-14 m s^{-}1. The bold text in Table 5 shows represents significantly different trends between NARR and *in situ* datasets.

Table 5: All results from wind speed values exceeding set thresholds at annual, seasonal and daily temporal scales for Niwot data span 1989-2008 and GLEES data span 1989-2009. Trend values in each threshold category are percentage of days per year that have increased or decreased over time. Significance codes: 0.01 '*'; 0.05 '+'; <0.1 '^'. The seasonal divisions are fall (September, October, November), winter (December, January, February), spring (March, April, May), and summer (June, July, August). Bold text represents statistically different trends between *in situ* and NARR in percent change per year (% a^{-1}).

Dataset	**Annual trends (percentage of days per year changing)**			**Seasonal Trends (percentage change per year)**			
	<5 m s^{-1}	**5 - 14 m s^{-1}**	**>14 m s^{-1}**		**<5 m s^{-1}**	**5 - 14 m s^{-1}**	**>14 m s^{-1}**
Niwot Ground	0. 028	-0.118	0.090	fall	-0.265	0.332	-0.068
				winter	0.242	**0.447**	0.205
				spring	-0.213	-0.111	0.323^
				summer	0.298	-0.305	n/a
Niwot NARR	-0.080	0.069	0.021^	fall	0.194	-0.191	N/A
				winter	-0.359	**0.359**	
				spring	-0.193	0.188	
				summer	0.213	-0.034	
GLEES Ground	0.144	0.043	**-0.186***	fall	0.0599	0.020	-0.262*
				winter	-0.025	0.486*	-0.562*
				spring	-0.100	0.017	-0.072
				summer	0.685	-0.692	N/A
GLEES NARR	-0.131	0.121	**0.010**	fall	0.060	-0.069	N/A
				winter	-0.384	0.355	
				spring	-0.357	0.557	
				summer	0.158	-0.158	

Blowing snow day trend analysis

Niwot *in situ* and NARR data for BSDs were not significant for both annual and seasonal temporal scales. The absence of trends could be caused by mean temperature increases, which would influence the positive response of BSDs. Another aspect influencing BSD trend differences between NARR and *in situ* data is the magnitude of recorded wind speeds (Figure 7). NARR rarely contains wind speed data above 14 m s^{-1} so identifying blowing snow days with faster wind speeds was limited. These higher wind speeds are critical when estimating the extent of blowing snow in the alpine.

GLEES had multiple significant results for BSDs. The lack of increasing temperature trends could be a contributing factor. Annually, GLEES *in situ* BSD data showed a negative trend of 0.182% per year when winds were >14 m s^{-1}. Seasonal results showed GLEES *in situ* winter data with a positive trend for >5-14 m s^{-1} at 0.724% per year and significance of p=0.05.

GLEES NARR BSDs showed, with varying significance, increasing trends for all thresholds and temporal scales. These positive trends, along with the other BSD results are presented in Table 6.

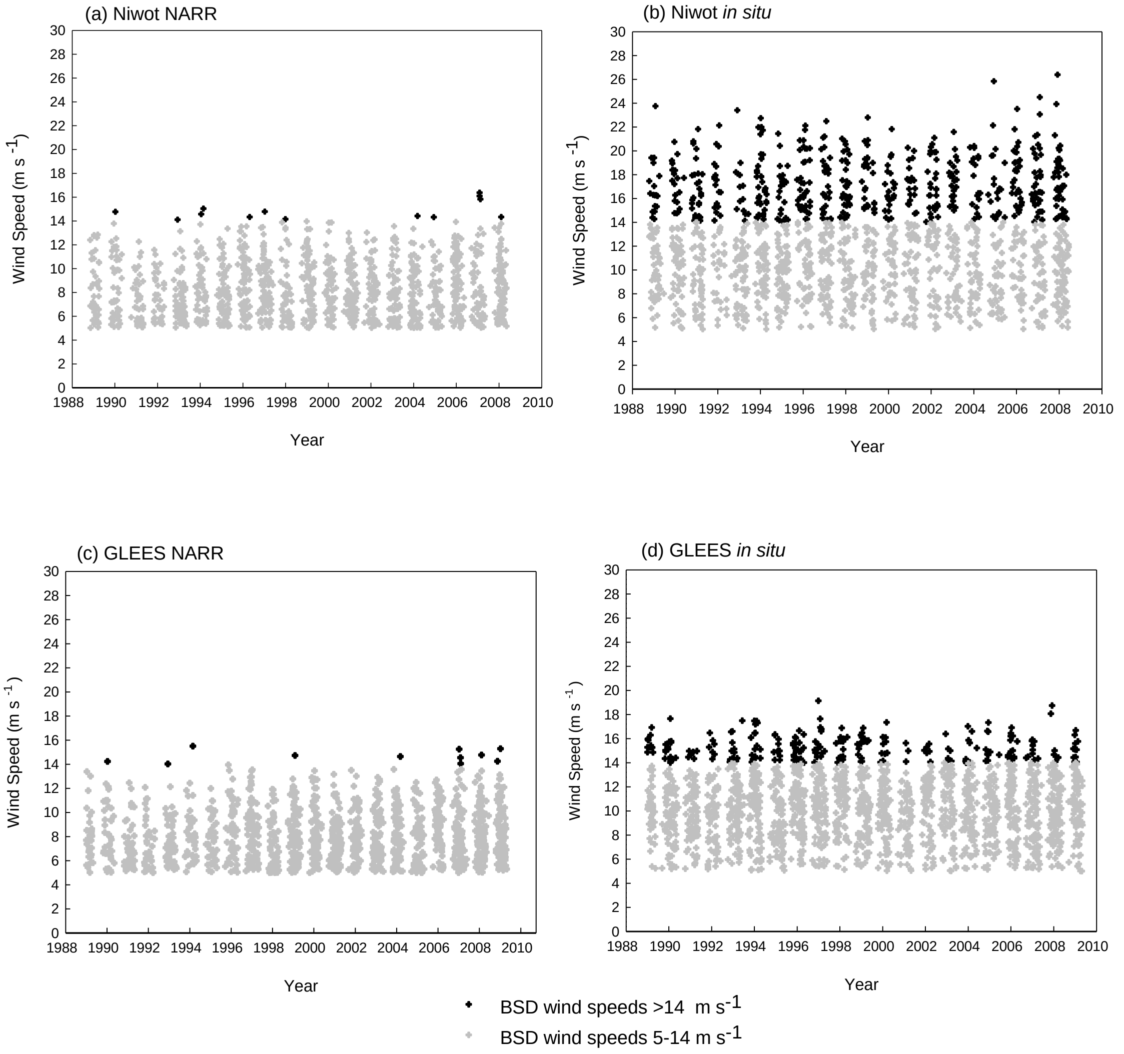

Figure 7: Blowing Snow Days for Niwot and GLEES datasets displayed as daily mean wind speeds. Qualifying Blowing Snow Days for Niwot and GLEES sites displayed as daily mean wind speeds, (a) Niwot NARR, (b) Niwot *in situ*, (c) GLEES NARR and (d) GLEES *in situ*.

Table 6: Blowing Snow Day trend values listed as percentage of change per year (% a^{-1}). Wind speeds (m s^{-1}) are also categorized into 5-14 m s^{-1} and > 14 m s^{-1}. Summer is not included due to minimal number of days where BSD conditions exist. Significance codes: 0.001 ''; 0.01 '*'; 0.05 '+'; <0.1 '^'. fall – September, October, November; winter – December, January, February; spring – March, April, May; summer – June, July, August. Bold text represents statistically different trends between data types.**

Dataset	**Annual trends (percent change per year)**		**Seasonal Trends (percent change per year)**		
	5 - 14 m s^{-1}	**>14 m s^{-1}**	**Months**	**5 - 14 m s^{-1}**	**>14 m s^{-1}**
Niwot ground	0.026	0.148	fall	0.004	0.188
			winter	**-0.075**	0.197
			spring	0.227	0.227
Niwot NARR	0.281	0.020	fall	0.176	N/A
			winter	**0.754**	
			spring	0.188	
GLEES ground	0.182	-0.130*	fall	0.154	-0.119
			winter	**0.724***	-0.349^
			spring	-0.084	-0.087
GLEES NARR	0.692***	0.010	fall	0.515^	N/A
			winter	**1.93*****	
			spring	0.325	

Discussion

Meteorological parameters have different variability and temporal continuity characteristics and, as a result, the observation accuracy of each parameter ranges. For example temperature data, even when accounting for diurnal effects, lack dramatic oscillations and are continuous (Hiemstra et al. 2006). As a result, temperature data tend to have higher correlation among datasets when compared to other meteorological parameters. This effect was present in this study and in a similar study by Hiemstra et al. (2006) who found temperature r^2 values ranged from 0.64 to 0.99 between NOAA's Local Analysis and Prediction System (LAPS) gridded data and 107 *in situ* station datasets. LAPS, similar to NARR, assimilates multiple observational meteorological datasets creating 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 U.S. They found the average temperature differences between the datasets was <2˚C. Results from this study were comparable, with an average 2.5˚ C temperature difference between all NARR and *in situ* data.

Precipitation data collection methods have long been plagued with accuracy issues. All precipitation gauges are affected by wind, wetting, evaporation, and inaccurate trace precipitation collection (Guirguis and Avissar 2008). For NARR, many issues inhibit accurate precipitation data. For starters, the spatial distribution of assimilated observational points is irregular and sparse. There is also a linear decrease in the number of observational datasets assimilated into NARR northward from 20˚N to 50˚N (Messinger et al. 2006). Dynamic meteorological processes may be missed in complex terrain due to the fewer number of stations as well (Hiemstra et al. 2006). Another issue concerning NARR precipitation data is the magnitude of daily precipitation totals. NARR records miniscule amounts of precipitation (e.g. 0.00004 mm) regularly, instead of less frequent and more realistic precipitation totals. Hiemstra et al. (2006) found r^2 values ranged from 0.01 to 0.76 between *in situ* stations and LAPS precipitation data. The smaller r^2 coefficients were observed at higher elevations and in areas with more topographic relief.

Precipitation data have shown more inconsistencies when temperatures drop below 0˚ Celsius and precipitation is in the form of snow. Sugiura et al. (2006) found zero gauge catch became more frequent when snowfall was present and wind speeds were 6 m s^{-1} or greater. Groisman and Legates (1994) showed gauges during the winter recorded 20% less precipitation compared to actual precipitation totals and the under-catch for individual storm was up to 75% less.

The lower correlation values for wind speed between *in situ* stations and NARR may be 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 smoothes 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 increase due to reduced surface friction and lower air density. Both *in situ* stations are at a higher elevation compared to the NARR grid cell, the difference is 767 m at Niwot and 619 m at GLEES. The difference in elevation likely contributes to higher wind speeds observed at the *in situ* sites. Hiemstra et al. (2006) found a similar and slight correlation between *in situ* stations and LAPS data for wind speed, the r^2 values ranged from 0.01 to 0.85 and the agreement declined with elevation gain.

