10.5

An Investigation into a Squall Line over Complex Terrain

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1. Introduction

The British Columbia (BC) Interior is characterized by numerous mountain ranges. Organized thunderstorms such as squall lines tend to be infrequent in areas of complex terrain found in BC. Although lines of convection are often observed during the convective season when linear forcing mechanisms exist, it is quite rare that these lines further develop into organized squall lines producing severe weather. Only four squall lines over the BC Interior have been reported since 2000. On 10 July 2008, a line of convection was initiated over the Central Interior and further evolved into an organized squall line in the morning. When the storm crossed the Southern Interior early in the afternoon, widespread tree damage and power outages were reported over southern BC. However, the most severe property damage and downed trees occurred over the populated Okanagan Valley. Boats on a number of the larger lakes in the valley were overturned with extensive damage at the Kelowna Marina. Record winds at Penticton Airport to 109 km/h were observed breaking the old July gust of 97 km/h set on July 12, 1958. Lundquist and Dudley (2008) conducted a damage survey for the storm. Charbonneau and Kohanyi (2008) did a case study for the storm mainly focusing on the forecast aspects.

With good detection coverage of Silver Star radar and a relatively dense surface observation network over the Southern Interior, this case offers a unique opportunity to study the structure and evolution of a squall line and the possible terrain effects on the squall line as well as the associated surface winds. Very little has been documented on these types of storms in BC. It is expected that this study will provide a good guidance for understanding the meteorology behind the storm and therefore improving forecast skills for a similar weather system.

In this paper, we begin with a quick review of the squall line and a brief introduction of the topography along the storm track. Then a pre-squall environment is analysed. This is followed by a description of the lifecycle of the squall line and a discussion for possible terrain effects on some unique structural and evolutional features observed during the storm lifecycle. We then investigate the surface characteristics accompanying the squall line in detail with focusing on the strong cold pool and damaging wind gusts over the populated Okanagan Valley. Finally, a summary of the case is presented.

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2. Storm tracks and terrain characteristics

Figure 1 (left panel) shows the evolution tracks of the squall line. The red solid lines are the leading edge of the squall line derived from both satellite imagery and radar echoes. At the early stage, the leading edge was determined by using visible satellite images as the lines were on the detection edges of both Silver Star (XSS) and Prince George (XPG) radars. When the lines moved southward towards XSS, the leading edge was represented by the 20-dBZ contour line, same as the method used by Teng and Chen (2000). The convective line was initiated as a straight line over the relatively flat Cariboo Plateau and then moved into the mountainous Southern Interior region early in the afternoon at an average speed of 55 km/h. Its shape changed to a convex curved line when it entered into the Southern Interior.

The Southern Interior is part of Pacific Cordillera with complex topography. The Coast Mountains lie to the west and the Columbia Mountains to the east. Both mountain ranges have average elevation of about 1600 metres and contain many peaks higher than 2000 metres. Between the two ranges, the Cariboo Plateau lies to the north and the Okanagan-Thompson Plateau to the south. The terrain is relatively flat over the Cariboo Plateau with a typical elevation of about 900 metres above see level. However, the Okanagan-Thompson Plateau to the south has the most complex terrain in the province. Its typical elevation is about 1200 metres, but the plateau embraces many mountain peaks that reach above 1500 metres. It also contains many deep valleys with the Fraser Canyon in the west, Thompson Valley in the north, Okanagan Valley in the east and Nicola Valley at the middle. These valleys have their bottoms of only a few hundred metres above the sea level. Among the valleys and mountain peaks, there are many steep slopes imposing local effects on weather system.

The Okanagan Valley (Fig. 1, right panel), where the record-breaking wind was observed and most property damage incurred, is just east of the Thompson Plateau. This is one of the narrowest, deepest and longest valleys in BC Interior. The north-south oriented valley is approximately 150 km long from Amstrong in the north to Osoyoos in the south. At the valley bottom, the Okanagan Lake, with average width of approximately 3 km, spreads from Vernon to Penticton. The elevation differences from the lake surface to the surrounding mountains are greater than 1000 metres at many locations. This valley imposes local effects on the passing weather systems and channelling effect is a typical one.

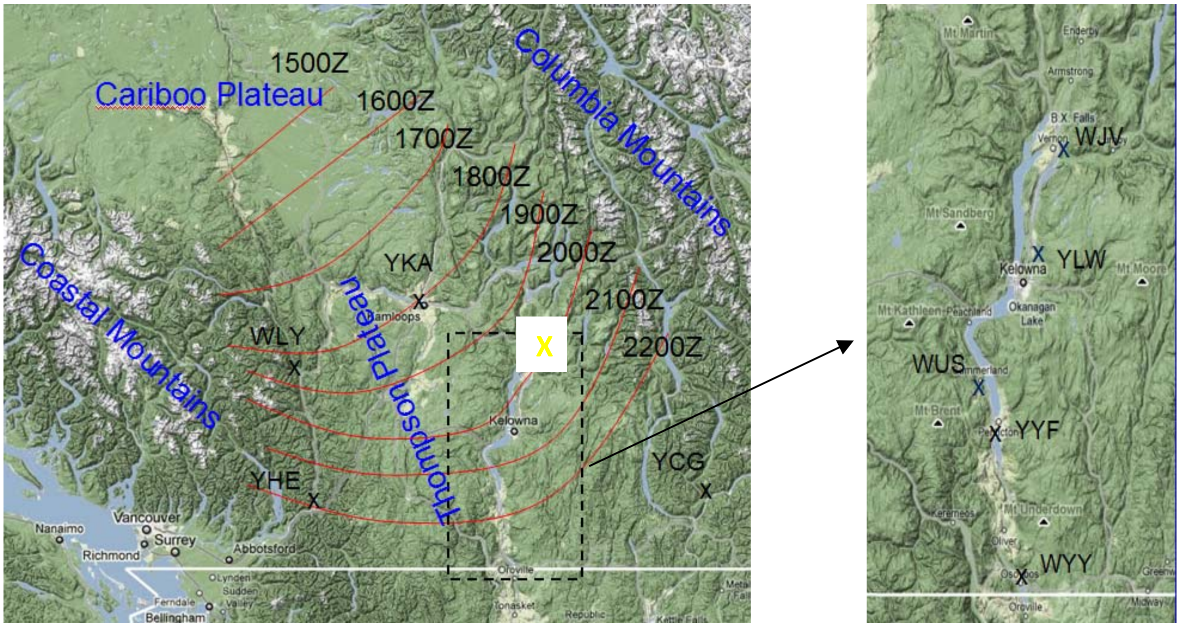

Figure 1 Evolution tracks of the squall line and the complex terrain. Red solid lines represent the leading edge of the squall line at each hour. Black “X”s are the surface stations with station ID and yellow “X” is the location of Silver Star Radar.

