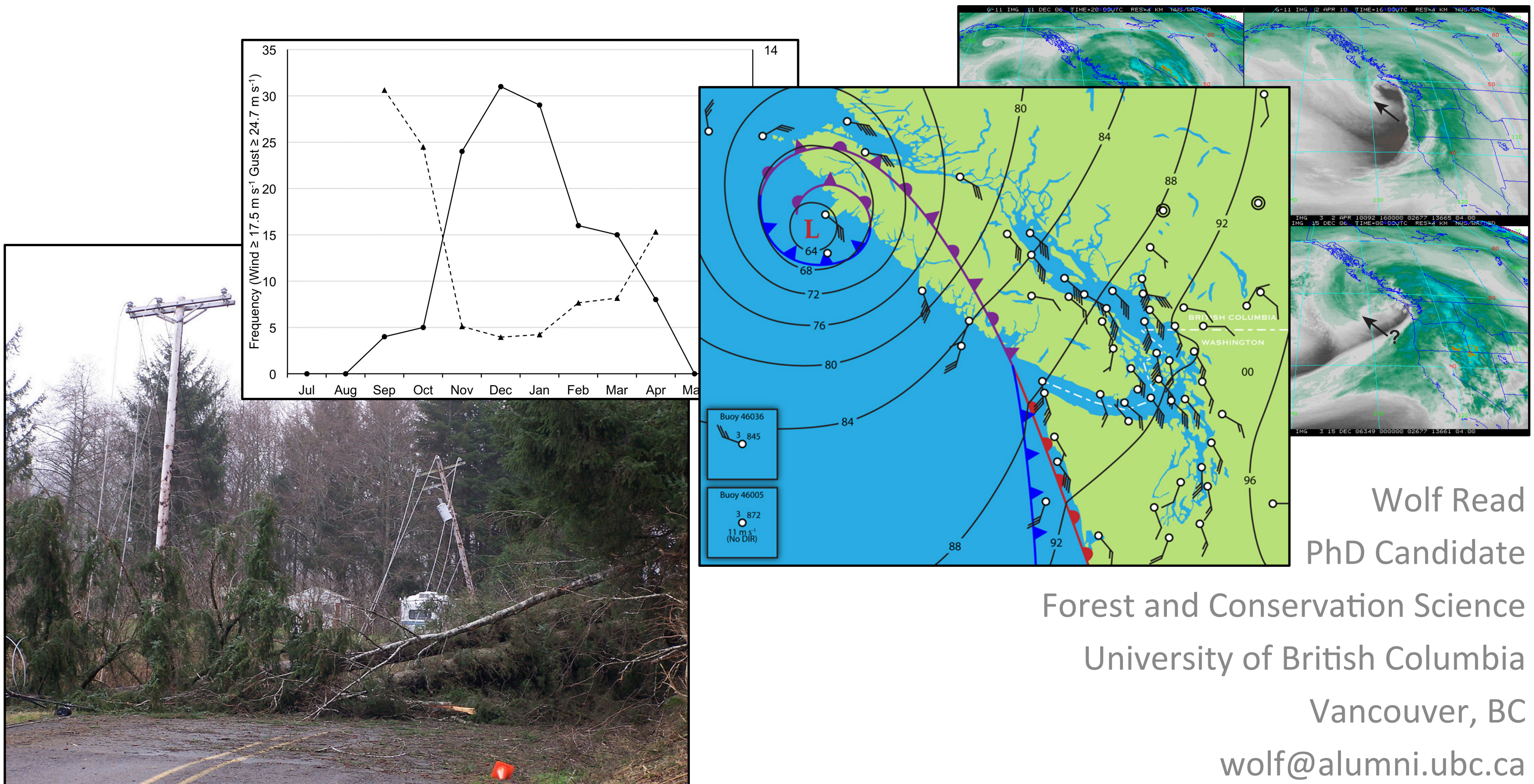
The Climatology and Meteorology of Windstorms that Affect Southwest British Columbia, Canada, and Associated Tree-Related Damage to the Power Distribution Grid



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Windstorms in British Columbia

- Windstorms that cause widespread loss of trees and attendant property damage are part of the southwest British Columbia (BC) climate

- For example, a series of windstorms occurred during November to January of 2006-07 (BC Hydro 2007)

- These storms repeatedly caused major damage to the BC Hydro power grid

Windstorm damage to the BC Hydro power grid Nov 2006 to Jan 2007:

Storm Period	Damaged Trans-mission Circuits	Damaged Distribution Circuits	Number of Customers Affected at Peak
15 Nov 2006	8	100	226,000
26 Nov 2006	12	150	92,600
11-15 Dec 2006	12	181	240,300
05-09 Jan 2007	7	88	120,399

Source: BC Hydro (2007)

Windstorms in British Columbia

- Improved understanding of southwest BC windstorms can help with forecasting these events

- Improved understanding of how the BC Hydro power grid responds to wind load can help with system resiliency:

  - Forecasting outages ahead of windstorms

  - More precise prepositioning of line crews—potentially faster repair times

  - Can also pinpoint circuits that are more vulnerable (system hardening)

Broad Research Goals

- Develop a climatology of windstorms for southwest BC
- Detailed intercomparison of windstorms from recent years to pinpoint key variables associated with the timing of peak winds
- Model the wind-speed dose response of the BC Hydro distribution grid using independent storms and hour-by-hour approaches

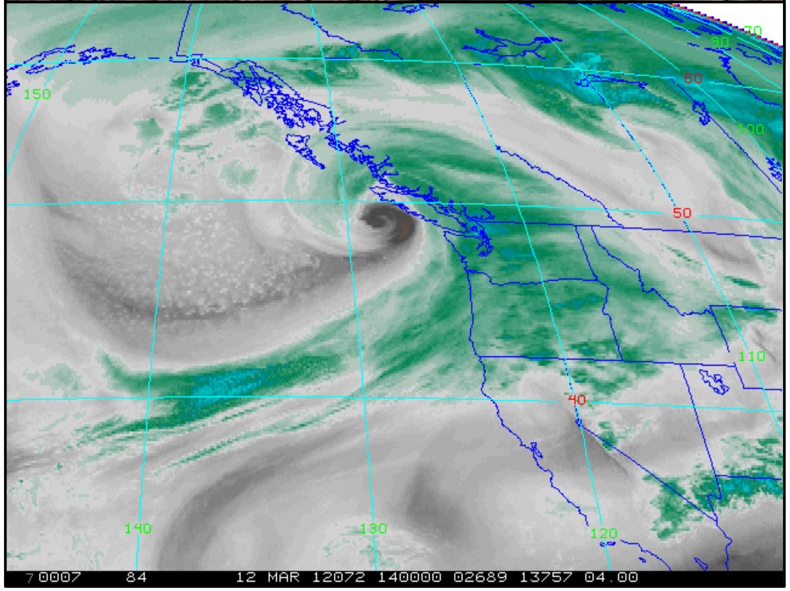
Presentation Overview

- Climatology of southwest BC windstorms
  - Storm tracks
  - Seasonality
  - Return intervals

- Meteorology of southwest BC windstorms
  - Synoptic and mesoscale analysis
  - The 2006 Hanukkah Eve Storm
  - The 12 Nov 2007 windstorm

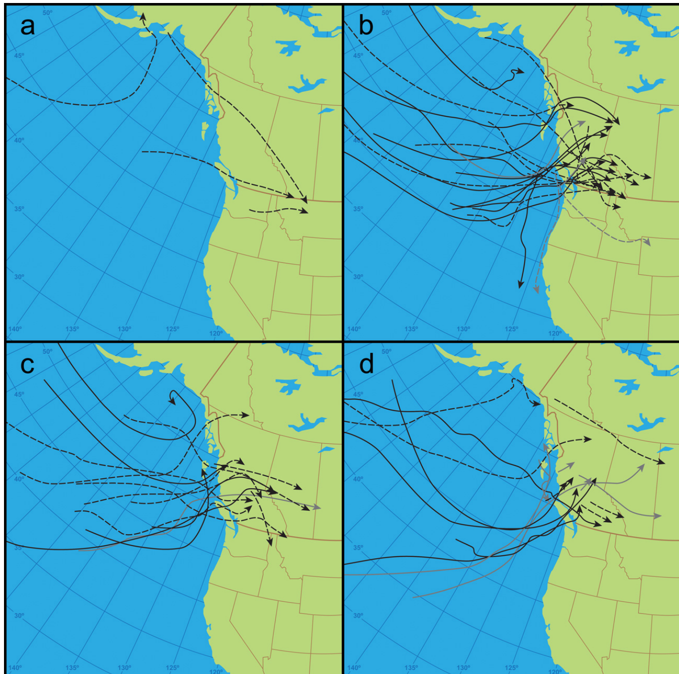
- Tree-related damage to the BC Hydro distribution grid
  - Hour-by-hour analysis of line faults
  - Independent storm peak wind and total line faults

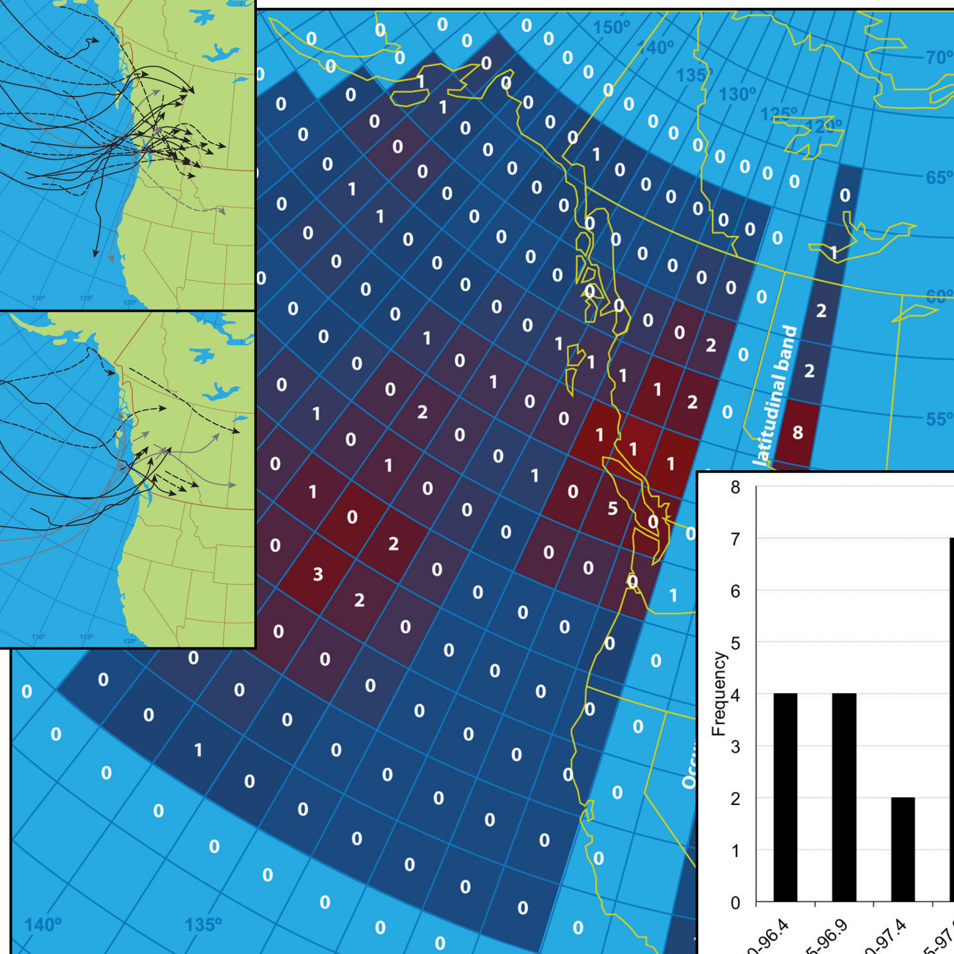
- Conclusions / Recommendations

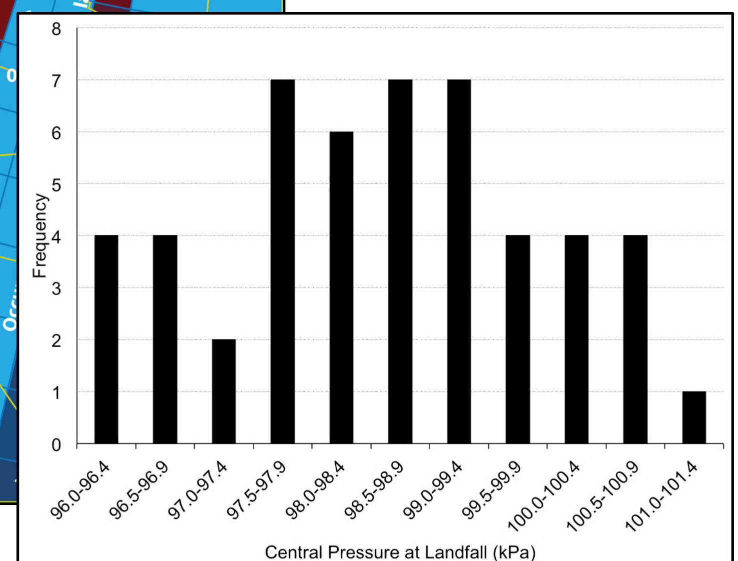


Satellite photo courtesy of the US. National Weather Service

Climatology of Southwest BC Windstorms







Climatology of Southwest BC Windstorms

Knowledge Gaps

- No systematic examination (i.e. climatology) of southwest BC windstorms has been done
- Mass and Dotson (2010):
  - Focused on western Oregon (OR) and Washington (WA), not BC
  - They note that even the number of detailed individual windstorm analyses is limited
- Broad studies of North Pacific ETC climatology such as Sanders and Gyakum (1980) and Mesquita et al. (2009)
  - Are not focused specifically on high-windstorms on the BC coast

