The Meteorology of Landslide-Initiating Storms in Southwestern Coastal British Columbia

May Wong
The University of British Columbia, Vancouver, British Columbia

Matthias Jakob
BGC Engineering, Vancouver, British Columbia

Roland Stull
The University of British Columbia, Vancouver, British Columbia

Doug McCollor
BC Hydro, Vancouver, British Columbia

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Corresponding author address: Roland Stull, Earth and Ocean Science Dept., The University of British Columbia, 6339 Stores Rd., Vancouver, BC V6T 1Z4.
E-mail for Roland Stull: rstull@eos.ubc.ca

ABSTRACT

Intense storms hitting the North Shore Mountains near Vancouver Canada in the period 1989 - 2007 were studied to develop a real-time landslide warning system. A total of 41 storms were analyzed, of which 21 were randomly selected as a basis for deriving meteorological conditions favouring landslide initiation. The set of derived criteria was then tested on the remaining 20 storms. Meteorological variables examined included jet-stream wind speed and direction, near-surface (at 850 hPa) wind speed and direction, and locations of fronts and their associated precipitation. Results show that landslides are more likely when: near-surface wind directions are within a certain range, fronts move through the study area, and sufficient moisture is entrained from the subtropics. The 850-hPa and 250-hPa wind speeds are particularly good indicators of the ability of an approaching front to cause intense orographic precipitation. To further identify the variables that best explain the occurrence of landslides, a discriminant function analysis was conducted. This analysis demonstrates that the average 250-hPa wind speed is the best predictor for landslide occurrence.

1. Introduction

a. Motivation

During 15 - 16 November 2006 an intense, Pacific winter storm struck the south coast of British Columbia (BC), Canada. The heavy rain triggered at least 16 landslides in the Greater Vancouver Regional District (GVRD). The synoptic situation and damage from this storm, summarized below, illustrate the nature of these storms that frequent the Pacific Northwest coast of North America.

On 15 November 2006, a deep 500-hPa trough was approaching BC from the eastern Pacific. An upper-level wind maximum on the east side of the trough indicated intense cyclogenesis was occurring at the surface along a northeast-southwest-oriented cold front lying across the BC central coast. The strong, moist southwest flow over the eastern Pacific deepened a 98-hPa surface low-pressure centre crossing Vancouver Island on the morning of the 15th (Fig. 1).

Heavy rain was reported across the BC South Coast and in the Columbia region in the BC southern interior (Fig. 2 shows place names). Surface winds on the coast were southeast in the 60 to 120 km h^{-1} range. Freezing levels were high over southern BC, at about 2500 m. This storm hit the BC coast hard, turning falling trees into missiles, knocking out power and leading to cancelled ferry sailings and float plane flights between the Lower Mainland and Vancouver Island. Wind and rainfall warnings were posted for most of the BC Lower Mainland and Vancouver Island.

Electricity was cut off before daybreak on 15 November to about 8,000 BC Hydro customers in Sechelt, Whistler, Bowen Island, and Quadra Island. Trees appeared to be bearing the brunt of the storm. Winds gusting at more than 100 km h^{-1} smashed trees into houses in West

Vancouver, forcing officials to evacuate about 30 homes in one subdivision.

Vince Louzon, of Port Alberni's city works yard, said people should just "stay home". He said storm drains were overflowing. Pumps were given out to some residents in a particularly hard-hit neighbourhood, but they were left useless when the power went out. "This is the worst rain event anybody in the yard can remember," Louzon said.

The Port of Vancouver, Canada's largest shipping center, was also forced to idle its container- and coal-loading operations at its Deltaport facility. The hardest hit areas were North Vancouver Island, Vancouver's North Shore, Surrey, Langley and the Fraser Valley. The storm peaked at around 1900 local time (LT = UTC – 7 h) on 15 November 2006 with 226,000 customers without power. BC Hydro said all of its repair crews and contractors had been called out. Utility representatives helped staff the Surrey Provincial Regional Emergency Operations Centre (PREOC) during the night. The storm also brought heavy rain to the region, which was still drying out from storms that had caused flooding in southwest British Columbia and western Washington state the previous week. Flood warnings were issued for several rivers on eastern Vancouver Island where rain fell at a rate of 10 mm h^{-1} for more than six hours at midday on the 15th.

This landfalling cyclone is one example of the type of storms that strike southwestern BC roughly five times every winter. The heavy rainfall associated with these storms can trigger another hazard in the mountains — debris flows. As greater Vancouver has expanded toward its current population of 2 million, suburbs have spread further up the North Shore Mountain slopes that border the city to the north. In one of these suburbs, North Vancouver, rainfall triggered landslides have become an increasing threat. Property damage in this high-housing-density region is high, stimulating a series of studies resulting in debris-flow mitigation projects costing several million dollars.

In 2003 the District of North Vancouver identified several high priority creeks where structural mitigation was advisable. However, the total capital expenditure needed for all proposed structures well exceeded the budget available to the District of North Vancouver. For this reason, a different risk-management strategy was sought.

Risk management can take the form of a warning system, in which affected residents are informed of increasing landslide threat. These residents can then evacuate or take measures to ensure their personal safety. An important input into a landslide warning system is the weather forecasts, hence, the motivation for this study.

b. Storm classification

This work details the development of a storm classification system for the North Shore Mountains of Vancouver, British Columbia, Canada as a part of a real-time debris-flow warning system. The classification is based on a case study of 41 landfalling mid-latitude cyclones, of which 14 had recorded landslides and 27 had no documented landslides affecting the North Shore portion of the Greater Vancouver Regional District (GVRD) during 1989 - 2007 (Jakob and Weatherly, 2002). In sections 3b-d, twenty-one of the 41 storms are analyzed to determine how to distinguish storms that trigger debris flows from those that do not, based on meteorological variables related to heavy precipitation (Jakob, et al. 2006). The set of criteria derived was then tested on the remaining 20 storms, and the results are in section 4.

2. Method

The storm classification system is based on examination of several types of synoptic weather analysis maps, satellite imagery, atmospheric sounding data from Quillayute, Washington (KUIL, 188 km southwest of the North Shore Mountains), and hourly-observed precipitation data at West Vancouver (WMO ID 71784, located at 49°21'N and 123°11.4'W, 8 km away from North Vancouver, and at elevation 168 m). Surface analyses are used to track frontal systems and surface low-pressure centres, and 850-hPa analyses are used to track the wind speed and direction at that level as one indicator of the frontal-system strength, and also to detect winds that could hit the mountains and cause orographic precipitation. Also used are 250-hPa analyses to track the flow of the jet stream and its strength. We limit our research to these data because these are the ones easily accessible to landslide meteorologists.

