5B.3 R2O: DEVELOPMENT OF NWS SNOW SQUALL WARNINGS

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1. INTRODUCTION

Snow squalls are brief bursts of heavy snow accompanied by gusty surface winds and characterized by a rapid onset and near-zero visibility. While snow squalls produce only modest snow accumulations (typically < 2 in, < 5 cm), the sudden reduction in visibility and potentially icy road conditions results in increased motor vehicle accidents and pileups, especially on highways and interstates where high travel speeds occur. Tragically, injury and loss of life have been documented in dozens of snow squall events since the late 1990's, in addition to millions of dollars in economic loss (Banacos et al. 2014, DeVoir and Ondrejik 2008). Further, per reports in *Storm Data*, snow squalls were the second leading cause of weather related fatalities across Pennsylvania over a ten year period ending in 2008, behind only flood related deaths.

A top priority of National Weather Service (NWS) Weather Forecast Offices (WFOs) is to protect lives and property via issuance of short-fused warnings for potentially life-threatening weather and water conditions. However, hazards associated with snow squalls challenge the traditional NWS watch/warning/advisory paradigm. First, snowfall accumulations typically fall short of criteria used to guide issuance of Winter Weather Advisories or Winter Storm Watches and Warnings. Second, the short duration (< 1 hr) and localized nature of a snow squall does not fit the intent of those longer-fused, and primarily zone/county based winter weather products. Third, a snow squall is a hazard to transportation, but not to those in stationary environments, say, at home or work; a snow squall is typically not a threat to infrastructure or power lines, as might occur with heavy wet snow or ice accretion.

Heretofore, NWS forecast offices issued Special Weather Statements (SPSs) to highlight snow squalls and associated hazards. Unfortunately, a "catch all" product such as the SPS does not command the same level of urgency or breadth of dissemination as a warning, resulting in a lengthy notification process to NWS core partners and a communication process that is not fully consistent between WFOs. In addition to being more consistent, warnings can potentially leverage the Emergency Alert System (EAS), Wireless Emergency Alerts (WEA), and also includes Valid Time Event Code (VTEC), all of which are important capabilities consistent with conveying potentially life threatening weather conditions. Evolving communication technologies can also be more readily leveraged with warnings.

An increased research emphasis into the meteorological and non-meteorological factors contributing to high impact snow squalls, and emerging mobile technologies to convey life-threatening information to travelers, have put the NWS in a strengthened position to fully message the hazard posed by snow squalls, with the goal of mitigating their societal impacts. The NWS has proceeded with a new short-fused (≤ 1 hr) warning for snow squalls. In winter 2017-18, the NWS introduced Snow Squall Warning (SQW) (Fig. 1) capabilities as an "operational demonstration" at six WFOs: Binghamton, NY; Burlington, VT; Cheyenne, WY; Detroit, MI; Pittsburgh, PA; State College, PA. The purpose of the SQW is to better warn drivers of potentially life threatening travel, in hopes of achieving reduced

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travel speeds and safe driving for the rapidly changing weather and road conditions. Based on favorable user feedback and success during the operational demonstration (Table 1, Fig. 2), the SQW program was implemented nationally at all WFOs for winter 2018-19.

The issuance criteria for a SQW are:

"WFOs should issue SQWs when there is radar or satellite indication and/or reliable reports of snow squalls meeting or exceeding: Visibility 1/4SM or less, sub-freezing ambient road temperatures or plunging temperatures along and behind an arctic front sufficient to produce flash freezes, gusty winds and blowing snow."

While the focus of this paper is the research-to-operations (R2O) process leading to development of the SQW, it is worth noting that the SQW is part of a "Ready-Set-Go" philosophy (Fig. 3) to highlight snow squall potential on a variety of time scales. The time scales range from ≤1 hr with the SQW, from hours to several days with various statements, partner briefings, and WFO Facebook/Twitter posts (Fig. 4), on up to seasonal preparedness time scales. Official NWS text products, such as the Area Forecast Discussion (AFD), Hazardous Weather Outlook (HWO) and long-fused SPSs are also utilized to convey snow squall potential for intermediate lead times ranging from hours to several days (Fig. 3). The longer lead times are necessary for strategic decision making. For example, road crews need time to prepare and potentially chemically pretreat roads before road conditions deteriorate owing to snow and potential ice formation with falling temperatures. Likewise, law enforcement may preposition resources in higher incidence locations to aid in reducing traffic speed. At short lead times (i.e., an hour or less), the goal of the SQW is to warn drivers of imminently dangerous and rapidly changing winter driving conditions. Driver anxiety and confusion have been identified as non-meteorological factors contributing to winter weather motor vehicle accidents (Eisenberg and Warner 2005), factors that a well communicated and understood SQW can hopefully mitigate in snow squall environments.