Climatology of Southwest BC Windstorms

Key Research Goals

- Utilize a track-typing method to identify key landfall locations of ETCs that generate high winds in the most populated region of BC
- Describe average storm tracks for classes of windstorm based on peak wind direction
- Assess seasonality and return periods of southwest BC windstorms

Climatology of Southwest BC Windstorms

Methods: Study Region

- The Salish Sea area

Climatology of Southwest BC Windstorms

Methods: Study Region

- The Salish Sea area
- With a focus on these three long-term airport stations:
  - Vancouver (CYVR)
  - Victoria (CYYJ)
  - Abbotsford (CYXX)

Climatology of Southwest BC Windstorms

Methods: Windstorm Definition

Organization	Coverage	Observation Frequency	Available Wind Observations
Environment Canada (EC)	1953-present	Hourly	Wind
EC	1994-present	Hourly and special	Wind and gust
EC	1953-present	Daily	Peak gust
National Climatic Data Center (NCDC)	1977-2010	Hourly and special	Wind and gust
Plymouth State Weather Center	1998-present	Hourly and special	Wind and gust

- Data sources for wind observations
- Availability of data, including weather maps, from 1994-present is largely what determined the main time period of the study (1994-2012)
- A 1964-2012 windstorm dataset is used for some aspects of this study

Climatology of Southwest BC Windstorms

Methods: Windstorm Definition

- In this analysis, windstorms are defined by having peak winds within high-wind criteria:
  - 2-min wind ≥ 17.5 m s^{-1} (63 km h^{-1})

    and/or

  - 5-s gust ≥ 24.7 m s^{-1} (89 km h^{-1})
- These cutoffs are slightly lowered from National Weather Service values to account for measurement error and bring in some additional storms

Climatology of Southwest BC Windstorms

Methods: Classification by Wind Direction

- Windstorms are also classified largely by wind direction as measured at CYVR, with some exceptions, including:
    - Wind direction from events that produced higher wind speeds at the other two stations (CYYJ and/or CYXX) is determined from the station with the highest speed
- Peak wind direction is often used, but there is also consideration of the wind direction behavior throughout the entire storm event

Climatology of Southwest BC Windstorms

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- Peak wind direction is often used, but there is also consideration of the wind direction behavior throughout the entire storm event
- These categories are imperfect and are somewhat subjective in nature

Climatology of Southwest BC Windstorms

Methods: Storm Tracks

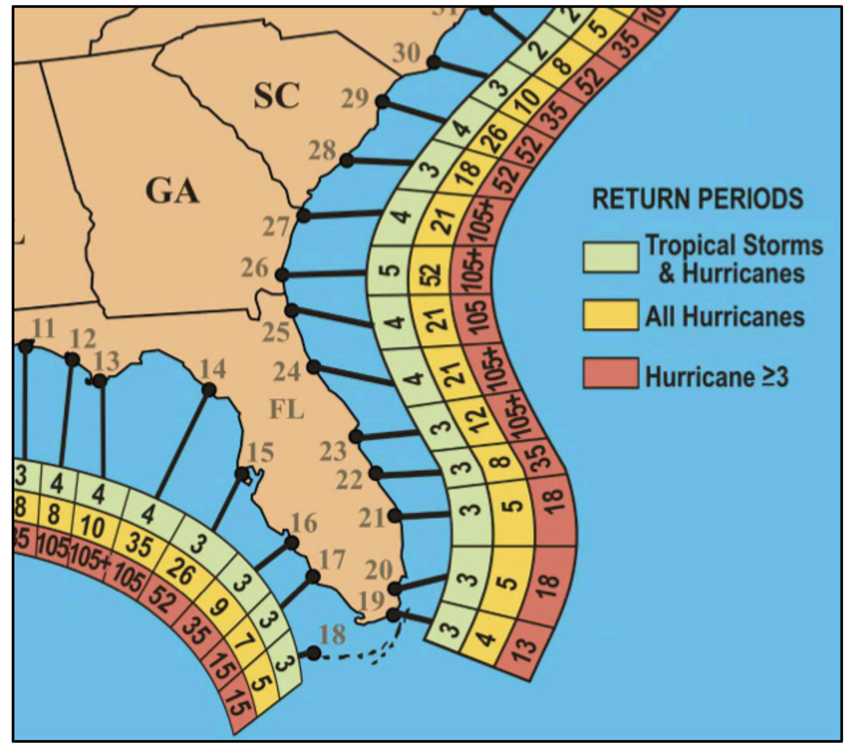
Organization	Coverage	Observation Frequency
EC Microfilm Library	~1973-present, even earlier in some cases	6-h
NCDC	1994-present	3-h, 6-h, 12-h

- Data sources for surface maps and in some cases satellite photos
- Generally used 6-h positions to determine storm tracks, using 3-h maps when available as a further guide
- Satellite photos available from the US. National Weather Service collected during storm events from 1999-2012 were also used
- Also collected central pressure information

Climatology of Southwest BC Windstorms

Methods: Storm Tracks and Return Intervals

- Track typing
- Inspired by work on tropical cyclones (TC) by Keim and Muller (2007)

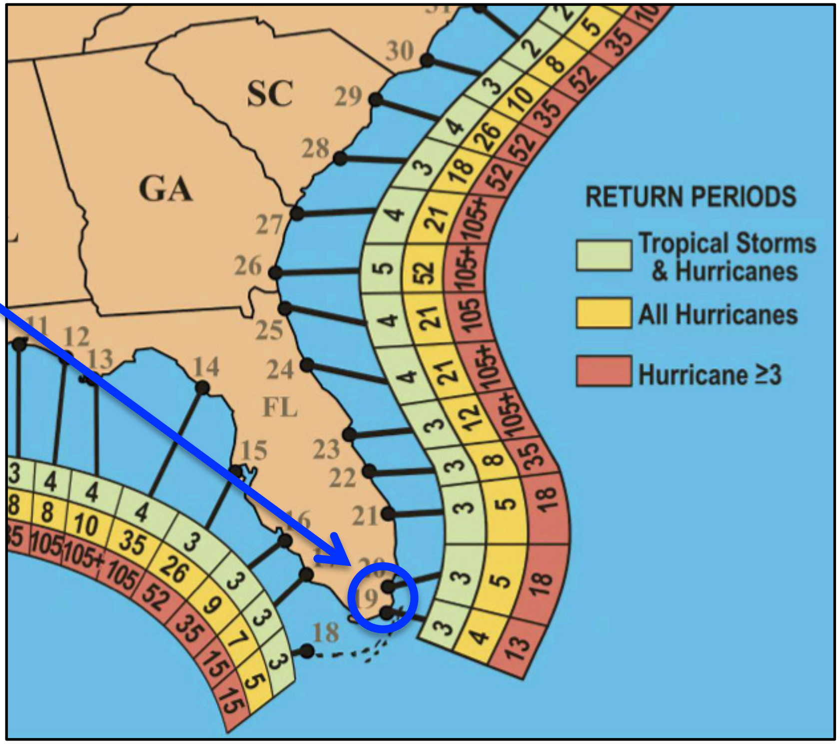


Adapted from Keim and Muller 2007

Climatology of Southwest BC Windstorms

Methods: Storm Tracks and Return Intervals

- My method differs from Keim and Muller due to a focus on one small region roughly the size of the circle that encompasses Miami and Key Largo, not an entire seaboard
- Also, Keim and Muller started with an already available TC track database (1901-2005)
- I used peak wind and gust at the 3 study stations to determine the storms and therefore the tracks (1994-2012)



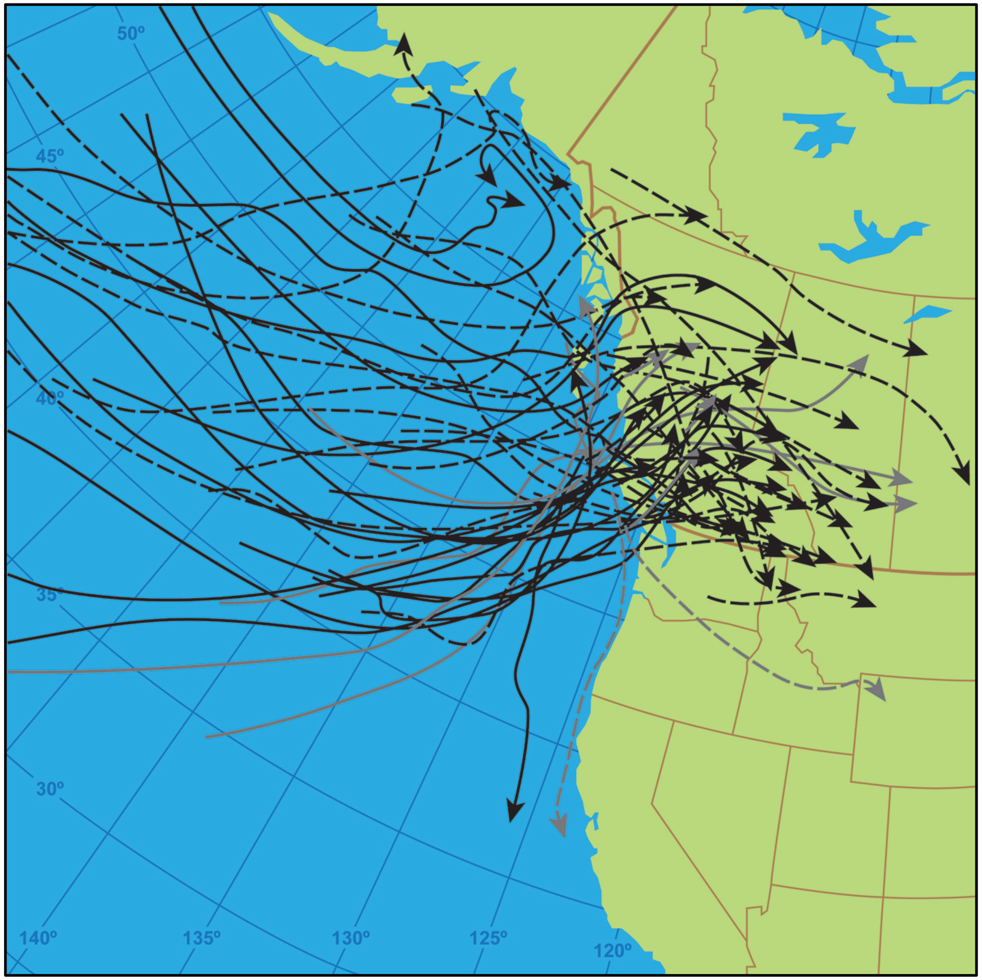
Adapted from Keim and Muller 2007

Climatology of Southwest BC Windstorms

Results: Storm Tracks

- Low-center tracks of all high-wind storms that affected Greater Vancouver and/or Victoria 1994-2012

- Line type based on peak wind direction at Vancouver:
  - Solid black, SE
  - Dashed black, W
  - Solid gray, S & SW
  - Dashed gray, E