3. Pre-storm environment

The CMC 500 hPa height and thickness analysis at 1200 UTC of 10 July 2008 (Fig. 2, left panel) indicates a positively tilted upper trough over northern BC. Strong westerly winds at 500 hPa reached 65 knots both at Port Hardy and Quillayute and 50 knots at Spokane., This synoptic pattern of strong upper level westerlies is one of four weather patterns conducive for severe thunderstorms over the BC Interior identified by Goosen (2010). Under this pattern, since strong dynamics play a key role, supercells or squall lines (if linear forcing exists) with potentials for severe weather could develop even normalized CAPE is as low as 500 J/kg. Note that unseasonable cold air advection (CAA) ahead of the trough over the southern part of the province was present. Pacific Storm Prediction Centre (PSPC) surface analysis at 0600 UTC of 10 July (not shown) clearly marked a surface cold front over the Central Interior with southwest to northeast orientation. IR satellite imagery confirmed the appearance of the front and the animation shows that the front moved slowly southward early in the morning. It was this cold front that provided a linear forcing mechanism to initiate a squall line over the relatively flat terrain of the Central Interior.

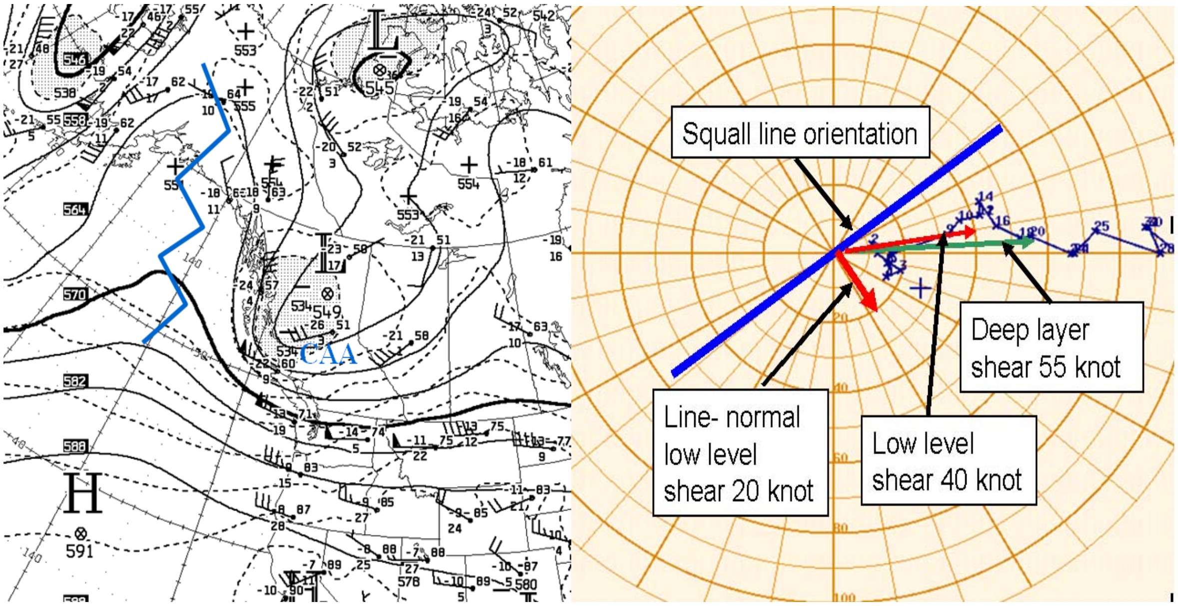

Figure 2: CMC 500 hPa thickness analysis (left) and Spokane Hodograph (right) at 1200 UTC of 10 July

Because no rawinsonde data was available from Kelowna, data from Spokane was examined for this period. The Spokane hodograph at 1200 UTC of 10 July (Fig. 2, right panel) shows a strong deep shear (1-5 km) of 55 knots and a low-level shear (1-3 km) about 40 knots with shear direction pointing to the east. This shear environment is favourable for supercells or multiple cells to develop if other conditions are met. Although the ambient low-level shear was 40 knots, the line-normal low-level shear was about 20 knots if considering the orientation of the squall line. Hence, the magnitude of low-level shear was within the weak to moderate category of shear strength (MCS: Squall lines and Bow echoes from http://www.meted.ucar.edu/topics_convective.php)

The Spokane tephigram at 0000 UTC 10 of July (Fig. 3, left panel) clearly indicates the dry nature of the airmass at the entire layer of the troposphere. The tephigram shows a very high mixing layer and level of free convection (LFC). Model-derived sounding from Penticton (not shown) predicted a mixing layer of 3-km and LFC reaching 4-km AGL. A surface dew point analysis at 1800 UTC (Fig 3, right panel) identifies a large dry area just ahead of the approaching squall line over the Thompson Plateau and Okanagan Valley with dew points as low as 0° C. With temperatures in the mid twenties, these dew points gave a relative humidity of only around 20% and a mixing ratio as low as 3 g/kg. Notice that there are two wet noses on the BC South Coast in the southwest and the Columbias in the northeast. Due to the dryness, little or no CAPE was seen from the Spokane sounding and Penticton forecast sounding. CMC severe weather outlook (not shown) also predicted a day of low buoyant energy for the entire interior with maximum CAPE of only 600 J/kg near Prince George in the Central Interior and less than 500 J/kg over the Southern Interior.

