SYNOPTIC METEOROLOGICAL CONDITIONS ASSOCIATED WITH SNOW DRIFT AND AVALANCHE ACTIVITY IN A HIGH ARCTIC MARITIME SNOW CLIMATE

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ABSTRACT: Avalanche activity in snow climates dominated by direct-action avalanches is primarily controlled by the local and synoptic scale meteorological conditions just prior to and during winter storm events. Previous work on Svalbard characterized the region's unique, direct-action snow climate as "High Arctic maritime" and demonstrated an association between periods of snow drift and regional avalanche activity. This study uses a record of road closures due to drifting snow on a mountain road to further investigate Svalbard's snow climate and avalanche regime by: 1) characterizing synoptic meteorological conditions leading to regional snow drift events, and 2) exploring the relationship between these periods of snow drift and regional avalanche activity using a case study approach. We couple a nine-year (2007-2015) record of road closures with local meteorological observations and NCEP/NCAR synoptic composite maps to characterize the local and synoptic weather conditions leading to and occurring during periods of snow drift near Longyearbyen, Svalbard's primary settlement. Then we compare this record of snow drift events with regional avalanche observations to illustrate the relationship between snow drift and avalanche activity on Svalbard. The results of this study will improve the understanding of Svalbard's unique maritime snow climate and will help advance avalanche forecasting efforts throughout the region.

KEYWORDS: snow drift, synoptic avalanche forecasting, Svalbard

1. INTRODUCTION AND BACKGROUND

In Svalbard, a Norwegian archipelago located in the Arctic Ocean, snow drift endangers infrastructure and human life by reducing visibilities, forming drifts near buildings and on roads, and elevating the risk of avalanche release above Longyearbyen, the region's principal settlement (Eckerstorfer, 2013; Hestnes, 2000; Jaedicke, 2001).

Previous work documents and describes central Svalbard's unique snow climate as "High Arctic maritime" based on a novel combination of meteorological conditions and resulting snowpack stratigraphy (Eckerstorfer and Christiansen, 2011a). In this snow climate, snow transported by the prevailing winds across the region's plateaus accumulates as cornices and wind slabs on leeward plateau margins, where subsequent cornice-fall and slab avalanche releases dominate avalanche activity (Eckerstorfer and Christiansen, 2011c).

In data sparse regions where weather forecasts are often relied upon in lieu of direct manual weather and snowpack observations to forecast avalanche hazard, knowledge of the weather patterns and conditions leading to past hazardous snow drift and avalanche activity can be used to improve future avalanche forecasts (Bellaire et al., 2011; Birkeland et al., 2001). This is especially true in Svalbard, where direct snow and avalanche observation has been impeded by the long polar night, frequent difficulties accessing avalanche terrain due to poor weather and travel conditions, and, until last winter, the lack of an established framework for systematic, continuous snow and avalanche observation (e.g. Eckerstorfer, 2013).

One approach to improving forecasts of snow and avalanche conditions has been through the study of the synoptic atmospheric circulation patterns leading to previous periods of hazardous snow and avalanche activity. Synoptic weather patterns have been analyzed with respect to snow and avalanche processes in Iceland (Björnsson, 1980), mainland Norway (Fitzharris and Bakkehøi, 1986),

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the European Alps (Hächler, 1987; Höller, 2009) western North America (Birkeland et al., 2001; Birkeland and Mock, 1996; Birkeland and Mock, 2001; Fitzharris, 1987), the Spanish Pyrenees (Esteban et al., 2005; García et al., 2009), and Mt. Shasta in California (Hansen and Underwood, 2012).

While to our knowledge such work is limited in Svalbard, other studies have investigated synoptic atmospheric circulation patterns in the North Atlantic with respect to avalanche activity in Iceland and Norway. For example, Björnsson (1980) identified stationary low pressure systems between Iceland and Norway as a key synoptic meteorological ingredient for major avalanche activity on Iceland.

On mainland Norway, Fitzharris and Bakkehøi (1986) found prolonged meridional flow and an abrupt switch from cold, dry northerly airflow to warm, moist southwesterly flow to be the characteristic synoptic circulation patterns of major avalanche winters.