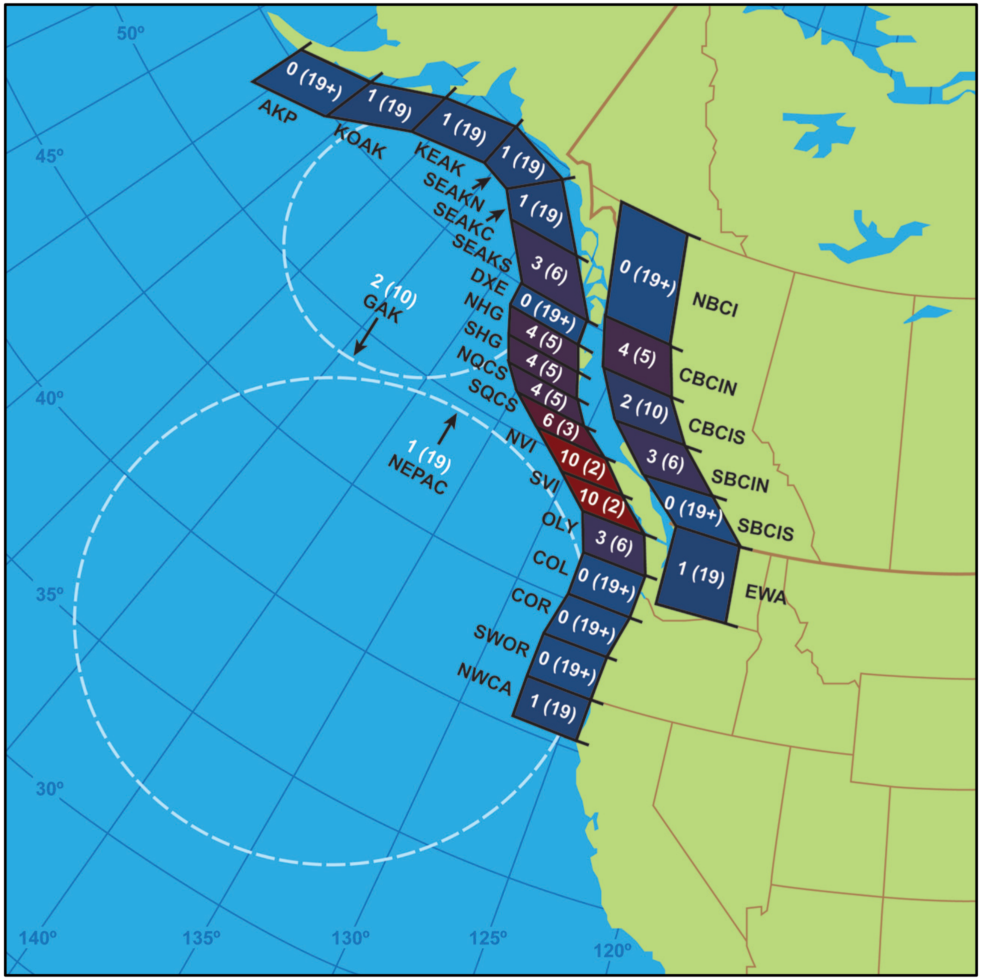
Number of tracks = 62

Climatology of Southwest BC Windstorms

Results: Storm Tracks

- Key landfall points:
  - Vancouver Island
  - Queen Charlotte Strait
  - Haida Gwaii

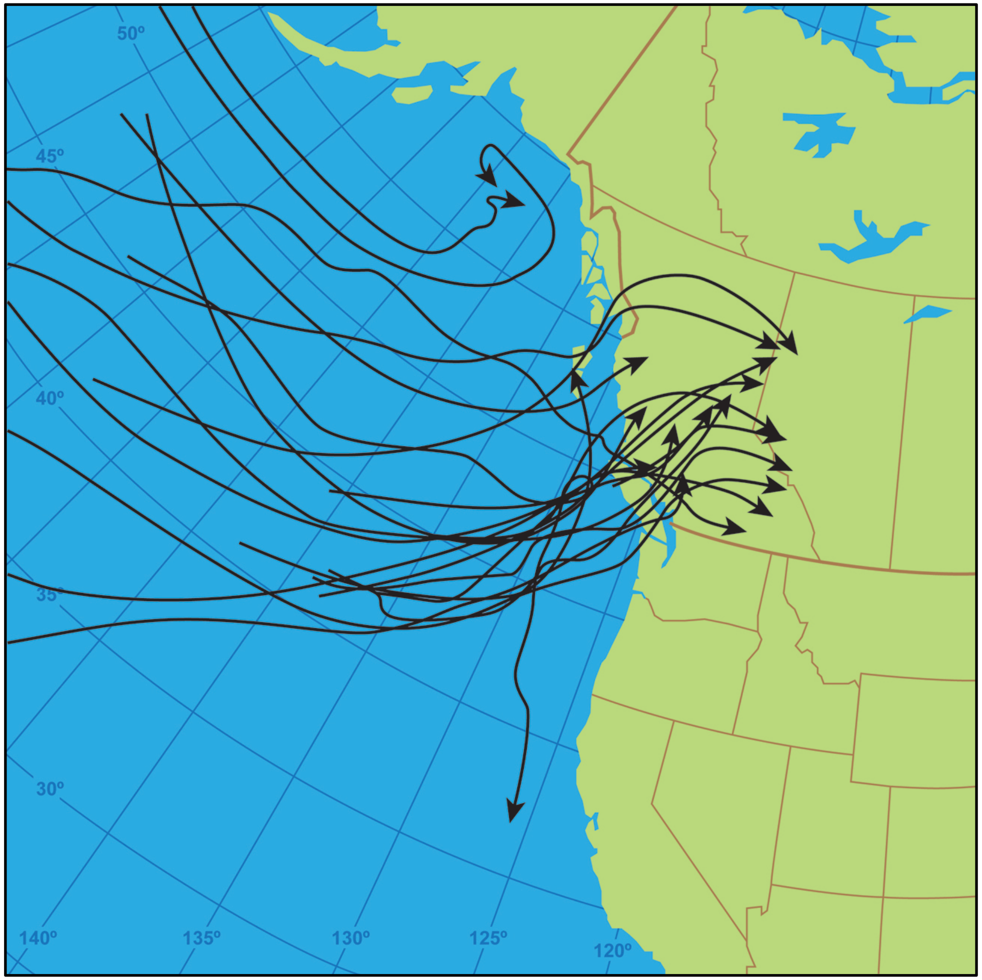
- On average, a Vancouver Island landfall (either north or south) causes a high windstorm in the study region on an annual basis



Climatology of Southwest BC Windstorms

Results: Storm Tracks

- Two wind direction categories dominate
- Southeasters (n = 21)



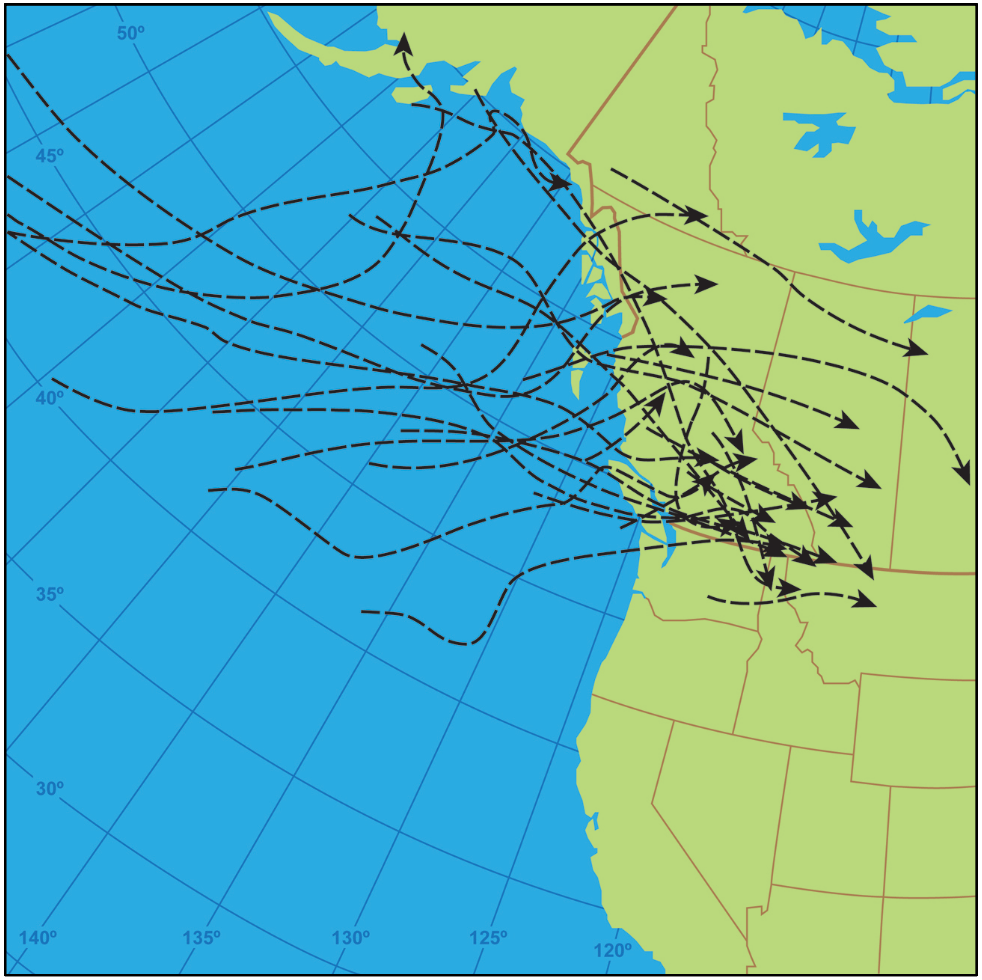
Climatology of Southwest BC Windstorms

Results: Storm Tracks

- Two wind direction categories dominate

- Southeasters
  (n = 21)

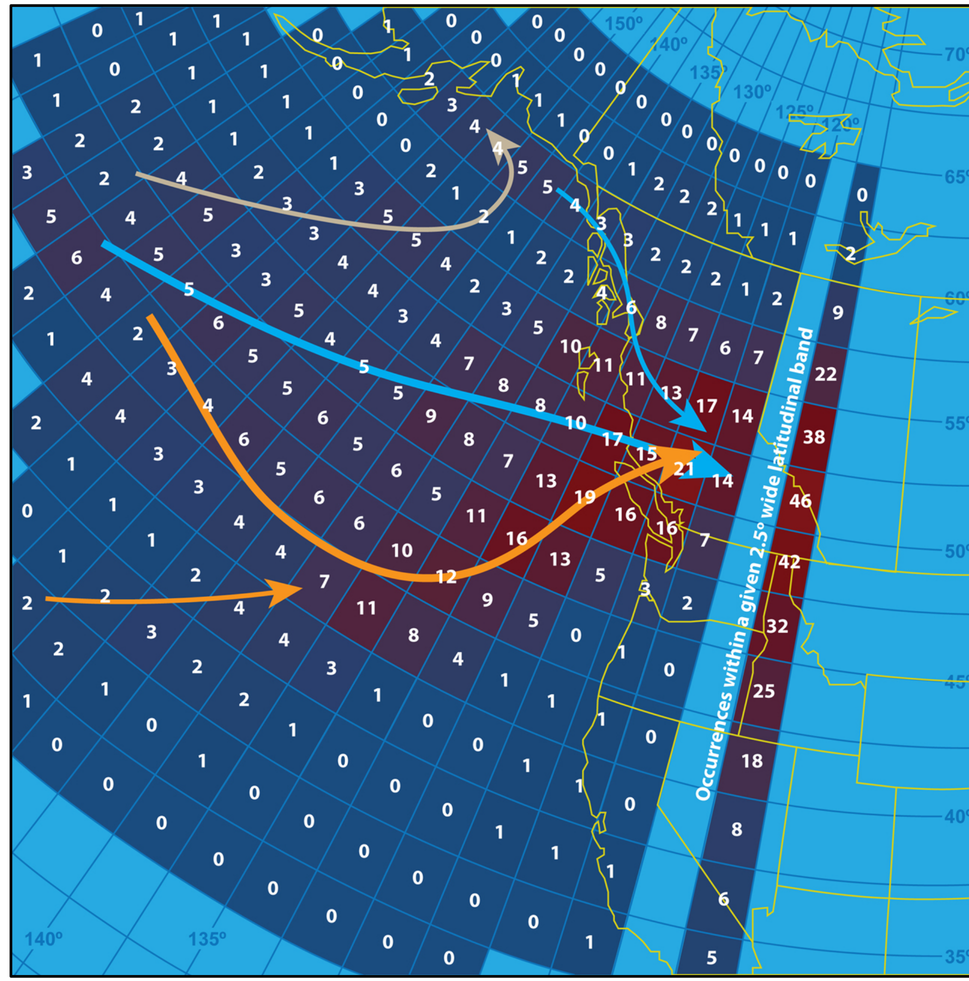
- Westerly windstorms
  (n = 29, 27 independent)