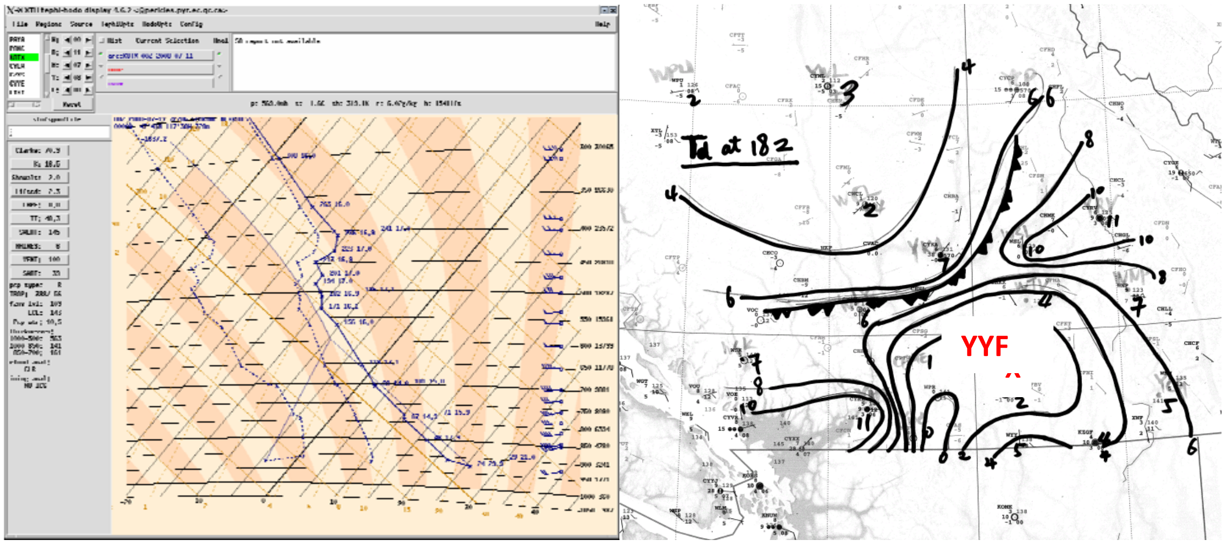

Figure 3 Spokane sounding at 0000 UTC of 11 July (left) and surface dew point analysis at 1800 UTC (right)

In summary, the squall line evolved in an environment with moderate wind shear and weak buoyant energy. The pre-squall atmosphere was dry in the entire layer from its boundary to the top of the tropopause. The PSPC in Vancouver did not expect thunderstorms for the Southwest Interior in its morning convective analysis since the conditions there were typically not favourable for convection.

4. The evolution of the squall line

The cold front over the Central Interior moved southward and weakened early in the morning. However, around 1500 UTC a short line of convection first appeared on satellite visible imagery just ahead of the cold front. This line intensified and the first lightning strike was reported at approximately 1600 UTC. Obviously, this was the initiation of the squall line triggered by the linear forcing from the cold front over the relatively flat Cariboo Plateau. The southwest-northeast oriented squall line then moved southeastward at an average speed of 55 km/h experiencing an approximately 7-hour lifespan.

The following paragraphs describe the lifecycle of the squall line.

4.1 Early stage (1600-1800UTC)

In the early stage, a short and straight line of convection with its orientation from southwest to northeast appeared on satellite imagery. When the line moved southward, it extended in length at its both sides with the west end reaching the Coast Mountains and the east end touching the Columbia Mountains. The shape of the line changed from straight to curved when the line entered into the Southern Interior. This phenomenon will be further discussed in the following section. Satellite visible imagery showed that two additional new lines were triggered ahead of the old lines and eventually replaced the old lines. During the early stage, radar echoes appeared to be unorganized and lightning was only isolated. As the convection continued to develop, lightning strikes increased and radar echoes became more organized. At 1800 UTC, a line of stronger echoes first appeared at the leading edge of the system (Fig. 4, left) along with the organized lightning (Fig. 4, right) suggesting that the squall line entered its mature stage.

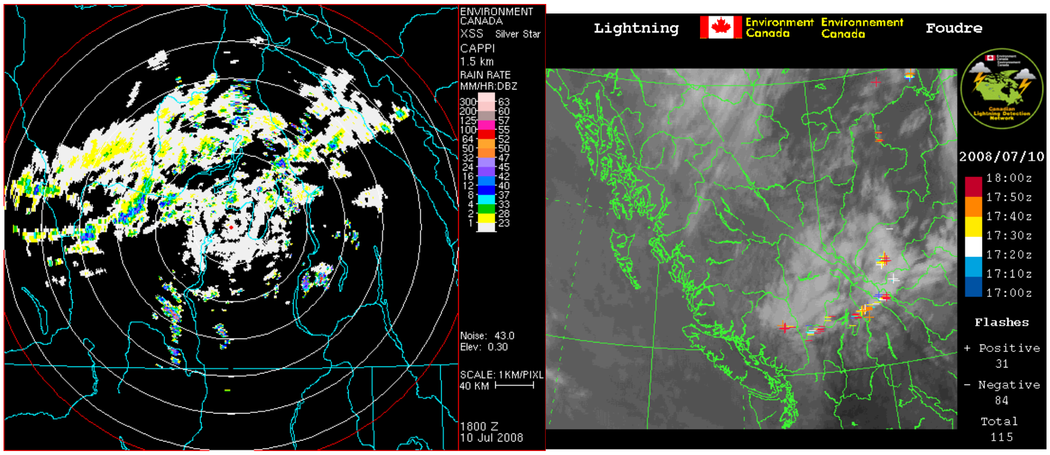

Figure 4 Radar echoes and lightning strikes at 1800 UTC

4.2 Mature stage (1800Z-2000Z)

At this stage, satellite visible imagery (Fig. 5, left panel) shows the squall line with a curved, well-defined leading edge separating the cold moist air mass in the north from the dry warm air mass in the south. Radar echoes (Fig. 5, central panel) represent a typical squall line structure consisting of a convective region at its leading edge and a stratiform region to its rear. Gust algorithm (Fig. 5, right panel) was triggered a few times during the mature stage. This algorithm looks for a divergent signature above a certain threshold along a line more than a certain length. Therefore, if this algorithm was triggered, a gust front with strong winds would be likely. However, the radar echoes were generally weak during the mature stage since the maximum reflectivity was only 50 dBZ and the echo tops were lower than 8 km. Only one new weak convective line was observed to form at this stage.