The investigation of 20 years of wind speed data at annual, seasonal and daily temporal scales and the daily mean sample variance showed a minimal number of significant trends. When variance and correlation were calculated to compare *in situ* and NARR temporal trends, most trends were not significantly different either. Meaning, the slope and the signature (positive or negative trend) of the trends were statistically similar between *in situ* and NARR data even when both signature and slope were opposite. This result was due to low slope angles of the trends that suggest only slight long-term trends exist. Another viable explanation pertains to the length of the dataset, different trends may 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} a^{-1} for 1960-2006 and a decreasing trend of -0.086 m s^{-1} a^{-1} for 1983 to 2006 (McVicar et al. 2010). It is possible that a few windy or still years or a different temporal scale could present different results in this research.

The division of wind speeds into threshold categories identifies how NARR and *in situ* datasets differ. For all categories the *in situ* stations record higher wind speeds. During the winter, when winds are the highest and blowing snow occurs, large discrepancies between

NARR and *in situ* data were observed for threshold frequency categories. Both the Niwot and GLEES *in situ* stations maintained wind speeds in the >14 m s^{-1} threshold category for 50% and 20% of the time, respectively. During the winter months NARR accounted for wind speeds in the >14 m s^{-1} category only 1% of the time and NARR over represented wind speeds in the <5 m s^{-1} and 5-14 m s^{-1}. Moore et al. (2006), in a historically windy location off the coast of Greenland, found NARR underestimated high winds as well. The inability of NARR to accurately estimate wind speeds, especially high winds, limits the use of NARR to analyze wind speed climates and blowing snow trends in alpine locations.

The results from BSD analyses showed trends as similar between NARR and *in situ* data. However, 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 affect trend comparisons for BSDs. For example, wind speeds captured by NARR were lacking the frequency (count) and intensity (wind speed) of wind speeds >14 m s^{-1}, which would likely minimize the degree of blowing snow in an alpine environment.

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 for alpine sites establishes a baseline for understanding how NARR is restricted and what type of improvements could be made so that it can continue to provide a dynamically consistent dataset for broad scale analyses.

Due to the numerous analyses conducted a table clearly describing the result of each hypothesis test is presented (Table 7). The results are listed as either accept or reject per hypothesis. To accept a hypothesis, means we accept the alternative hypothesis or fail to reject the null hypothesis because a significant trend or correlation of data was present. Reject indicates that the hypothesis was not supported with trends significantly different from zero.

Table 7: Summarization of each hypothesis test for all analysis conducted.

Hypotheses	**Analysis**	**Niwot *in situ***	**Niwot NARR**	**GLEES *in situ***	**GLEES NARR**
Temperature, precipitation and wind speed data are highly correlated between NARR and *in situ* datasets	Temperature Precipitation Wind speed	Accept Reject Reject		Accept Reject Reject	
Mean wind speeds show a significant change (increase or decrease) of temporal trends for annual, seasonal and daily data	Annual Seasonal Daily	Reject Reject Reject	Reject Reject Reject	Reject Reject Reject	Reject Reject Reject
The daily mean wind speeds show a significant change in sample variance (increase or decrease) per season, over time.	Fall Winter Spring Summer	Reject Accept Accept Reject	Reject Reject Reject Reject	Reject Reject Reject Reject	Reject Reject Reject Reject
Wind speed trends are statistically similar between both datasets at each temporal increment	Annual Seasonal Daily	Accept Accept Accept	Accept Accept Accept	Accept Accept Accept	Accept Accept Accept
There has been a change in the percentage of winds at the <5, 5-14 and >14 m s^1 thresholds per year	<5 5-14 >14 m s	Reject Reject Reject	Reject Reject Accept	Reject Reject Accept	Reject Reject Reject
The number and intensity of blowing snow days show significant temporal trends	annual seasonal	Reject Reject	Reject N/A	Accept Accept	Accept N/A

Conclusion

The advantage of using NARR to assess alpine meteorological processes and blowing snow trends over time was to expand spatial and temporal coverage. The lack of correlation between *in situ* and NARR data for alpine meteorological processes led to limitations in assessing long-term wind speed and blowing snow trends across the Front Range of the Rocky Mountains. Results from comparing these data indicated that temperature data were the highest correlated, on average, with an r^2 of 0.845. Precipitation data agreement was lower with an average r^2 value of 0.094. Precipitation correlation disparities were likely a combination of observational errors, NARR measurement limitations, and complications associated with precipitation as snow. Wind speed data achieved an average r^2 value of 0.37. NARR wind speed data were consistently lower than *in situ* data and likely contributed to the lower r^2 values. Although the intensity of wind speeds was missed by NARR, the frequency of wind speeds was comparable to *in situ* data. The lack of agreement between meteorological parameters showed that blowing snow processes were better assessed by observational datasets. The slight and varied significance for temporal trends from all datasets calls for additional analyses of *in situ* alpine station meteorological data to understand if similar long-term trends are local or widespread.

Long-term changes and the variability of wind speeds would 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 U.S. where climate change projections indicate decreases in annual snowpack (IPCC 2007).

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APPENDIX I: LITERATURE REVIEW

The literature review supplies an overview of research pertaining to wind and snow interactions. First, the broader impacts of wind and snow influencing human activities are covered to highlight the importance of blowing snow. An overview of recent wind research follows and includes an overview of inter-annual variability, seasonality, elevation effects and instrumentation issues pertaining to wind speed. Next, the basics of snow hydrology and snow transport information are covered. This section discusses physical snow processes such as metamorphism, blowing snow, types of snow transport and sublimation. Lastly, there is a description of the North American Regional Reanalysis dataset.

The impacts of wind and snow on human activities

The ability to identify or predict wind trends and snow distribution patterns could significantly improve prediction and planning for winter road hazards, water resources, evapotranspiration rates, avalanche safety, alpine ecology, fire season conditions, agricultural practices, and livestock safety.

Drifting and blowing snow on roadways can cause obstacles and decreased visibility, and increase risks and life-threatening situations for motorists, snow removal vehicle drivers and outdoor recreationalists (Audrey et al. 2003; Thompson and Nakhla 2002). Nonetheless, people still travel during hazardous winter conditions. Due to the increasing population regular travel and travel to recreation destinations has also increased (Rice et al. 2002). The rise in recreational travel was accounted for by Colorado skier visits, which has grown from 800,000 to over 11 million in the past three decades (http://www.coloradoski.com/page/cscusa-history-contact

2010). The 2010-11 winter season hosted 6.9 million winter vacationers in Colorado, an increase of 2.6% from the previous season (http://www.coloradoski.com/page/cscusa-history-contact 2011). This was also observed throughout the Rocky Mountain Region (CO, NM, ID, UT, MT, and WY), where winter vacationers increased by approximately a half of a million people from 2009/10 to 2010/11 (http://www.nsaa.org/nsaa/press/historical-visits.pdf 2011).

Snow avalanches are a winter safety concern, for both recreational and motorists activities. In Colorado approximately 278 avalanche paths affect roadways and are actively monitored and controlled (CDOT 2009). Out of all the western states, including Alaska, Colorado ranks highest in avalanche mortality between 1950 and 2009 (CAIC 2010). Avalanche safety is a growing concern because the number of deaths caused by avalanches has steadily increased across the country and predominantly affected backcountry recreational activities (i.e., snowshoeing, skiing and snowboarding, snowmobiling, and hiking/climbing). Snowmobile triggered avalanche fatalities and accidents are the highest ranking and fastest increasing of all activities due to the requirement of open, undeveloped backcountry terrain (CAIC 2010; Scott 2003). Fewer avalanche risks and fatalities have been observed at resorts and on roadways because professional patrols mitigate known avalanche slide zones (Page et al. 1999).

Avalanches can develop under a variety of conditions; the prime conditions include new snow, increased wind speed and changes in wind direction (McCollister 2004). An increase in wind speeds can cause the magnitude of an avalanche to grow and become unstable (McCollister et al. 2003; Rice et al. 2002; Bader and Salm 1990). However, in some cases, the probability of a slide occurring is lower when wind redistributes snow from more frequent slide paths to less common slide paths (McCollister et al. 2003). This causes avalanche activity to be more difficult to identify and mitigate.

The cattle industry has been impacted by snow and blowing snow. During 2006 the High Plains received over 76 cm of snow. The snow was paired with extreme winds causing blizzard condition winds and resulted in large snow drifts. Harsh weather cause cattle to turn away from oncoming winds and group together to create a natural wind break. Snow drifts accumulate on top of the cattle and can cause freezing, suffocation and sometimes death (Paul et al. 2007). The cattle, in this instance, were unable to reach food or water sources for many days and the deep snow drifts prohibited road access to the cattle as well. Cattle mortality in Colorado was estimated at 15,000 head, which cost ranchers millions (Paul et al. 2007). Due to the severity of the blizzard disaster-level attention was focused on safety and survival of stranded livestock (Paul et al. 2007). President Bush allocated federal support for 114 counties across the high plains (13 counties in Colorado), and state National Guards dropped emergency supplies to stranded cattle and human populations. The 2006 blizzard highlights a recent event; however, historically blizzards on the Eastern Plains have occurred at a similar intensity (CAIC 2010).

Wind research

There are a variety of methods for collecting wind speed data leading to summarization and comparison challenges when assessing global wind climates trends. One issue with global wind data is the lack of both continuity and consistency temporal and spatial (Groisman et al. 2004; McVicar et al. 2008). Table 8 provides a list of wind-related research worldwide, and datasets include *in situ* stations, reanalysis, Global Climate Models (GCM). The table includes information covering location, author of the research, data collection type, time frame and observed trends. This body of research revealed similarities among mid-latitude *in situ* stations for mean wind speed trends. Mean wind speeds, in general, have decreasing over the past 30-50 years in Australia (McVicar et al. 2008), China (Jiang et al. 2009; McVicar et al. 2010), Switzerland (McVicar et al. 2010), Europe (Pirazzoli and Tomasin 2003) and the contiguous U.S. (Pryor et al. 2009; Klink 1999). However, pockets of increasing mean wind speed trends were also evident in these regions. While *in situ* station datasets in high-latitudes (>65º) showed general increasing wind speed trends (Seidel et al. 2008). Reanalysis datasets showed similar mean wind speed declines as the *in situ* station data (McVicar et al. 2008). North American Regional Reanalysis (NARR) data showed declining trends over much of the western U.S. (Pryor et al. 2009). However, NARR annual mean wind speeds are negatively biased compared to *in situ* stations (Pryor et al. 2009). Another reanalysis dataset, the European Center for Medium-Range Weather Forecasts' Reanalysis (ERA-40), showed decreasing wind speed trends in the southwestern U.S. and increasing wind speed trends along the Rocky Mountain spine. Pryor et al. (2009) asserted that observational and reanalysis datasets showed considerable inconsistencies for temporal characteristics of wind trends, while RCMs seemed to align more closely with *in situ* observations.