The remainder of this paper focuses on the R2O process leading to the implementation of NWS issued SQWs.

2. COMPONENTS OF THE R2O PROCESS

2.1 Operationally-oriented research

As with any forecast problem, research is required to better understand the necessary conditions for the phenomena and societal impacts. In the case of snow squalls, this includes meteorological and non-meteorological factors. Non-meteorological factors, such as traffic volume at certain times of day, road design, driver skill, etc., can all affect the potential impact from these events, making for highly variable risk factors even for the same meteorological conditions.

Other than the WINDEX technique (Lundstedt 1993), it is noteworthy that previous meteorological work on non-lake effect snow squalls was generally limited to a small handful of case studies (e.g., Pettegrew et al. 2009; Milrad et al. 2011). The 36 event composite study of Banacos et al. (2014) using the North American Regional Reanalysis (NARR; Mesinger et al. 2006) dataset over northern New York and Vermont helped establish generalized conditions favorable for snow squalls, including gravitational instability, steep near-surface lapse rates, frontogenetic forcing, low-level moisture, and vertical temperature profiles conducive for snow. An operational situational awareness tool, the non-dimensional *snow squall parameter,* was also developed based on the composite study. Banacos et al. (2014) proposed that snow squalls are best viewed as mesoscale convective systems in low CAPE / strong shear environments, leveraging environmental and forecast analogies from other types of convective events many forecasters are already familiar with (e.g., dynamics similar to low-dewpoint derechos documented by Corfidi et al. (2006), except with snow as the precipitation type). A similar study in

Ohio and western Pennsylvania using observed soundings from Wilmington, Ohio (ILN) and Pittsburgh, PA (PBZ) for 47 events, further affirmed favorable meteorological conditions in the snow squall environment (Kurz and Haines 2016).

Concurrently, the need for better methods of communication in high-impact, sub-advisory (HISA) winter weather events was being established as an important requirement to mitigate motor vehicle accidents (DeVoir 2004, Eisenberg and Warner 2005, DeVoir and Ondrejik 2008). Better understanding of winter weather multi-vehicle crashes (commonly called "pileups") was also developed with respect to time of day and other factors, with 85% of such events being "convective" or "convective hybrid", and nearly half of events in the United States being HISA events (Thompson and Mann 2017). It was also found that a clear diurnal distribution in pileups existed, with over 80% of events occurring between 900 and 1600 local time, suggesting the importance of traffic flow and the reinvigoration of convection during daylight hours (Thompson and Mann 2017).

Conclusions reached in these research projects were instrumental in establishing the needed understanding of snow squall events from a meteorological and societal impact standpoint, leading to operational training.

2.2 Training and tools

Training development for operational forecasters poses a challenge as well; NWS forecasters work rotating shifts and operations are ongoing 24/7. Also, preferred learning formats vary from forecaster to forecaster. Thus, it is imperative that training is delivered in a variety of formats in order to be effective.

Some training is presented *synchronously*, meaning groups of forecasters taking the training at the same time in a lecture type setting via slideshow (e.g., Powerpoint), with the presenter attending either in person or remotely (e.g., conference or video call). Examples of this type of training include required semi-annual seasonal readiness workshops, staff meetings, or occasional "brown bag lunch" seminars. The authors have presented synchronous training on snow squall forecasting to a number of NWS forecast offices - both in person and remotely - to provide information contained in references listed in Section 2a. The drawback of synchronous training is that it is generally not possible to get 100% office participation due to the nature of shiftwork and persistent operational duties. Presentations can be recorded for later viewing, but this removes potential real-time interaction and can lower overall engagement of the trainee.

Other training opportunities are presented *asynchronously*, meaning the training is completed on an individual basis either on quiet forecast shifts or during non-operational professional development time. Such asynchronous training for snow squalls took the form of two recorded/narrated Powerpoint modules placed on the agency's Commerce Learning Center (CLC). Part I of the training focused on meteorological definitions, key environmental features associated with snow squalls, non-meteorological factors that modulate societal impact, conceptual models (e.g., Fig. 5), and the motivation for SQWs. Part II of the training focused on operational actions surrounding snow squalls, following a "Ready-Set-Go" philosophy at different time ranges leading up to issuance of SQWs (within 1 hour of occurrence). Part II also included software "knoblogy" and technical details important for SQW issuance. The presentations are available for viewing on the NWS Warning Decision Training Division YouTube channel (Part I and Part II).