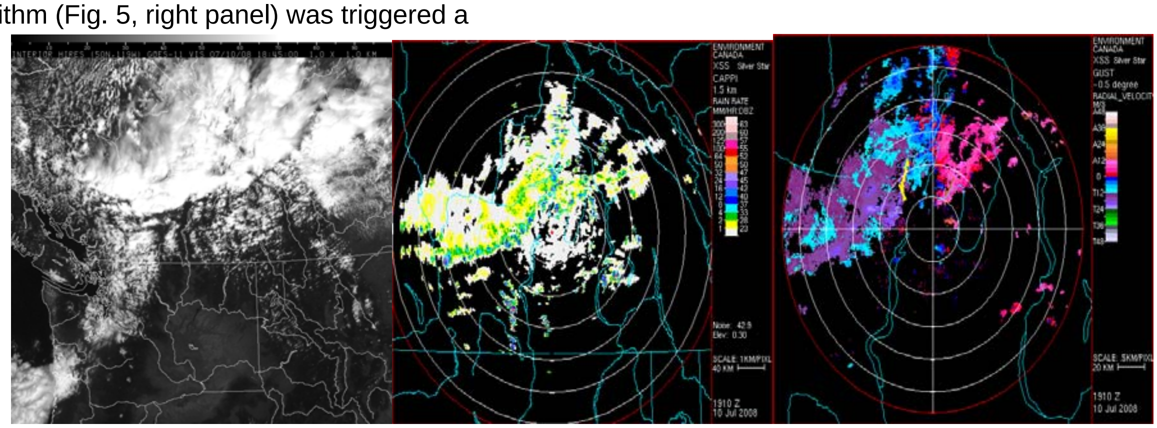

Figure 5, Satellite visible image and radar echoes during the mature stage

4.3 Dissipating stage (2000-2300 UTC)

The dissipating stage started at around 2000 UTC when the central portion of the squall line moved just over the northern sections of the Okanagan Valley. Along with weakening radar reflectivity and reducing lightning strikes, a unique feature at this stage was that the squall line broke into two parts with the narrow, deep Okanagan Valley as a divider. A gap parallel to the valley was visible on the satellite visible imagery (not shown) and radar products confirm the breakdown of the line (Fig. 6, left panel).

Lightning strikes (Fig. 6, right panel) during this stage were reported mainly at both ends of the line. The dissipating stage went though quickly, lasting less than three hours. After the dissipation of the squall line, another line of convection developed in the Kootenay area producing local damaging winds. Considering the time interval and the horizontal distance, the latter line of convection was categorized as a separate system.

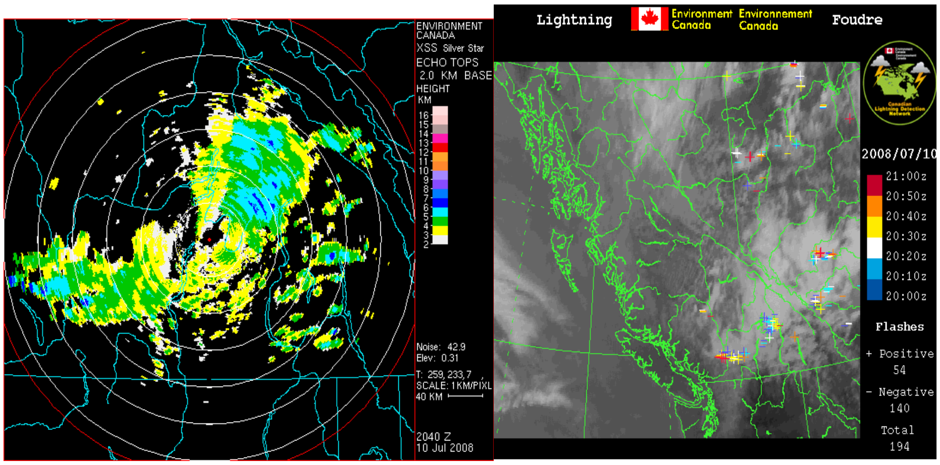

Figure 6 Radar echoes and lightning strikes in the dissipating srage

4.4 Discussion

As described in the previous section, the squall line experienced a 2-hour early stage, 2-hour mature stage and 3-hour dissipating stage totalling a 7-hour lifespan. However, a typical squall line under moderate shear category identified in COMET module (MCS: Squall lines and Bow echoes) has a 2-hour early stage, up to 6 hour mature stage and 8 hour dissipating stage with maximum 16 hour lifespan. A squall line under strong shear environment has even longer longevity. While a time span of 2 hours in early stage of the present case is same as that identified in COMET module, the mature and dissipating stages of this case are significantly shorter. What are the meteorological reasons leading to the short longevity of the storm? Did the complex terrain have strong impacts on the storm evolution?

Rotunno et al. (1988) revealed that low-level ambient wind shear interacting with a surface cold pool plays an important role on the maintenance of strong, long-lived squall line. At the leading edge of squall line, new cells form due to the low-level convergence of moist environment air and cooler descending mid-level air. Part of the descending air moves forward, colliding with the advancing warm, moist environmental air in the boundary layer. This mechanism generates a new convective line to replace the old line, hence maintains a long-lived storm. However, this mechanism may not work well over the complex terrain. Teng and Chen (2000) found that when a squall line encounters a mountain, the low-level cold pool behind the leading edge is unlikely to move upslope and the mountain range cuts off the moisture supply as it blocks the incoming front-to-rear storm related flows. In the Southern Interior of BC, the deep valleys and steep mountain slopes as described in Section 2 would block the forward-spreading cold air and cut off the incoming warm moist air. These terrain effects on the storm in turn restrict new convective cells to form, and limits lifespan of the squall line.

The dry boundary layer in the Southern Interior is another reason for inhibiting new cells from developing. In Section 3, we described the pre-squall environment as very dry with high LFC of about 4 km. Under such a situation, the front-to-rear storm related incoming flow is dry and needs stronger lift in order to reach its high LFC. However, since the mechanism of shear and cold pool interaction does not work well over the complex terrain, it is less likely to provide those strong lift when the storm moved to the mountainous Southern Interior. If a new cell does develop, it is expected to be weak due to its high base. As mentioned in the previous section, there were three new convective lines that developed in the early stage over the Central Interior but only one weak new line observed in the mature stage over the Southern Interior. This indicates that the complex terrain together with the dry pre-squall environment prohibited the ability of the system to generate new cells and led to a short mature stage.