Sizeable differences between annual mean wind speed trends and interannual variability were observed among Regional Climate Models (RCM), reanalysis products, and direct observations (Pryor et al. 2009). Additionally, conflicting trends were seen between reanalysis and Regional Climate Model datasets. Overall, no simple summarizations could be made concerning wind speed trends over time, St. George and Wolfe (2009) attribute the inconsistencies as an artifact of the differing temporal extents among all datasets. If wind speeds have an increasing or decreasing trend, then these trends may be better observed by synoptic and large scale flows (Pryor et al. 2009). Pielke et al. (2001) has assessed large scale flows at the 200 mbar level and found wind speeds to have increased from 1958 to 1997.

Table 8: Wind Research: Review of recent studies assessing wind speed trends.

Location and Author	**Data Set & Spatial extent**	**Time Period**	**Trend and time step**	**Additional results**
China – mountainous region (McVicar et al. 2010)	25 *In situ* Stations 6 stations >2500m	1960-2006 Seasonal	Decrease of -0.0138 m s^{-1} a^{-1} Each season was had observable declines	Higher elevation sites exhibit greater decreasing trends compared to low elevation sites during winter months (NDJF)
Switzerland - mountainous region (McVicar et al. 2010)	69 *In situ* Stations 2 stations > 2500m	1970-2006 Seasonal	Increase of 0.0067 m s^{-1} a^{-1}	Higher elevation sites exhibit greater decreasing trends compared to low elevation sites during all months except June and July
		1983-2006 Seasonal	Decrease -0.0086 m s^{-1} a^{-1} Each season was had observable declines	
United States - 8 data sources (Pryor et al. 2009; Pryor and Ledolter 2010)	NCDC[1]-6421 Hourly data 336 *In situ* station	1973-2000 (inclusive)	Statistically significant declining wind speeds – very similar to the NCDC – DS3505 data set	Negative trends for annual mean wind speed. Positive trends in interannual variability.
	NCDC[1] –DS3505 193Ground station 0000 UTC and 1200 UTC recorded times	1973-2005 (inclusive) station not moved more than 5km over period – all airports/military station)	0000 UTC 50th percentile trends: 150 stations –decrease 33 stations –no trend 10 stations – increasing 1200 UTC 90th percentile: 146 stations -decrease 36 stations – no trends 11 stations- increase	Significant negative trends in annual mean wind speed (P=0.1) for ~50% stations. Equal probability of positive and negative trends for interannual variability.
	NCEP-1 (NCEP-NCAR[2]) 2.5˚ x 2.5˚ grid	1948-2006 (inclusive)	Annual mean wind speeds: 50th percentile trends General decrease (Central US more dominant) 90th percentile trends Statistically significant increases (All US)	Equal tendencies for: positive and negative trends for annual mean wind speeds / interannual variability

		Truncated 1973-2005	50th and 90th percentile increase for most of Contiguous US. Most cases show statistical significance (especially the Midwest). Magnitude at the 90th percentile is higher when expressed as percent change	
	NCEP-2 (NCEP-DOE[3]) 1.9˚ x 1.9˚ grid	1979-2006 (inclusive) -assimilation from raw observations	Similar to NCEP-1 however does not show significant trends at the 50th percentile.	Both positive and negative annual mean wind speeds; Generally increasing interannual variability (generally smaller trends than *in situ* stations or RCM)
	ERA-40[4] 2.5˚ x 2.5˚ grid	1973-2001 (inclusive)	Evenly divided annual mean trends of increasing, decreasing, and no change. Declines in Southwestern US; Increases along the Rocky Mountain spine. No increasing trends for Midwest at 50th or 90th percentiles.	-generally increasing interannual variability (generally smaller trends than *in situ* stations or RCM)
	NARR[5] 32 x 32 km grid	1979-2006	Declining trends at 0000 UTC Increasing trends in 1200 UTC	-statistically significant decline in annual mean wind speeds -declining interannual variability (but not uniform)
	RCMs[6] (MM5[7]) 52km grid	1979-2004	General declining 50th and 90th percentile	Increases in annual mean wind speed are larger than decreases in interannual variability
	RCMs[6] (RSM[8]) 50km grid	1979-2004	Prevalence of positive trends (not very spatially coherent) Larger magnitude at 0000	Contain both increasing and decreasing trends Tendency towards declining trend

			UTC for 50th and 90th percentile are more common	in annual mean wind speeds and interannual variability
Europe (Pryor et al. 2006)	NCEP/NCAR 1.875˚ x 1.875˚ grid	1960-1989 12 year normalized period of 1990-2001used to compare 30 year trends before and after normalized period	Lower annual wind speed means for 1960-1989 when compared to 1990-2001	Tied to frequency and intensity of North Atlantic oscillation (NAO) during the 2nd half of the 20th Century. High degree of covariance and interannual variability which is linked to latitude at 45˚N – increasing to the north and decreasing to the south of this latitude.
	ECMWF ERA-40 2.5˚ x 2.5˚ grid	1960-1989 Annual	Lower annual wind speed means when compared to 1990-2001	
	HadCM3-AOGCM[9] 2.5˚ x 3.75˚ grid	1990-2099 Stimulation w/ global temperature increase of 4˚ C.	Projected in 30 year increments –similar trends in interannual variability and annual mean (normalized by 1990-2001)	No indication of increasing variability Spatial coherence of annual wind indices is under estimated along latitudes
Australia (McVicar et al. 2008)	160 *in situ* stations 2 m height; stations within 47km of coast; 1 km grid	1979-2006 Monthly, seasonal and annual trends	-Average annual trend is decreasing at a rate of -0.009 m s^{-1} a^{-1}	88.6% of Australia shows decreasing trends; 57.5% are significantly decreasing (P=0.05); 12% shows increasing trends
	1 km *in situ* station grid	1979-2001 Annual	-0.013 m s^{-1} a^{-1}	Reanalysis data sets mask wind trends seen in *in situ* stations
	NCEP/DOE		-0.002 m s^{-1} a^{-1}	
	NCEP/NCAR		-0.004 m s^{-1} a^{-1}	
	ERA40		-0.002 m s^{-1} a^{-1}	
Australia (Roderick et al. 2007)	41 *in situ* stations	1975-2004	-0.0010 m s^{-1} a^{-1}	
USA (lower 48)	207 *in situ* stations	1962-1990	-0.005 m s^{-1} a^{-1}	

Hobbins 2004				
USA - lower 48 (Klink 1999)	176 *in situ* stations	1960-1990	-0.004 m s^{-1} a^{-1}	
Yangtze River, China (Xu et al. 2006)	150 *in situ* stations	1960-2000	-0.008 m s^{-1} a^{-1}	
China (Xu et al. 2006)	305 *in situ* stations	1969-2000	-0.020 m s^{-1} a^{-1}	
Loess Plateau, China (McVicar et al. 2007)	52 *in situ* stations	1980-2000	-0.010 m s^{-1} a^{-1}	
Tibetan Plateau **(**Shenbin et al. 2006)	101 *in situ* stations	1960-2000	-0.013 m s^{-1} a^{-1}	
Tibetan Plateau **(**Zhang et al. 2007)	75 *in situ* stations	1960-2003	-0.017 m s^{-1} a^{-1}	
Italy (Pirazzoli and Tomasin 2003)	17 *in situ* stations	~1955 - ~1996	-0.013 m s^{-1} a^{-1}	1955-1975 ~ -0.026 m s^{-1} a^{-1} 1975-1996 ~ -0.002 m s^{-1} a^{-1}
Canada (Tuller 2004)	4 *in situ* stations (West coast, CAN)	~1950 - ~1990	-0.017 m s^{-1} a^{-1}	
Antarctica **(**Turner 2004)	11 *in situ* stations	~1960 - ~2000	+0.006 m s^{-1} a^{-1}	

[1] National Climate Data Center; [2] National Centers for Environmental Prediction-National Center for Atmospheric Research; [3] Department of Energy; [4] European Center for Medium-Range Weather Forecasts' Reanalysis data; [5] North American Regional Reanalysis; [6]Regional Climate Models [7]Mesoscale Model 5; [8] Regional Spectral Model [9] Atmospheric-Ocean Global Climate Model

The general decrease of mean wind speed trends has become known as a ‘stilling phenomenon’ (Roderick et al. 2008). The ‘stilling’ effect for most mid-latitude locations was on the scale of -0.01 m s^{-1} a^{-1} (McVicar et al. 2010). The stilling of winds was observed over a large geographic region suggests there synoptic level circulation patterns have changed (St. George and Wolfe 2010; Tuller 2004). Factors contributing to the temporal change in wind speeds may include instrument relocation, measurement precision, global circulation pattern change, increases in surface roughness, decreases of synoptic weather systems intensity or some unique combination of all (Vautard et al. 2010). Vautard et al. (2010) and Pielke et al. (2001) found upper-air flows wind speeds recorded by rawinsonde or weather balloons have not shown similar declines. Vautard et al. (2010) suggested that changes in the earth’s surface roughness has caused the general ‘stilling’ of winds by the changes in sensible heat fluxes and altercations of the convection processes. The surface roughness changes were assessed using Normalized Difference Vegetation Index (NDVI) and showed vegetation in northern regions has increased (Vautard et al. 2010). This study then modified land-cover by increasing grassland-roughness in the NCAR Mesoscale Model – 5th generation (MM5 model). These results were able to mimic the wind speed trend declines observed by other studies (Vautard et al. 2010).

A reduction in convection processes and atmospheric mixing occurs when wind speeds are weaker and the result is less efficient heat and moisture mixing and warmer surface temperatures (Klink 2002). In Australia, Roderick et al. (2008) found changes in temperature and humidity between1975-2004 was too small to influence pan evaporation rates. Pan evaporation is sensitive to the degree of humidity, temperature, radiation and wind speed and many areas have experienced changes in evaporative rates (Roderick et al. 2008). Decreasing wind speeds play a more dominate role in the decline of evapotranspiration but solar irradiation rates may also contribute (Roderick et al. 2008). Declines in pan evaporation at a rate of -2 to -5 mm a^{-1} a^{-1} (mm per annum per annum) have been observed in the United States, China, Canada, Australia, New Zealand, the Tibetan Plateau and Russia (Roderick et al. 2008). The pan evaporation declines are supported by observed wind speed declines in most of these regions (McVicar et al. 2010). India and Thailand lack wind analyses to support pan evaporation declines that were calculated at -10 to -12 mm a^{-1} a^{-1} (Roderick et al. 2008).

Global circulation and climate models

Global circulation is the balance of high-latitude and low-latitude convections. Seidel et al. (2008) used multiple datasets and found the tropical belt or Hadley cell has increased in size and volume since the 1970's. The growth was by several degrees poleward, tens of meters in height and 5% in volume. The observed change of the tropical belt has pushed the jet stream more poleward and has caused the jet stream to be wider and less intense (Chase et al. 2000). As a result, weather patterns have noticeably shifted during the winter months in the Northern Hemisphere (Chase et al. 2000). Chase et al. (2000) indicated the widening of the tropical belt was likely caused by the reduction of vegetative cover in tropical regions. Less vegetative cover in the tropics causes increased surface heating and warmer upper-level tropical circulation. Due to the connectivity of global circulation, high-latitude regions have received warmer air masses from the tropics. It is likely changes in global circulation dynamics have influenced wind speed climates (Pielke et al. 2001).

