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Collision of a Pineapple Express with an Arctic Outbreak over Complex Terrains of British Columbia, Canada – Forecast Challenges and Lessons Learned

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Abstract

The interaction of a moisture-laden Pacific southwesterly flow, known as "Pineapple Express", with very cold air from a strong arctic outbreak during 1 – 5 December 2007 produced a record number of high impact weather events across British Columbia of Canada. Among the weather hazards are bitterly cold wind chills, heavy snow, freezing rain, heavy rain, and strong winds. The unusual collision of two contrasting air masses caused unprecedented forecast challenges for both the Global Environmental Multiscale (GEM) models and meteorologists at the Pacific Storm Prediction Centre (PSPC) of Environment Canada. In this study, the evolution of the weather systems and the observed severe weather events during this storm cycle are analyzed. Weather forecasts by the GEM models and PSPC meteorologists are compared with the observed high impact weather events during the storm. It is demonstrated that meteorologists at PSPC greatly improved the model forecasts by considering various local effects of the complex terrain in British Columbia that the GEM models cannot resolve well. In particular, with warm advection aloft, it is acknowledged that the GEM regional model tends to underestimate the cold air entrenched in some narrow valleys. The model guidance was therefore doomed to failure at forecasting the widespread and prolonged freezing rain in the midst of the storm.

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1. Introduction

Forecasting winter weather in British Columbia (BC) Canada is very challenging, due to the complex terrain of the province (Fig. 1) and the lack of observed data over the North Pacific (e.g., Hacker *et al*. 2003). During the winter, an area of high pressure often forms in the very cold air over Alaska and northern Canada. The arctic air pushes southwards into the northern and central interior of BC before coming to rest; at least once or twice each year, the advance of the cold arctic air is so strong in BC that it spreads into the southern interior and flows through the mountain valleys to the coastal regions (Jackson and Steyn 1994; Johnson and Mullock 1996) Meanwhile, numerous marine storms are generated in the North Pacific each winter. Some of them follow the Pacific storm track toward BC, ensuring mild, wet, and windy conditions along the coast. On a few occasions, an area of low pressure over the Northeast Pacific is capable of maintaining an influx of warm, moist air stretching from near the Hawaiian Islands to the west coast of North America (e.g., Fig. 2). This moist air current, frequently called the "Pineapple Express" (hereafter PE; Heidorn 2004, Mass 2008), is the most important ingredient for producing heavy precipitation and flooding along the coast from northern California to central BC (Lyons 1901; Loukas and Quick 1996; Lackmann and Gyakum 1999). When a PE collides with an arctic outbreak over the complex terrain of BC, widespread weather hazards are almost inevitable, and that is just what transpired in early December 2007.

2. Evolution of the weather systems

An area of high pressure was building over the Yukon Territory toward the end of November 2007 (Fig. 3). This high had pushed the cold arctic air southward into the BC Interior in the morning of 28 November. In the afternoon, northerly outflow winds began to develop along the coastal valleys and inlets as the cold air spilled out across the Coast Mountains. The arctic high over Yukon reached its peak strength with a 1055 hPa center at 0000 UTC 1 December (not shown). Locally heavy snow began to develop along the east coast of Vancouver Island, where the northerly outflow through the mainland inlets served as an onshore flow (see Jackson and Steyn 1994). A rapidly deepening low off Vancouver Island (Fig. 4) also play an important role in producing snow across the BC South Coast on 1 December and the following day (see further discussion in the next section).

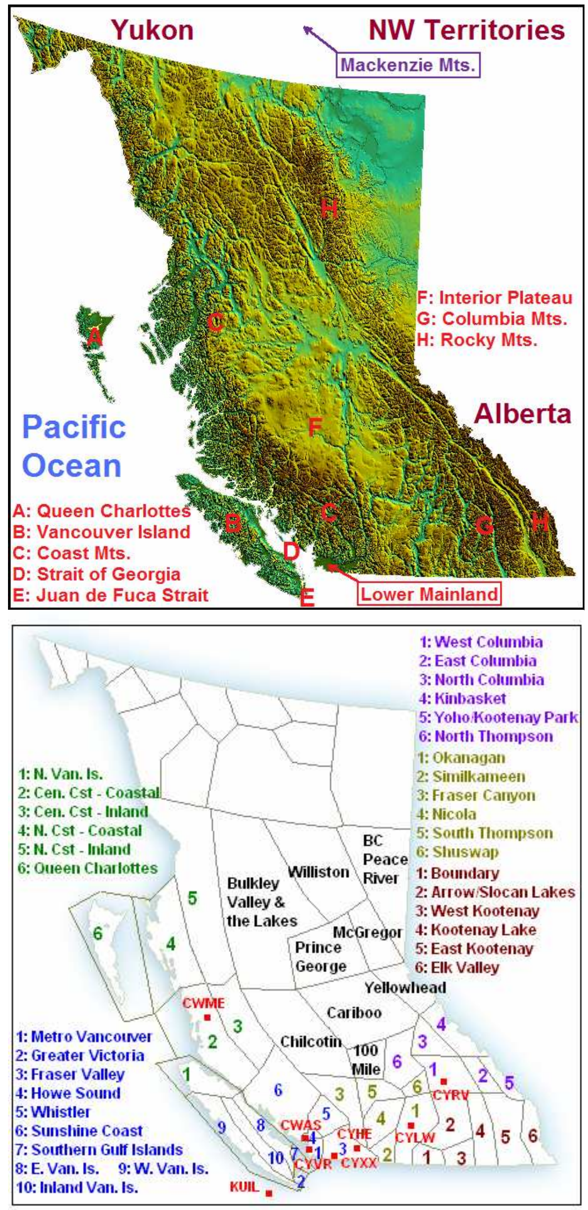

FIG. 1. Physiographic and public forecast regions of British Columbia, Canada.