Climatology of Southwest BC Windstorms

Results: Storm Tracks

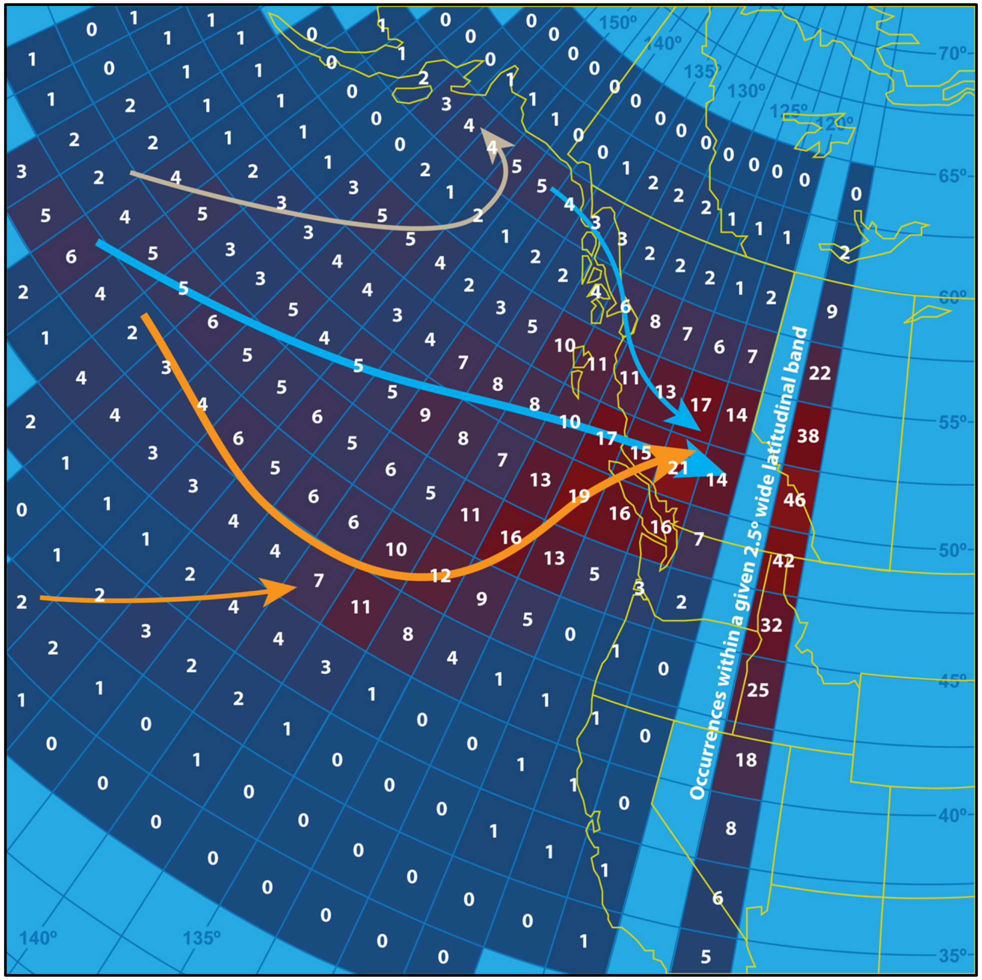
- Looking at the number of times high-wind-generating ETCs track through a given quadrilateral
  - Method is similar to Sanders and Gyakum 1980
- Orange: Southeasterly windstorms
- Blue: Westerly windstorms



Climatology of Southwest BC Windstorms

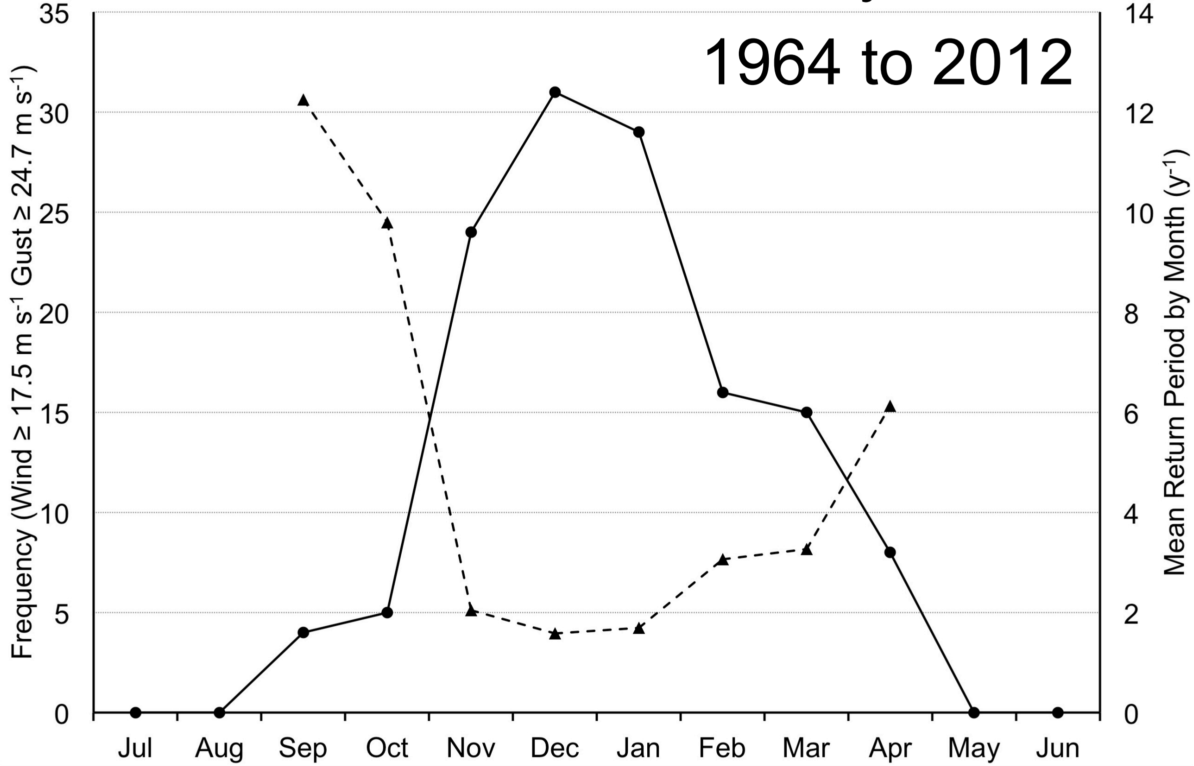
Results: Storm Tracks

- Westerly windstorms tend to have tracks that are nearly due west to east
- Southeaster track directions tend to be northeasterly
- Southeasters also tend to have more southern tracks



Climatology of Southwest BC Windstorms

Results: Seasonality



- Windstorm occurrence is seasonal, occurring primarily from November through March
- This is congruent with the rainy season and is a product of seasonal changes in the global circulation

Climatology of Southwest BC Windstorms

Results: Return Intervals Based On Peak Wind Speed

Windstorm Category	Peak Wind Magnitude among CYVR, CYYJ and CYXX ($m\ s^{-1}$)	Total Number of Events in 49 y	Mean Events Per Year	Mean Years Between Events	Example
Catastrophic	≥ 25.0	<1	<0.02	>49.0	12 Oct 1962
Severe	22.5-24.9	6	0.12	8.2	15 Dec 2006
Strong	20.0-22.4	14	0.29	3.5	15 Nov 2006
Endemic	17.5-19.9	76	1.55	0.6	02 Apr 2010
Moderate	≤ 17.4	>76	>1.55	<0.6	14 Apr 2002

- Summarizes windstorms with high-wind criteria peak *2-min wind* from 1964 to 2012
- Return intervals strongly increase across a small range of peak wind

Climatology of Southwest BC Windstorms

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Moderate	≤ 17.4	>76	>1.55	<0.6	14 Apr 2002

- Windstorms are endemic to the region, with low-end events occurring more than once a year on average

Climatology of Southwest BC Windstorms

Results: Return Intervals Based On Peak Wind Speed

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Endemic	17.5-19.9	76	1.55	0.6	02 Apr 2010
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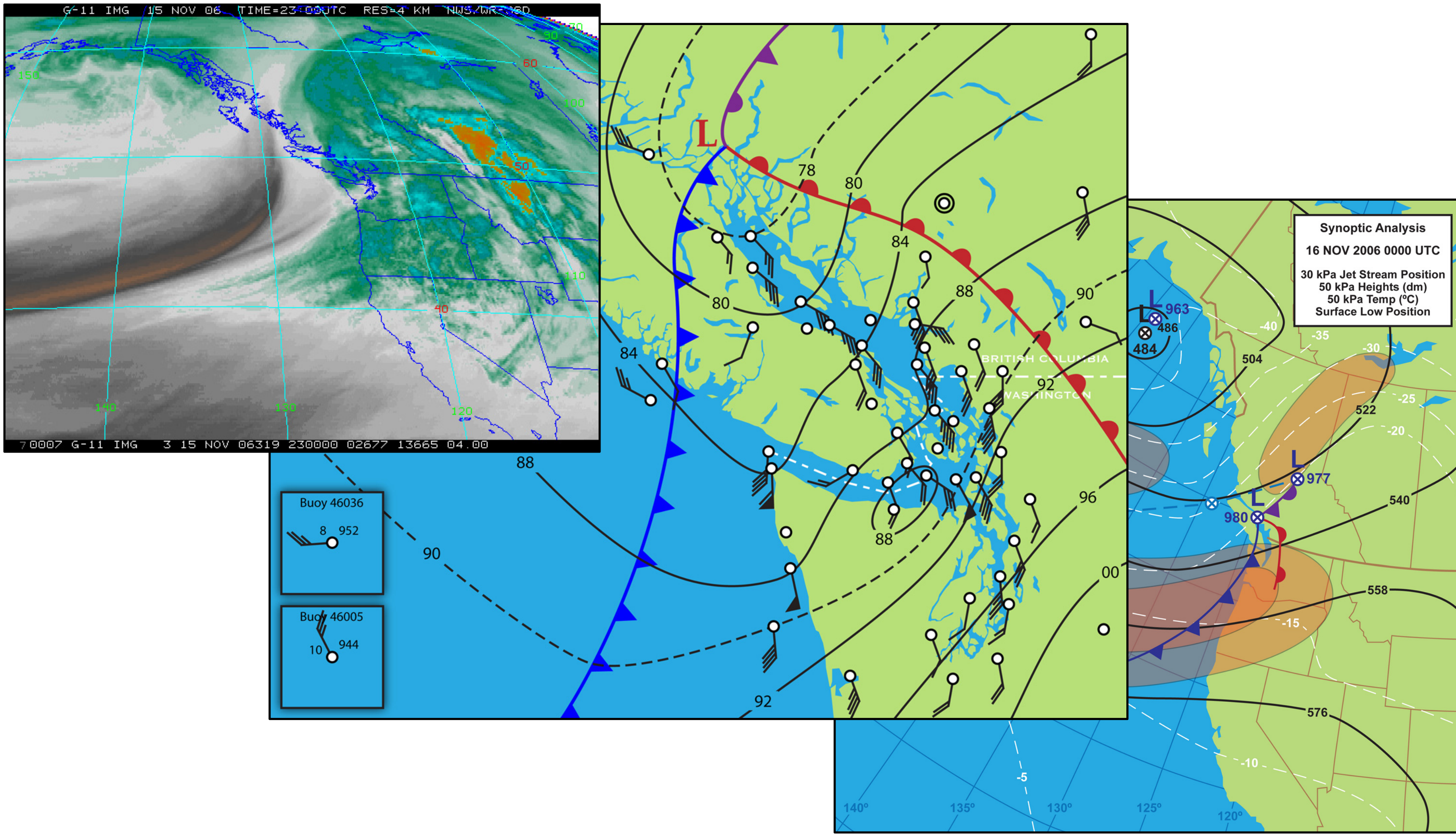
- Strong and severe windstorms occur less frequently, but appear to visit the region routinely on the time scales of around a decade

Climatology of Southwest BC Windstorms

Key Conclusions

- The majority of windstorms result from landfalls between southern Vancouver Island and northern Haida Gwaii
- Southeasters tend to result from closer and more meridional tracks than westerly windstorms
- Windstorm frequency is seasonal, with the majority occurring during the fall and winter months
- Windstorms are endemic to the region

Meteorological Analysis of Strong Windstorms that Affect Southwest BC



Meteorology of Southwest BC Windstorms

Knowledge Gaps: Windstorm Meteorology

- Detailed intercomparison of southwest BC windstorms has not been done

- Lynot and Cramer (1966) briefly compare key historic storms from 1962 and earlier
  - Primarily focused on WA and OR and analysis of the Columbus Day Storm

- My own intercomparison of windstorms that affected the Pacific Northwest (Office of the Washington State Climatologist)
  - Focused primarily on surface analysis
  - Does not include BC

Meteorology of Southwest BC Windstorms

Key Research Goals

For the strongest windstorms:

- Examine patterns of variability of synoptic conditions between storms at the upper levels and surface
- Produce and analyze mesoscale surface maps for the period around peak winds in the study region to help pinpoint features associated with wind maxima
- Develop conceptual models for southeasterly and westerly windstorms tailored to the region of interest