Influence of cyclones - seasonality

Large-scale atmospheric circulation patterns are composed of cyclone and anticyclone. The frequency and intensity of these systems influence annual wind speed characteristics (Pryor et al. 2006). One explanation for regional variation for wind speed trends could be attributed to the number of cyclones per year. Wind speeds vary seasonally and stronger wind speeds generally occur during the winter and spring seasons. Stronger wind speeds during the winter and spring are created from larger pressure gradient differences and tend to occur when synoptic fronts dominate (St. George and Wolfe 2010; Klink 2002). Klink (2002) found the decrease in wind speeds were attributed to declines in cyclone and anticyclone patterns for Minnesota *in situ* station datasets spanning 22-35 years.

Colorado has the greatest cyclone count compared to the Great Basin, Gulf of Mexico, Alberta and the East Coast of the U.S. The highest counts in Colorado were observed during March and fewest in July (Whittaker and Horn 1981). In Colorado the position of the polar jet stream and the dramatic change in topography from the Rocky Mountains to the plains causes higher cyclone frequencies (Whittaker and Horn 1981). European countries showed the change in wind speed trends was centered at 45˚N using NCAR/NCEP and ECMWF reanalysis datasets (1958-2001) (Pryor et al. 2006). European countries north of 45˚N experienced increased wind speeds and countries south of that latitude were subject to decreased wind speeds. In regions north of 60˚N from 1966 to1993, a significant increase in cyclone counts were observed, whereas latitudes ranging between 30˚- 60˚N showed a decrease (McCabe et al. 2001; Serreze et al. 1997). Wind speeds at 200 mbar heights showed a decrease centered at 40˚ N for winter and early spring (Pielke et al. 2001).

Interannual variability

For most of northern Europe, Pryor et al. (2006) found high interannual variability for mean wind speed. Wind speeds in Northern Europe are dictated by the North Atlantic Ocean (NAO), and predominantly a winter phenomenon. A strong NAO patterns create zonality and larger pressure gradients and result in stronger westerlies and faster wind speeds (Pryor et al.

2003). The oscillation of strong and weak NAO patterns between 1960 and1989 were related to the annual mean wind speed.

Baltic region (52˚N - 65˚N) wind speed trends were analyzed for the winter months using the NCEP/NCAR dataset. Results showed wind speeds increasing in the upper quartile for both magnitude and frequency and slight decreases in the lower quartile (Pryor et al. 2003). In the Canadian Plains winds showed considerable interannual variability as well, but given the length of the datasets (1953-2006), trends were difficult to broadly characterize (St. George and Wolfe 2010). However, St. George and Wolfe (2010) found wind speed in the Canadian Plains were considerably lower for up to 18 months during 'moderate' and 'strong' El Nino-Southern Oscillation (ENSO). On the west coast of Canada, Tuller (2004) saw a decrease in the percentage of strong winds and increase in weak winds for 3 of 4 locations north of 49˚N.

High elevation wind speed changes

Surface winds increase as land elevation increases from the reduction of drag and air density. In one study wind speeds at higher-elevation sites showed trends declining at a more rapid rate when compared to lower elevations in China and Switzerland (McVicar et al. 2010). McVicar (2010) concluded that Switzerland high-elevation sites have increasing wind speed trends over a 47 year period (1960-2006) of 0.0067 m s^{-1} per year and with lower wind speeds observed during the 1960's. To compare wind speed trends to other high elevation sites in China, the Switzerland dataset was shortened to 1983-2006. The results from this timeframe showed mean wind speed decreasing at a rate of -0.0086 m s^{-1} a^{-1}. The decline in mean wind speed for China's high elevation sites was similar at -0.0138 m s^{-1} a^{-1} (McVicar et al. 2010). In both datasets the 'stilling' affect became more dominant in the 1970's. However, the Switzerland dataset when analyzed at the longer extent showed an increasing trend which, highlights how a temporal extent influenced trend results.

Anemometer history

Cup anemometers measure wind speed and were originally developed in 1846. Different instruments yielded highly variable results until calibration became standard in the 1920's (Kristensen 1998). Once calibration was consistently practiced, an *overspeeding* phenomenon was observed in the data. Also, turbulent winds affected anemometers and caused in higher wind speed values compared to constant wind speeds of the same magnitude (Kristensen 1998). Additionally, vertical components of wind dynamics can influence anemometer responses. For example, when winds are not perpendicular to the anemometer shaft, *underspeeding* can occur. Wind speeds also have to reach a certain threshold in order to initiate movement of cup anemometers and once in motion take longer to slow or stop. The threshold to initiate movement varies with anemometer type and age. Other anemometer types, such as propeller anemometers, harbor similar errors as cup anemometers but also can have directional errors (Wyngaard 1981).

Wind collection devises such as vanes can be used to orient anemometers or used alone to record wind direction. Sonic anemometers are the most modern and sophisticated wind collection instruments and measure acoustic pulses traveling through the air between the transmitters and receivers. Sonic anemometers can record ten to twenty wind speeds per second and record in three directions, but they are highly sensitive to temperature and humidity (Wyngaard 1981).

Complications for all anemometers occur when temperatures are near or below freezing when rime ice can form and inhibit movement or reduce sonic pulses. Wind gauges during icy conditions tend to underestimate wind speeds from 10-30% (Kimura et al. 2001; Fortin et al.

2005). The slower values are not always eliminated by quality control methods and remain in the dataset resulting in a misrepresentation of winter wind speeds.

Aspects of snow hydrology

Metamorphism

From the moment a snow crystal is formed, it is in a continuous state of metamorphism. The metamorphism of snow on the ground includes, but is not limited to, advection of warm air masses, sharp temperature gradients, wind, humidity, radiation, and/or rain (Pomeroy et al. 1997; Li and Pomeroy 1997a). Metamorphism rates within the snow pack are highly dependent on temperature gradients and as temperatures rise above the snowpack metamorphism becomes more rapid. When temperatures are above freezing a liquid layer develops among the snow crystals and causes melt-metamorphism to occur and results in densification of the surface of the snowpack. A subsequent freeze bonds snow crystals creating a solidified crust layer at the surface of the snow pack (Prowse and Owens 1984). When temperatures remain cold (i.e., -40^{o} C) crystal metamorphism is slowed (Cabanes et al. 2003).

Creep, saltation, suspension, and sublimation

Snow is transported as creep, saltation, and suspension. The source of blowing snow is either snow falling as precipitation or unbonded snow from the surface of the snowpack. The transport of snow begins as creep and is the initial movement of the snow on the surface of the snowpack.

Saltation occurs as snow crystals roll, jump, and collide only a few centimeters above the snow surface. The particle trajectories are rarely uniform during saltation. The trajectories were observed and measured using photographs taken in a wind tunnel by Uematsu et al. (1991). The relationship between wind speed and saltation was found as linear, meaning as wind speed increases, saltation increases. When wind speeds increase, the height of snow crystal travel can also increase (Pomeroy and Gray 1990).

The concentration of snow particles in motion above the snow surface varies according to height. Saltating particles in the lowest 10 centimeters are the densest. Once a snow particle has risen above the lowest 10 cm it is considered suspended. Strong winds can carry the particles to heights exceeding tens of meters (Bintanja 2001; Pomeroy et al. 1997; Pomeroy and Gray 1990). Suspended snow can be classified as blowing or drifting snow. Blowing snow is defined as snow lifted greater than two meters from Earth's surface, whereas drifting snow is classified as snow transported within two meters off the snow surface (Pomeroy et al. 1993; Li and Pomeroy 1997b).

Surface crystals once dislodged impact the snow surface and rebound as saltating particles through a shatter and rebound process (Pomeroy and Gray 1990) and are broken down into smaller ice grains (Pomeroy and Gray 1990; Schmidt 1980, 1982). When wind speeds increase cohesion and rebound is greater from impact velocity (Pomeroy and Gray 1990). Stronger winds result in greater cohesion, compaction and bonding with the surface snow causing a decreased amount of transported snow (Hood et al. 1999).

Sublimation is the phase change of snow from a solid to a gaseous state (Schmidt 1986). Snow crystals due to the high surface area to mass ratio result in rapid transfer rates to water vapor (Pomeroy et al. 1997). Blowing snow conditions cause atmospheric layers to mix more readily, the increased ventilation causes water vapor from the snowpack to be absorbed more rapidly into the atmosphere. Water balances in arctic and alpine regions have low humidity and are highly sensitive to precipitation and sublimation throughout the year (Liston and Sturm 2004; Pomeroy et al. 1997).

Snow loss from sublimation is an integral part to consider when calculating annual snowpack and snow water equivalent totals. Six different studies in Canada and Alaska found sublimation to account for 15-45% of snowpack loss (Marsh 1999). A catchment in northwestern Canada experienced a sublimation rate of 19.5% for the 1992-93 winter (Pomeroy et al. 1997). At Niwot Ridge, Colorado sublimation rates were approximately 15% for the 1994-95 winter and the mean wind speed was 7.3 m s^{-1} (Hood et al. 1999). Additional analyses of sublimation totals at Niwot Ridge for the combined 1973-74 and 1974-75 winters were approximated to account for 30-51% of precipitation (Berg 1986). Berg (1986) using the same dataset found mean wind speeds during winter months (NDJFMA) to be 12.4 m s^{-1} and the maximum winds ranged from 30-41 m s^{-1}. Sublimation rates at Niwot Ridge are closely related to wind speeds. Wind speeds are typically high at Niwot Ridge from the high elevation location and proximity to the continental divide and sublimation rates are closely related to wind speeds.

Transport threshold

The extent of snow transport depends on numerous snow surface and environmental characteristics such as crystal type, structure and bonding, time since the last snow event, available snow, and temperature (Huang et al. 2008; Michaux et al. 2002; Uematsu et al. 1991; Li and Pomeroy 1997b; Marsh 1999; Schmidt, 1980, 1981, 1982, 1986). There is a strong relationship between the amount of blowing snow and snow surface conditions (Pomeroy et al. 1997; Schmidt 1986). Freshly fallen snow is more likely transported to a greater extent because shear stress is minimal (Pomeroy and Gray 1990). As time increases after a snow fall the wind speed for snow transport increases from snow crystal settling and bonding processes (Schmidt 1980). The freeze-thaw process and cohesion through wind compaction increases surface bonding, friction and hardness and as a result higher wind speeds are needed to initiate transport

(Li and Pomeroy 1997b). The bonds that form during deposition must be broken by higher wind speeds so that movement can be initiated (Schmidt 1980).