The geostationary satellite information includes infrared images to track the frontal system and its extent. The water-vapour images are used to identify the source latitude of moisture conveyer belts coming from over the Pacific Ocean, such as the so-called Pineapple Express coming from near Hawaii. For images archived after year 2000, the source of moisture for the approaching cyclones can be better determined due to extended coverage of the whole Pacific Ocean (extends northwestward to 10°N, 150°E); the older satellite photos as available from the Environment Canada (EC) archive cover only Eastern Pacific (extends northwestward to 20°N, 180°).

As another indicator of when the frontal system passes the study area, precipitation amount was examined using hourly observed data in West Vancouver (a suburb just west of North Vancouver). The West Vancouver auto-station (WMO ID 71784) was the closest weather station that provides hourly observations. For cases when precipitation data was not available from West Vancouver (including all storms prior to 1994), daily precipitation data was used from the West Vancouver Capilano Golf & Country Club (Environment Canada climate station ID 1108825; latitude 49°21.0'N, longitude 123°7.2'W, elevation 200.90 m).

After collecting these data, the following variables were analyzed from the sounding data, analyses, and satellite imagery: approximate latitude (°) of the upstream moisture source over the Pacific, speed and direction of jet stream (at elevation level of 250 hPa), near-mountain-top (at elevation level of 850 hPa) wind speed and direction, coincidence of the study area with the warm sector of the frontal system, and the occurrence of preceding storm(s).

3. Observation data

The criteria of the classification system were determined using a training data set of 21 landfalling mid-latitude cyclones (denoted by '*' in Table 1), of which seven were randomly selected from the subset of storms with documented landslides, and 14 randomly selected from the subset of storms without documented landslides. The resulting criteria were then independently tested on the remaining 20 landfalling mid-latitude cyclones (storms), which included seven with documented landslides and the 13 storms without. All of these storms were taken from the periods 1989-91 and 1998-2007, and none from 1992-97 since there was a lack of readily available archived data during that period.

Even though no landslides were recorded for some of the storm cases, this does not prove conclusively that the storm did not trigger any landslides. This uncertainty stems from the fact that even though the GVRD flies over its watersheds after significant storms to count landslides in remote areas, a low ceiling or poor weather conditions may impede visibility. Thus, it is likely that some landslides occur but are not counted. Given the character of the often inaccessible wilderness area of the North Shore Mountains uphill of the North Vancouver suburban area, this problem cannot be removed. The uncertainty of landslide occurrences must be incorporated into the interpretation of the results.

The temporal averages of the winds at 850 hPa and separately at 250 hPa were calculated using values recorded when the West Vancouver study area is within the warm sector of an approaching mid-latitude cyclone, and when the heaviest rainfall was recorded within the storm period in West Vancouver (Table 1).

4. Determination of criteria

a. 250-hPa (Jet Stream) Wind Speed and Direction

The wind speed at 250 hPa can be relevant for two reasons. (1) A faster jet stream is often associated with strong baroclinicity via the thermal wind relationship, and baroclinicity leads to strong cyclones with possibly heavy rain. (2) A faster jet could indicate the presence of an upper-level conveyor belt.

Figure 3 shows that 250-hPa wind speeds for storms that triggered landslides (marked with ‘o’) tend to be higher in values than those obtained from storms that did not trigger any landslide (marked with ‘x’). The average of the 250-hPa wind speeds for the seven storm cases with documented landslides examined here is 55 m s^{-1} (107 knots, with a standard deviation, $\sigma_{DL} = \pm 13.5$ knots), while that for the 14 storm cases with no documented landslides is 39 m s^{-1} (75 knots, with $\sigma_{NDL} = \pm 18.6$ knots).

Wind direction at 250 hPa was studied because it could indicate if upper-level winds come from over a warm ocean (i.e., a moisture source) or over cold land. For the wind direction at the 250-hPa level, the average wind direction for the cases with recorded landslides examined here (Fig. 4) is 273° (west, with a standard deviation, $\sigma_{DL} = \pm 14.4°$), and that for all the cases with no recorded landslides is 251° (west southwest, $\sigma_{NDL} = \pm 26.4°$). Thus, wind direction is a poor indicator of landslide occurrence for these cases.

Based on these data, the predictor criteria in Table 2 give the best discrimination between landslide and nonlandslide events for 250-hPa wind speed and direction.

b. 850 hPa-level (1.5 km above sea level) Wind Speed and Direction

The range of 850 hPa-level wind speeds and directions for the storm periods, as retrieved from the Quillayute soundings, appears to be narrower than that for the 250-hPa winds (Fig. 5). The 850-hPa winds at Quillayute are representative of the general synoptic flow in the region just above the top of the North Shore Mountains, as might create orographic precipitation if from a direction to cause upslope flow. As shown in Figure 5, all seven storms with recorded landslides examined here have wind speeds exceeding 18 m s^{-1}. The average speed of 850-hPa winds in landslide-triggering storms is 20.8 m s^{-1} (40 knots, with standard deviation $\sigma_{DL} = \pm 5.4$ knots), while that for winds in the 14 non-landslide-triggering storms is 17.0 m s^{-1} (33 knots, with standard deviation $\sigma_{NDL} = \pm 12.3$ knots). Discriminator criteria for 850-hPa winds are suggested in Table 2.

The average direction of 850-hPa winds (Fig. 6) in the landslide-triggering storms is 228° (with standard deviation, $\sigma_{DL} = \pm 14.6°$), and that in non-landslide-triggering storms is 217° (with standard deviation, $\sigma_{NDL} = \pm 15.2°$). Thus, wind direction is not a good discriminator of landslide occurrence.

c. Moisture-source Latitude

Sometimes strong low-altitude pre-frontal jets occur in approaching cyclones, which advect moisture towards Vancouver and Seattle from southwest over the Pacific Ocean. Such a moisture conveyor belt is nicknamed the “Pineapple Express” by local forecasters, particularly if the entry into this jet is in the subtropics near Hawaii. Access to such subtropical moisture is crucial if a landfalling cyclone is to produce heavy precipitation.

The source of moisture (in degrees latitude over the Pacific Ocean) for each storm was determined by examining the corresponding satellite imagery. Unfortunately, this resource was not easily available for cases before 1992, so the discussion in this section will be limited to 15 of the 21 storms used to determine the criteria. Figure 7 shows the latitude of the moisture source for each storm.

The dotted line in Figure 7 indicates the northward-most source location of moisture in storm cases that triggered debris flow. Having subtropical moisture alone does not guarantee a landslide-triggering condition as indicated by many of the non-landslide-triggering storm cases (marked with 'x' below the dotted line). Table 2 shows the moisture-latitude criterion for discriminating between landslide and non-landslide storms, where it is found that moisture sources north of 30°N are unlikely to provide sufficient moisture for rainfall-caused landslides at North Vancouver.

d. Warm sector

Comparing the precipitation amount at West Vancouver (WMO ID 71784) with the analyzed frontal passages from the surface analysis charts, it is observed that most continuous precipitation is associated with the passage of a warm front, where temperatures are milder and the frontal slope is gentler. Because temperatures are higher when the study area is within the warm sector (behind the warm front, but ahead of cold front), in winter, "warmer" rain is more likely to enhance snowmelt and run-off on the North Shore Mountains.