Meteorology of Southwest BC Windstorms

Methods

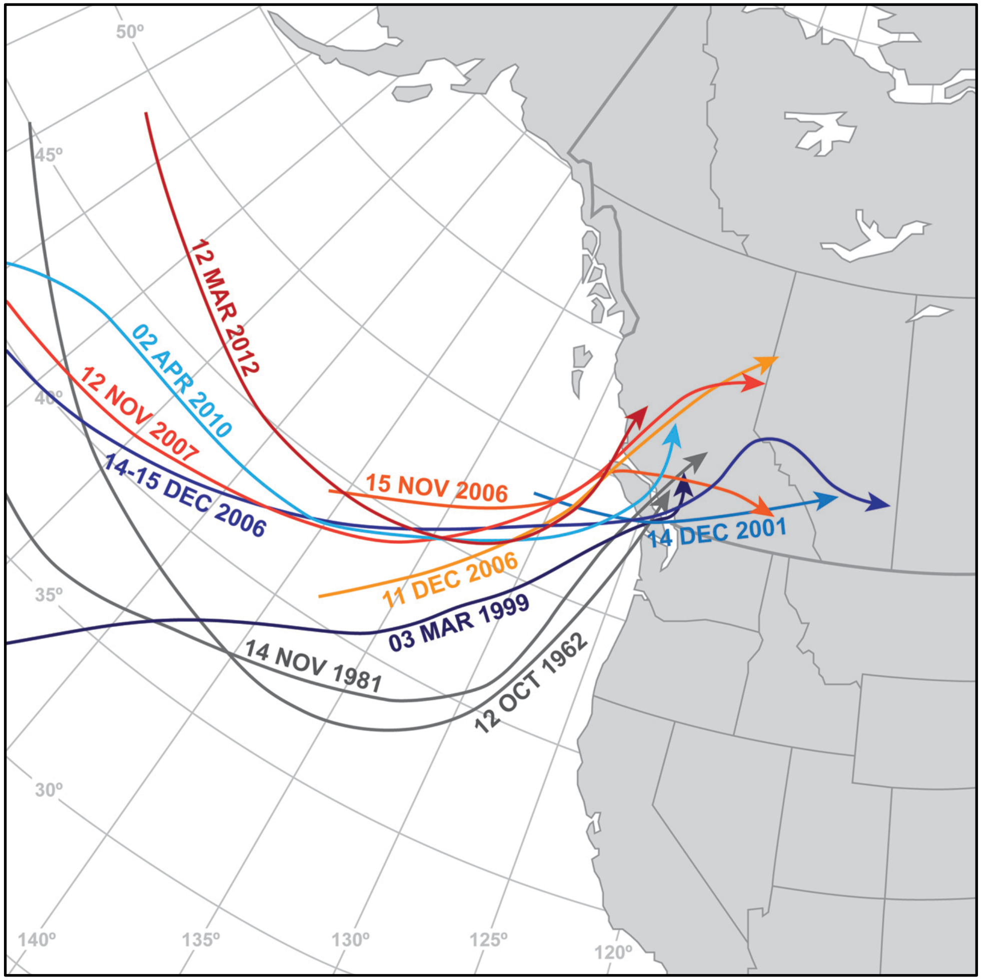
For the detailed synoptic and mesoscale analysis:

- Selected eight of the 20 windstorms with Vancouver Island tracks
  - Favored the strongest storms determined by the average peak gust of CYVR, CYXX and CYYJ
  - Chose storms from 1999-2012 due to having more data available
  - Four had north Vancouver Island tracks
  - The other four had south Vancouver Island tracks
  - Six were southeasters and two were westerly windstorms

Meteorology of Southwest BC Windstorms

Methods

- Tracks and dates of the selected eight strong to severe windstorms that struck BC between 1999 and 2012
- The paths of the catastrophic 1962 Columbus Day Storm and a major windstorm that occurred on 14 Nov 1981 are also shown for reference



Meteorology of Southwest BC Windstorms

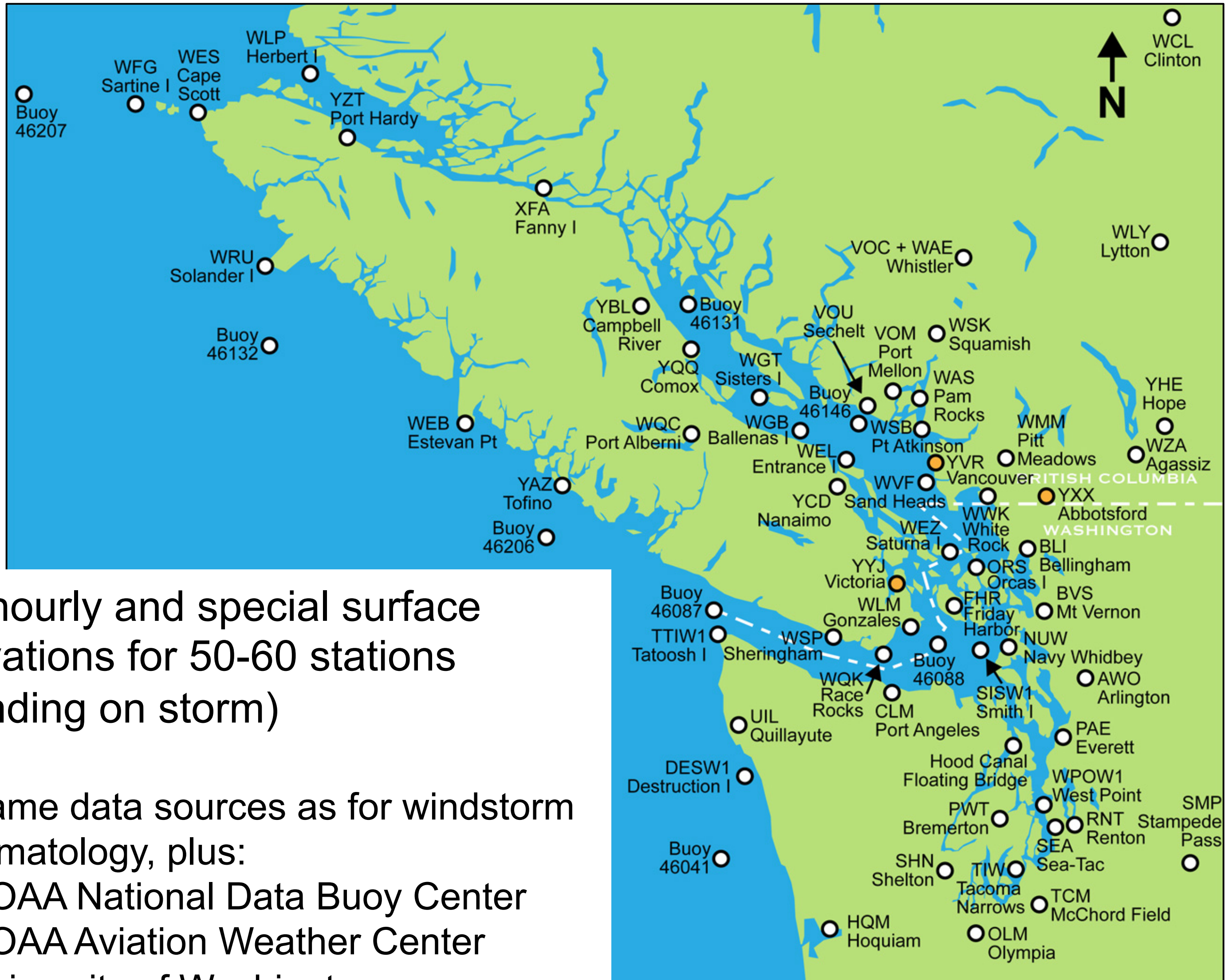
Methods

For the detailed synoptic and mesoscale analysis:

- Used upper-air and surface maps from:
  - US. National Oceanic and Atmospheric Administration (NOAA) Daily Weather Maps Project
  - US. National Climatic Data Center
  - US. Weather Prediction Center (including satellite photos)
  - Environment Canada (including satellite photos)
  - US. National Weather Service (satellite photos)

Meteorology of Southwest BC Windstorms

Methods



- Used hourly and special surface observations for 50-60 stations (depending on storm)
    - Same data sources as for windstorm climatology, plus:
    - NOAA National Data Buoy Center
    - NOAA Aviation Weather Center
    - University of Washington

Meteorology of Southwest BC Windstorms

Methods

- Applied standard surface analysis techniques (e.g. Vasquez 2002 and 2008)
- Analysis was also informed by detailed studies of North Pacific and North Atlantic ETCs (e.g. Steenburgh and Mass 1996, Shapiro and Keyser 1990)

Meteorology of Southwest BC Windstorms

Methods

For conceptual modeling:

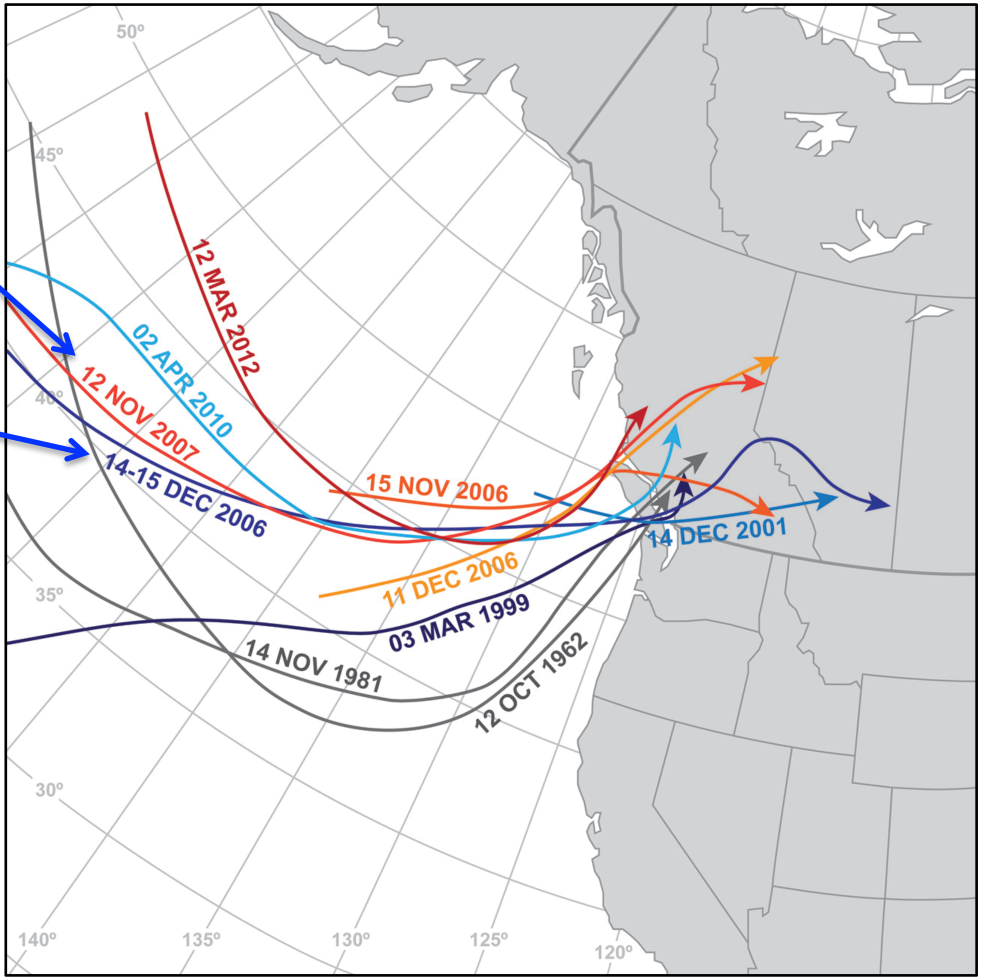
- Based on the four-step conceptual model of Mass and Dotson (2010)

Stage	Key Conditions / Features
1: Pre-frontal	• Low well offshore • Cold surface layer emplaced • Strong gap winds (NE to E)
2: Post-frontal	• Cold surface layer scoured out • Warming temperatures • Increasing winds (SE to S)
3: Bent-back trough	• Strongest pressure gradient • Strongest winds (S to SW)
4: Termination	• Weakening low • Slowing winds (SW to W)

Meteorology of Southwest BC Windstorms

Results

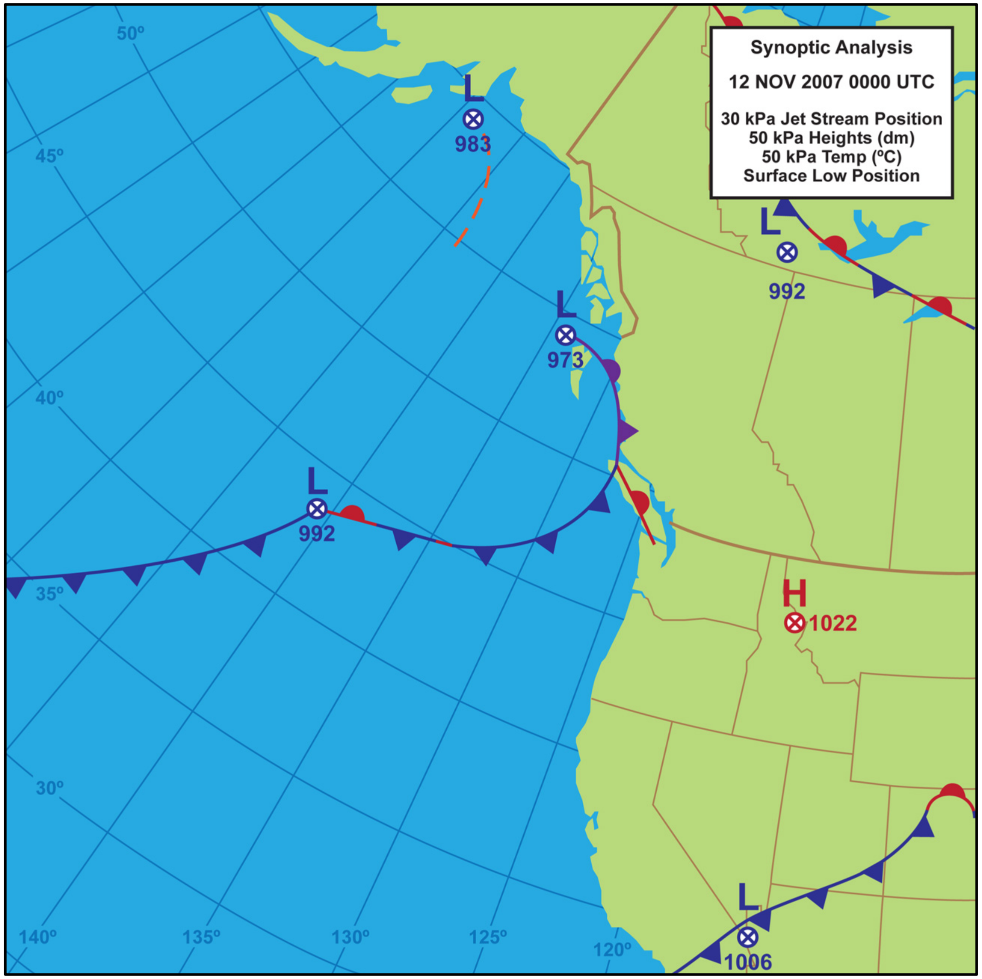
- Will focus on just two storms
- 12 Nov 2007, a southeaster
- 14-15 Dec 2006, a westerly windstorm