The threshold is the minimum wind speed required to initiate or sustain snow transport (Schmidt 1986; Pomeroy and Gray 1990). Wind speeds between 3-8 m s^{-1} recorded at a height of 10 meters are great enough to transport unbonded snow (Li and Pomeroy 1997b). Berg (1986) and Schmidt (1982) found wind speeds of 4-6 m s^{-1} recorded at a one meter height were needed to initiate transport at Niwot Ridge, Colorado. Snow particle size can also be used to estimate threshold speeds (Schmidt 1981). However, many studies use an average wind speed of 5 m s^{-1} for snow to initially dislodge from the snowpack (Berg 1986; Mellor 1965; Li and Pomeroy 1997b). The 5 m s^{-1} threshold is not always used; research in the Antarctic determined that snow transport threshold to be approximately 14 m s^{-1} (Li and Pomeroy 1997a). Bond strength of the snow crystals can increase to such an extent that even the highest wind speeds cannot initiate transport (Schmidt 1980). It has been seen that wind speeds greater than 40 m s^{-1} were sometimes necessary to transport snow particles bonded by settling or atmospheric changes (Schmidt 1980).

Snow transport rates are higher during constant winds than during short strong gusts (Michaux et al. 2002). Snow transport also occurs when precipitation is absent. In the Canadian Prairie and Arctic, Baggaley and Hanesiak (2005) found 28% of snow transport events occurred without concurrent precipitation. In arctic locations blowing snow has occurred for weeks after a precipitation event due to low temperatures and dry conditions. At Niwot Ridge blowing snow occurred without precipitation 22% of the time during 1973-74 and 1974-75 winters (Berg 1986).

North American Regional Reanalysis

North American Regional Reanalysis (NARR) is a dataset that provides high spatial and temporal coverage of hydrological and meteorological processes. The data are generated every three hours from 1979 to present and cover all of North and Central America. Each horizontal grid cell is 0.3˚ (32 km) and contains 29 vertical pressure levels are present in each cell (Mesinger et al. 2006).

NARR affords both better accuracy and resolution for meteorological processes due to the inclusion of multiple parameters. NARR couples the Eta model with Noah Land Surface Model to stimulate surface energy and water budgets (Ek et al. 2003). Land cover was included from National Environmental Satellite Data and Information services (NESDIS) to account for different land cover types and seasonal vegetation variability. Elevation and topography are derived from USGS 30-second Global Elevation data and each grid cell is assigned a mean elevation and land cover type. Land cover types were classified when the area of the cover type was 50% or more (NCEP 2010)**.**

The improvements to NARR were made by assimilating *in situ* station precipitation data, surface winds from NCEP Global Reanalysis-2 (GR2), surface pressure from Meteorological Data Laboratory (MDL) and wind from National Center for Atmospheric Research (NCAR). Additionally, winds were transposed to 10-meter heights and re-written as earth-relative vector directions. Surface temperatures were simulated at a 2-meter height. NARR datasets and improved aspects of NARR are listed in Tables 2 and 3.

Table 9: Datasets incorporated into NCEP–DOE GR2 and NARR (Mesinger et al. 2006).

Dataset	**Details**	**Source**
Rawinsondes	Temperature, wind, moisture	GR2[1]
Dropsondes	Same as above	GR2
Pibals	Wind	GR2
Aircraft	Temperature and wind	GR2
Surface	Pressure	GR2
Geostationary satellites	Cloud drift wind	GR2

*** 1. GR2: Global Reanalysis 2 (Kanamitsu et al. 2002)**

Table 10: Additional or improved data used in NARR (Mesinger et al. 2006).

Dataset	**Details**	**Source**
Precipitation, disaggregated into hours	CONUS[1] (with PRISM[2]), Mexico, Canada, CMAP[3] over oceans (< 42.5°N)	NCEP[4]/CPC[5], Canada, Mexico
TOVS-1b[6] radiances	Temperature	NESDIS[7]
NCEP surface	Wind, moisture	GR2
MDL[8] surface	Pressure, wind, moisture	NCAR[9]
COADS	Ship and buoy data	NCEP/EMC[10]
Air Force snow	Snow depth	Air Force Weather Agency
SST	1° Reynolds, with Great Lakes SSTs[11]	NCEP/EMC, GLERL[12]
Sea and lake ice	Contains data on Canadian lakes and Great Lakes	NCEP/EMC, GLERL, Ice Services Canada
Tropical cyclones	Locations used for blocking CMAP precipitation	Lawrence Livermore National Laboratory

*** 1. CONUS: Contiguous United States; 2. PRISM: Parameter-Elevation Regressions on Independent Slopes Model; 3. CMAP: Central Processing Unit (CPC) Merged Analysis of Precipitation; 4. NCEP: National Centers for Environmental Prediction; 5. CPC: Climate Prediction Center; 6. TOVS-1b: Television Infrared observation Satellite (TIROS) Operational Vertical Sounder; 7. NESDIS: National Environmental Satellite, Data, and Information Service; 8. MDL: Model Development Laboratory; 9. NCAR: National Center for Atmospheric Research; 10. EMC: Environmental Modeling Center; 11. SST: Sea surface temperature; 12. GLERL: Great Lakes Environmental Research Laboratory;**

NARR's greatest advantage is the incorporation of observed precipitation data, which affords a closer depiction of the hydrologic cycle. Point measurements from the Continental U.S. (CONUS) observation stations are used to extrapolate a continuous 1/8 degree grid of precipitation. An inverse distance weighting scheme and an orographic enhancement technique was applied to these data and developed by Daily et al. (1994) called Parameter-elevation Regressions on Independent Slopes Model (PRISM). A vertical latent heat profile created from

PRISM data was assimilated into NARR. Thus, precipitation assimilation processes occur indirectly through latent heat fluxes (Mesinger et al. 2006).

Research has demonstrated that precipitation achieves “extremely high agreement” between observed and NARR data (Mesinger et al. 2006), although some researchers are critical of these findings. One factor limiting more accurate precipitation data is the unequal spatial distribution of observational points which inhibits a better representation of precipitation data. Traveling northward from 20˚N to 50˚N, there is a linear decrease in the number of observational datasets assimilated into NARR (Mesinger et al. 2006). Also, throughout the North American extent grid sizes vary. The continental U.S. PRISM data are analyzed on a grid of 1/8th ˚, whereas in Mexico and Canada the grid size is 1˚, creating resolution and accuracy issues. Apparent weaknesses have been confirmed in regions of Canada where fewer observational gauges exist (Mesinger et al. 2006). Kistler et al. (2001) asserted the performance of reanalysis datasets for precipitation was also hindered by complex terrain and cumulus convective events. Other parameters, such as wind, have been analyzed and results showed a negative daily bias of -1 m s^{-1} for both summer and winter wind speeds (Mesinger et al. 2006).

Conclusion

Extensive research has been conducted analyzing how snow redistributes across a landscape, however minimal information exists concerning temporal wind speed trends and influence snow transport. Wind speed trends, on the global level, are difficult to assess due to the unique nature of local wind regimes. Additionally, the collection methods, period of record and data types have caused discrepancies and inhibited comprehensive comparisons of temporal wind speed trends. In alpine regions *in situ* stations are spatially and temporally limited and the ability to analyze alpine wind speeds becomes difficult. The NARR dataset may be a suitable option for improving the spatial and temporal coverage so alpine meteorological process over time can be better assessed. However, limited information exists analyzing the agreement between *in situ* and NARR datasets in alpine locations. An increased understanding of wind speeds and blowing snow processes will be beneficial for future water resource planning, climate change analysis and the use of NARR for large scale alpine analyses.

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APPENDIX II: DATA ORGANIZATION

Description of contents

This appendix includes all of the scripts used to extract, format and organize data.

Script to extract data from NARR grids

Script developed by Glen Liston to extract specific NARR grids from his personal download of the NARR dataset. Glen then gave the extracted grids in raw form to me. The code is limited to 2 years (1979 and 1980) as examples; the code should be duplicated to extract each year.

```
**
'reinit'
**
 'open /data7/narr/narr_grads/narr_1979.ctl'
**
 'open /data7/narr/narr_grads/narr_1980.ctl'
 'open /data7/narr/narr_grads/narr_1981.ctl'
 'open /data7/narr/narr_grads/narr_1982.ctl'
 'open /data7/narr/narr_grads/narr_1983.ctl'
 'open /data7/narr/narr_grads/narr_1984.ctl'
 'open /data7/narr/narr_grads/narr_1985.ctl'
 'open /data7/narr/narr_grads/narr_1986.ctl'
 'open /data7/narr/narr_grads/narr_1987.ctl'
 'open /data7/narr/narr_grads/narr_1988.ctl'
 'open /data7/narr/narr_grads/narr_1989.ctl'
**
 'open /data7/narr/narr_grads/narr_1990.ctl'
 'open /data7/narr/narr_grads/narr_1991.ctl'
 'open /data7/narr/narr_grads/narr_1992.ctl'
 'open /data7/narr/narr_grads/narr_1993.ctl'
 'open /data7/narr/narr_grads/narr_1994.ctl'
 'open /data7/narr/narr_grads/narr_1995.ctl'
 'open /data2/narr/narr_grads2/narr_1996.ctl'
 'open /data2/narr/narr_grads2/narr_1997.ctl'
 'open /data2/narr/narr_grads2/narr_1998.ctl'
 'open /data2/narr/narr_grads2/narr_1999.ctl'
**
 'open /data2/narr/narr_grads2/narr_2000.ctl'
 'open /data2/narr/narr_grads2/narr_2001.ctl'
 'open /data2/narr/narr_grads2/narr_2002.ctl'
 'open /data2/narr/narr_grads2/narr_2003.ctl'
 'open /data2/narr/narr_grads2/narr_2004.ctl'
 'open /data2/narr/narr_grads2/narr_2005.ctl'
```

```
 'open /data2/narr/narr_grads2/narr_2006.ctl'
 'open /data7/narr/narr_grads/narr_2007.ctl'
 'open /data7/narr/narr_grads/narr_2008.ctl'
 'open /data7/narr/narr_grads/narr_2009.ctl'
**

 'set x 175 178'
 'set y 109 113'

* Niwot.
*'set x 178'
*'set y 109'
*********************
* Glees.
*'set x 176'
*'set y 113'
**********************************************
**********************************************
'set gxout fwrite'
  fname = 'narr_jamie_4x5_1979-2009.gdat'
* fname = 'narr_jamie_N_1979-2009.gdat'
* fname = 'narr_jamie_S_1979-2009.gdat'
  say fname
 'set fwrite 'fname
**********************************************
**********************************************
*1979
 'set dfile 1'
  tt = 1
  while (tt<=2920)
   'set t 'tt
    say '1979 'tt
   'd apcpsfc'
   'd tmp10m-273.16'
   'd sqrt(ugrd10m*ugrd10m+vgrd10m*vgrd10m)'
   'd snodsfc'
   'c'
    tt = tt + 1
  endwhile
**********************************************
**********************************************
*1980
 'set dfile 2'
  tt = 1
  while (tt<=2928)
   'set t 'tt
    say '1980 'tt
   'd apcpsfc'
   'd tmp10m-273.16'
   'd sqrt(ugrd10m*ugrd10m+vgrd10m*vgrd10m)'
   'd snodsfc'
```

```
  'c'
   tt = tt + 1
 endwhile

**********************************************
**********************************************
 'disable fwrite'
**********************************************
```