To illustrate the association between continuous precipitation and the warm sector of a frontal system, Figure 8 shows the hourly and accumulated precipitation measured in West Vancouver (WMO ID 71784) for the storm during November 13-14, 1998 (a different storm than the one described in the

Introduction). Points A-F indicate synoptic changes in the weather around the study area, as shown by surface analysis charts and satellite imagery. At point A, a warm front passed the study area, bringing much precipitation to the region. But within six hours, at point B, a cold front followed. This first frontal system was associated with a low-pressure centre, deepest at 999.5 hPa, which moved farther inland through the north coast of British Columbia (BC). Although the cold front had passed, the area was still receiving rain (point C) due to a second low-pressure system following behind, with its pressure centre located at 43°N 144°W at 12 UTC on November 13 that was propagating towards BC.

This second low-pressure centre induced another set of fronts to form north of the study area such that it was once again in a warm sector. At point D, the warm front of the second low-pressure system passed through the study area, bringing another peak of precipitation to the region. At point E, the associated cold front passed the region, moderating the precipitation amount. There was still a large amount of rainfall received at point F due to the low-pressure centre remaining stationary at 50°N 130°W from 06 to 18 UTC on November 15, entraining much of the remaining moisture towards the coast.

In summary, this section used a training-set of data from 21 storms to determine criteria to help discriminate between non-landslide and landslide-triggering storms. In the next section, these criteria are tested against the 20 additional storms that were set aside for independent tests.

5. Independent test of the criteria

The quantitative criteria for all the weather variables except for the 250-hPa wind directions, listed in the previous section, worked well together. To show this, the 850-hPa and 250-hPa wind speed criteria were first applied on the 20 independent test cases and were used to classify them into two groups: landslide-triggering and non-landslide-triggering (Fig. 9). Then the results were evaluated by examining the remaining variables, namely 850-hPa and 250-hPa wind directions and moisture source, of the storms in the two groups.

Out of the 20 storms tested against the criteria for 850-hPa and 250-hPa wind speeds, 11 were classified to be landslide-initiating, five of which did not have any actual landslides recorded (Fig. 9). Although no landslides were recorded for the five storms, it is still possible that landslides were triggered in remote areas that were not reported.

Figure10 shows the 850-hPa wind directions for all 20 storms. As shown in the plot, most storms have 850-hPa winds blowing from the southwest, be they landslide-triggering or non-landslide-triggering. This dominance shows that even though all but one storm identified as landslide-triggering satisfy the wind-direction criteria, the criteria alone are insufficient to identify landslide-triggering storms.

The storms represented by black-filled circles and triangles met at least one of the criteria set for the near-surface (at 850 hPa) and jet-stream (at 250 hPa) wind speeds. The white-filled circles and triangles indicate the ones that did not meet any of the two criteria, among which one storm, on 17 November 2002, did actually trigger one landslide, affecting the Capilano Watershed in North Vancouver, where 40 percent of Greater Vancouver's Lower Mainland drinking water comes from.

Also, among the seven test cases with documented landslides (circles in Fig. 10), one did not satisfy the criteria for near-surface wind direction, although its recorded average wind direction (of 192°) was fairly close to the threshold. Coincidentally, these two cases have the least 48-hour rainfall intensity recorded at West Vancouver, indicating that they may be marginal landslide-triggering storms. As was found in the previous section, 850-hPa wind direction is not a good discriminator of landslide-causing storms.

Figure 11 shows the 250-hPa wind directions for the storms that met at least one of the 850-hPa and 250-hPa wind-speed criteria (black-filled circles and triangles) and those that did not meet any of the two (white-filled circles and triangles). The two-level wind speed criteria identified at least 60% of the non-landslide-triggering storms, and almost 90% of the landslide-triggering storms, of which the criteria for jet-stream direction alone is incapable. The observed values from only three of the seven cases with documented landslides (circles) fell in the range $245° \leq \theta \leq 300°$, where θ is the direction of the jet stream over the region. On the other hand, six of the 13 storms that had no landslide observations (triangles) also had values in the same range. The low number of values satisfying the criteria for wind direction indicates that 250-hPa wind directions can vary widely, and are weak indicators of landslide-triggering storms.

Figure 12 shows the latitude of the moisture source for each storm. It also shows that, of the cases that were classified as potential landslide-triggering storms (black-filled circles and triangles), their moisture sources satisfy the criterion set for this variable. As a general rule, cases with subtropical moisture may not trigger any landslides (as indicated by the triangles below the threshold), but cases identified to potentially trigger landslides are likely to have moisture fed from near-subtropics or the subtropics.

6. Discussion

Returning to the 15 - 16 November 2006 storm described in the Introduction, we can illustrate the use of the landslide-storm criteria, knowing that this storm triggered over 16 landslides. Table 5 shows a summary of the observations, using 850-hPa and 250-hPa winds from Quillayute, WA (KUIL), soundings during the period of heavy precipitation in West Vancouver (WWA). All of the heavy-rainfall landslide-triggering criteria were satisfied for this storm. Figure 13 shows the hourly and accumulated precipitation, with key frontal passages and other synoptic events highlighted.

A discriminant function analysis (DFA) was conducted for this storm. The method used was a forward stepwise DFA with a tolerance (defined as 1-r^2) of 0.01 and an F to enter of 1.0. Histograms of the individual variables were plotted and tested for normalcy. The underlying hypothesis was that the two populations of storms (landslide-producing and non-landslide producing) can be separated by choosing the meteorological variables that make the most contribution to the discrimination.

The DFA was stopped after entering the second variable in the model. The two variables retained were the 250-hPa average wind speed and the 250-hPa maximum wind speed. The second variable was subsequently removed from the model runs because it is highly correlated with the first ($r = 0.91$) and the p-value (0.22) indicates that the variable contribution is not statistically significant at a 5% significance level.

After removal of the 250-hPa maximum wind speed, the only variable retained given the input parameters was the 250-hPa average wind speed. A review of summary statistics indicates a Wilks' lamda (λ) of 0.71 for the 250-hPa wind speed. Keeping in mind that a λ of 0 indicates perfect discriminatory power and a λ of 1.0 indicates no discriminatory power, the result is somewhat disappointing, though the significance level of 0.002 indicates that the variable itself is highly significant.

The classification matrix indicates that only 53% or roughly half of the landslide-producing storms are classified correctly, while 89% of the non-landslide producing storms are classified correctly. The average thus results in 76% of all cases correctly classified. While 76% is a reasonable number, the fact that there is only a 50% chance of correctly predicting the more important landslide-producing storms, suggests that the 250-hPa average wind speed cannot be used alone to predict if a given storm will likely result in landslides.