This study uses a record of road closures due to snow drift on the SvalSat Road near Longyearbyen, Svalbard (Fig. 1) to create a record of regional snow drift events. We then characterize the synoptic and resulting local meteorological conditions during these events. Finally, we investigate two periods during which snow drift events and regional avalanche activity coincided to illustrate how the synoptic conditions leading to winter storms on Svalbard influence these processes. Results show synoptic patterns conducive to southwesterly flow over Svalbard are the conditions most frequently associated with winter storm activity throughout the region, but other less common synoptic conditions can also lead to snow drift and major avalanche cycles.

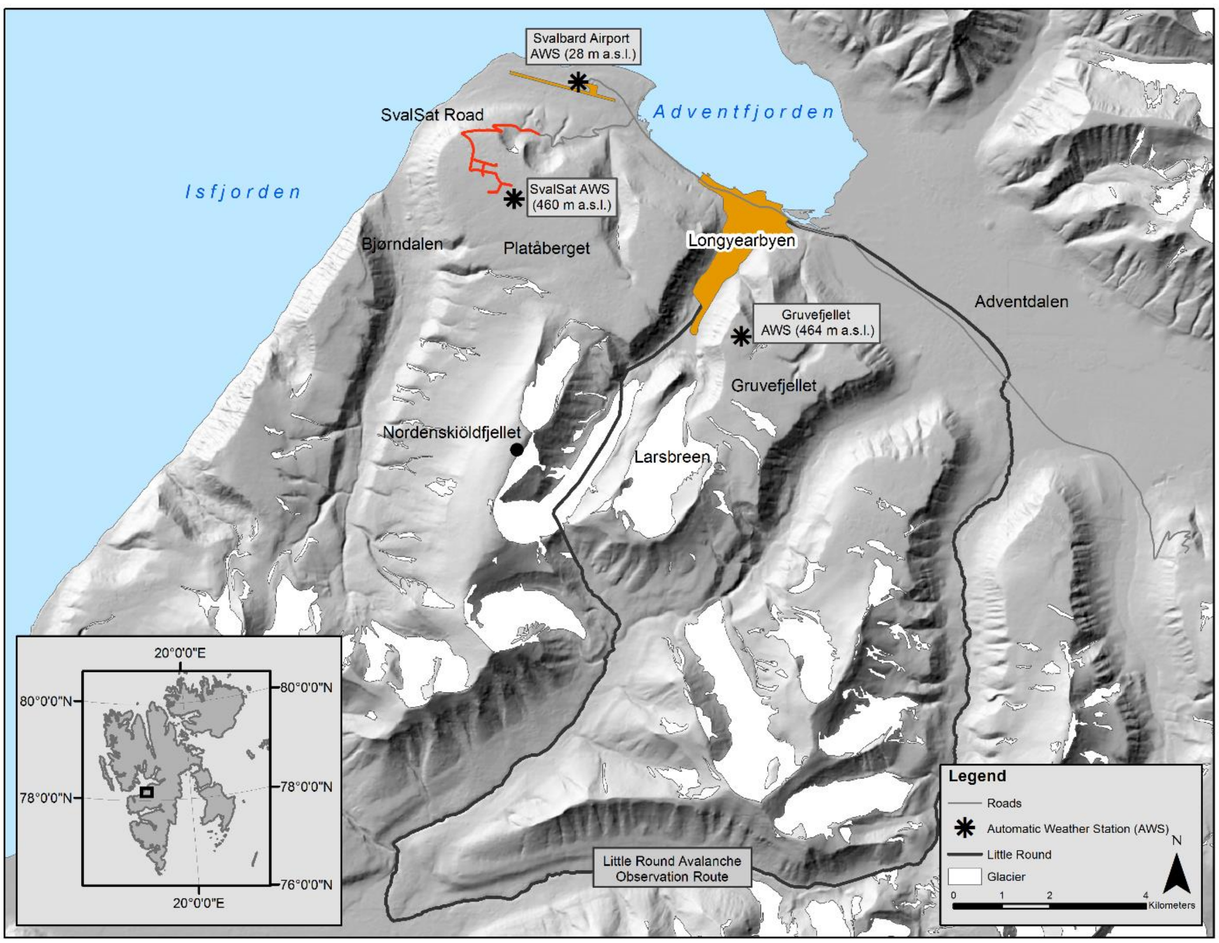

Fig. 1: Regional overview of the study area. The SvalSat Road is indicated in red.