Forecasters at the six WFOs participating in the winter 2017-18 operational SQW demonstration were required to take the CLC modules and accompanying multiple choice quizzes (totaling about one hour of training time) prior to the SQW start date in mid-January 2018. Forecasters had to pass each quiz with a score of 70% or higher to be marked "complete" on their training. The asynchronous training has the advantage of being taken at the convenience of the forecaster. Also, the training is uniform, knowledge can be tested (via the quizzes), and completion rates tracked. While required asynchronous training reaches near 100% participation rate, the level of engagement is more difficult to assess, and opportunities for discussion and sharing of experiences are much more limited in this format.

A third type of forecaster training utilized for the SQW rollout was *one-on-one training* using the Weather Event Simulator (WES; Magsig and Page 2002). The WES allows displaced real-time simulations and prototype software to be demonstrated and used in a practice setting, where the trainee is guided through relevant applications by a subject matter expert in the office, or follows a series of "job sheets". The WES training allowed each forecaster to become comfortable with the "knobology" of SQW issuance in the Advanced Weather Interactive Processing System (AWIPS) warning software (WARNGEN), in addition to other AWIPS and Graphical Forecast Editor (GFE) displays, which exactly mimic operations. Procedures showing relevant diagnostics (frontogenesis, surface pressure rise/fall couplets, the Snow Squall Parameter, etc.) could be demonstrated. GOES-16 color tables customized specifically for snow squalls could be shown, GFE text formatter options could be explained, and winter-adjusted model and observed CAPE color tables (starting at 10 J kg^{-1} and moving upward in 10 J kg^{-1} increments for the low instability environments of winter) could also be explained. Customized settings and procedures can be saved and recreated on demand on operational AWIPS workstations, allowing for direct utilization of items learned in the one-on-one training. Though time intensive for the trainer(s), the advantage of the one-on-one training is the high level of trainee engagement, and ability to ask questions and steer the discussion in manner that maximizes the learning experience for each individual.

Other types of training include: (1) reading research papers, (2) review of local office documentation, often in the form of local Wiki or Google Site pages or intranet material where office policies and procedures can be referenced in a concise format, and (3) formal or informal "post event" reviews of events to assess what worked well and what didn't. Again, multiple types of learning experiences are necessary to engrain the necessary knowledge and skills, especially when new science and forecast products/warnings are involved. Incorporating a range of learning experiences on a consistent basis keeps NWS forecasters at a high level of operational readiness and skill, which is particularly important in life-threatening weather situations.

2.3 Operational implementation and evaluation

The SQW operational demonstration began on 16 January 2018. The first SQW was issued on 2 February 2018 by WFO Binghamton, New York (Fig. 1). In addition, as short-lived convective systems, the Storm Prediction Center provided guidance to the field offices in the form of Mesoscale Convective Discussions describing snow squall development and evolution. This section describes some of the advantages and lessons learned with the SQW during the operational demonstration.

a. Enhanced communication and IDSS

One of the most crucial benefits of implementing a formal Snow Squall Warning is the simultaneous and instantaneous dissemination of life-saving information across many platforms. Formal SQWs, when fully implemented, will trigger Wireless Emergency Alerts (WEA) and possibly Emergency Alert System (EAS), notifying law enforcement, road weather/traffic management officials and the general public within seconds of NWS warning issuances. Instantaneous WEA and EAS notifications reduce the need for multiple dissemination calls, saving forecaster time for other operational duties and continued monitoring. Likewise, social media "auto posts" of SQWs allow for further dissemination. Local and national broadcast media can also instantaneously display the SQW information for viewers.

b. Survey results from operational demonstration

There were 61 public surveys completed during the operational demonstration of the SQW in the winter of 2017-18. User communities included the general public, local/state and federal governments, private industry, and news media. The survey results (Fig. 2a-c) indicate overwhelmingly positive feedback (on a scale of 1 to 10, where 10 is the most positive) on the product's technical quality, accuracy, timeliness (8.5 average out of 10), and ease of interpretation (8.7 average out of 10). Also, 95% answered affirmatively that it is appropriate for the NWS to issue SQWs. As part of the survey, written comments were also accepted. A summary of these comments is included in Table 1.