Previously we mentioned that the shape of the squall line changed from a straight line to a convex curve when it moved southward. This was due to mountain blocking. The Coast Mountains in the west and the Columbia Mountains in the east (Fig. 1) served as barriers to slow down the movement of the squall line at both sides. However, the central section of the line moved faster due to relative lower elevation of the Thompson Plateau. This is similar to an orographic effect case investigated by Teng et al. (2000). In their case, when an eastward-propagating, north-south oriented squall line over the Taiwan Strait entered into the complex mountainous areas of the island, the leading edge moved slower in the mountain ridge areas and faster over the valleys. As a result, the squall line orientation became approximately parallel to the terrain contours.

The uneven propagation speed associated with the present squall line due to mountain blocking imposed a stretch to the central part of the storm. An animation of satellite visible imagery (not shown) indicates the central part of the line getting thinner during the dissipating stage suggesting the possible stretching. When the line moved across the Okanagan Valley, the strong down slope winds could serve as a trigger to split the line into two parts (Fig. 6). The surface dry area ahead of the central portion of the line (Fig 3, right panel) probably provided a favourable environment for the split as well. There is little doubt that the split accelerated the decaying of the squall line and led to a significantly shorter dissipating stage.

5. The cold pool

It is well known that negatively buoyant air parcels, which descend from convective storms and propagate horizontally, have been studied for many years since they are associated with damaging winds and have the capacity to trigger new cells. Investigating the characteristics of the cold pool is important to understand the mechanisms behind thunderstorms and hence assist making warning decisions. The strength of a cold pool can be measured through a variety of parameters, like the depth of cold pool, air density, temperature, propagation speed and so on. However, surface pressure and temperature changes after squall line passage are also good indicators of the strength of cold pool, as these characteristics link to surface damaging winds.

The maximum 1-hour temperature drops and pressure rises at the Southern Interior stations after the passage of the squall line gust front were presented in Figure 7 up left panel. The average 1-hour temperature drops of these stations was 7° C with greatest drop of 9° C occurred at Kelowna Airport (YLW) in the Central Okanagan. Meanwhile, the 1-hour pressure rises were in a range from 2.2 to 5.9 hPa with an average rise of 4.7 hPa. The upper right panel in Figure 7 shows actual pressure tendency analysis at 2200UTC. In the chart, the blue dash lines represent pressure rise contours and red dash lines represent the pressure fall contours. The diagram shows a pressure rising centre with a local maxima of more than 5.2 hPa per hour behind the leading edge of the squall line just west of the Okanagan Valley. These data are indicative of a strong cold pool associated with the squall line.

The lower left panel in Figure 7 shows the surface 3-hour temperature and pressure changes. This period represents the dominant portion of these changes associated with the squall line cold pool since temperatures started to rise and pressure increase slowed down significantly 3 hours after gust front passed at most stations in the case. Therefore, these 3-hour changes may better represent the strength and depth of the cold pool. The chart indicates that except at Kamloops (YKA), the average 3-hour pressure rises was about 9 hPa with highest rise reaching10.8 hPa at Osoyoos (WYY), the southern tip of the Okanagan Valley.

It was possible that the 3-hour pressure rise was even greater than 10.8 hPa somewhere due to the sparseness of surface stations. The lower right panel in Figure 7 is the CMC GEM Regional forecast for 3-hour pressure rise at 2100 UTC of 10 July. It shows that the predicted pressure rising centre lies over the Thompson Plateau just west of the Okanagan Valley with an 8 hPa rise at the centre. The model appears to have done a good job in simulating the location of the cold pool. However, the predicted maximum 3-hour pressure rise was less than the observed indicating that model under forecast pressure tendency.