Meteorology of Southwest BC Windstorms

Synoptic Evolution

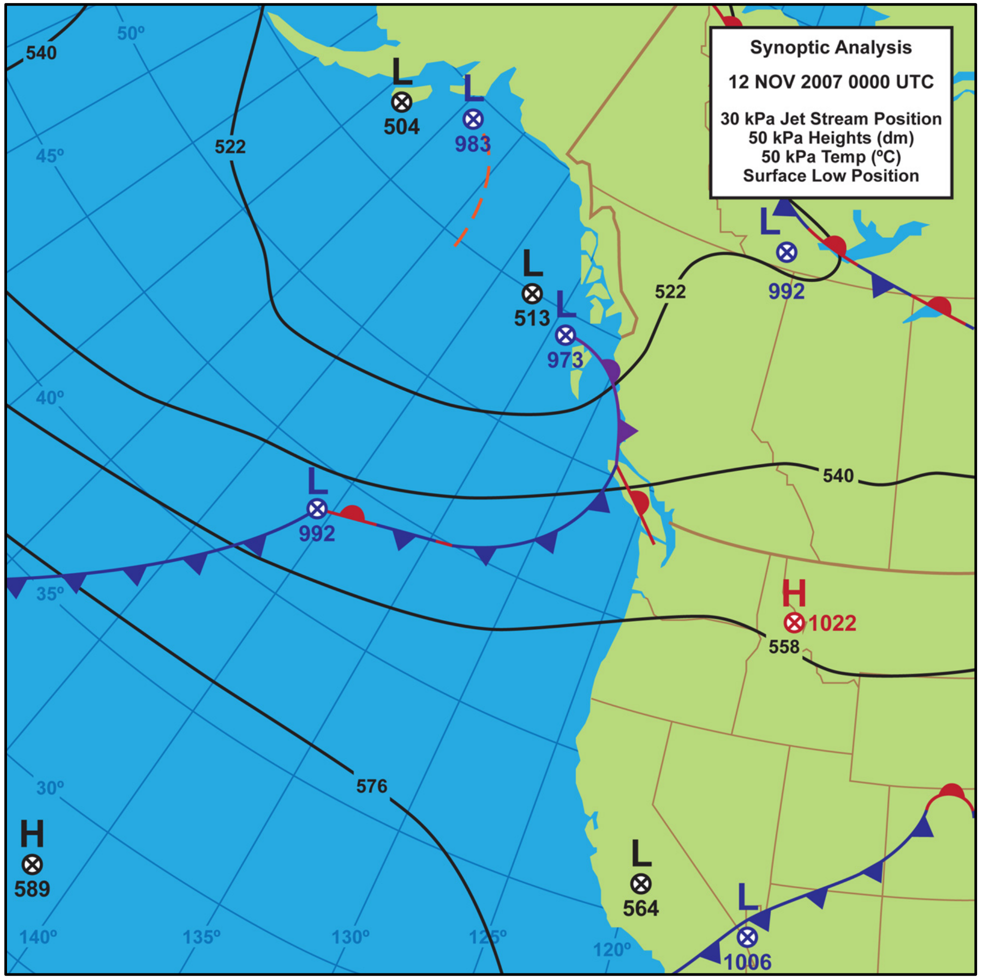
- Looking at the surface, the 12 Nov 2007 windstorm started far off of the southwest Oregon coast…



Meteorology of Southwest BC Windstorms

Synoptic Evolution

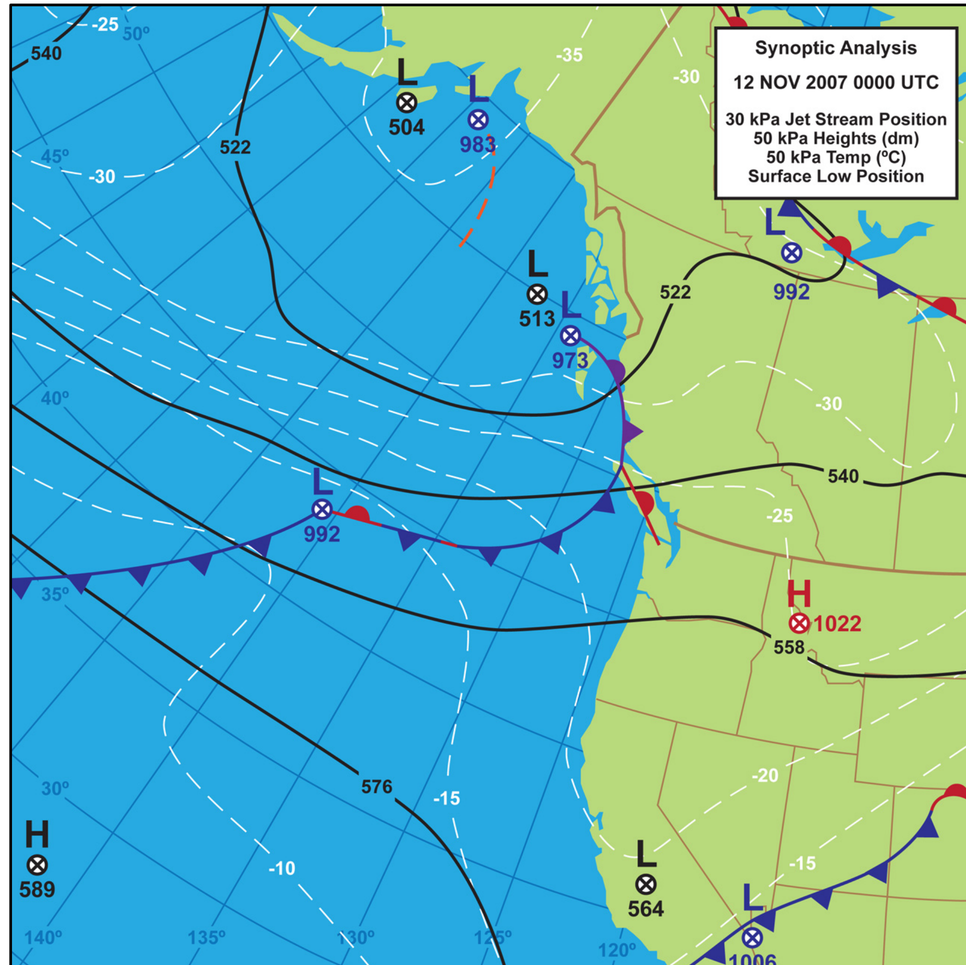
- Looking at the surface, the 12 Nov 2007 windstorm started far off of the southwest Oregon coast…
- Near the base of a broad 50 kPa trough…



Meteorology of Southwest BC Windstorms

Synoptic Evolution

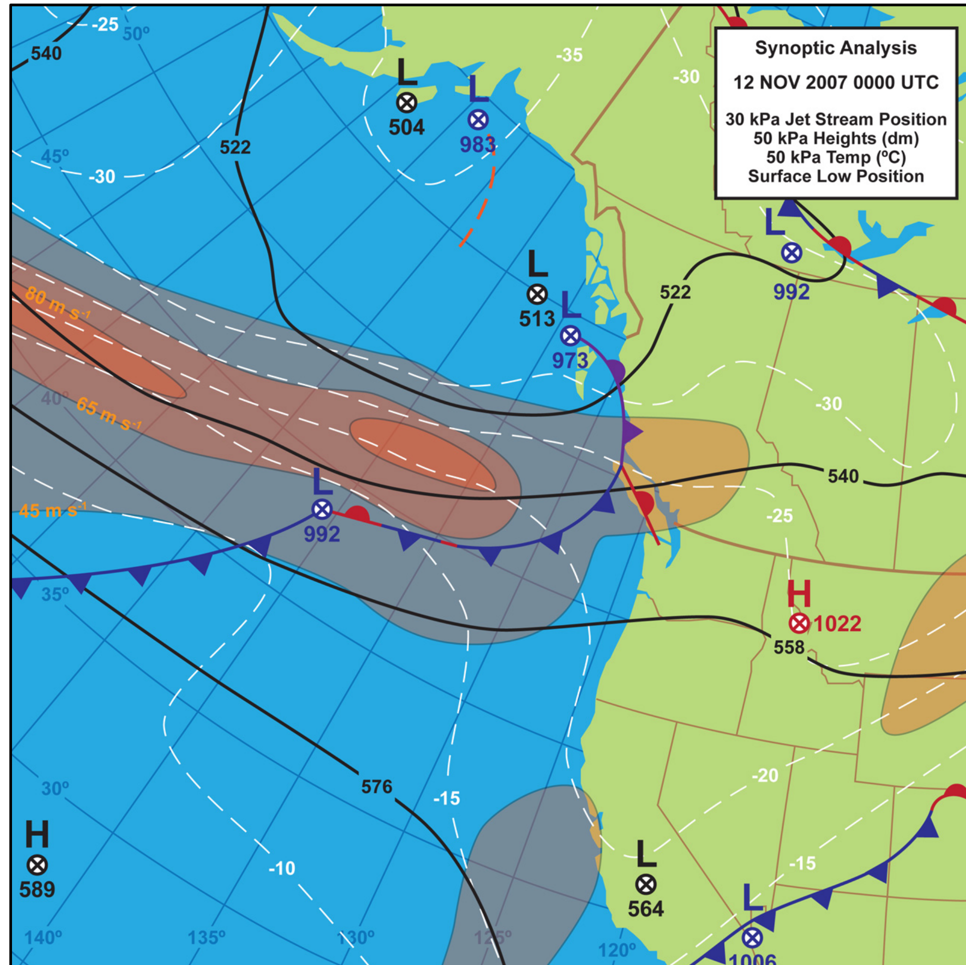
- Looking at the surface, the 12 Nov 2007 windstorm started far off of the southwest Oregon coast…
- Near the base of a broad 50 kPa trough…
- In a baroclinic region with warm advection (50 kPa T shown) moving toward the West Coast…



Meteorology of Southwest BC Windstorms

Synoptic Evolution

- Looking at the surface, the 12 Nov 2007 windstorm started far off of the southwest Oregon coast…
- Near the base of a broad 50 kPa trough…
- In a baroclinic region with warm advection (50 kPa T shown) moving toward the West Coast…
- And under the *right entrance* region of an ~80 m s^{-1} 30-kPa jet streak

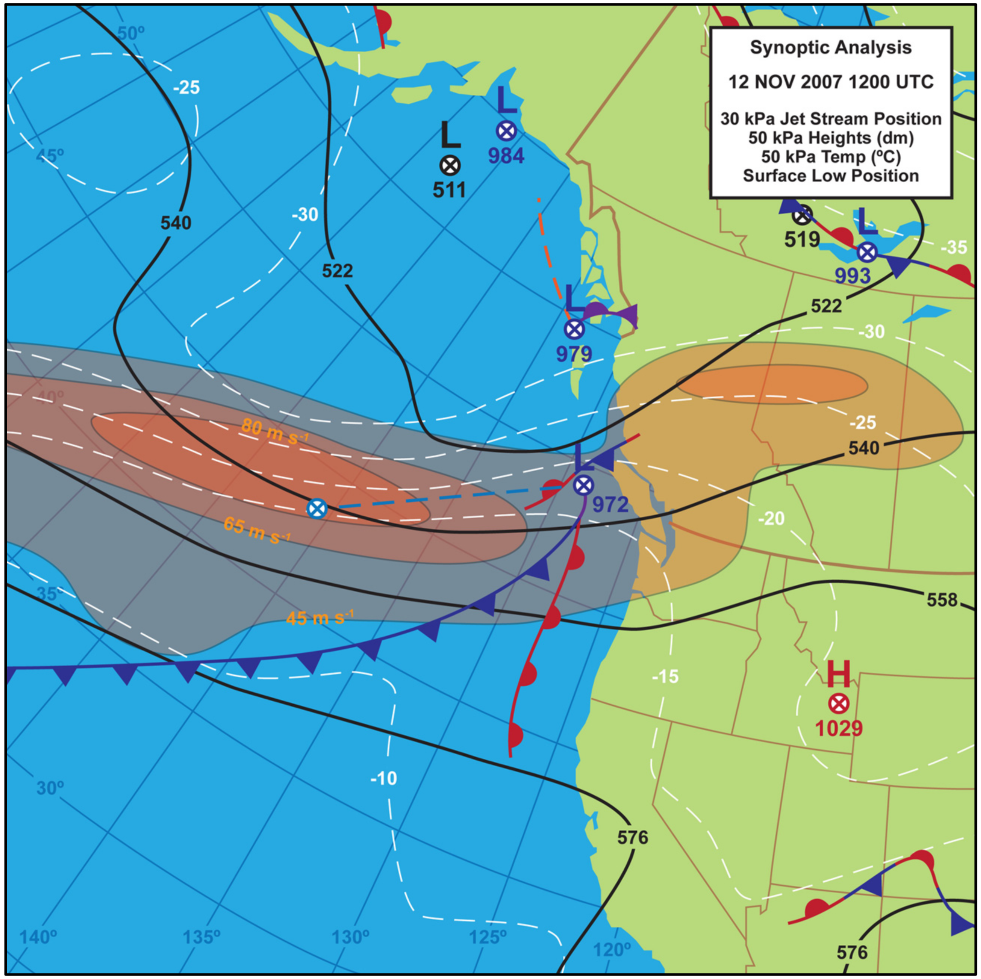


Shapiro and Keyser (1990) stage: I

Meteorology of Southwest BC Windstorms

Synoptic Evolution

- Over the next 12 h…
- The surface low moved, roughly, under the left exit region of a second jet streak
- And into the southeast side of the 50 kPa trough
- Following the upper steering currents, the low tracked northeast toward northern Vancouver Island
- Deepened 20 hPa (12) h^{-1}