On 2 December, a low pressure system began to develop rapidly in the middle of the Pacific (Fig. 5). Animation of satellite images further reveals that this low was fed by the remnants of at least one tropical depression and two named typhoons (Mitag and Hagibis). It was this low that set a powerful PE in motion, as clearly visible in the weather-satellite image shown in Fig. 2. At 1200 UTC 3 December, the center of the low was about 1500 km southwest off Vancouver Island (Fig. 5b). However, a warm front accompanying the PE had already spread moist subtropical air flows over southern BC (Fig. 2). The PE arrival forced the cold arctic airmass to retreat from the South Coast and the Southern Interior of BC, where, as expected, heavy rain and strong winds began to develop on 3 December. The low itself eventually arrived and moved onshore from the Central Coast on 4 December (Fig. 5c); its collision with the arctic airmass put an end to this dramatic period of early-winter storminess in BC (Fig. 5d).

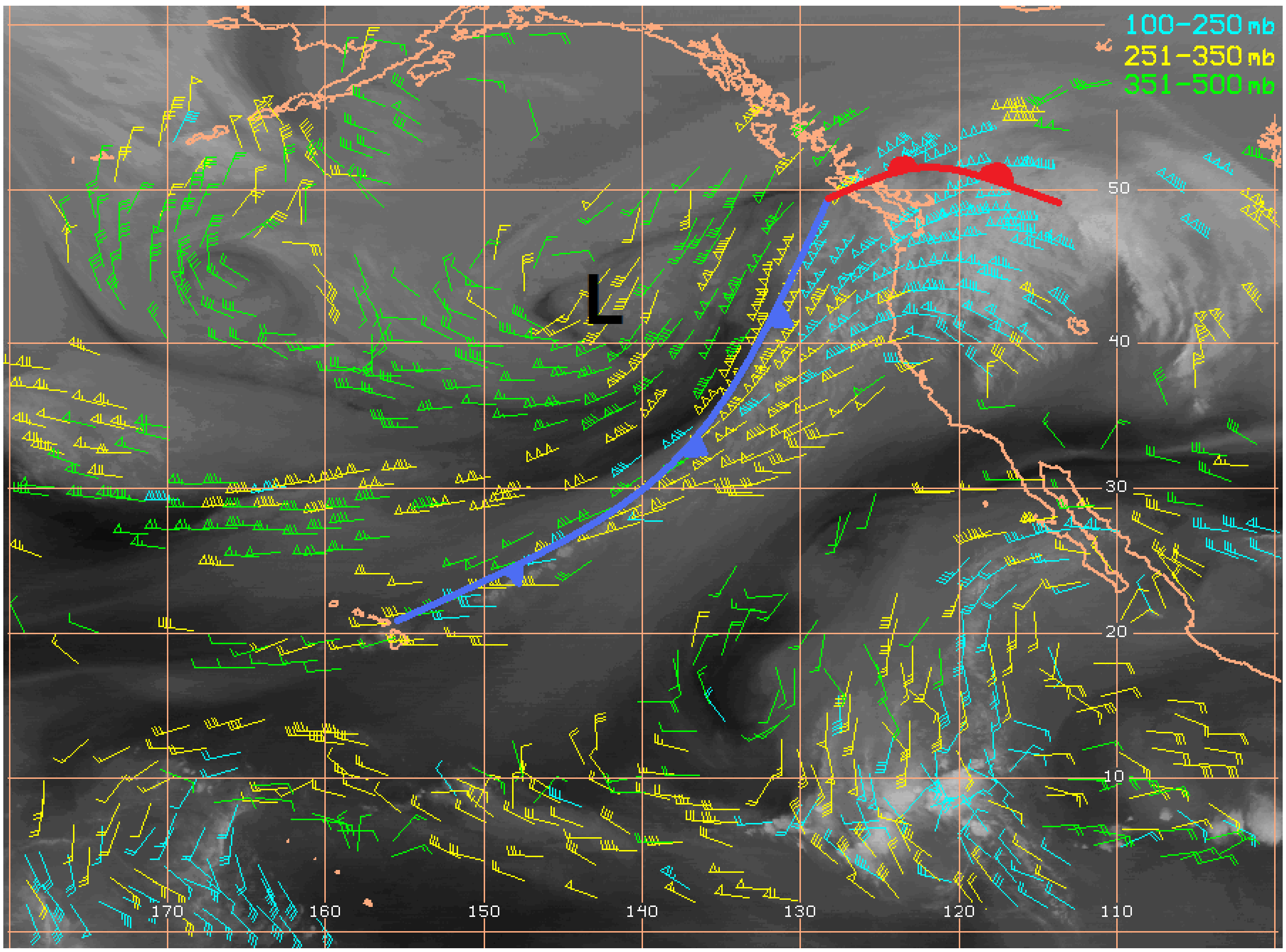

FIG. 2. The “Pineapple Express” phenomenon, illustrated by the satellite (GOES-West) water vapor image with derived winds at 1200 UTC, 3 December 2007. The black letter L marks a low center of sea level pressure. Note that Hawaii (where the *pineapple* reference comes from) is located at the southwest end of the cold front.