2. METHODS

2.1 *Drift Event Record*

We investigate case studies of snow drift events that resulted in road closures on the SvalSat Road near Longyearbyen between 2007 and 2015 to: (1) characterize the local and synoptic scale meteorological conditions leading to regional snow drift events and; (2) explore the relationship between these periods of snow drift and regional avalanche activity.

As the SvalSat Road passes through an avalanche release area frequently wind loaded by the prevailing southeasterly winds from across Platåberget's broad summit fetch (Fig. 1), closures on this road corridor due to snow drift and associated avalanche activity serve as good proxies for regional snow drift events.

We identified 138 days classified as drift events during the 2006/2007 through 2014/2015 winter seasons (October 1st – May 31st). We classified a day as a drift event if:

- The SvalSat Road was closed due to hazardous snow drift conditions, or
- Average hourly wind speed at the SvalSat AWS (Fig. 1) exceeded 10 m/s on a day or multiple days directly preceding a road closure.

2.2 *Avalanche Observations*

We use avalanche observations taken by Eckerstorfer (2013) during the 2006/2007 through 2010/2011 winter seasons on the Little Round and near the SvalSat Road to build our case studies (Fig. 1). The majority of these avalanche observations can still be accessed online at the Cryoslope Svalbard database (http://www.skred-svalbard.no). Additional papers documenting the January 2010 case study include Eckerstorfer and Christiansen (2010) and Eckerstorfer and Christiansen (2012).

2.3 *Meteorological Analyses*

We used the NCEP/NCAR Reanalysis Project dataset (Kalnay et al., 1996) and the plotting tool available from the NOAA/ESRL Physical Science Division's website to produce daily 500 mb geopotential height maps for each day classified as a drift event. We then manually classified each daily 500 mb height map into a synoptic type grouping based on patterns of high and low elevation geopotential heights over Scandinavia and the North Atlantic region.

We use hourly data from the Gruvefjellet automatic weather station (AWS) and daily precipitation data from the Svalbard Airport AWS to characterize local weather for each synoptic type. These data are free and readily available online from UNIS (http://www.unis.no/resources/weather-stations-and-web-cameras/) for the Gruvefjellet AWS and eklima.no (a service from the Norwegian Meteorological Institute) for the Airport AWS.

We differentiated drift events from average winter conditions on the basis of observed local meteorological conditions using the Kolmogorov-Smirnov (K-S) two-sample test.

3. RESULTS AND DISCUSSION

3.1 *Synoptic Types*

We identified five synoptic types associated with regional drift events (Tbl.1). Upper air and sea level pressure maps for each synoptic type are displayed in Fig. 2. Drift events on Svalbard are most commonly associated with synoptic types conducive to meridional southwesterly flow (Synoptic Types 1 and 2). These patterns allow warm, moist cyclonic activity to be transported northward on the North Atlantic storm track. Near Longyearbyen, these synoptic types result in strong winds from the southwest, high air temperatures, and heavy precipitation.

Synoptic Type 3 conditions are typified by strong low pressures centered northwest of Iceland and high pressure over northwestern Russia. This synoptic pattern results in southeasterly winds, relatively high air temperatures, and modest daily precipitation totals (Tbl. 1).

Synoptic Type 4 conditions are representative of more zonal upper air conditions. Synoptic Type 4 circulation patterns result in strong winds from either east-southeasterly or south-southwesterly directions and elevated air temperatures. Daily precipitation values are relatively high for this synoptic type (Tbl. 1).

The least common drift event synoptic type (Synoptic Type 5) is characterized by low pressure over northern Scandinavia and the Barents and Norwegian Seas. Locally, this results in strong east-southeasterly winds, relatively meager precipitation totals, and warm air at the Gruvefjellet AWS (Tbl. 1).