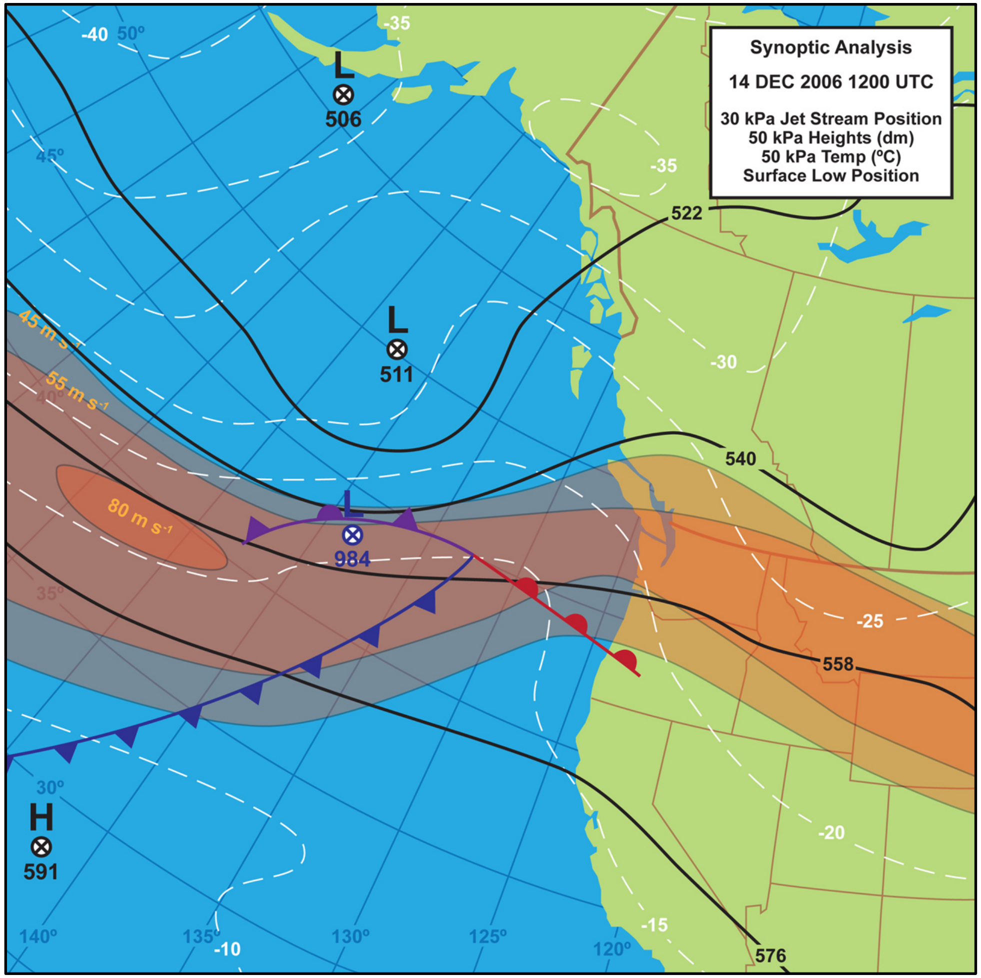


Shapiro and Keyser (1990) stage: II

Meteorology of Southwest BC Windstorms

Synoptic Evolution

- The 15 Dec 2006 windstorm began in similar fashion
- Near the base of a broad 50 kPa trough and in a baroclinic zone
- But this time under the left exit region of an 80 m s^{-1} jet streak, a more classic start

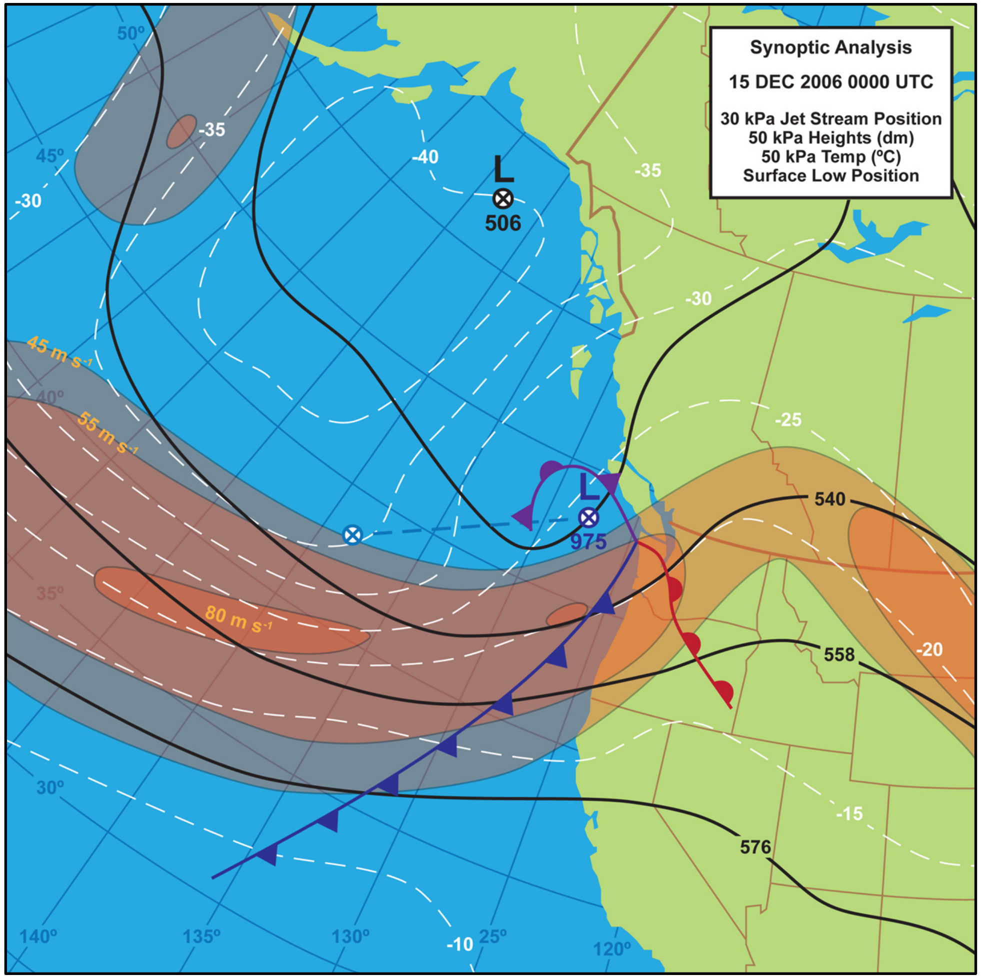


Shapiro and Keyser 1990 stage: II

Meteorology of Southwest BC Windstorms

Synoptic Evolution

- Over 12 h, the surface low tracked northeast and neared southern Vancouver Island
- Moved to the southeast side of the 50 kPa trough
- Still near jet support
- Deepened 9 hPa (12) h^{-1}

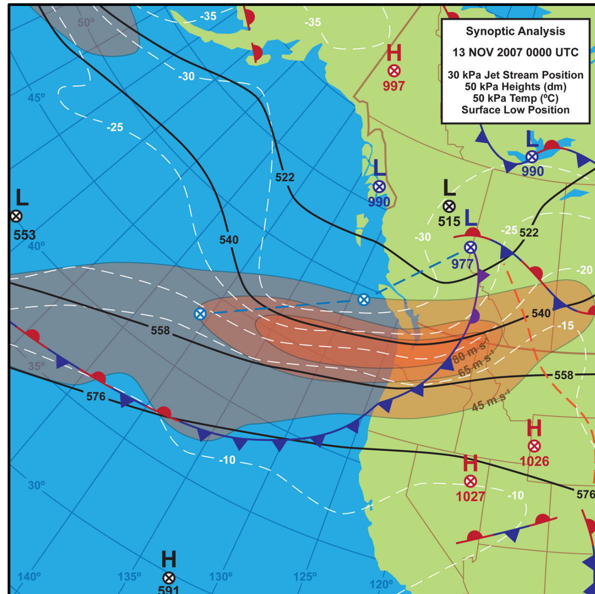


Shapiro and Keyser 1990 stage: III

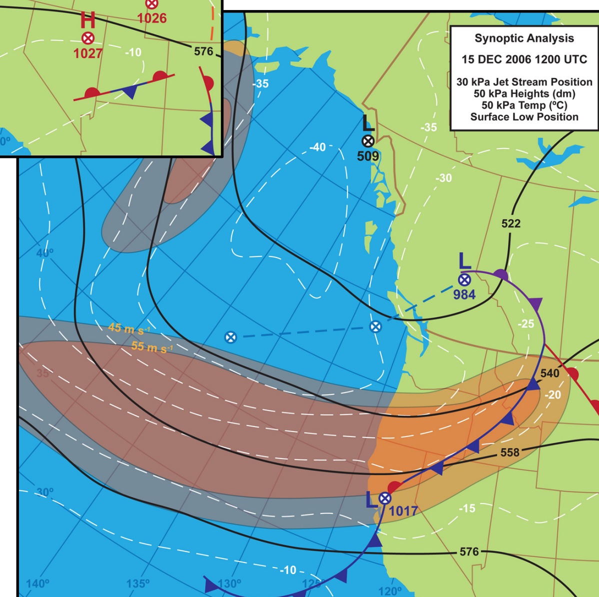
Meteorology of Southwest BC Windstorms

Synoptic Evolution

- Synoptically, the two windstorms shared many similarities
- Yet they had different peak wind directions (SE vs. W)
- The fine details, including their exact tracks across Vancouver Island, explain the difference



12 Nov 2007

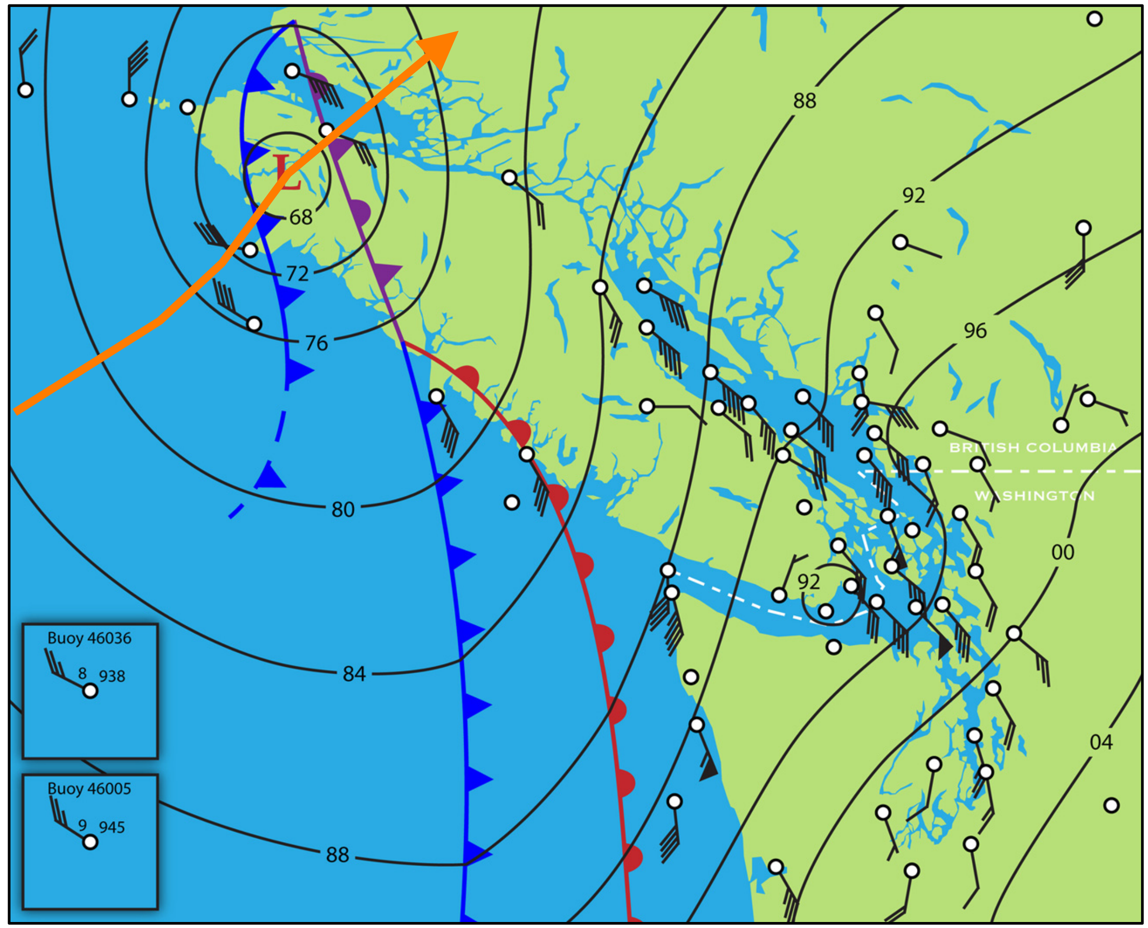


15 Dec 2006

Meteorology of Southwest BC Windstorms

Mesoscale Analysis

- 96.6 kPa low center tracks across northern Vancouver Island
- E to ESE pressure slope (Lange 1998) supportive of SE winds at the study stations
- Strong secondary cold front (i.e. bent-back front) behind low tracks north of the study region