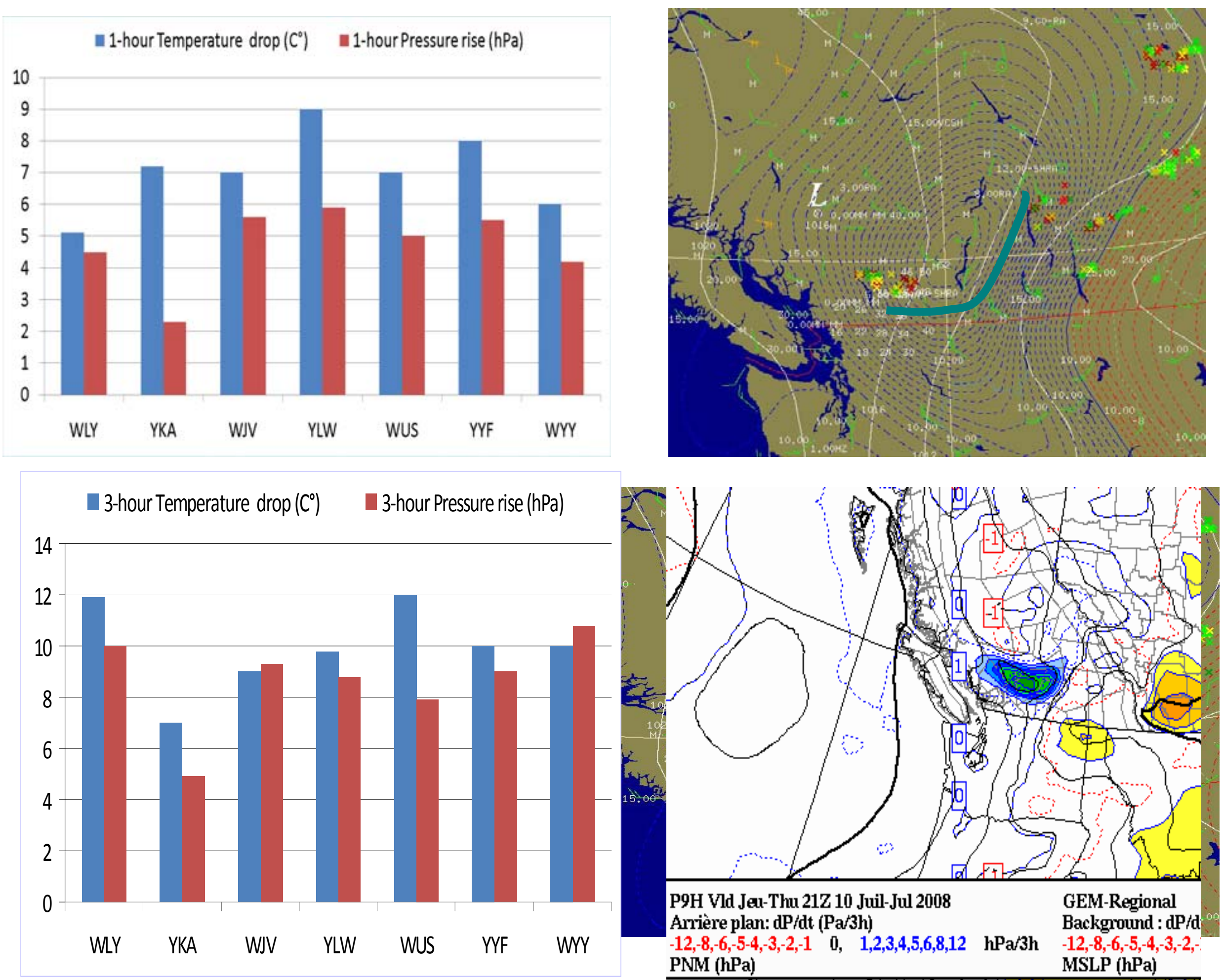

Figure 7 1-hour temperature and pressure changes (up left), AMX pressure tendency analysis (up right), 3-hour pressure rise (down left) and GEM Regional 3-hour pressure rise (down right)

Mahoney (1988) investigated 115 isolated and interacting thunderstorm gust fronts over northern Colorado during the warm season and illustrated morphological and kinematical features of 30 gust fronts that met certain criteria. He revealed a variety of features from the 30 gust fronts and the associated cold pool cases, like cold pool shape and depth, propagation speed and surface characteristic changes during the passage of these gust fronts. The observed surface pressure rises in the study were ranged from 0.2 to 2.8 hPa with an average of 0.6 hPa. Meanwhile the temperature drops had an average of 3.5° C within a range from a minimum of 1.8° C to a maximum of 7.2° C. Obviously, the magnitude of pressure and temperature changes in the present case are significantly greater than those in Colorado storms.

Takemi (1999) investigated a squall line associated with a disastrous dust storm in an arid region over Northwest China. This squall line evolved in an extreme dry environment with surface water vapour mixing ratios less than 2.5 g/kg and a deep, dry mixed layer reaching about 4 km AGL. When the squall line passed through Minqin AWS, surface pressure rose about 7 hPa and potential temperature dropped by approximately 14° K, which is about 13° C when conversed to temperature at the 850 hPa level (the ground level of the station). The surface characteristics indicated a great strength of cold pool in the case. Under extreme conditions with high mixed layer, evaporative cooling is very efficient as rainfall evaporation occurs readily beneath convective cloud and no precipitation was able to reach the ground. This evaporation process in turn contributes to strong downdrafts and the production of a very strong cold pool. The magnitudes of pressure and temperature changes in the present case are comparable to those in Takemi's dust storm case.

What are the possible factors to contribute to the great pressure change and the strong cold pool? Obviously, as with Takemi's dust storm case, evaporative cooling from the convective downdraft played a key role here since the pre-squall environment was very dry. Associated with these pressure rises, the average dew point rose 3.5 ° C 1 hour after the gust front passage and the average relative humidity increased 40% within the 3 hours. However, the evaporative process was not as efficient as that in Takemi's case because the airmass was not as dry and showers were reported almost anywhere. Therefore, other factors could be involved to enhance the cold pool. Previously we mentioned a synoptic scale cold air advection (CAA) ahead of the positively tilted trough and a surface cold front over the Central Interior. This synoptic scale CAA could work together with the convective scale evaporative cooling resulting in a strong cold pool along the leading edge of the squall line. It is worth to mention that model may be able to handle synoptic scale CAA well, but tends to under forecast the evaporative cooling from convective downdraft due to its parameterized convective scheme and the relatively coarse grid resolution.

6. Damaging winds

Damaging winds were the only severe weather observed from the squall line. The accompanying thundershowers were light or very light and no hail was reported. The maximum gusting wind speeds, directions and the occurring times at the main Southern Interior stations are presented in Table 1. Surface winds came from northwest to north normal to the orientation of the squall line. Maximum wind was stronger at Lytton (WLY) in the north-south oriented Fraser Canyon Valley than at Kamloops (YKA) in the west-east oriented South Thompson Valley. Within the Okanagan Valley (blue in the table), winds were stronger in the southern Okanagan at Summerland (WUS) and Penticton (YYF) than in the central and northern Valley at Kelowna (YLW) and Vernon (WJV). The record-breaking winds occurred at YYF near the southern end of Okanagan Lake. Winds at Castlegar (YCG) are identified to come from another storm.

Table 1 Maximum Gusting Winds

Station ID	YHE	YKA	WLY	WJV	YLW	WUS	YYF	WYY	YCG
Time (UTC)	2100	1800	1900	1948	2003	2049	2100	2200	2243
Wind direction	290	330	350	280	290	350	010	350	290
Wind speed (km/h)	46	61	78	35	56	70	109	63	89

Since the major damage occurred in the populated Okanagan Valley, here we will focus on wind characteristics over the area. Note that winds were only 35 km/h at WJV and 56 km/h at YLW in Table 2 since these two stations are protected when winds come from the northwest. According to Lundquist and Dudley (2008), wind gusts to 105 km/h at BC Forest Service (BCFS) Helipad in Vernon were estimated at approximately 1945 UTC and wind gusts of 90 km/h were measured at Dudley's place in southeastern Kelowna with a handheld anemometer at 2000 UTC. These two sites are more exposed and closer to the Okanagan Lake (Fig. 9). This suggests that the strong winds occurred near the water over the Okanagan Lake and the 80% of boats damaged at Kelowna Marina confirm the strong winds over the Lake. Although Vernon and Kelowna are about 40 km apart, the timing difference of peak winds between the two cities was only 15 minutes.

XSS Doppler scan did not suggest a mid-level rear-inflow-jet. However, a boundary layer jet was detected approximately at the station level of 1888 metres during the mature stage of squall line. Doppler low angle of -0.5 degree scan indicated the maximum velocity of a boundary layer being 21 m/s (75 km/h) coming from northwest. This jet was primarily pressure gradient driven due to the cold pool produced from the combination of synoptic CAA and evaporative cooling. With the complex terrain over the Thompson Plateau, boundary layer flows near the ground could be weaker than the maximum velocity due to friction. Peak wind of 61 km/h at YKA was probably the representative winds at the surface during the early mature stage (at 1800 UTC). However, surface winds could be stronger than 75 km/h along the valley gaps, especially the northwest-southeast oriented valleys. Due to the curved nature of the squall line, the leading edge of the squall line became somewhat parallel to the orientation of the Okanagan Valley when the storm approached the valley at 1930 UTC (Fig. 9). The fast-moving cold air over the mountains behind the leading edge of the squall line flowed about 1000 metres down to the lake surface like density current producing severe winds (Fig. 9). This down slope winds were responsible for severe damage incurred over the North and Central Okanagan area.