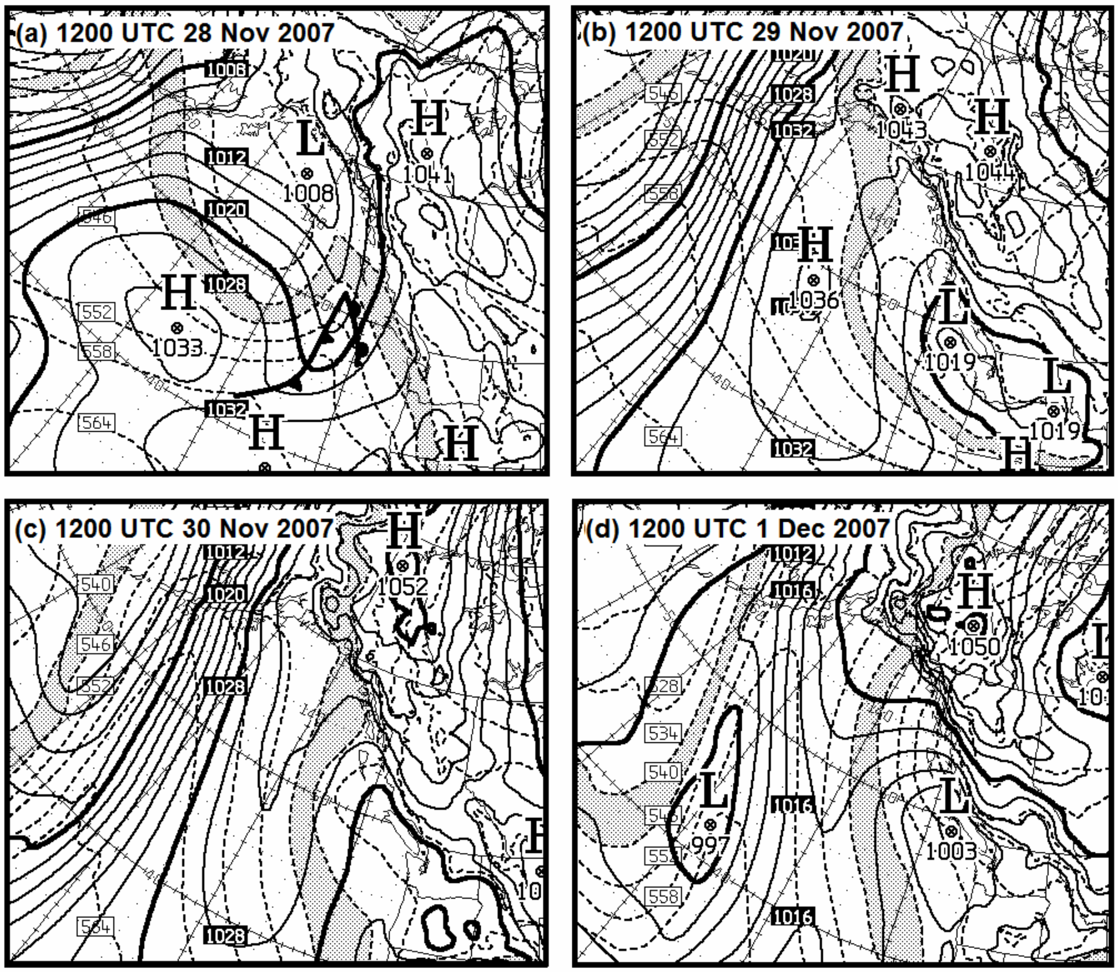

FIG. 3. The 1200 UTC mean sea level pressure (contour interval 4 hPa, solid) and 1000-500 hPa thickness (contour interval 6 dam, dashed) for the period of 28 Nov. – 1 Dec., 2007, from the GEM regional model operational analysis. The surface front drawn in (a) was kept from reaching the BC coast by the strong northeasterly outflow; it moved onshore from the Washington coast instead in the evening of 28 November.