For this reason, a combined envelope approach as described in this paper is more sensible, in which several conditions have to be met for a given storm to be classified as a potential landslide producer. Namely, some of the criteria variables that, by themselves, are poor predictors, can add value when used with the other predictors. For example, by counting the number of predictors in Table 1 that satisfy the landslide criteria in Table 2 for each storm, one finds that the average landslide-triggering storm satisfies 4.7 of the 6 possible predictor criteria, while the average non-landslide-triggering storm satisfies 3.5. The 7th possible predictor from Table 2, "preceding storms", was not listed in Table 1 and not included in the average counts above. However, antecedent rain is often extremely important in destabilizing slopes, even though it was not specifically included in this study.

Despite this result, the analysis has shown that the 250-hPa average wind speed is an important predictor variable, which should be emphasized in a multifaceted debris flow warning system.

7. Conclusion

Our results suggest that valuable predictions of landslide weather are possible for the North Shore Mountains of British Columbia, Canada. Table 2 shows a summary of the criteria for a storm to potentially trigger landslide. The results from this study show that each of the criteria complements one another, except for the wind directions, and if most criteria are satisfied then the storm is likely to induce landslides in the region. Of all the weather variables, the jet stream and near-surface wind speeds best distinguish landslide-triggering storms from non-landslide-triggering storms, with greater values representing a stronger and more intense frontal system. But a landslide-triggering storm should also satisfy the remaining criteria.

Recalling that the purpose of this study is to meteorologically define the characteristics of a landslide-triggering storm and apply them in a real-time operational debris-flow warning system, these conditions are valid only when the storm makes landfall over or near the study area. One way to identify a landslide-triggering storm ahead of time is to track fronts and cyclones using short-range forecasting techniques, such as by extrapolation. These techniques work well for very short-range forecasts up to 6-12 hours, and can be implemented operationally to serve as a part of a real-time landslide warning system.

For longer-range forecasts, a better alternative is to track frontal systems using numerical weather prediction (NWP) models, which can predict the evolution and development of low-pressure centers, especially for forecasts beyond 12 hours. NWP models also provide forecast values for wind speeds and directions at different elevations in the atmosphere (usually including 250-hPa and 850-hPa levels) and precipitation for any location within their domain. Using these values would be an efficient way to compare the forecast conditions of the storm with the criteria derived in this study, and is the focus of future work.

Acknowledgements.

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List of Figures

TABLE 2. Summary of the criteria of certain meteorological variables for landslide to be potentially triggered.

Discriminator	Criteria for Triggering Landslide
Average 250-hPa Wind Speed	>43.7 m s^{-1} (> 85 knots)
Average 250-hPa Wind Direction	$245° \leq \theta \leq 300°$
Average 850-hPa Wind Speed	> 18 m s^{-1} (> 35 knots)
Average 850-hPa Wind Direction	$200° \leq \theta \leq 250°$
Source of moisture	Between equator and 30°N
Preceding storm(s)	Yes
In warm sector	Yes

TABLE 3. Example of Table 2, applied to the 15 - 16 Nov 2006 storm.

Discriminator	Criteria for Triggering Landslide	Storm Values	Criterion Satisfied
Avg. 250-hPa Wind Speed	> 85 knots	106 knots	√
Avg. 250-hPa Wind Direction	245° ≤ θ ≤ 300°	248°	√
Avg. 850-hPa Wind Speed	> 35 knots	61 knots	√
Avg. 850-hPa Wind Direction	200° ≤ θ ≤ 250°	220°	√
Source of moisture	Between equator and 30°N	15° - 20°	√
Preceding storm(s)	Yes	Yes	√
In warm sector	Yes	Yes	√

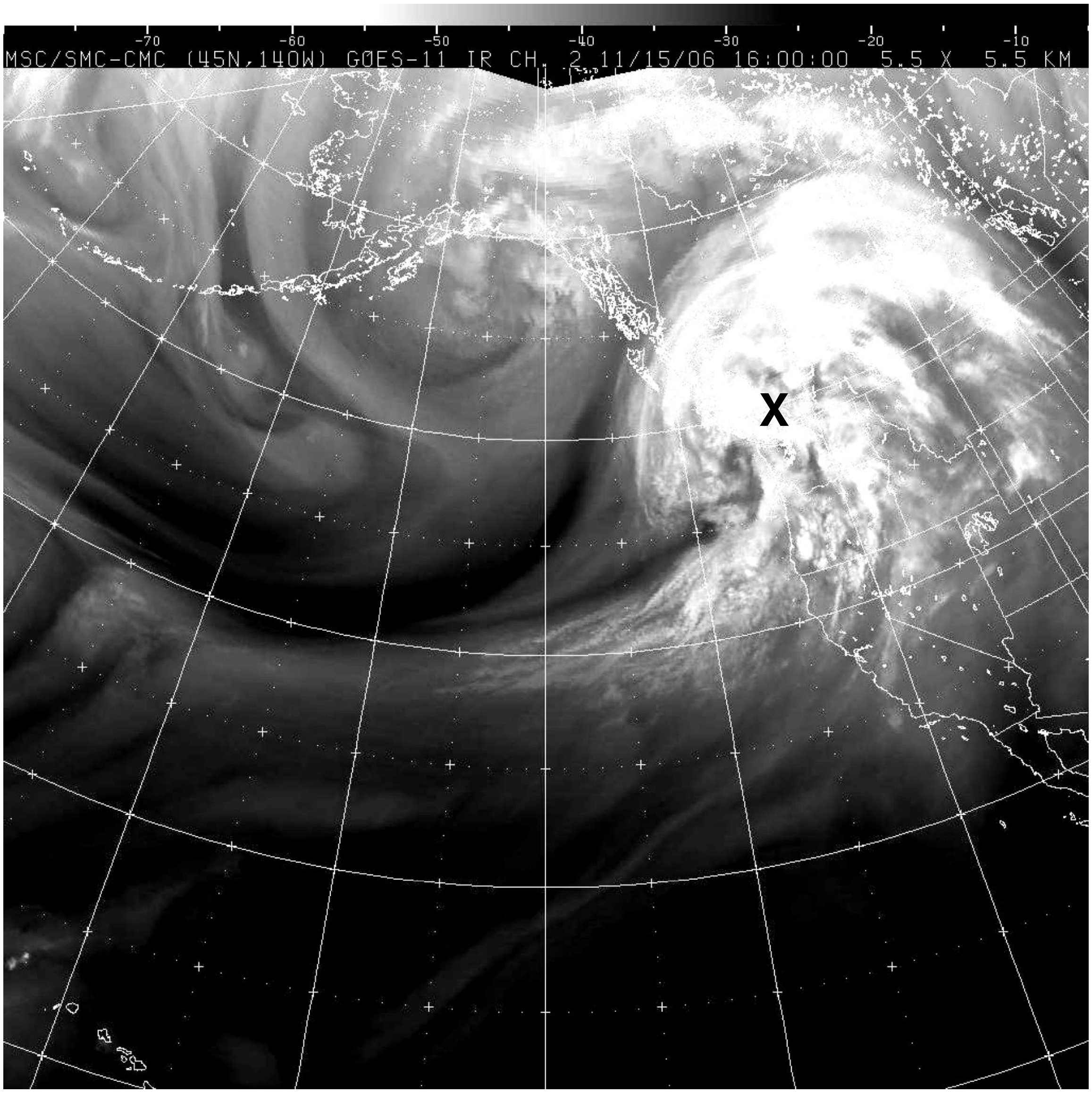

FIG. 1. Water-vapour satellite imagery showing the storm event on 15 - 16 November 2006 approaching British Columbia, Canada. X indicates the landslide region near North Vancouver.