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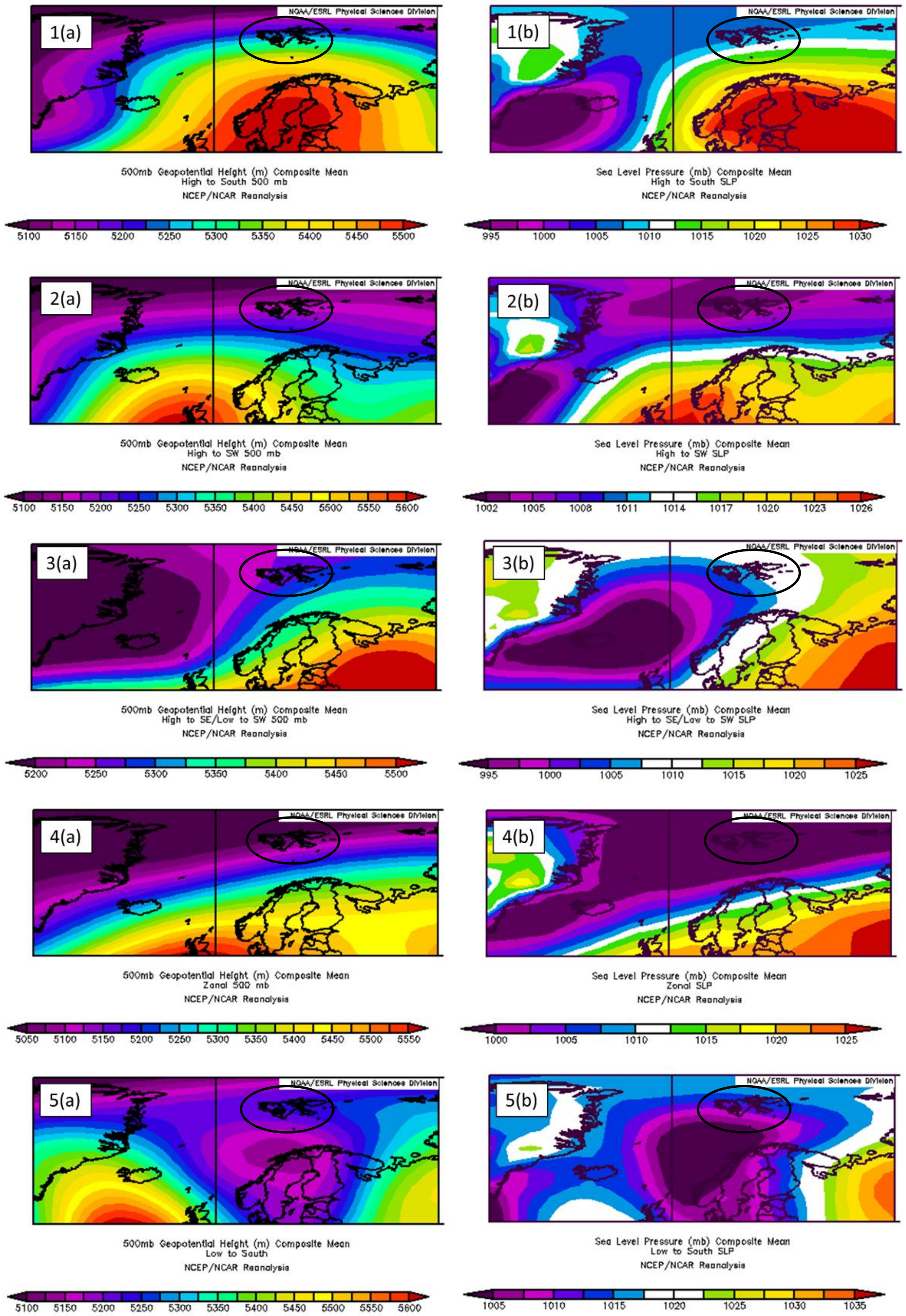

Fig. 2: Composite mean geopotential height and sea level pressure (SLP) maps for the five synoptic typeswith (a) maps showing mean composite 500 mb geopotential heights (m) and (b) maps showing mean composite sea level pressure (SLP; mb). Svalbard is located inside the black oval.Tbl. 1: Meteorological conditions summary for the different event types included in this study.