3. SUMMARY AND FUTURE VISION

3.1 Summary

The R2O for the SQW followed a traditional cycle in operational meteorology. First, the operational snow squall forecast problem was identified. The snow squall forecast problem included gaps in both meteorological understanding and gaps in the ability to communicate the threat; the preexisting suite of NWS products and warnings was determined to be inadequate to properly mitigate the societal impact of snow squall events. Second, operationally-oriented research was conducted to better understand societal risk factors and the dynamics of the snow squalls environment. Suitable diagnostics were developed to help in operational forecasting of snow squall events. In the end, this included understanding snow squalls as mesoscale convective systems, often in low CAPE and strongly forced environments (Banacos et al. 2014). This also included rescaling displays so that the very low but important CAPE environments of winter could be adequately "seen" in visual displays. In addition to diagnostics such as CAPE, low-level moisture, isallobars, and low-level frontogenesis, a snow squall parameter was also developed as a situational awareness tool, to aid in the "time crunch" that can characterize the operational forecast environment, and to serve the varied preferences of forecasters. Third, operational forecasters were trained about snow squalls via synchronous, asynchronous, and one-on-one opportunities. This included conveying meteorological and non-meteorological factors (traffic flow, time of day) relevant to the overall risk posed to motorists during snow squall events. Prior to the SQW becoming official, formalized training occurred via the CLC. The Weather Event Simulator also permitted forecasters hands-on practice and understanding of the "knobology" of warning issuance. Fourth, operational implementation of the snow squall warning occurred, first at six demonstration WFOs in winter 2017-18, with availability to all WFOs for winter 2018-19.

3.2 *Vision*

How might SQWs change moving forward? The U.S. Department of Transportation led "Pathways Project" emphasized the continual need for collaboration between the public/private weather enterprise with transportation departments to keep commerce moving and the traveling public safe (US DOT 2016). Consistent with that, as nationwide SQW issuance occurs and as feedback is received, the SQW is likely to evolve to better meet the needs of NWS core partners and the traveling public. Likewise, verification of snow squall warnings presents several challenges owing to gaps in observations and non-meteorological factors influencing impact; further attention to verification will be needed moving forward.

Here are some important future considerations with respect to SQWs:

- The ability for drivers to directly receive the SQW safely from their vehicles is instrumental in the vision and success of the warning. Variable Message Boards (VMBs) are widely spaced on interstates and not available in all areas. Thus, mobile phone-vehicle pairing and other vehicle technologies (satellite-based internet services) are key in "push notifications" via WEA to car dashboard displays in modern and future vehicle design. Such a system could give a notification before entering a SQW polygon. Audio or visual messaging might state: “Dangerous snow squalls 10 miles ahead with zero visibility and icy roads”. Over time, receiving warnings in this manner allows a greater percentage of drivers to anticipate rapid deterioration of visibility and road conditions prior to encountering them, without reliance on VMBs or AM/FM radio to communicate warnings to drivers by happenstance.

- How will the SQW evolve within Hazard Simplification (“HazSimp”)? As the NWS strives to build a “Weather-Ready Nation” there are ongoing changes to simplify the traditional NWS Watch/Warning/Advisory paradigm. While it was important to baseline the SQW to fulfill immediate societal mitigation needs (and have the hazard be accounted for in HazSimp planning), as HazSimp tackles short-fused warnings, it could evolve the deterministic, polygon-based SQW.
- One possibility related to HazSimp is that of Forecasting a Continuum of Environmental Threats, or FACETs (Rothfusz et al. 2018). This proposed reinvention of the short-fused warnings framework may ultimately make all warnings more probabilistic, and have aspects of rapidly refreshing numerical models as input (e.g., the “Warn-on-Forecast” concept). These ideas are in development, but probabilistic hazard information stemming from FACETs may fundamentally change short-fused convective and winter weather warnings, including the SQW, in the future.
- Another consideration is the development of autonomous vehicles. How might a robot vehicle respond to changing winter road conditions? If such an autonomous vehicle enters an active SQW polygon (or future FACETs oriented probability based warning exceeding a certain threshold), might it be automatically engineered to slow down, or not exceed a certain speed? Integration of NWS warnings into the engineering of such vehicles would potentially serve to make roadways safer when hazardous weather or water situations are encountered.

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Table 1. A summary of comments received from various user communities via the SQW survey directed by NWS Headquarters.