NARR 3-hour to daily

```
'Script developed in Microsoft Visual Basic by Jamie D. Fuller (Colorado State University)
'Converts North American Regional Reanalysis (NARR) 3-hourly data
'into daily averages (wind and temp) and daily totals (precipitation and snow depth)
'then exports to a new sheet

Sub AverageJulianDays()
Dim Precip As Double
Dim Temperature As Double
Dim WindSpeed As Double
Dim SnowDepth As Double
Dim Row As Long
Dim Column As Long
Dim Year As Long
Dim Julian As Long
Dim Day As Integer
Dim j As Integer
Dim i As Integer
Dim DayCounter As Integer
Dim NumSamples As Integer

Row = 2
DayCounter = 0

Do While Cells(Row, 1) <> "" ' loop until we have a blank at the end of the spreadsheet
 ' setup variables for one day
        Day = Cells(Row, 1)
         NumSamples = 0
        WindSpeed = 0
        Precip = 0
        Temperature = 0
         SnowDepth = 0
        Year = Cells(Row, 2)

' Sum the values for one day
        Do While Cells(Row, 1) = Day
                Precip = Precip + Cells(Row, 7)
                Temperature = Temperature + Cells(Row, 8)
                WindSpeed = WindSpeed + Cells(Row, 9)
                SnowDepth = SnowDepth + Cells(Row, 10)
```

```
                NumSamples = NumSamples + 1
                Row = Row + 1
           Loop

   ' Find the averages for the day
           WindSpeed = WindSpeed / NumSamples
           Precip = Precip
           Temperature = Temperature / NumSamples
           SnowDepth = SnowDepth

 ' Store the averages and send to a new sheet
           Sheets("NewSheet").Cells(DayCounter + 1, 2) = Year
           Sheets("NewSheet ").Cells(DayCounter + 1, 4) = Day
           Sheets("NewSheet ").Cells(DayCounter + 1, 6) = Precip
           Sheets("NewSheet ").Cells(DayCounter + 1, 7) = Temperature
            Sheets("NewSheet ").Cells(DayCounter + 1, 8) = WindSpeed
           Sheets("NewSheet ").Cells(DayCounter + 1, 9) = SnowDepth

           DayCounter = DayCounter + 1
 Loop
End Sub
```

Blowing snow days

```
'Script developed in Microsoft Visual Basic by Jamie D. Fuller (Colorado State University)
‘Finds a probable blowing snow day (temp <0degrees; wind >5m/s; precipitation >0 including the 4 days
‘following if other parameters are met. This script works for both NARR and In situ stations. Data is
'then exports to a new sheet

Sub BSD+4days()

           Dim Precip As Double
           Dim Temperature As Double
           Dim WindSpeed As Double
           Dim SnowDepth As Double
           Dim Dateline As String
           Dim Row As Long
           Dim Column As Long
           Dim Year As Long
           Dim Month As String
           Dim WaterYear As Integer
           Dim Day As Double
           Dim j As Integer
           Dim i As Integer
           Dim DayCounter As Integer
           Dim BSD As Boolean
           Dim DistanceFromLast As Integer

           Row = 2
           DayCounter = 0
```

```
        DistanceFromLast = 100

' setup variables for one day
        Do While Cells(Row, 1) <> "" ' loops until we have a blank at the end of the spreadsheet
                Dateline = Cells(Row, 1)
                 Year = Cells(Row, 2)
                 WaterYear = Cells(Row, 3)
                 Day = Cells(Row, 4)
                Month = Cells(Row, 5)
                Precip = Cells(Row, 6)
                Temperature = Cells(Row, 7)
                WindSpeed = Cells(Row, 8)
                SnowDepth = Cells(Row, 9)

' Find the days which meet parameters
        BSD= False
        If (DistanceFromLast < 4 And Temperature <= 0 And WindSpeed >= 5) Then
                BSD = True
                Else
                If Precip > 0 And Temperature <= 0 And WindSpeed >= 5 Then
                BSD = True
                DistanceFromLast = 0
                End If
        End If

   ' Store the Values if BSD is true

         If BSD Then
              Sheets("Sheet1").Cells(DayCounter + 1, 1) = Dateline
              Sheets("Sheet1").Cells(DayCounter + 1, 2) = Year
              Sheets("Sheet1").Cells(DayCounter + 1, 3) = WaterYear
              Sheets("Sheet1").Cells(DayCounter + 1, 4) = Day
              Sheets("Sheet1").Cells(DayCounter + 1, 5) = Month
              Sheets("Sheet1").Cells(DayCounter + 1, 6) = Precip
              Sheets("Sheet1").Cells(DayCounter + 1, 7) = Temperature
              Sheets("Sheet1").Cells(DayCounter + 1, 8) = WindSpeed
              Sheets("Sheet1").Cells(DayCounter + 1, 9) = SnowDepth
              DayCounter = DayCounter + 1
        End If
        Row = Row + 1
        DistanceFromLast = DistanceFromLast + 1
Loop
End Sub
```

APPENDIX III: GIS AND STATISTICAL INFORMATION

Description of contents

Scripts used to run statistical analysis are listed below and were run using R Statistical packages.

Maps were created with ESRI ArcGIS 9.3 package.

GIS information

NARR grids were obtained from the website: http://nomads.ncdc.noaa.gov/#narr_datasets.

Digital elevation models for Wyoming and Colorado were also downloaded from internet sources http://www.uwyo.edu/wygisc/ and from Geospatial Centroid @ CSU http://www.gis.csu.edu, respectively.

Linear regression model

```
###Script for assessing linear regression of mean, daily variance and percentage data. File folders specific to each
###data set. Adapted from online R script examples.

setwd("C:/R/ filefolder_here ") ###Set the working directory
###Read in the data and look at it###
data<- read.csv("file_name_here.csv", header=T, sep=",", na.strings="x")
attach(data)
names(data)
hist(Wind)
hist(Year)
tsp(Wind)
Wind
plot(Wind)
plot(Year,Wind)
tsYear<-ts(data[1], start==(enter start year- without parenthesis), frequency=(specific # here-without parenthesis))
tsWind<-ts(data[2], start==(enter start year- without parenthesis), frequency=(specific # here-without parenthesis))
#ts.plot(tsWind)
###Generate residuals using LM###
lmWind<-lm(tsWind~Year)
#plot(lmWind)
summary(lmWind)
```

Correlation between *in situ* and NARR linear model

```
###Script for assessing linear regression of mean and percentage data. File folders specific to each
###data set.  Adapted from online R script examples.
setwd("C:/R/ filefolder_here ") ###Set the working directory
###Read in the data and look at it###
data<- read.csv("file_name_here .csv", header=T, sep=",", na.strings="x")
attach(data)
names(data)
hist(NARR)
hist(In situ)
plot(NARR,In situ)
linearModel<-lm(In situ~NARR)
summary(linearModel)
summary(NARR)
summary(In situ)
```

Autocorrelation regression model for daily mean data

```
###Script for assessing dependence in daily mean data. Daily data were given specific dates within each
###year so the dependence is accounted for. File folders specific to each data set.

setwd("C:/R/filefolder_here") ###Set the working directory
###Read in the data and look at it###
data<- read.csv("file_name_here.csv", header=T, sep=",", na.strings="x")
attach(data)
names(data)
hist(Wind)
hist(Year)
tsp(Wind)
Wind
plot(Wind)
plot(Year,Wind)
tsYear<-ts(data[1], start=(enter start year- without parenthesis), frequency=(specific # here-without
parenthesis))
tsWind<-ts(data[2], start=(enter start year- without parenthesis), frequency=(specific # here-without
parenthesis))
ts.plot(tsWind)
summary(tsWind)
##Open Library for GLS function
library(nlme)

#create new variable "year"
year <- floor(Year)
#create a new variable "time"
u <- unique(year)
d <- length(u)
tm <- numeric(length(year))
    for(i in seq(1,d))
{
  keep <- year == u[i]
```

```
  tm[keep] <- year[keep] + seq(1,sum(keep))/(sum(keep) + 1)
}
windData <- data.frame(cbind(year, tm, Wind))
lm(Wind~tm)
lmTemp<-lm(Wind~tm)
summary(lmTemp)
out <- gls(Wind~tm, windData, correlation = corAR1(form = ~ 1 | year))
summary(out)
```

Trend comparison equation

$$\frac{\beta_{1\ \mathit{In\ situ}} - \beta_{1\ \mathrm{NARR}}}{\sqrt{\ }\ \delta^{2\ \mathit{In\ situ}} + \delta^{2\ \mathrm{NARR}}}$$