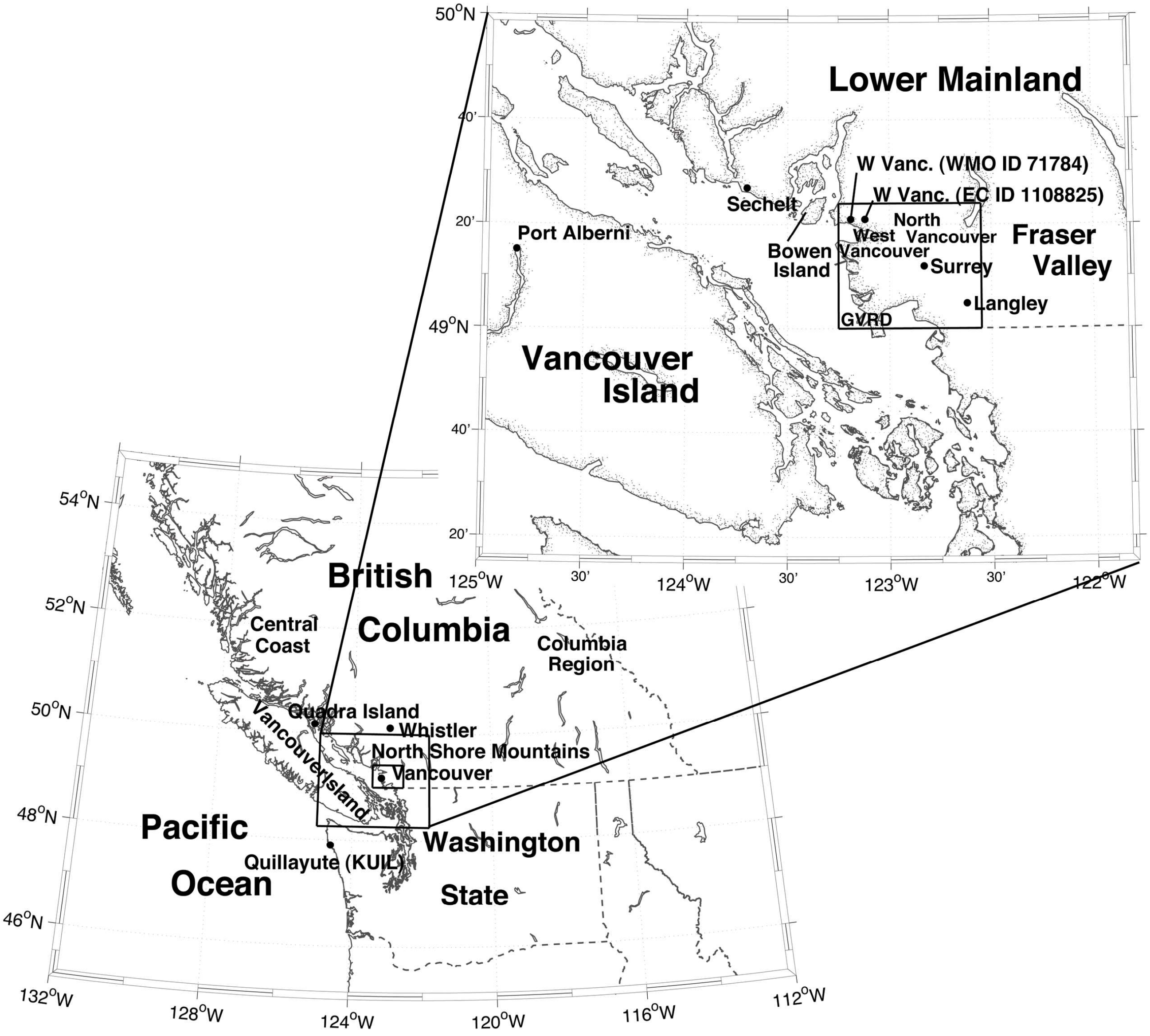

FIG. 2. Map of British Columbia, including areas affected by the storm on 15 November 2006, and locations of observation stations.

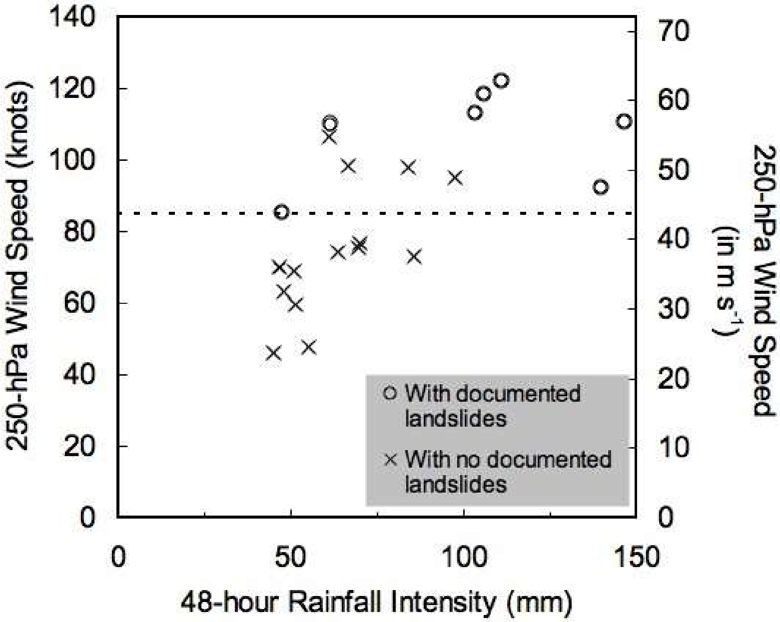

FIG. 3. Plot of average 250-hPa wind speed versus 48-hour rainfall intensity (mm) from the 21 randomly selected cases used to determine the criteria. The dotted line indicates the minimum threshold of 250-hPa wind speed for landslide-triggering cases. (1 m s^{-1} ≈ 2 knots)