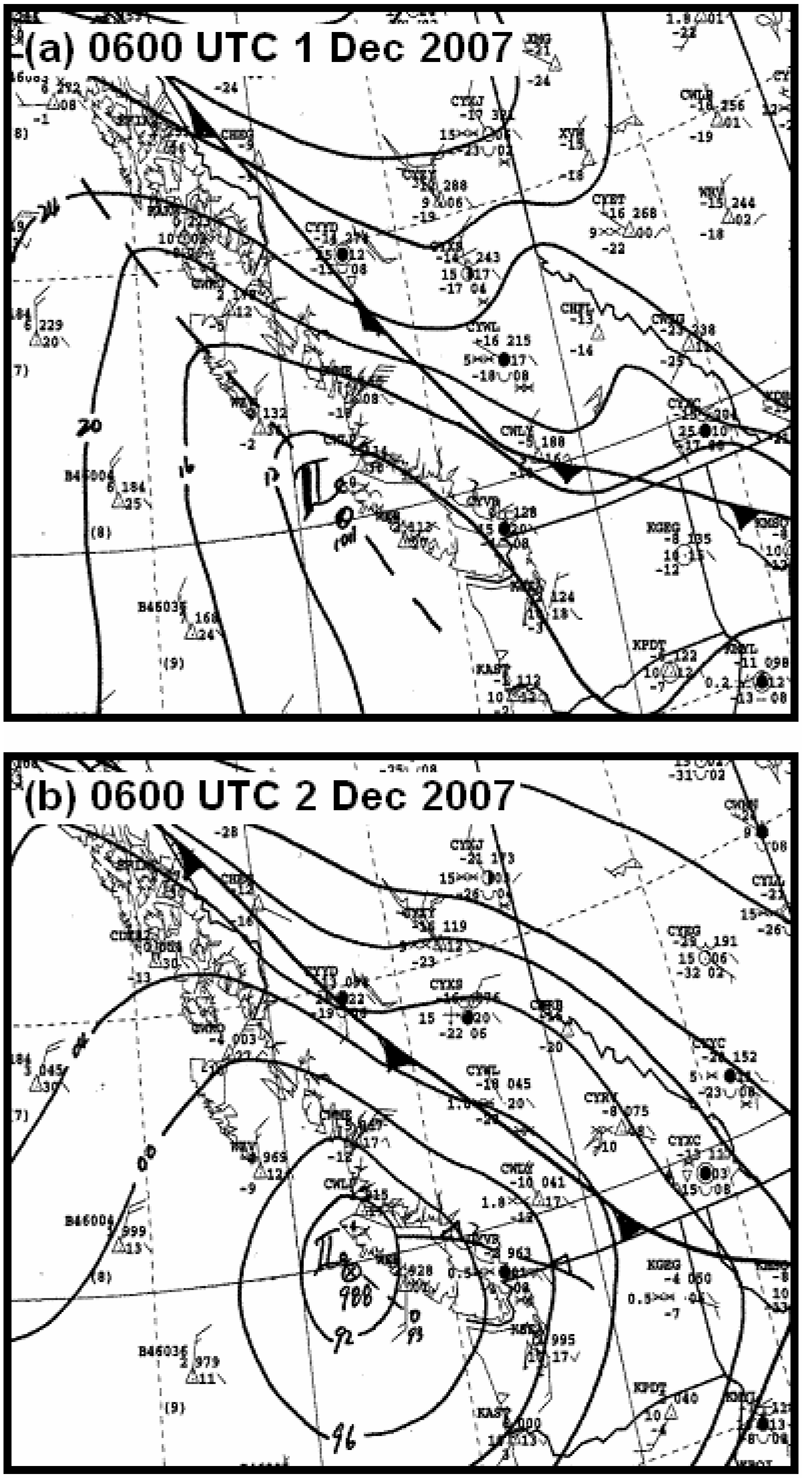

FIG. 4. PSPC surface analysis showing the rapid development of an outflow-induced lee low to the west of Vancouver Island. The central pressure of the low fell by 23 hPa during the 24-h period from 0600 UTC 1 December (1011 hPa) to 0600 UTC 2 December (988 hPa).

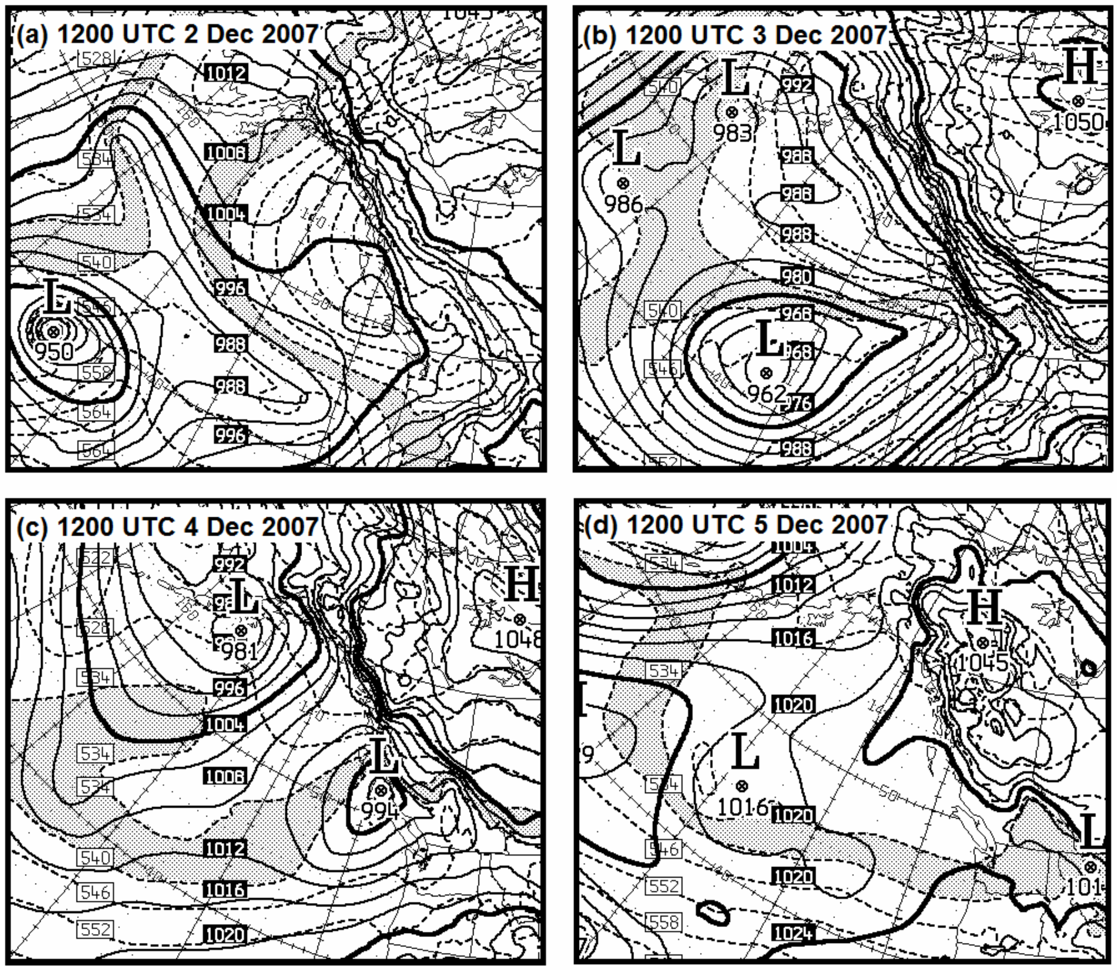

FIG. 5. The 1200 UTC mean sea level pressure (contour interval 4 hPa, solid) and 1000-500 hPa thickness (contour interval 6 dam, dashed) for the period of 2 – 5 Dec. 2007, from the GEM regional model operational analysis.

3. Observed severe weather events

Fig. 6 shows the observed severe weather events that exceeded the public weather warning criteria in BC during 1 – 5 December 2007. Cold wind chills, strong winds, heavy precipitation, and extended periods of freezing rain affected most parts of the province.

3.1 Cold wind chills and strong winds

As shown in Fig. 6a, strong arctic outflow winds combined with cold temperatures produced wind chill values lower than -20°C for a long period over the North and Central Coast. Extreme wind chill values (lower than -40°C) were observed in the BC Peace River District. Meanwhile, strong southerly winds spread across the BC South Coast with the arrival of the PE system at about 1200 UTC 3 December. Southeasterly winds were observed over most of the exposed areas of BC South Coast.