Comment	User Community
“Similar to how thunderstorms work in summer so having a new snow squall warning with localized counties/places makes sense.”	Media
“After-effects of severe squalls in recent years has been frightening. Multi-vehicle pileups have got to be more common in squalls than fog. Vital asset to have among NWS products.”	Media
“We forward these warnings to multiple municipal governments and school districts in our county, allowing them to get quick updates on changing weather conditions that can be potentially dangerous.”	State/Local Government
“Polygon based warnings are the most effective because you avoid warning unnecessary people.”	Media
“I will include it on my radar maps showing warning areas. I’m glad we have something more than just radar to show the impact of snow squalls.”	TV Meteorologist
“This warning will help with delayed starts and dismissals.”	Federal Government
“Will be disseminated through Reverse 911, social media postings, media outlets and email.”	State/Local Government
“I liked the specifics provided regarding areas impacted and timeliness.”	School Superintendent
“Best use of our tax dollars.”	State/Local Government
“This will help us better warn our local populations to better protect them and give them the information that they need to make good choices.”	State/Local Government
“We will use this to help coordinate our ambulance service response and to help us prepare for winter events as necessary.”	Emergency Medical Services Agency
“Employee safety is paramount, and this is one way to alert employees about the weather hazards.”	Federal Government
“The snow squall warnings will assist in narrowing the area warned. It won’t be countywide.”	State/Local Government

“I like that it is targeted to local warning polygons. It will be taken seriously like the tornado and severe thunderstorm warnings.”	State/Local Government
“Delivering a new potentially life-saving foundational warning product to the enterprise in a format that maximizes value and takes advantage of event driven nature of snow squalls. Believe this product will make a big difference for driver safety and situational awareness.”	Business/Industry
“Accuracy is always difficult with small-scale features such as snow squalls, but having something like this is a massive improvement over using special weather statements.”	Business/Industry
“It will enhance the NWS’s ability to warn of life threatening weather events.”	State/Local Government
“Please hurry this along! It has been too long in the making.”	State/Local Government

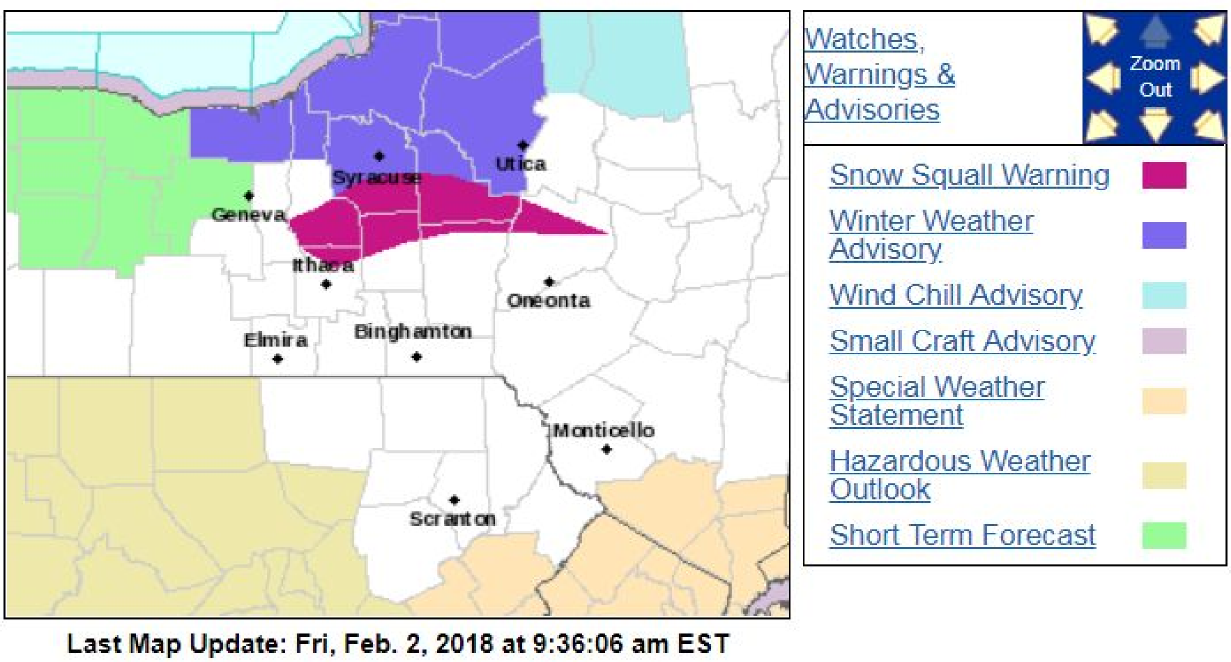


Figure 1. The first official SQW polygon issued by NWS Binghamton, New York on 2 February 2018.