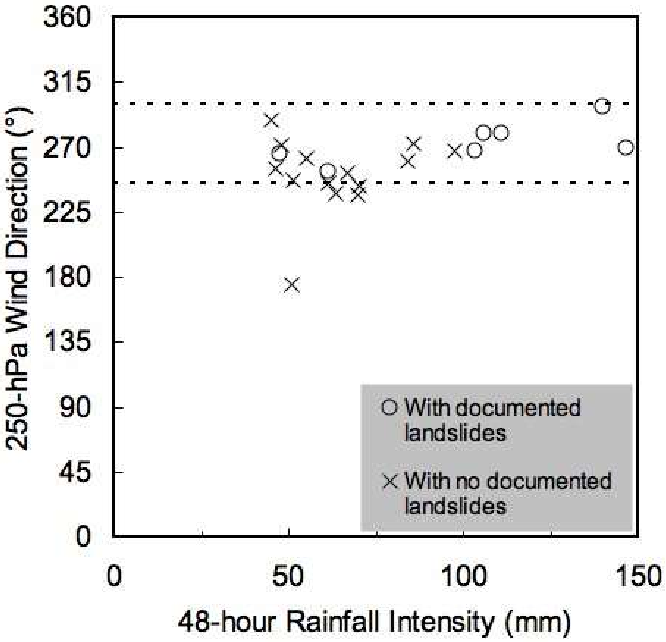

FIG. 4. Plot of average 250-hPa wind direction (°) versus 48-hour rainfall intensity (mm) from 21 randomly selected cases used to determine the criteria. Dotted lines indicate the minimum and maximum thresholds for 250-hPa wind direction.

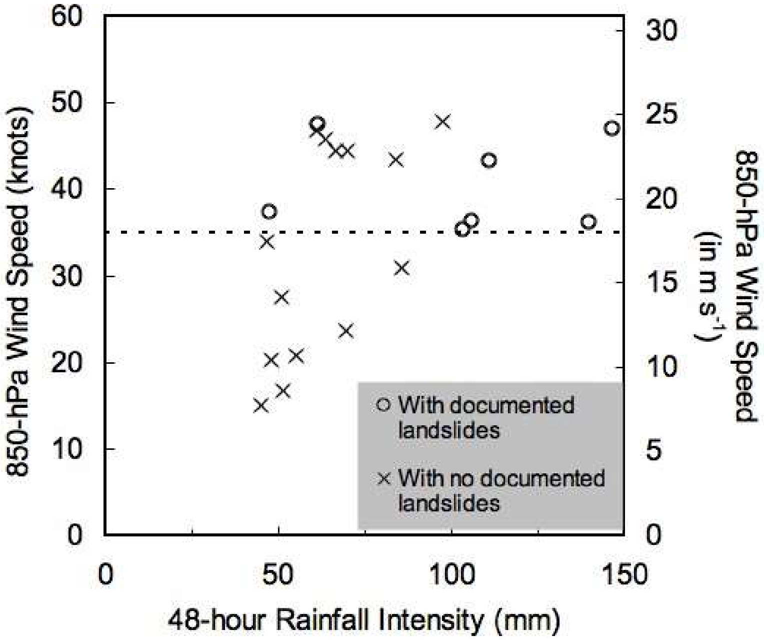

FIG. 5. Plot of average 850-hPa wind speed (knots) versus 48-hour rainfall intensity (mm) from the 21 randomly selected cases used to determine the criteria. Dotted line represents the minimum threshold of average 850-hPa wind speeds for storm cases to be potentially triggering landslides.

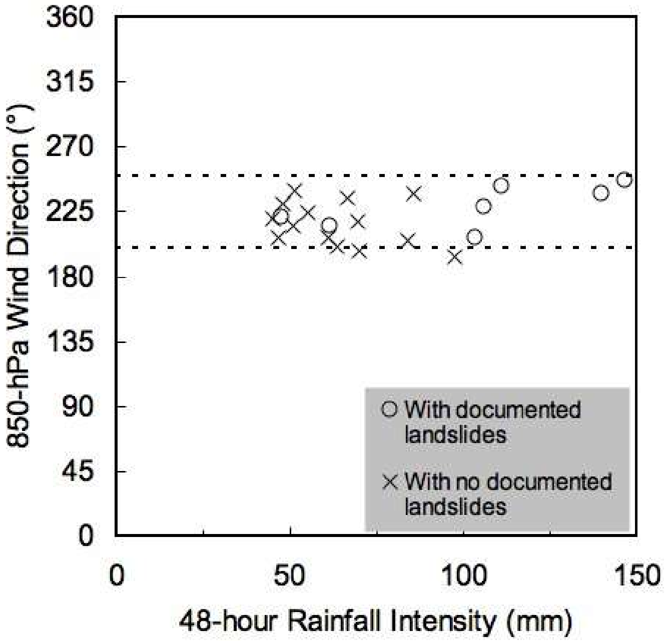

FIG. 6. Plot of average 850-hPa wind direction versus 48-hour rainfall intensity (mm) from the 21 randomly selected cases used to determine the criteria. Dotted lines indicate the range of wind directions at which storms are more prone to initiate landslides.

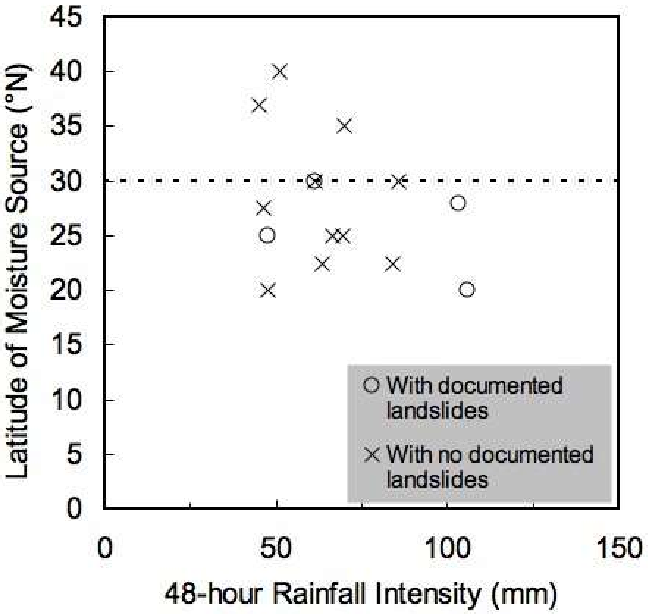

FIG. 7. Plot of source location of moisture (in ° latitude) versus 48-hour rainfall intensity (mm) from the 21 randomly selected cases used to determine the criteria. Dotted line indicates the northward-most source location of moisture in cases where landslides associated with the storms are likely.