3.2 Heavy snow

The first major snowfall event occurred on 1 December. Dry outflow winds, soaking up moisture over the Strait of Georgia, deposited as much as 46 cm of snow over the east side of Vancouver Island. Meanwhile the lee low offshore helped spread snow across much of the remainder of the South Coast. On 2 December, the PE system began to spread snow across a wider swath of BC. East Vancouver Island, Howe Sound, and Whistler were hit hard, receiving between 35 and 50 cm of snow in 24 hours. Heavy snowfall was also observed in some interior regions such as Fraser Canyon, West Columbia and East Columbia.

3.3 Freezing rain

Warm air associated with the PE system moving over the arctic air entrenched in the boundary layer produced widespread and prolonged freezing rain in the southern and central sections of the province. Fig. 6c shows that Howe Sound, Whistler and Fraser Canyon received up to 50 mm of freezing rain that lasted 10 to 20 hours. Some other regions in southern BC also reported 5 to 10 mm of freezing rain lasting up to 10 hours.

3.4 Heavy rain

As the warm and moist air accompanying the PE storm pushed further inland, the arctic airmass retreated to northern BC. Most of the snow or freezing rain across southern BC changed to heavy rain. More than 100 mm of rain fell over most areas of the South Coast on 3 December . West Vancouver Island and Howe Sound reported 218 mm and 170 mm of rainfall in 24 hours, respectively.

4. Forecast guidance from the GEM models

Generally speaking, the Canadian GEM models provided reasonably good forecast guidance for this storm cycle. The GEM global model initialized at 0000 UTC 28 November forecast heavy rain over the BC South Coast on 3 December, with 116 mm at Squamish and 105 mm at Vancouver International Airport (Table 1). These exceptionally large amounts of precipitation, which continued to show up in the subsequent model runs, served as an early wake-up call (144-hour lead time) to the oncoming PE storm, and caught the forecaster's attention immediately. Snow was forecast 72 hours ahead for many regions of the South Coast. The 1 December global model run initialized at 0000 UTC 29 November (not shown), was in good agreement with the observations (Fig. 6b). The same model run also predicted 10 to 20 mm of precipitation on 2 December, and over 100 mm on December 3 for most areas of the South Coast.

Fig. 7 shows the GEM regional model forecasts (up to 48-hour lead time) of the mean sea level pressure and 1000-500 hPa thickness for 1200 UTC 3 December. As compared with the analysis shown in Fig. 5b, positions of the Pacific low and the warm front across southern BC were well forecast. The strength of the low, however, was somewhat over-forecast. Note that both the strength and position of the arctic high over northern Canada were well forecast.

Both the strength and position of the offshore low at 1200 UTC 2 December (Fig. 5a) was also well forecast by the GEM regional model (Fig. 8). However, both of the arctic high over northern Canada and the outflow-induced lee low along the BC coast were over-forecast; the deeper lee low in the model brought in stronger southerly winds to the Inner South Coast and the Lower Mainland, as shown in Fig. 9. The stronger warm advection resulted in misleading forecast guidance for the area. For example, the guidance for Metro Vancouver, based on the model run initialized at 1200 UTC of Saturday 1 December (Fig. 8c), was given as follows:

*"…**Tonight**..Snow changing to rain near midnight. Snowfall amount 5 cm. Becoming windy. Low zero with temperature rising to 6 by morning. **Sunday**..Rain. Temperature steady near 5."*

As it turned out, the warm advection brought in by the lee low was much weaker. Temperatures observed at Vancouver Airport were steady near -2°C through Saturday night and the maximum temperature on the following day was only 2.4°C. Snow in Metro Vancouver did not change to rain until Sunday evening when stronger warm advection from the PE system arrived.

Our verification reveals that the GEM regional model failed to forecast all but one of the 14 freezing rain events in BC during 1 – 5 December 2007. This poor performance is due to the poor model resolution that cannot resolve the complex terrain in BC (i.e., the model topography is much smoother than the reality, with shallower valleys and lower mountains). This leads to the cold air at low levels being "scoured out" too quickly by the warm advection in the model.

Model performance for rain and snow events was generally better. The GEM regional model correctly forecast 63% of the snowfall warning events and 60% of the rainfall warning events during 1 – 5 December 2007. Still, the model did struggle in certain areas. Virtually all precipitation warning events over East Vancouver Island and the eastern sides of the Coast and Columbia Mountains were missed by the model. Meanwhile, the model over-forecast the precipitation amounts on the windward (western) sides of the mountains. Again, the lack of resolution in the model topography is believed to have contributed to these errors in orographic precipitation.