Synoptic Type	*Key circulation characteristics*	*Number of days*	*Mean hourly wind speed (m/s)*	*Mean hourly wind direction (°)*	*Mean hourly air temperature (°C)*	*Mean daily precipitation (mm)*
NA	Average Winter	2128	4.3	147	-10	0.1
NA	All Drift Events	138	6.4	189	-7.6	2.5
1	High to the South	47	6.4	189	-6.1	4.3
2	High to the Southwest	31	6.1	213	-8.6	0.7
3	Low to the Southwest	21	6.1	126	-5.9	0.9
4	Zonal	31	5.7	190	-9.9	2.9
5	Low to the South	8	6.9	121	-9.2	0.6

Relative to average winter conditions, the locally higher wind speeds (p-value<0.001), generally southwesterly or southeasterly winds, elevated air temperatures (p-value<0.001), and increased daily precipitation values (p-value<0.001) characterizing drift events of all five synoptic types are consistent with winter storm condition descriptions from previous studies of Svalbard's meteorology (e.g. Førland et al., 1997; Hanssen-Bauer et al., 1990; Humlum, 2002). Winter storms on Svalbard provide the ingredients for regional drift events – strong winds combined with a sufficient supply of recently precipitated snow – that may be lacking at other times. As such, the five synoptic types identified in this study represent atmospheric conditions conducive to cyclonic activity near Svalbard. As these low pressure cyclones move meridionally up the North Atlantic storm track, they transport warm air, precipitation, and strong winds to Svalbard. The relative locations of the synoptic scale high and low pressure centers control the more specific location of the storm track and the resulting local winds. Synoptic Types 1 and 2 are more conducive to winter storm passage to the west of Svalbard, resulting in southwesterly winds and warm air advection from the warm sector of the cyclone. Synoptic Types 3 and 5 generally result in cyclonic activity tracking to the east of Svalbard, with locally southeasterly winds and slightly cooler air. Synoptic Type 4 condition likely encompass more variable airflow patterns, as local wind directions fluctuate more than for the other synoptic types.

3.2 Case Studies

In this section, we present case studies of two multi-day drift event periods that coincided with cycles of regional avalanche activity as identified by Eckerstorfer (2013). These case studies provide an opportunity to show how patterns in synoptic and local scale meteorological conditions during drift events can influence regional avalanche activity in this region of Svalbard.

The March 2007 case study likely represents a lower-magnitude higher-frequency avalanche cycle, while the January 2010 cycle represents a more extreme, high-magnitude, low frequency event.

MARCH 2007

The March 2007 (March 22-26, 2007) drift event period (Fig. 3) occurred entirely under Synoptic Types 2 and 1 conditions, with southeasterly or southwesterly winds and modest precipitation totals. Under Synoptic Type 2 conditions on March 22, winds were southeasterly – a deviation from the generally southwestern winds characterizing this synoptic type – but abruptly switched to the south-southwest as synoptic conditions changed to Synoptic Type 1. The main frontal passage occurred late on March 23, as both temperatures and wind speeds rose abruptly and precipitation intensified and continued through March 26.

Avalanches observed on primarily easterly aspects on March 25 and 26 likely reflect the predominantly southwesterly wind direction during which the majority of the precipitation fell (March 24 and 25), as wind transported snow accumulating on leeward, easterly aspects would prime these slopes for avalanche release. Similarly, a switch to southeasterly winds on March 26 was followed by observed avalanches on generally westerly aspects on March 28, although some avalanches were also observed on easterly aspects. This case study illustrates direct snow drift control on observed avalanche activity, where snow drift processes concentrated modest precipitation totals on leeward aspects, resulting in avalanche release.