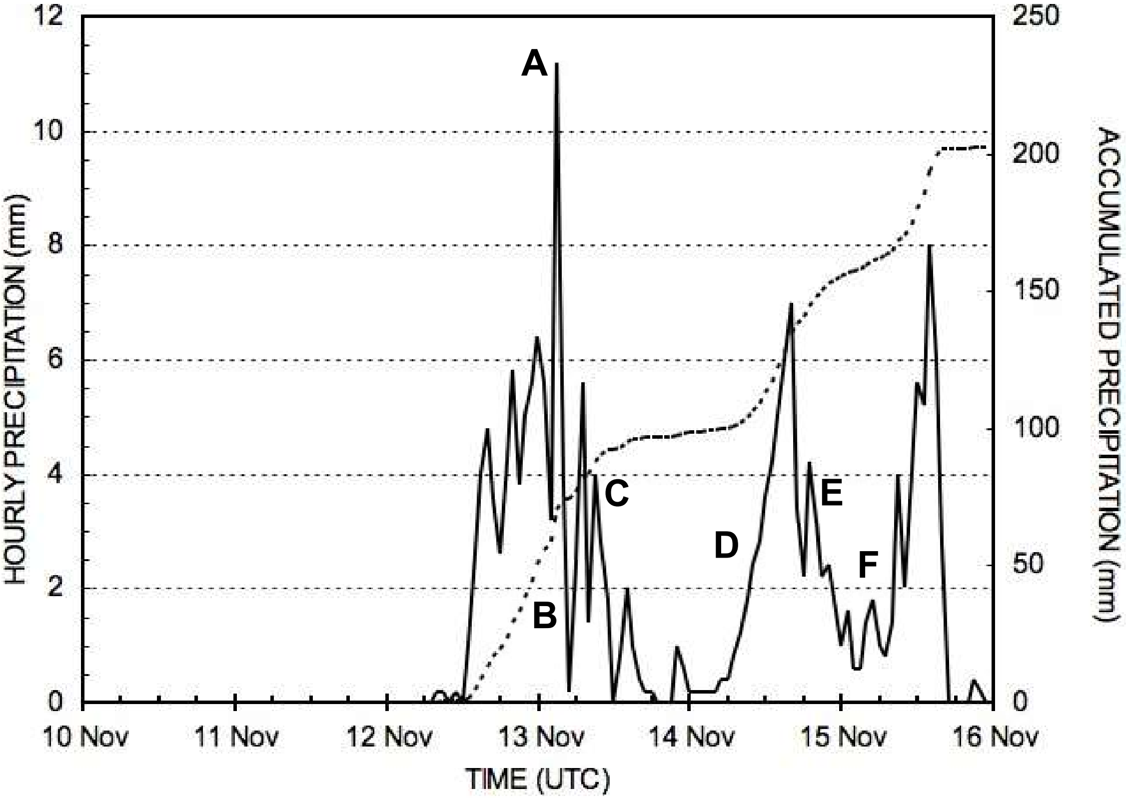

FIG. 8. Time series of hourly precipitation (solid line) and accumulated precipitation (dotted line) from two days before event on 13 – 14 Nov 1998 to one day after the event measured in West Vancouver. Letters refer to case-study events.

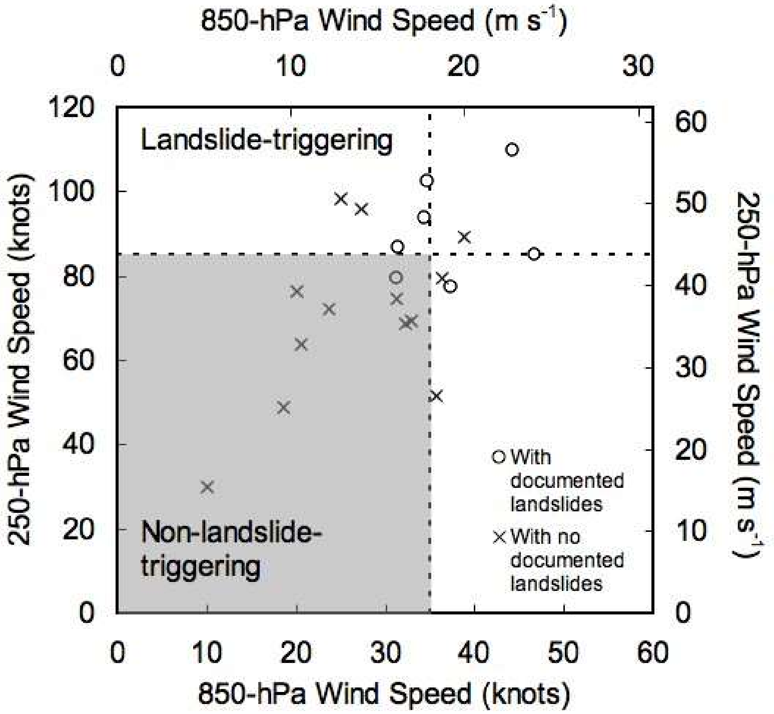

FIG. 9. Plot of 250-hPa wind speeds versus 850-hPa wind speeds from the 20 independent cases. Grey region indicates storms classified as non-landslide-triggering using the two levels' wind speed criteria.

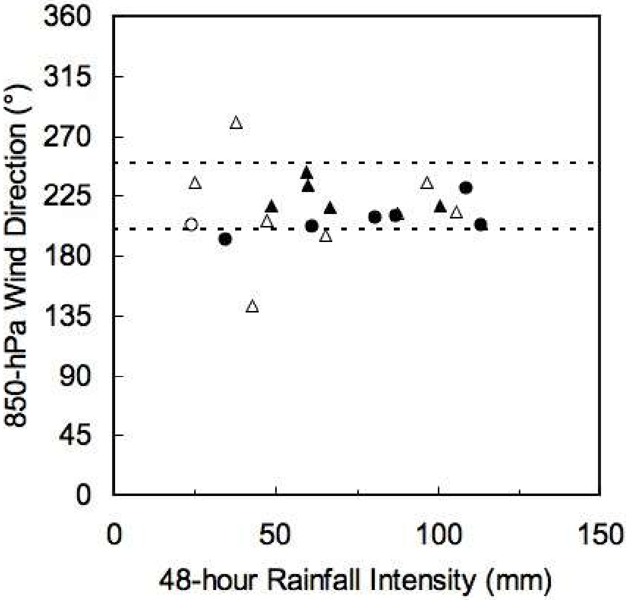

FIG. 10. Plot of 850-hPa wind directions from the 20 independent test cases versus 48-hour rainfall intensity as measured in West Vancouver. Black-filled circles and crosses indicate storms that met either one or both of the 850-hPa and 250-hPa wind-speed criteria. White-filled circles and crosses indicate storms that did not meet any of the 850-hPa and 250-hPa wind-speed criteria.