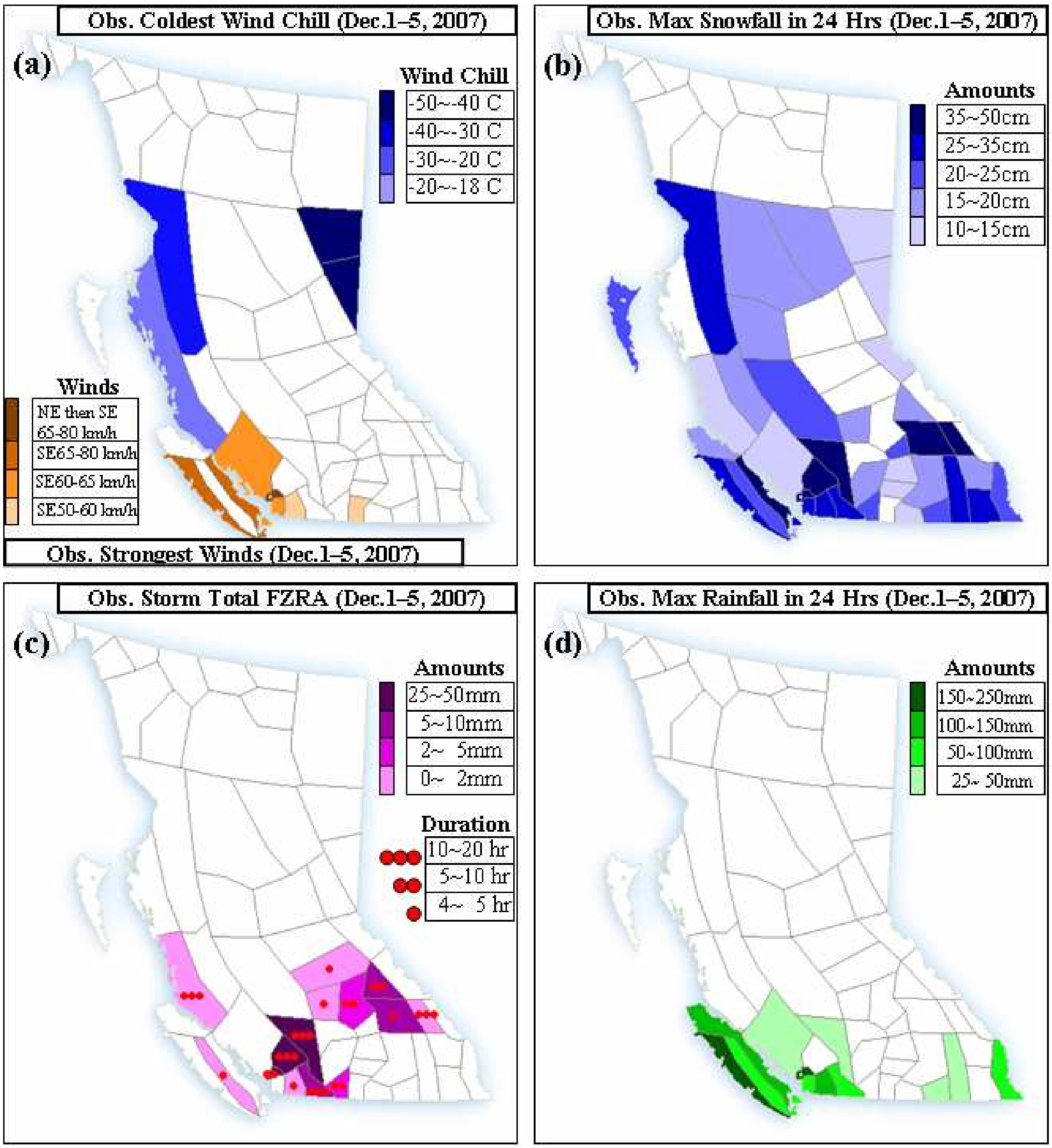

FIG. 6. The observed severe weather events that exceeded public weather forecast warning criteria during 1 – 5 December 2007 over British Columbia. (a) Coldest wind chills and strongest winds, (b) maximum snowfall in 24 hours, (c) storm total freezing rain, and (d) maximum rainfall in 24 hours.

Table 1: 24-h precipitation amounts (00Z-00Z water equivalent in mm) for selected cities on 3 December 2007, forecast by the GEM global model 0000 UTC runs of 28-30 November 2007 and observed on 3 December 2007.

	Port Alberni	Victoria	Vancouver	Squamish	Abbotsford	Hope
00Z 28th	114	57	105	116	96	56
00Z 29th	109	72	141	175	135	110
00Z 30th	72	57	102	121	117	98
Observed	95	81	54	119	43	69