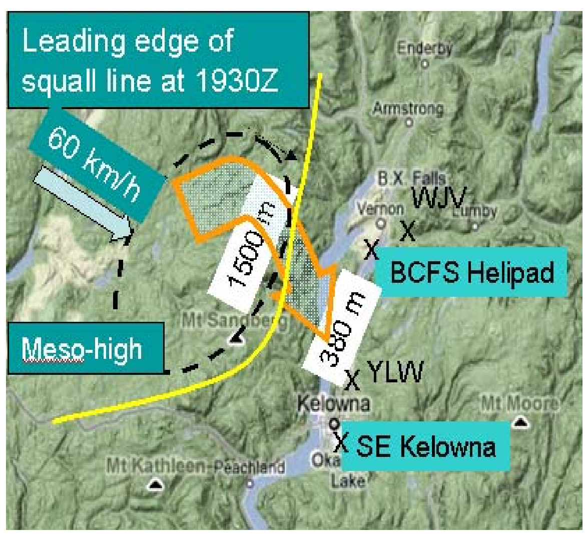

Figure 9 Down slope winds over northern Okanagan

When the cold air accumulated over the northern section of the Okanagan Lake, the associated meso-high combining with so-called pre-squall meso-low created a north-south oriented pressure gradient force paralleling to the Okanagan lake. It was this pressure gradient force that accelerated the already high momentum cold air moving southward. Some unique features were observed during this time period. Figure 10 shows temperature drops 1 hour before and after the maximum gust wind occurred at the main stations in the Okanagan. We see that the temperature decreased by only about 1° C 1 hour before maximum winds were reached, but by 7– 9° C 1 hour after the maximum wind occurred. This fact suggests that the peak winds occurred right at the leading edge of the cold pool outflows.

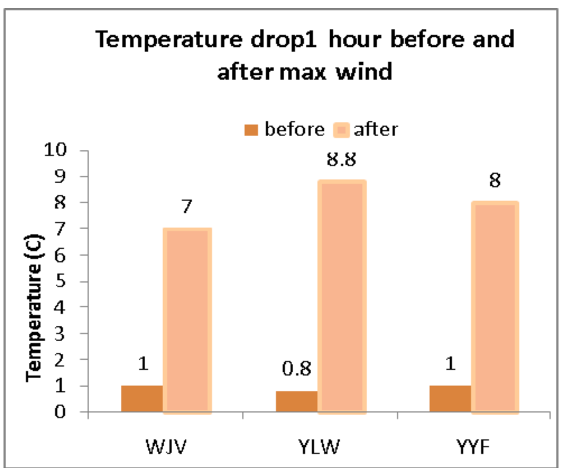

Figure 10 Surface temperature changes

Table 2 shows the hourly surface observations at YLW and YYF. YLW observations indicate that gusting wind reached its maximum of 30 knots (56 km/h) immediately when it shifted from southwest to northwest at 2003 UTC. At Penticton, the record-breaking gusting wind occurred at 2100 UTC when winds shifted from northwest to north. A detailed look at surface characteristics suggests that the northwest winds at Penticton before 2100 UTC did not come from the thunderstorm outflow but instead from the southern band of the “Trepanier split”. Trepanier split is referred to localized thermal-driven winds during a summer afternoon, which flow down from the mountains west of the Okanagan Lake through Trepanier Creek to Central Okanagan and split northeastward and southeastward along the lake. The sudden wind shift and the timing of maximum winds support the ideal that peak winds were observed along the gust front of the cold pool outflows. It is notable that rain showers at both stations were observed after peak winds were reached, indicating the gust front surged well ahead of the squall line.

Table 2 Surface observations

Kelowna Airport	**Penticton Airport**
CYLW 102000Z AUTO 22025KT 9SM	CYYF 102000Z 31013G22KT 15SM
CYLW **102003Z** AUTO **30020G30KT** 7SM	CYYF **102100Z 01036G59KT**
CYLW **102053Z** AUTO 36021G28KT 9SM **-RA**	CYYF **102119Z** 01030G41KT 15SM **-SHRA**

The propagation speed of cold outflow gust front can be estimated from the surface pressure changes using gust front speed equation discussed in Seitter and Muench (1985) and Mahoney (1988):

$$V=k*(\Delta P/\rho)^{1/2}$$

where ρ is the density of warm air, ΔP is the pressure change and k is internal Froude number. Seitter and Muench (1985) used k=0.79 to estimate a gust front speed and found that the predicted speed well matched the observed speed. By adopting the same Froude number of 0.79, we use surface data from YLW and YYF to calculate the gust front speeds at the two locations, to be approximately 60 km/h, which is close to the actual storm motion speed (55 km/h) at the dissipating stage. The maximum surface wind is generally greater than the propagation speed of the gust front. Goff

(1976) proposed an empirical relationship between the two speeds:

$$U_{Max}=1.49Vprop$$

According to the equation, a gust front from a cold pool with propagation speed of 60 km//h could produce the maximum surface gusting wind of up to 89.4 km/h. This predicted wind is very close to the 90 km/h measured in southern Kelowna. However, the record-breaking wind of 109 km/h at Penticton is 19.6 km/h stronger than the predicted wind. If the predicted wind is reasonable, an additional force could exist to enhance the winds. What was the possible force?