Extrapolating missing *in situ* data with slope

$Y= \beta_0 + \beta_1 * X$

Missing *In situ* data = $\beta_0 + \beta_1$ * NARR daily mean

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APPENDIX IV: ALL RESULTS

Niwot results

Table 11: Niwot *in situ* station data statistical results 1989-2008

Wind Speed Means	β_o	β_1	δ	r^2	**p-value**
Niwot *In situ* Annual means	-1.9418	0.0058	0.0157	0.0075	0.7162
Niwot *In situ* Seasonal fall	4.0554	0.0032	0.0379	0.0004	0.9343
Niwot *In situ* Seasonal winter	-35.2269	0.0238	0.0316	0.0306	0.4600
Niwot *In situ* Seasonal spring	-45.4847	0.0274	0.0306	0.0428	0.3812
Niwot *In situ* Seasonal summer	32.6488	-0.0132	0.0195	0.0249	0.5061
Niwot *In situ* Daily fall	22.6314	-0.00614	0.0195	0.0001	0.7530
Niwot *In situ* Daily winter	-22.1647	0.0173	0.0207	0.0004	0.4050
Niwot *In situ* Daily spring	-7.6898	0.0085	0.0167	0.0002	0.6080
Niwot *In situ* Daily summer	39.4728	-0.0166	0.0111	0.0013	0.1355
Wind Speed at different Thresholds	β_o	β_1	δ	r^2	**p-value**
Niwot *In situ* annual % <5	-0.3739	0.0003	0.0013	0.0027	0.8280
Niwot *In situ* annual % >5	1.3736	-0.0003	0.0013	0.0027	0.8280
Niwot *In situ* annual % >5,<14	2.9798	-0.0012	0.0016	0.0277	0.4830
Niwot *In situ* annual % >14	-1.6062	0.0009	0.0011	0.0335	0.4400
Niwot *In situ* fall% <5 fall	5.4185	-0.0026	0.0020	0.0882	0.2040
Niwot *In situ* fall% >5-14	-5.9993	0.0033	0.0028	0.0714	0.2550
Niwot *In situ* fall% >14	1.5835	-0.0007	0.0030	0.0029	0.8220
Niwot *In situ* winter% <5	-4.7455	0.0024	0.0014	0.1357	0.1100
Niwot *In situ* winter% >5-14	9.4378	-0.0045	0.0027	0.1349	0.1112
Niwot *In situ* winter% >14	-3.6947	0.0021	0.0030	0.0255	0.5011
Niwot *In situ* spring% <5	4.3793	-0.0021	0.0022	0.0482	0.3520
Niwot *In situ* spring% >5-14	2.9446	-0.0011	0.0014	0.0344	0.4340
Niwot *In situ* spring% >14	-6.3218	0.0032	0.0017	0.1703	0.0705 .
Niwot *In situ* summer% <5	-5.5708	0.0030	0.0033	0.0445	0.3720
Niwot *In situ* summer% >5-14	6.6761	-0.0030	0.0029	0.0568	0.3120
Niwot *In situ* summer% >14					
Blowing Snow Days	β_o	β_1	δ	r^2	**p-value**
Niwot *In situ* BSD annual >5	-2.6197	0.0015	0.0017	0.0414	0.3900
Niwot *In situ* BSD annual >5,<14	0.2150	0.000003	0.0011	0.0000003	0.9980
Niwot *In situ* BSD annual >14	-2.8347	0.0015	0.0010	0.1124	0.1480
Niwot *In situ* BSD fall >5-14	0.1229	0.000038	0.0027	0.000010	0.9900
Niwot *In situ* BSD fall >14	-3.6464	0.0019	0.0019	0.0512	0.3370
Niwot *In situ* BSD winter>5-14	1.8312	-0.0007	0.0024	0.0055	0.7560
Niwot *In situ* BSD winter>14	-3.6576	0.0020	0.0032	0.0210	0.5420

Niwot *In situ* BSD spring>5-14	-4.4651	0.0023	0.0015	0.1178	0.1380
Niwot *In situ* BSD spring>14	-5.1513	0.0028	0.0040	0.0260	0.4970

Table 12: Daily Niwot *in situ* station data accounting for dependence within the data 1989-2008–GLS Model.

GLS Model	**β_o**	**β_1**	**δ**	**phi Φ**	**p-value**
Niwot *In situ* Daily fall	12.4016	-0.0010	0.0346	0.5279818	0.9761
Niwot *In situ* Daily winter	-25.8563	0.0191	0.0353	0.4946789	0.5880
Niwot *In situ* Daily spring	-7.5877	0.0085	0.0276	0.4728691	0.7583
Niwot *In situ* Daily summer	39.6113	-0.0167	0.0180	0.4515178	0.3528

Table 13: NARR at Niwot statistical results 1989-2008

Wind Speed Means	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
Niwot NARR Annual	-10.0886	0.0078	0.0103	0.0306	0.4600
Niwot NARR Seasonal fall	19.7138	-0.0071	0.0158	0.0105	0.6580
Niwot NARR Seasonal winter	-46.1260	0.0265	0.0245	0.1873	0.2920
Niwot NARR Seasonal spring	-19.0240	0.0123	0.0165	0.0285	0.4640
Niwot NARR Seasonal summer	10.9118	-0.0035	0.0088	0.0081	0.6980
Niwot NARR Daily fall	41.8239	-0.0182	0.0092	0.0021	0.0495*
Niwot NARR Daily winter	-65.8740	0.0364	0.0114	0.0056	0.00150**
Niwot NARR Daily spring	-22.5140	0.0140	0.0084	0.0015	0.0948.
Niwot NARR Daily summer	30.6334	-0.0133	0.0057	0.0030	.0198 *
Wind Speed at different Thresholds	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
Niwot NARR Annual %<5	2.1233	-0.0008	0.0015	0.0144	0.6050
Niwot NARR annual % >5	-1.1233	0.0008	0.0015	0.0144	0.6050
Niwot NARR annual % >5,<14	-0.8909	0.0007	0.0015	0.0107	0.6560
Niwot NARR annual % >14	-0.4148	0.0002	0.0001	0.0494	0.0580.
Niwot NARR fall% <5	-3.3861	0.0019	0.0033	0.0183	0.5590
Niwot NARR fall% >-5-14	4.3285	-0.0019	0.0032	0.0182	0.5600
Niwot NARR winter% <5	7.4809	-0.0036	0.0026	0.0894	0.1880
Niwot NARR winter% >5-14	-6.4809	0.0036	0.0026	0.0894	0.1880
Niwot NARR spring% <5	4.3226	-0.0019	0.0033	0.0183	0.5590
Niwot NARR spring% >5-14	-3.2108	0.0019	0.0032	0.0178	0.5650
Niwot NARR summer% <5	-3.4466	0.0021	0.0026	0.0365	0.4200
Niwot NARR summer% >5-14	0.8736	-0.0003	0.0025	0.0009	0.8960
Blowing Snow Days	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
Niwot NARR BSD Annual 5-14	-5.3486	0.0028	0.0012	0.0970	0.0278*
Niwot NARR BSD fall 5-14	-3.3220	0.0018	0.0021	0.0343	0.4210
Niwot NARR BSD winter 5-14	-14.5049	0.0075	0.0032	0.2243	0.0301*
Niwot NARR BSD spring 5-14	-3.4603	0.0019	0.0029	0.0221	0.5200

Table 14: Daily Niwot NARR data accounting for dependence within the data 1989-2008 – GLS Model.

GLS Model 1989	β_o	β_1	δ	**phi Φ**	**p-value**
Niwot NARR Daily fall	35.9555	-0.0153	0.0174	0.567956	0.3799
Niwot NARR Daily winter	-66.6875	0.0368	0.0206	0.537609	0.0747
Niwot NARR Daily spring	-25.1123	0.0153	0.0142	0.486462	0.2793
Niwot NARR Daily summer	30.0848	-0.0131	0.0104	0.538535	0.2076

Table 15: NARR at Niwot Statistical Results 1979-2009.

Mean Wind Speed	β_o	β_1	δ	r^2	**p-value**
Niwot NARR Annual 79	-3.5172	0.0045	0.0063	0.0176	0.4850
Niwot NARR Seasonal fall 79	-11.3305	0.0084	0.0090	0.0000	0.3570
Niwot NARR Seasonal winter 79	-16.7565	0.0119	0.0157	0.0195	0.4540
Niwot NARR Seasonal spring 79	-13.6731	0.0096	0.0097	0.0327	0.3300
Niwot NARR Seasonal summer 79	3.2366	0.0004	0.0053	0.0002	0.9460
Niwot NARR Daily fall 79	1.2919	0.0021	0.0049	0.0001	0.6670
Niwot NARR Daily winter 79	-16.6108	0.0118	0.0061	0.0014	0.0517 .
Niwot NARR Daily spring 79	-9.9184	0.0077	0.0045	0.0010	0.085 .
Niwot NARR Daily summer 79	5.9827	-0.0010	0.0029	0.00004	0.7240
Wind Speed at different Thresholds	β_o	β_1	δ	r^2	**p-value**
Niwot NARR % Annual Wind >5	-1.8325	0.0012	0.0010	0.0422	0.2680
Niwot NARR % Annual Wind >5-14	-1.6916	0.0011	0.0010	0.0391	0.2870
Niwot NARR % Annual Wind >14	-0.1409	0.0001	0.0001	0.0315	0.3400
Niwot NARR % fall Wind >5-14	-1.9150	0.0019	0.0019	0.0066	0.5300
Niwot NARR % winter Wind >5-14	-1.4471	0.0011	0.0019	0.0132	0.5830
Niwot NARR % spring Wind >5-14	-4.8918	0.0027	0.0018	0.0719	0.1450
Niwot NARR % summer Wind >5-14	0.4449	0.0001	0.0014	0.0003	0.9290
Blowing Snow Day	β_o	β_1	δ	r^2	**p-value**
Niwot NARR BSD Annual 5-14	-5.3831	0.0028	0.0008	0.3050	0.00128 **
Niwot NARR BSD fall 5-14 1979	-1.3217	0.0008	0.0011	0.0964	0.5110
Niwot NARR BSD winter 5-14 1979	-13.3230	0.0070	0.0020	0.2955	0.00158 **
Niwot NARR BSD spring 5-14	-2.6168	0.0015	0.0016	0.0293	0.3570

Table 16: Daily Niwot NARR data accounting for dependence within the data 1979-2009 – GLS Model.

GLS Model 1979-2009	**β_o**	**β_1**	**δ**	**phi Φ**	**p-value**
NARR Niwot Daily fall	1.1635	0.0022	0.0091	0.564664	0.8128
NARR Niwot Daily winter	-17.8002	0.0124	0.0111	0.5471992	0.2628
NARR Niwot Daily spring	-11.6593	0.0086	0.0082	0.5121608	0.2957
NARR Niwot Daily summer	5.6596	-0.0008	0.0051	0.5257449	0.8684

Table 17: Niwot NARR and *in situ* daily mean wind speed results 1989-2008

NIWOT	**βo**	**β1**	**δ**	**r^2**	**p-value**
Niwot *in situ* SON	267.62	-0.12	0.13	0.05	0.35
Niwot *in situ* DJF	-638.63	0.33	0.19	0.14	0.0991.
Niwot *in situ* MAM	-307.22	0.16	0.08	0.18	0.05932.
Niwot *in situ* JJA	22.83	-0.01	0.08	0.00	0.92
Niwot NARR SON	-12.87	0.01	0.05	0.00	0.85
Niwot NARR DJF	-89.02	0.05	0.05	0.08	0.37
Niwot NARR MAM	-79.38	0.04	0.03	0.04	0.23
Niwot NARR JJA	-16.14	0.01	0.02	0.01	0.65

GLEES results

Table 18: GLEES *in situ* station statistical results 1988-2009

Wind Speed Means	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
GLEES *In situ* Annual means	48.24674	-0.02033	0.01955	0.05384	0.31200
GLEES *In situ* Seasonal fall	49.83952	-0.02122	0.05091	0.00906	0.68200
GLEES *In situ* Seasonal winter	26.97267	-0.00849	0.04691	0.00172	0.85800
GLEES *In situ* Seasonal spring	46.92280	-0.01957	0.02716	0.02660	0.48000
GLEES *In situ* Seasonal summer	65.98258	-0.03039	0.01526	0.17270	0.0610 .
GLEES *In situ* Daily fall	94.26646	-0.04340	0.015280	0.00434	0.00457 **
GLEES *In situ* Daily winter	12.96115	-0.00149	0.01490	0.00001	0.92000
GLEES *In situ* Daily spring	61.51112	-0.02687	0.01257	0.00163	0.0327 *
GLEES *In situ* Daily summer	72.68814	-0.03374	0.00822	0.00865	0.0000423***
Wind Speed at different Thresholds	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
GLEES *In situ* annual <5%	-2.59996	0.00144	0.00133	0.05754	0.29500
GLEES *In situ* annual % >5	3.59996	-0.00144	0.00133	0.05754	0.29500
GLEES *In situ* annual % >5,<14	-0.18227	0.00043	0.00147	0.00445	0.77400
GLEES *In situ* annual % >14	3.78223	-0.00186	0.00067	0.29010	0.0118 *
Glees *In situ* fall% <5	-0.94902	0.00060	0.00257	0.00284	0.81800
Glees *In situ* fall% >5	1.94902	-0.00060	0.00257	0.00284	0.81800