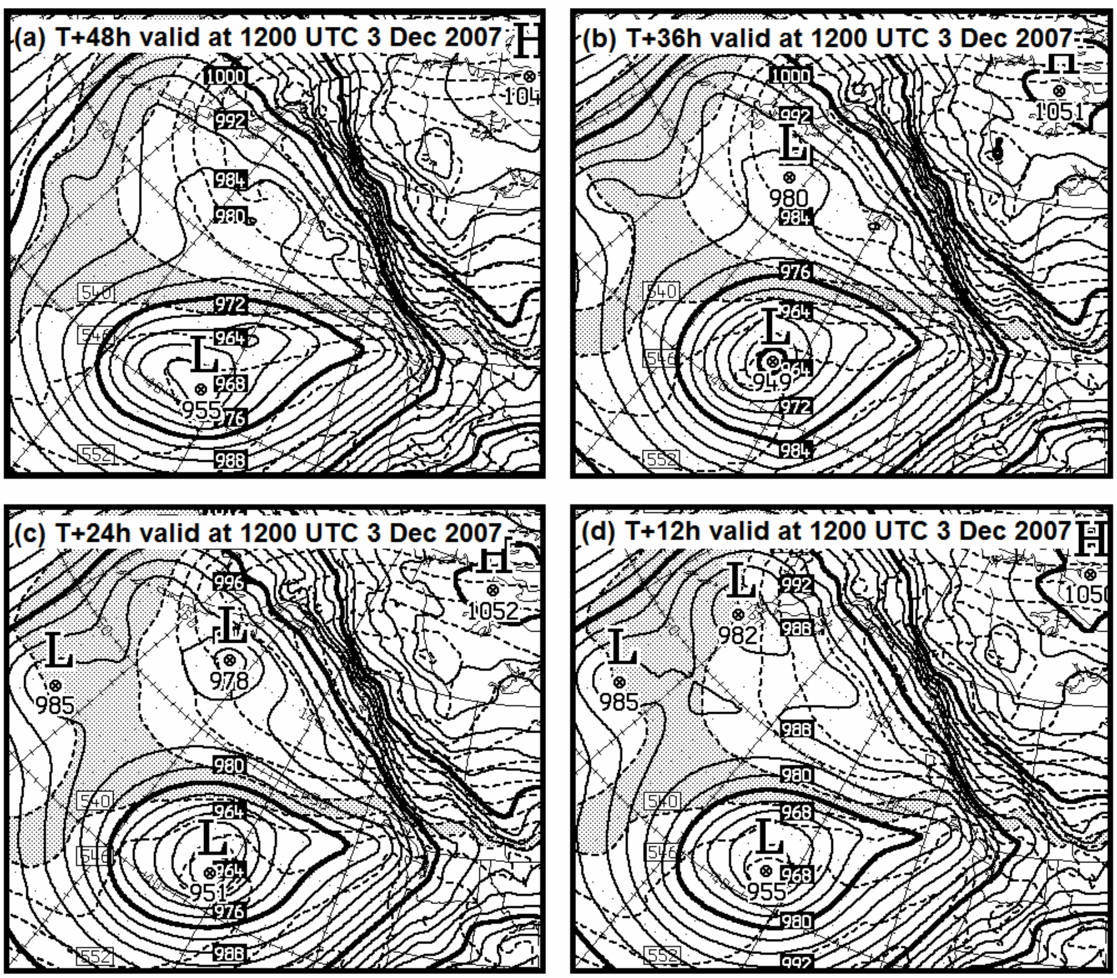

FIG. 7. Mean sea level pressure (contour interval 4 hPa, solid) and 1000-500 hPa thickness (contour interval 6 dam, dashed), valid at 1200 UTC of 3 December 2007, forecast by the GEM regional model. Fig. 5b is the corresponding analysis chart.

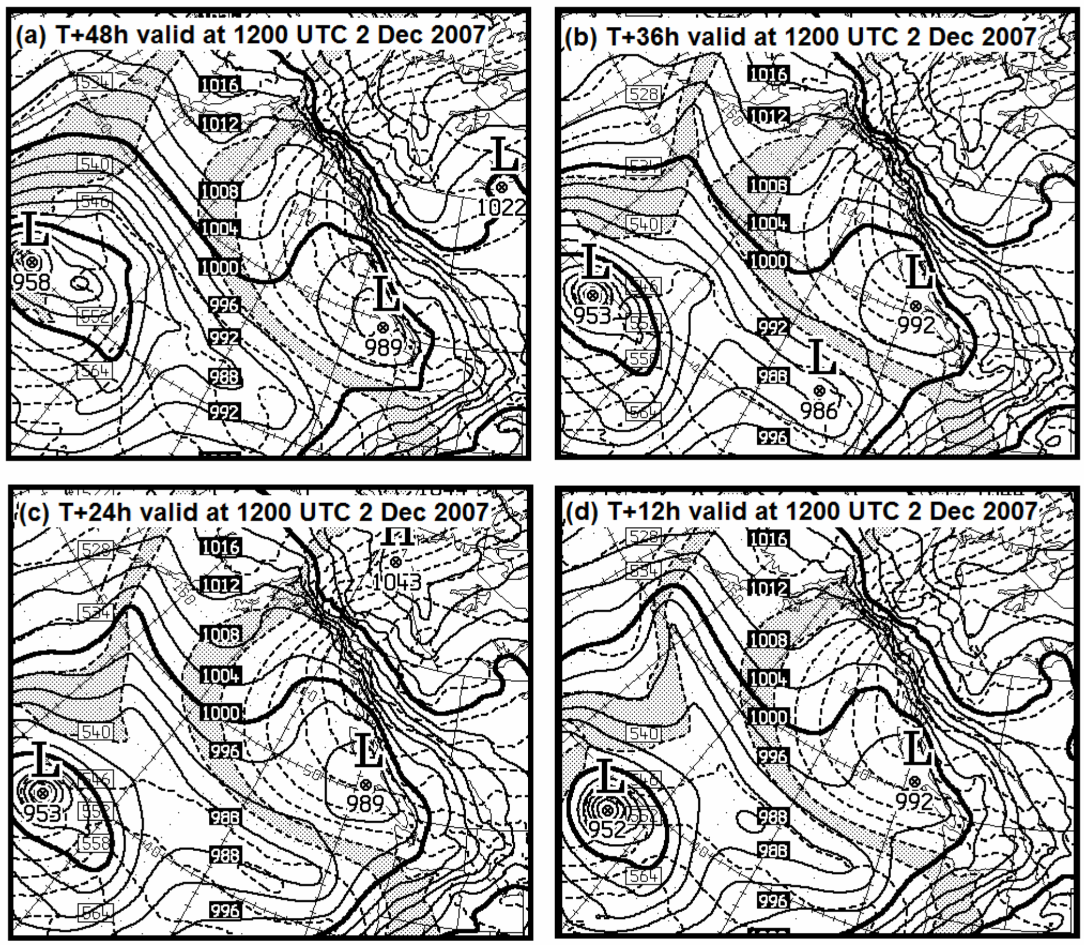

FIG. 8. Same as Fig. 7, except valid at 1200 UTC of 2 December 2007. Fig. 5a is the corresponding analysis chart.

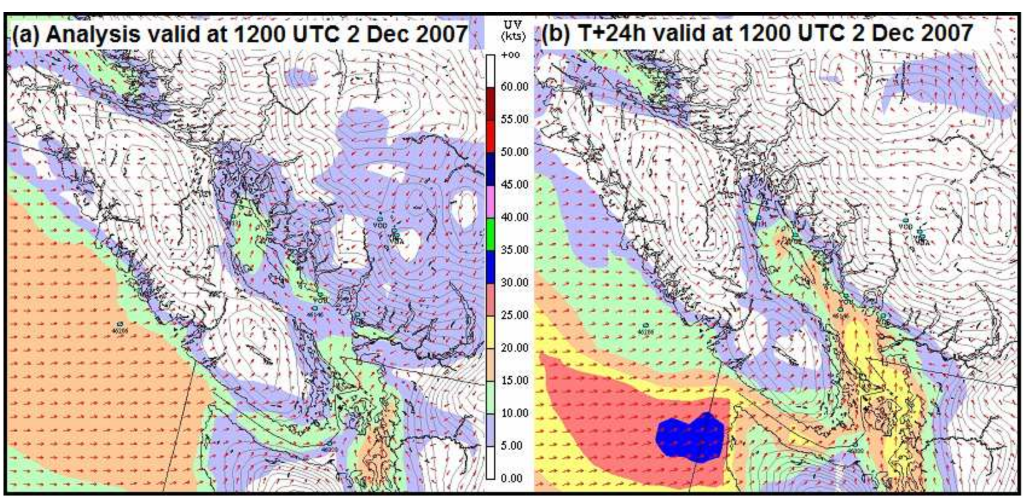

FIG. 9. Analysis (left panel) and forecast (right panel) surface winds over the BC South Coast at 1200 UTC of 2 December 2007. The thin lines are elevation contours. Fig. 8c shows the corresponding forecast mean sea level pressure.