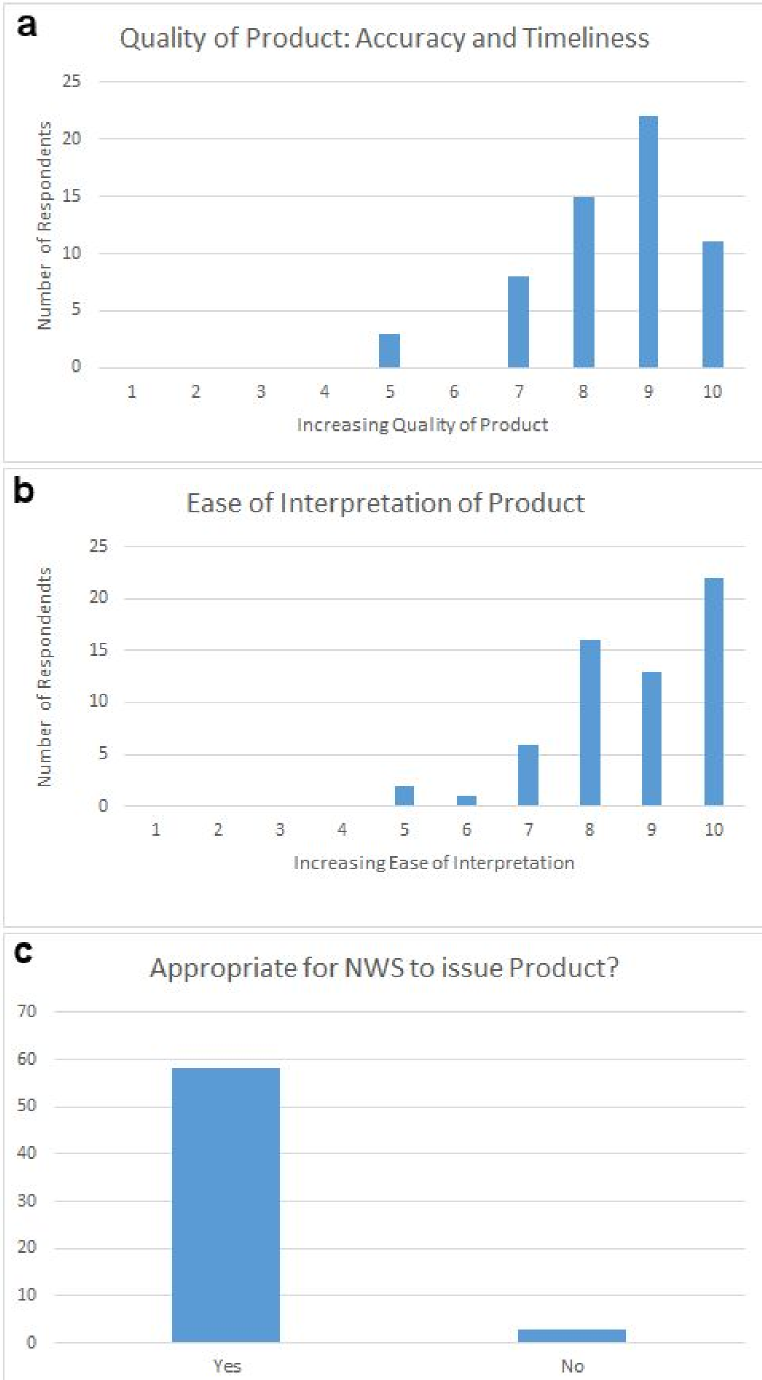
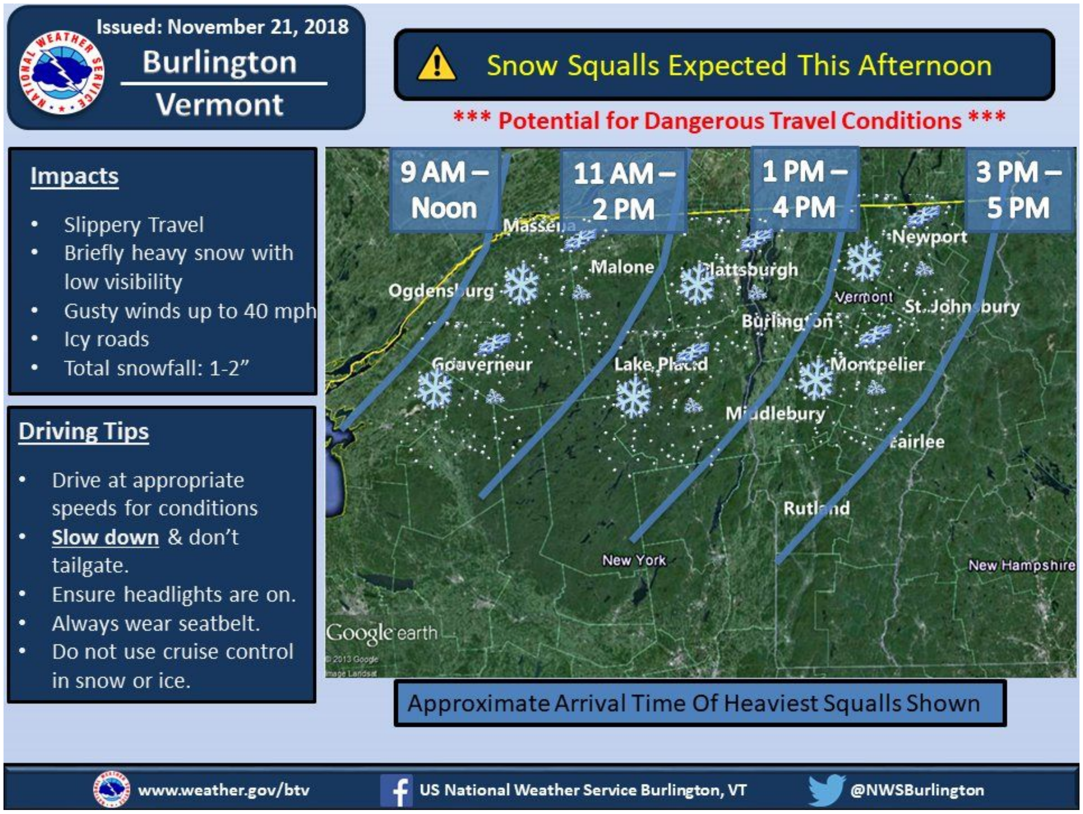