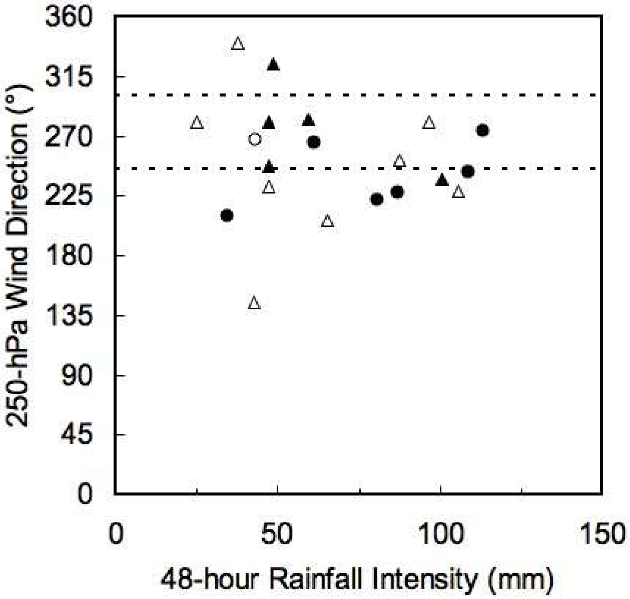

FIG. 11. Plot of 250-hPa wind directions from the 20 independent cases versus 48-hour rainfall intensity as measured in West Vancouver. Black-filled circles and crosses indicate storms that met the 850-hPa and 250-hPa wind-speed criteria. White-filled circles and crosses indicate storms that did not meet the 850-hPa and 250-hPa wind-speed criteria. This graph suggests that 250-hPa wind direction is not a good discriminator of landslide-triggering storms.

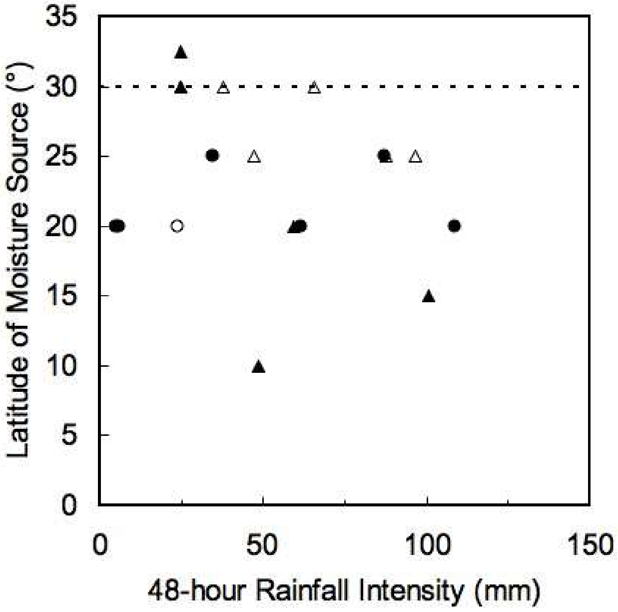

FIG. 12. Plot of moisture source in ° latitude versus 48-hour rainfall intensity as measured in West Vancouver. Black-filled circles and crosses indicate storms that met the 850-hPa and 250-hPa wind speed criteria. White-filled circles and crosses indicate storms that did not meet the 850-hPa and 250-hPa wind speed criteria.

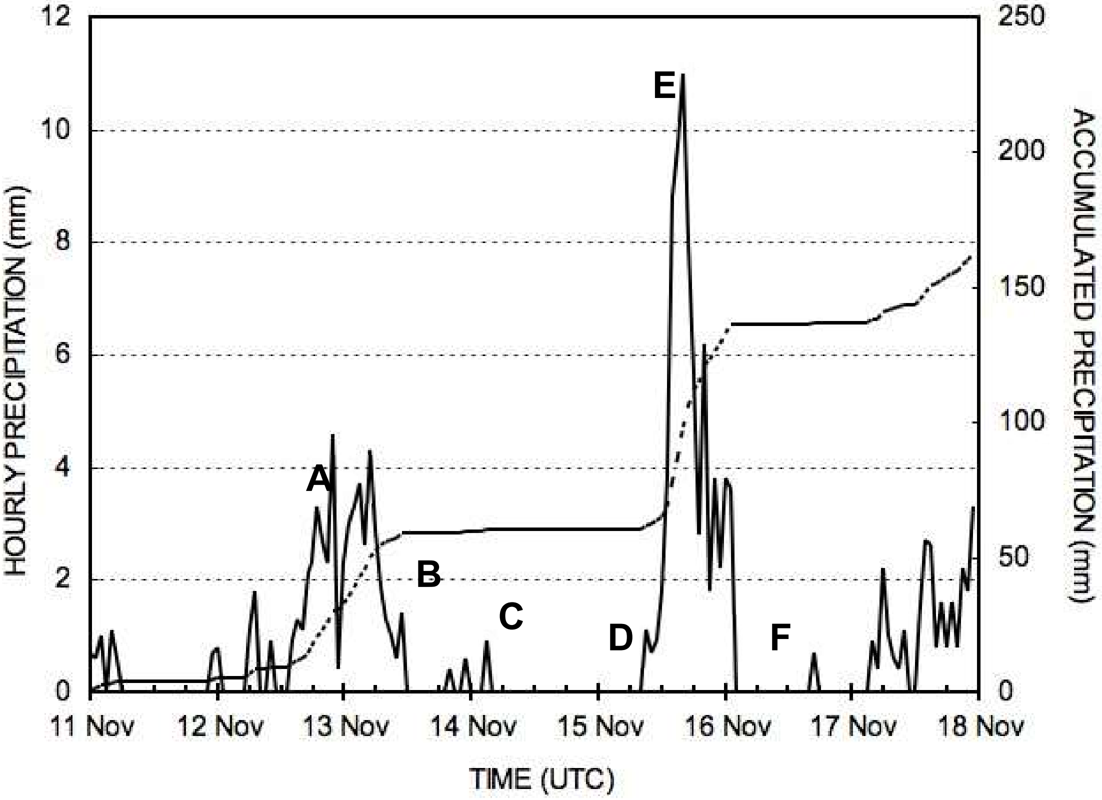

FIG. 13. Hourly and accumulated precipitation from the 15 - 16 Nov 2006 landfalling midlatitude cyclone. (A) A developed low-pressure system of 99 kPa approached the study area with pressure center at 46°N latitude and 134°W longitude, bringing much moisture to the region. (B) The low-pressure center propagated eastwards south of the study area. (C) Another low-pressure center (of 99.5 kPa) quickly moved pass the region. The region was in the warm sector for less than 6 hours. (D) A warm front extended from a 97.5 kPa low-pressure center, at latitude 57°N and longitude 140°W, passed the study area. (E) Study area remains within warm sector. (F) The associated cold front passed the study area, ending the heavy rainfall.