5. Forecasts by PSPC

Through the period of 1 – 5 December 2007, PSPC meteorologists issued a total of 79 severe weather warnings across BC. The critical success index for all warning events for this storm cycle is 0.68 (see Table 2), which can be considered as a very successful skill score. Specifically, all the wind chill events over the BC Peace River region and the North and Central Coast were successfully forecast. PSPC achieved a POD (probability of detection) of 0.77 for the snowfall warning events across the province, as compared with the model POD of 0.63. Out of the 14 freezing rain events, PSPC successfully forecast 7, and the model picked up only one of them. The PSPC forecast also achieved a higher score than the model forecast for the heavy rainfall events, with a POD of 0.8 as compared to the model POD of 0.6.

6. Concluding remarks

A strong arctic outbreak at the end of November 2007 and its collision with a warm, moist subtropical southwesterly flow produced a large number of high impact weather events across BC during the period of 1 – 5 December. Given the complex terrain of the province, this great storm posed significant forecast challenges for both numerical models and operational meteorologists.

Generally speaking, the Canadian GEM models provided reasonable forecast guidance for this storm. In particular, the arrival of the warm Pacific moisture conveyor (Pineapple Express) with heavy precipitation across southern BC on 3 December was forecast by the GEM global model with a 6-day lead time. However, the models have some difficulty dealing with the complex terrain of BC. It is noticed that the outflow-induced lee low along coastal BC on 2 December (Fig. 5a) was over-forecast by the GEM regional model (Fig. 8). This deeper low in the model produced stronger warm advection across southern BC. As a result, the model provided misleading guidance calling for snow changing to rain for some coastal areas on 2 December. The reason for this model error is not clear. It could be related to the occasional over-forecast of the arctic ridge over northern Canada by the GEM models.

It was further pointed out that the model forecast for BC has always been too warm in situations where there is warm advection. We believe the root of the problem is the model's handling of the topography. The actual mountains in BC are quite steep with deep narrow valleys that cannot be resolved at 15 km of the GEM regional model resolution. The model topography, therefore, is smoother than the real one, leading to the cold air at low levels being scoured out too quickly in the model. Cold air in the real world has more staying power than the model indicates. This has several consequences: (1) the inland sea level pressures fall too quickly in the model because cold air in the valleys is not resolved, leading to weaker northeasterly outflow winds or stronger southwesterly inflow winds; (2) warmer surface temperatures are forecast; (3) snow changes to rain too quickly, leaving little room for freezing rain to develop; (4) snow is under-forecast and rain is over-forecast in the valleys.

TABLE 2. Weather warning verifications for the period of 1-5 December 2007.

	Events		Scores
Number of Hits	58	Probability of Detection	0.73
Number Missed	22	False Alarm Ratio	0.08
Number of False Alarms	5	Frequency of Hits	0.92
Number Unverifiable	16	Bias	0.79
Total	101	Critical Success Index	0.68

It was noticed that precipitation was under-forecast on the leeward sides and over-forecast on the windward sides of the mountains by the GEM regional model. A possible explanation for such precipitation bias is that the smoother topography in the model encourages more air to flow over as opposed to around the mountains. On the windward side, stronger upward air motion and weaker low-level horizontal divergence lead to heavier precipitation, and the opposite applies to the leeward side. Another possibility is that the model underestimates the 'spillover' of precipitation to the lee sides of the mountains. Browning *et al.* (1975) pointed out that the spillover precipitation depends mainly on the contribution of mid-level convection. This is because orographically induced enhancement mid-level convection gives rise to precipitation of fairly high intensity which, owing to its high level of origin and slow fall-speed above the melting level, is carried over the mountain tops by the strong winds. The smoother topography in the model results in weaker mid-level convection and, therefore, less lee-side spillover precipitation.

Acknowledgments.
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References

Browning, K. A., C. W. Pardoe, and F. F. Hill, 1975: The nature of orographic rain at wintertime cold fronts. *Quart. J. Roy. Meteor. Soc.*, **101**, 333-352.

Hacker, J. P., E. S. Krayenhoff, and R. B. Stull, 2003: Ensemble experiments on numerical weather prediction error and uncertainty for a North Pacific forecast failure. *Wea. Forecasting*, **18**, 12-31.

Heidorn, K.C., 2004: *The BC Weather Book: From the Sunshine Coast to Storm Mountain*, Fifth House Ltd, 300 pp.

Jackson, P. L. and D. G. Steyn, 1994: Gap winds in a fjord. Part I: Observations and numerical simulation. *Mon. Wea. Rev.*, **122**, 2645-2665.

Johnson, K. and J. Mullock, 1996: *Aviation Weather Hazards of British Columbia and the Yukon*. Environment Canada, 136 pp.

Lackmann, G.M. and J.R. Gyakum, 1999: Heavy cold-season precipitation in the northwestern United States: Synoptic climatology and an analysis of the flood of 17–18 January 1986. *Wea. Forecasting*, **14**, 687–700.

Loukas, A. and M. C. Quick, 1996: Spatial and temporal distribution of storm precipitation in southwestern British Columbia. *J. Hydrol*., **174**, 37-56.

Lyons, C. J., 1901: The storms of the Hawaiian Islands. *Mon. Wea. Rev*., **29**, 68-68.

Mass, C., 2008: *The Weather of the Pacific Northwest*. University of Washington Press, 180 pp.