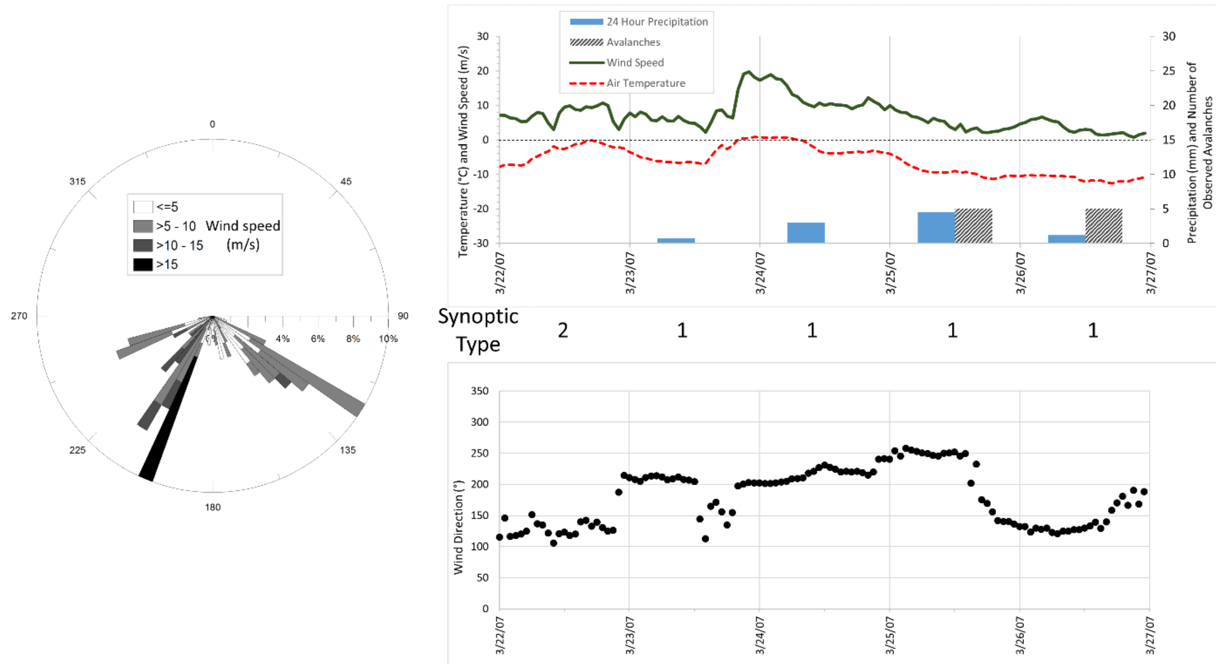

Fig. 3: Meteorological and avalanche activity summary for the March 2007 drift event period case study. Synoptic conditions are denoted by their numeric identifier between the upper and lower right panels.

JANUARY 2010

Persistent Synoptic Type 1 conditions dominated the period from January 14 – 23 (with the exception of a single day of Synoptic Type 4 conditions on January 19) resulting in air temperatures near or above 0°C, heavy rain at the Svalbard Airport AWS, and southwesterly winds generally between 5 and 10 m/s (Fig. 3). A more progressive synoptic pattern began on January 23, as Synoptic Type 1 conditions transitioned to Synoptic Type 2 on January 24 and 25, and to Synoptic Type 4 on January 26. A dramatic shift in local weather accompanied a transition from Synoptic Type 4 to Synoptic Type 5 conditions on January 26 and 27, as air temperatures dropped rapidly, hourly wind speeds approached 20 m/s, winds abruptly shifted from the southwest to the southeast, and precipitation resumed.

Avalanche activity that occurred during this drift event period is documented in Eckerstorfer and Christiansen (2010) and Eckerstorfer and Christiansen (2012) and coincides with two periods of noteworthy synoptic and local meteorological conditions. Slushflow avalanches observed January 15 released under persistent Synoptic Type 1 conditions that allowed cyclonic activity in the North Atlantic to bring warm air and sustained heavy liquid precipitation to the region. The extreme wet slab avalanche cycle on January 28 followed the progression from Synoptic Type 1 to Synoptic Type 5 conditions. During this time precipitation falling as snow under decreasing temperatures would have been rapidly transported by strong easterly winds and loaded a snowpack already destabilized by the previous weeks' rain. Slab avalanches of unprecedented extents were primarily observed on easterly aspects, however, suggesting wind and snow transport direction prior to this cycle did not exert a strong control on the spatial pattern of the largest avalanche releases. Similarly, smaller slabs were observed on all aspects and do not appear to follow a spatial pattern based on regional wind direction prior to the avalanche cycle.