GLEES *In situ* fall% >5-14	-3.33429	0.00202	0.00251	0.03301	0.43100
GLEES *In situ* fall% >14	5.28331	-0.00262	0.00126	0.18460	0.05190.
Glees *In situ* winter% <5	0.5674094	-0.0002465	0.001439	0.001542	0.866
Glees *In situ* winter% 5	0.43259	0.00025	0.00144	0.00154	0.86600
GLEES *In situ* winter% >5-14	-8.93630	0.00486	0.00201	0.23540	0.0258 *
GLEES *In situ* winter% >14	9.36889	-0.00462	0.00195	0.22770	0.0287 *
Glees *In situ* spring% <5	2.2091952	-0.0009961	0.0026831	0.007202	0.715
Glees *In situ* spring% 5	-1.20920	0.00100	0.00268	0.00720	0.71500
GLEES *In situ* spring% >5-14	-2.66915	0.00171	0.00248	0.02444	0.49900
GLEES *In situ* spring% >14	1.45995	-0.00071	0.00074	0.04644	0.34800
Glees *In situ* summer% <5	-13.16151	0.00685	0.00343	0.17320	0.0605 .
Glees *In situ* summer% >5	14.16151	-0.00685	0.00343	0.17320	0.0605 .
GLEES *In situ* summer% >5-14	14.29429	-0.00692	0.00341	0.17820	0.0566 .
Glees *In situ* summer% >14	-0.13280	0.00007	0.00018	0.00774	0.70500
Blowing Snow Days	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
GLEES *In situ* BSD annual >5	-0.67263	0.00052	0.00182	0.00430	0.77800
GLEES *In situ* BSD annual >5,<14	-3.32026	0.00182	0.00162	0.06239	0.27500
GLEES *In situ* BSD annual >14	2.64763	-0.00130	0.00059	0.20220	0.0409 *
GLEES *In situ* BSD fall >5-14	2.80629	0.00154	0.00348	0.01017	0.66400
GLEES *In situ* BSD fall >14	2.40067	-0.00119	1.78589	0.08478	0.19500
GLEES *In situ* BSD winter>5-14	-13.87781	0.00724	0.00273	0.26980	0.0158 *
GLEES *In situ* BSD winter>14	7.09375	-0.00349	0.00172	0.17800	0.0568 .
GLEES *In situ* BSD spring>5-14	2.10130	-0.00084	0.00324	0.00349	0.79900
GLEES *In situ* BSD spring>14	1.75741	-0.00087	0.00056	0.11260	0.13700

Table 19: Daily GLEES *in situ* station data accounting for dependence within the data 1979-2009 – GLS Model.

GLS Model	**β_o**	**β_1**	**δ**	**phi Φ**	**p-value**
GLEES *In situ* Daily fall	91.61751	-0.042090	0.033270	0.6648093	0.20590
GLEES *In situ* Daily winter	18.14136	-0.00409	0.02897	0.5914272	0.88780
GLEES *In situ* Daily spring	61.33009	-0.02677	0.02347	0.5633664	0.25410
GLEES *In situ* Daily summer	74.94426	-0.03486	0.01471	0.5307415	0.01790*

Table 20: NARR at GLEES data statistical Results 1989-2009.

Means 1989-2009	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
GLEES NARR Annual	-23.60958	0.01479	0.00907	0.12270	0.11950
GLEES NARR Seasonal fall	12.47067	-0.00319	0.01468	0.002483,	0.83020
GLEES NARR Seasonal winter	-73.06079	0.04017	0.02014	0.17310	0.0606 .
GLEES NARR Seasonal spring	-37.77503	0.02188	0.01641	0.08558	0.19800
GLEES NARR Seasonal summer	3.58700	0.00049	0.00999	0.00012	0.96200
GLEES NARR Daily fall	6.54246	-0.00022	0.00838	0.00185	0.97900
GLEES NARR Daily winter	-68.54741	0.03791	0.00957	0.00822	0.0000777***

GLEES NARR Daily spring	-29.74669	0.01786	0.00757	0.00287	0.0185 *
GLEES NARR Daily summer	21.57846	-0.00853	0.00670	0.00098	0.20300
Wind Speeds at Different Thresholds	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
GLEES NARR annual % <5	3.00032	-0.00131	0.00148	0.03958	0.38700
GLEES NARR annual % >5	-2.00163	0.00131	0.00148	0.03958	0.38700
GLEES NARR annual % >5-14	-1.80453	0.00121	0.00147	0.03429	0.42200
GLEES NARR annual % >14	-0.19710	0.00010	0.00009	0.05575	0.30300
GLEES NARR fall% <5	-0.86330	0.00060	0.00294	0.00218	0.84100
GLEES NARR fall% >5-14	2.03290	-0.00069	0.00294	0.00286	0.81800
GLEES NARR winter% <5	7.87522	-0.00384	0.00256	0.10580	0.15000
GLEES NARR winter% >5-14	-6.30549	0.00355	0.00251	0.09523	0.17400
GLEES NARR spring% <5	7.52051	-0.00359	0.00329	0.05895	0.28900
GLEES NARR spring% >5-14	-6.46510	0.00356	0.00324	0.05954	0.28600
GLEES NARR summer% <5	-2.50312	0.00158	0.00278	0.01677	0.57600
GLEES NARR summer% >5-14	3.50312	-0.00158	0.00278	0.01677	0.57600
Blowing Snow Days	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
GLEES NARR BSD Annual 5-14	-13.56531	0.00692	0.00149	0.57400	0.000270 ***
GLEES NARR BSD fall 5-14	-10.08386	0.00515	0.00247	0.21390	0.0533.
GLEES NARR BSD winter 5-14	-38.06348	0.01936	0.00394	0.60150	0.000156 ***
GLEES NARR BSD spring 5-14	-6.25190	0.00325	0.00306	0.06615	0.30300

Table 21: Daily GLEES NARR data accounting for dependence within the data 1989-2009 – GLS Model.

NARR - 1989-2009	**β_o**	**β_1**	**δ**	**r^2**	**p-value**
GLEES NARR Daily fall	0.389579	0.002852	0.0159	0.575501	0.9902
GLEES NARR Daily winter	-70.29899	0.03878	0.01742	0.544326	0.02610*
GLEES NARR Daily spring	-31.90243	0.01893	0.01340	0.523133	0.15790

Table 22: NARR at GLEES data statistical results 1979-2009.

GLEES Means	β_o	β_1	δ	r^2	p-value
GLEES NARR Annual	-12.42683	0.00920	0.00544	0.08962	0.10200
GLEES NARR Seasonal fall	-21.51318	0.01379	0.00816	0.08978	0.10100
GLEES NARR Seasonal winter	-13.45209	0.01038	0.01249	0.02326	0.41300
GLEES NARR Seasonal spring	-24.00956	0.01500	0.00938	0.08102	0.12100
GLEES NARR Seasonal summer	8.53233	-0.00199	0.00609	0.00368	0.74600
GLEES NARR Daily fall	-16.99239	0.01154	0.00459	0.00231	0.0120 *
GLEES NARR Daily winter	-14.11632	0.01071	0.00539	0.00138	0.0468 *
GLEES NARR Daily spring	-20.15705	0.01306	0.00424	0.00332	0.00208 **
GLEES NARR Daily summer	10.64837	-0.00305	0.00292	0.00038	0.29520
Wind Speeds at Different Thresholds	$\boldsymbol{\beta_o}$	$\boldsymbol{\beta_1}$	$\boldsymbol{\delta}$	$\boldsymbol{r^2}$	**p-value**
GLEES NARR % Annual Wind >5	0.03627	0.00029	0.00093	0.00330	0.75900
GLEES NARR % Annual Wind >5-14	0.16882	0.00022	0.00093	0.00196	0.81300
GLEES NARR % Annual Wind >14	-0.13260	0.00007	0.00005	0.05482	0.20500
GLEES NARR % fall Wind >5-14	-0.95547	0.00081	0.00175	0.00728	0.64800
GLEES NARR % winter Wind >5-14	1.78582	-0.00049	0.00150	0.00372	0.74500
GLEES NARR % spring Wind >5-14	-4.04832	0.00235	0.00180	0.05528	0.20300
GLEES NARR % summer Wind >5-14	3.52900	-0.00160	0.00171	0.02916	0.35800
Blowing Snow Days	$\boldsymbol{\beta_o}$	$\boldsymbol{\beta_1}$	$\boldsymbol{\delta}$	$\boldsymbol{r^2}$	**p-value**
GLEES NARR BSD Annual 5-14	-7.60550	0.00394	0.00080	0.45350	0.000033***
GLEES NARR BSD fall 5-14	-5.83760	0.00302	0.00114	0.20160	0.0128 *
GLEES NARR BSD winter 5-14	-19.55059	0.01010	0.00227	0.40650	0.000114 ***
GLEES NARR BSD spring 5-14	-0.77670	0.00052	0.00149	0.00415	0.73100

Table 23: Daily GLEES NARR data accounting for dependence within the data 1979-2009 – GLS Model.

GLEES Daily GLS Model	**β_o**	**β_1**	**δ**	**phi Φ**	**p-value**
GLEES NARR Daily fall	-17.44401	0.01176	0.00854	0.5625773	0.16840
GLEES NARR Daily winter	-16.17518	0.011734	0.009845	0.5490577	0.2334
GLEES NARR Daily spring	-20.38421	0.01317	0.00771	0.5441591	0.08780.
GLEES NARR Daily summer	10.18341	-0.00281	0.00533	0.5468137	0.59780

Table 24: GLEES NARR and in situ daily mean wind speed variance results 1988-2009.

GLEES	**βo**	**β1**	**δ**	**r^2**	**p-value**
GLEES *in situ* SON	-4.4834	0.0039	0.0174	0.0026	0.8260
GLEES *in situ* DJF	220.0842	-0.1046	0.0767	0.0892	0.1884
GLEES *in situ* MAM	147.7512	-0.0690	0.0615	0.0126	0.2760
GLEES *in situ* JJA	32.5237	-0.0139	0.0646	0.0024	0.8320
GLEES NARR SON	16.1386	-0.0058	0.0395	0.0011	0.8855
GLEES NARR DJF	67.4016	0.0368	0.0435	0.0364	0.4080
GLEES NARR MAM	21.6153	-0.0089	0.0306	0.0044	0.7750
GLEES NARR JJA	0.3449	0.0008	0.0183	0.0001	0.965