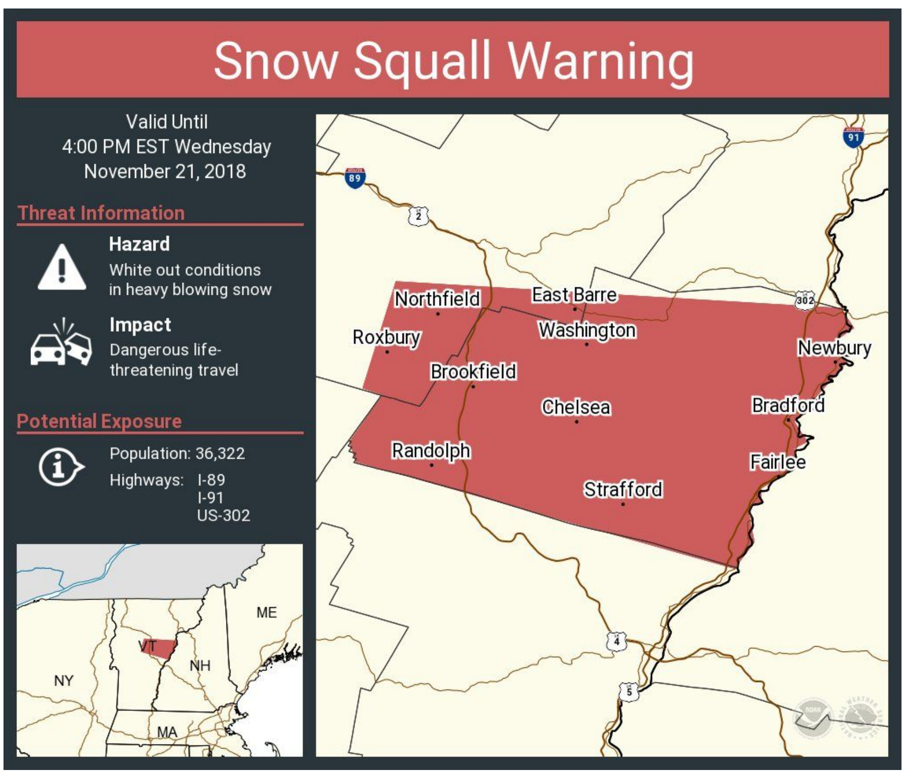