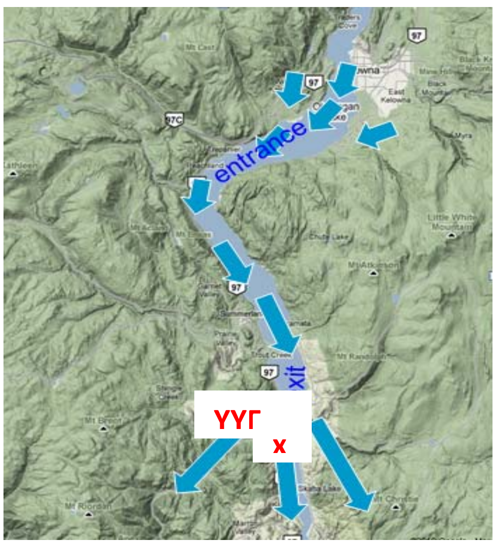

Figure 11 Gap winds due to channelling effect

Figure 11 illustrates the gap winds due to channelling effect. The north-south oriented Okanagan Lake is an ideal channel. Over the southern section of the lake, the average lake width is only 3 km and the surrounding mountains can be as high as 1000 metres above the lake surface. The 60 km lake fetch between Kelowna and Penticton is long enough to accelerate the cold air. Previously we mentioned the pressure gradient force drove the cold air southward. The cold air moved along the narrow gap over the smooth lake surface with minimal friction. Channelling effect worked efficiently to accelerate the southward movement of the cold air and the wind speed finally reached its maximum of 109 km/h at YYF. Winds could be stronger at the southern tip of the lake just near the water since YYF is about 4 km away from the water.

Figure 12 gives a conceptual model for the winds over the Okanagan. Winds over the Thompson Plateau were primary pressure gradient force driven. However, cold air accelerating down to the valley bottom from the mountains created strong down slope winds to the north/central sections of Okanagan Lake. After this cold air descended upon the lake, a meso-high was established and pressure gradient force drove cold air southward with the gust front surging ahead of the squall line, as indicated with red and blue lines at 2000 UTC. The channelling effect accelerated the gust front southward further away from the squall line (red and blue lines at 2100 UTC) and winds reached the maximum at the southern tip of the lake.

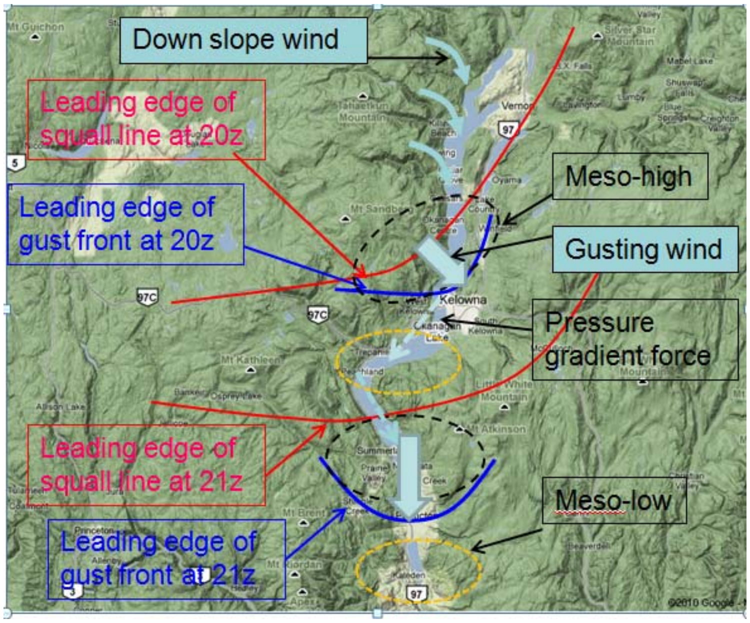

Figure 12 A conceptual model for severe winds over Okanagan

It is worthwhile to mention that the squall line had entered its dissipating stage at 2000 UTC and began to break down into two parts thereafter. The dissipating stage is not a typical time period to observe the strongest wind since most thunderstorms are more energetic during the mature stage. This could mislead forecasters to think that the strongest winds should be mainly over the northern and central Okanagan. However, the southern Okanagan observed the strongest winds and incurred the most severe tree and property damage. For this reason, understanding and recognizing channelling effects are very important to assist making warning decisions under such circumstances.

7. Conclusions

A short-lived squall line over the BC Southern Interior on 10 July 2008, which resulted in a widespread tree and property damage with record-breaking winds at Penticton, has been investigated. The complex terrain over southern BC and the pre-squall dry environment characterized the evolution of the squall line and the associated surface winds.

The squall line was initiated over the relatively uniform terrain in the Central Interior in the morning and moved into the mountainous terrain in the Southern Interior in the early afternoon at an average speed of 55 km/h. A surface cold front accompanied with cold air advection provided linear forcing mechanism to trigger the squall line. The squall line then evolved in an environment of low convective available potential energy and moderate wind shear. The pre-squall environment was very dry with low mixing ratio and high level of free convection. Severe winds occurred over southwest interior in a day that was not a typical day for convection due to dry atmosphere and low CAPE.

The squall line experienced a 7-hour lifecycle, which is significantly shorter than an average squall line that develops over the uniform terrain. While the life span of the early stage was comparable with an average one, the mature and dissipating stages were significantly shorter. A combination of the complex terrain over the Southern Interior and the dry pre-squall environment inhibited new cells from forming and thus led to a shorter mature stage. The possible terrain induced storm split, on the other hand, accelerated the decaying of the windstorm in the dissipating stage.

The convective storm produced a strong pool of cold air. A comparison of the magnitudes of the pressure and temperature changes with those associated with squall lines observed in other locations indicates the characteristic changes in the current storm are of a comparable magnitude (e.g., extreme dry conditions in arid region of China). The evaporative cooling from convective downdraft played a key role to the strength of the cold pool. However, in this case, the synoptic scale cold air advection made a contribution as well. Models under-forecast the strength of cold pool associated with the evaporative cooling, as models have limited ability to handle the process due to their parameterization and coarse grid resolution.

Although the strong winds were widespread over southern BC accompanying the squall line, the most severe winds and the associated property damage occurred within the populated Okanagan Valley. Pressure gradient from a meso-high and meso-low couplet was the primary force to generate the strong winds. While down slope winds were responsible for enhancing the severe winds over the north and central Okanagan, gap winds due to channelling effect played a key role for the southern Okanagan severe winds. It is uncommon to have strongest winds reported at Penticton Airport in the storm dissipating stage but the unique terrain has the ability to make it happen. Therefore, understanding terrain effects is critical for doing forecasts and making warning decisions.

Acknowledgement

We would like to thank to Alyssa Charbonneau and Louis Kohanyi for providing some diagrams, to Ruping Mo and Ian Okabe for valuable discussions. Thanks go to Doug Lundquist for providing some detail information. Special thanks also go to Ford Doherty with data collection from his Archives.

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