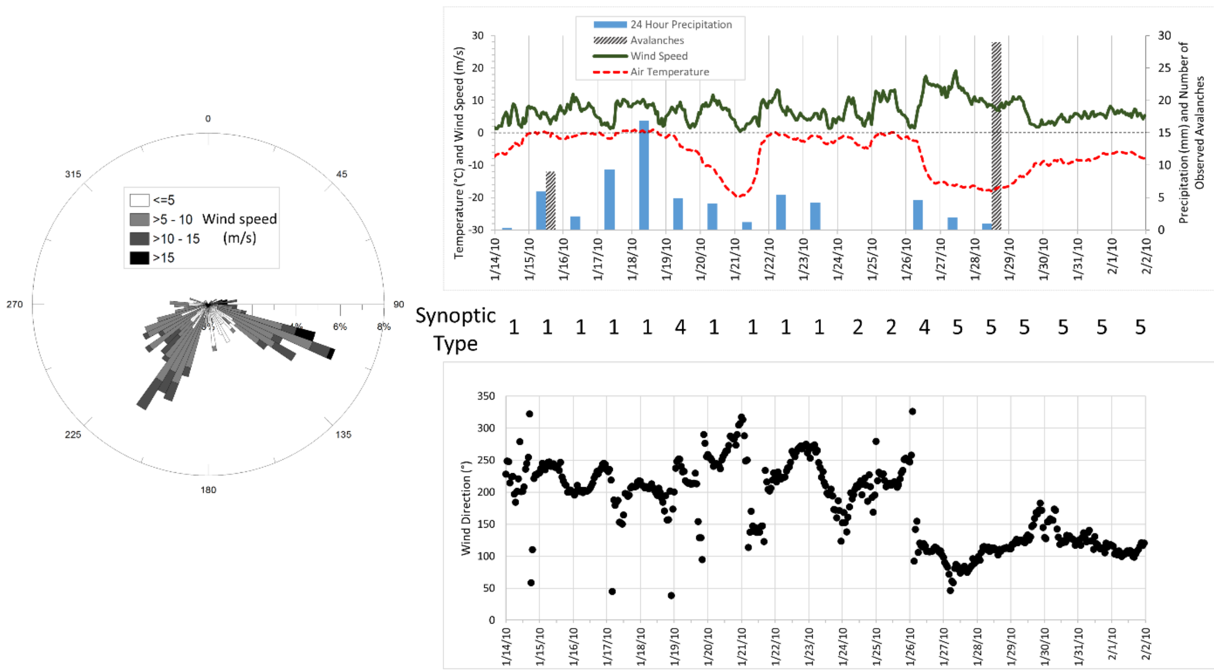

Fig. 4: Meteorological and avalanche activity summary for the January 2010 drift event period case study. Synoptic conditions are denoted by their numeric identifier between the upper and lower right panels.

These case studies illustrate that while snow drift processes and avalanche activity often occur simultaneously during winter storms induced by passing low pressure cyclonic activity, other factors such as heavy rainfall may exert as much control as snow drift on regional avalanche activity, especially during low-frequency, extreme avalanche cycles. Wind loading of avalanche terrain likely exerts a considerable influence on regional avalanche activity during lower magnitude precipitation events (e.g. the March 2007 case study), but more localized topographic controls – such as valley channeling of regional winds (Christiansen et al., 2013) – on snow deposition not represented by the regional airflow measured at the Gruvefjellet AWS may govern the specific spatial patterns of avalanche release. The January 2010 case study demonstrates a more complex relationship between snow drift and avalanche activity, where synoptic patterns conducive to warm air advection and moisture transport from lower latitudes to Svalbard result in strong winds and heavy precipitation of varying types.

4. CONCLUSIONS

Regional drift events on Svalbard as defined by this study are characterized by higher wind speeds, increased air temperatures, and heavier precipitation than average winter conditions. On Svalbard, these conditions occur primarily during winter storm events. Synoptic types identified by this study as resulting in regional drift events correspond with findings from previous work recognizing common synoptic conditions conducive to more frequent cyclonic activity in the seas around Svalbard (Rogers et al., 2005; Serreze et al., 1993), demonstrating moisture transport to the Arctic from lower latitudes via low pressure cyclonic activity is critical to developing hazardous snow drift conditions near Longyearbyen.

Case studies of periods during which snow drift and avalanche activity coincided illustrate how synoptic weather patterns influence Svalbard's High Arctic maritime snow and avalanche climate. While our case study approach limits the applicability of these results to a descriptive nature, these analyses further underline the importance of the synoptic controls on winter storms to the development of hazardous snow and avalanche conditions on Svalbard.

As snow drift events characterized by this study and avalanche cycles described by Eckerstorfer (2013) are both controlled primarily by the passage of low pressure cyclones over Svalbard, regional snow and avalanche forecasts can be improved with a knowledge of the local weather conditions expected from the different synoptic types conducive to winter storm events on the archipelago. This knowledge can be used to refine avalanche forecasts by assisting in the prediction of the spatial patterns of avalanche activity resulting from a particular synoptic type.

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