Figure 2. Snow Squall Warning (SQW) survey results. For panels (a) and (b), the rating scale is from 1 (worst) to 10 (best). For panel (a), the question wording was as follows: “On a scale of 0 to 10 (10 highest), rate technical quality of this product/service (e.g., forecast accuracy, timeliness, problems with display).”. For panel (b), the question wording was: “On a scale of 0 to 10 (10 highest), rate how easy you found the product/service to interpret and use. For panel (c), the question wording was: “Do you feel it is appropriate for the NWS to provide this product/service?”.

Figure 3. A summary (from NWS training slide) of potential NWS actions ("Ready-Set-Go" philosophy) at various time scales leading up to snow squall events and issuance of SQWs within 1 hour of occurrence. NWS text product acronyms include the Area Forecast Discussion (AFD), Hazardous Weather Outlook (HWO), and Special Weather Statement (SPS). NWSChat refers to instant messaging software used by NWS personnel to exchange critical warning decision expertise and other types of significant weather information essential to the NWS's mission of saving lives and property with the emergency management and media communities.



(a)



(b)

Figure 4. Example images posted to Twitter by WFO Burlington, Vermont (@NWSBurlington) on 21 November 2018 at (a) 1340 UTC in advance of snow squall threat, and (b) 2047 UTC via "auto post" to Twitter upon issuance of one of the SQWs.

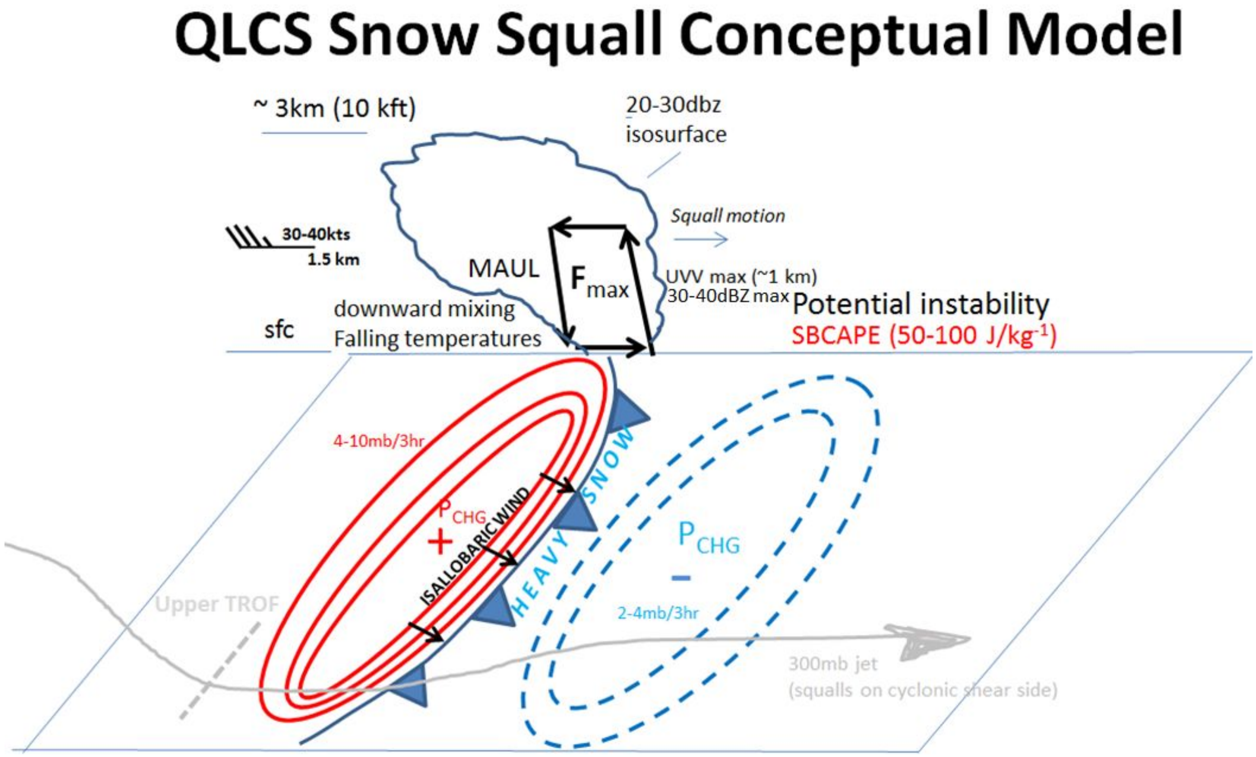


Figure 5. Quasi-Linear Convective System (QLCS) snow squall conceptual model, as presented in NWS training slide. P_{CHG} refers qualitatively to sea-level pressure changes, with positive (negative) changes in red (blue). SBCAPE refers to surface-based convective available potential energy (J kg^{-1}). F_{max} is the location of a low-level, thermally direct, frontogenetic circulation. MAUL stands for moist absolute unstable layer (Bryan and Fritsch 2000), and UVV is the location of maximum upward vertical velocity. Representative radar reflectivity values are shown in dBZ.