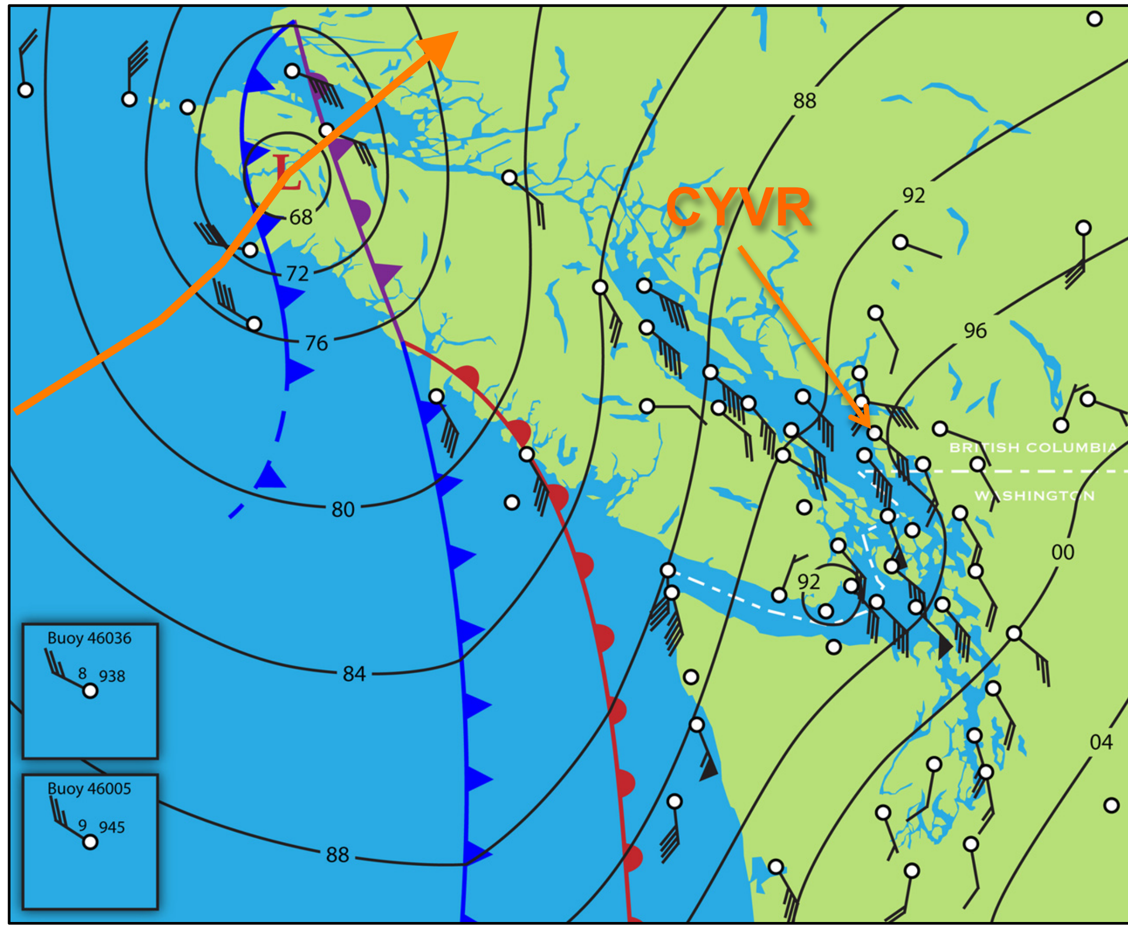


1500 UTC 12 Nov 2007

Meteorology of Southwest BC Windstorms

Mesoscale Analysis

- Peak winds in the study region (e.g. CYVR) occurred around the time of landfall
  - Before the low significantly weakened due to terrain-forced ageostrophic flow
- Peak winds also occurred well ahead the main fronts

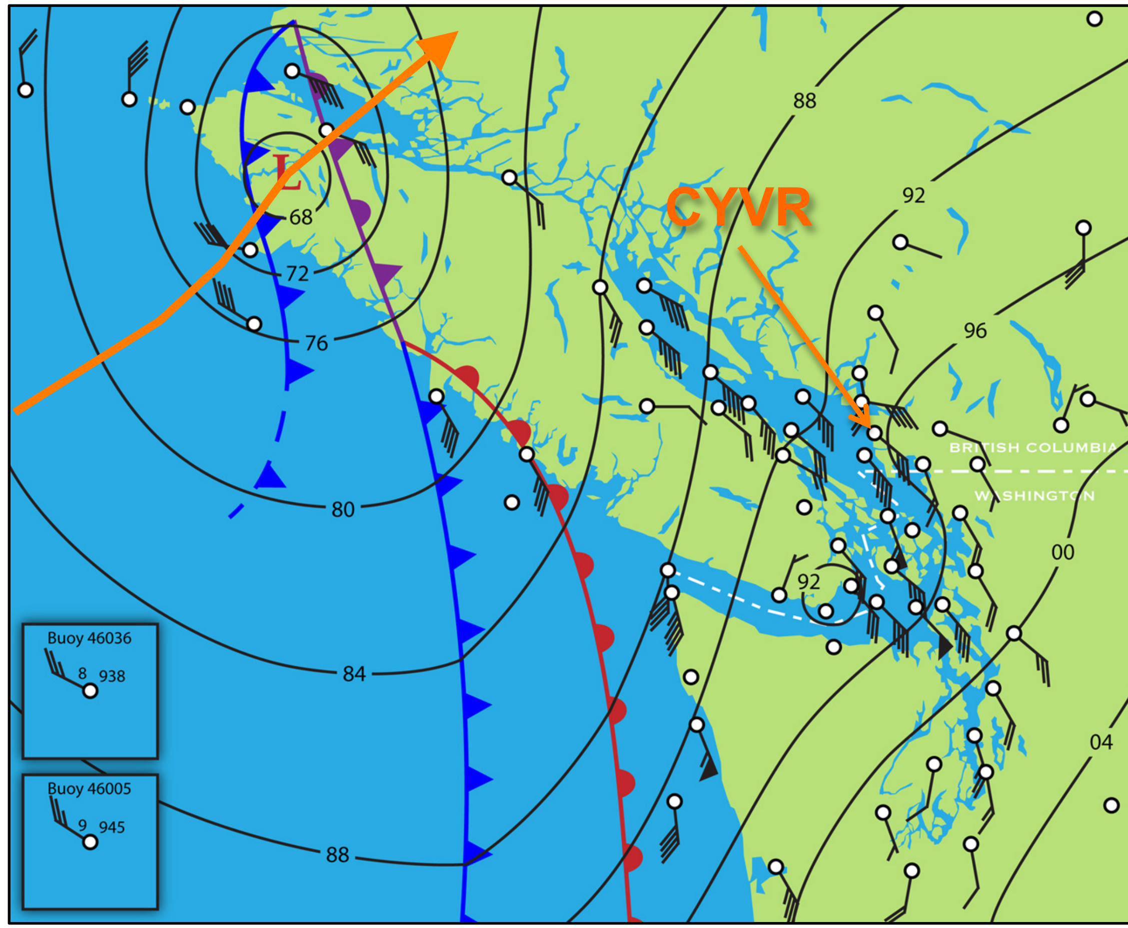


1500 UTC 12 Nov 2007

Meteorology of Southwest BC Windstorms

Mesoscale Analysis

- The secondary cold front tracked too far to the north and west to make a significant contribution to peak wind magnitude or timing

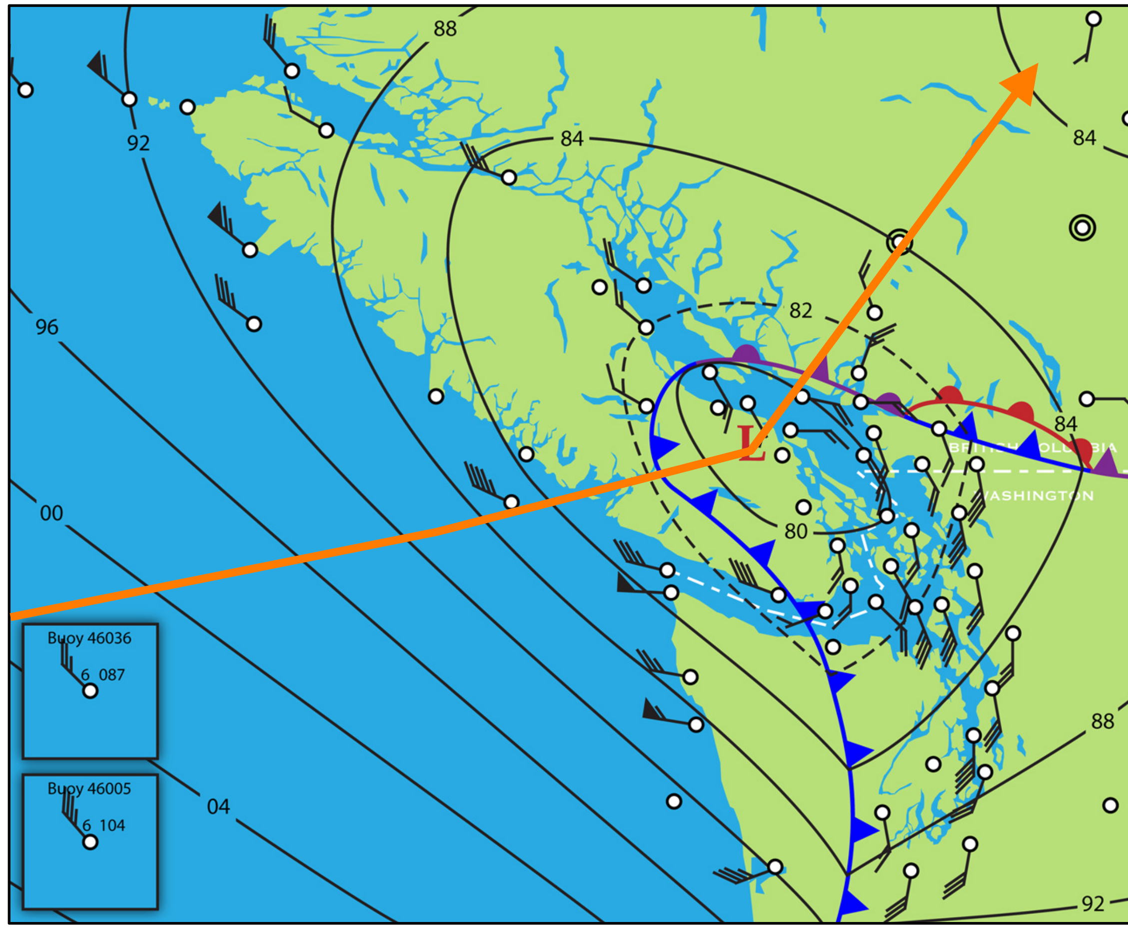


1500 UTC 12 Nov 2007

Meteorology of Southwest BC Windstorms

Mesoscale Analysis

- 97.6 kPa low tracks across *southern* Vancouver Island
- East to east-northeast pressure slope ahead of low supports E winds at the study stations
  - Save at stations affected by the warm sector (e.g. CYXX)
- Secondary cold front behind low tracks through the region, bringing W winds



0800 UTC 15 Dec 2006

Meteorology of Southwest BC Windstorms

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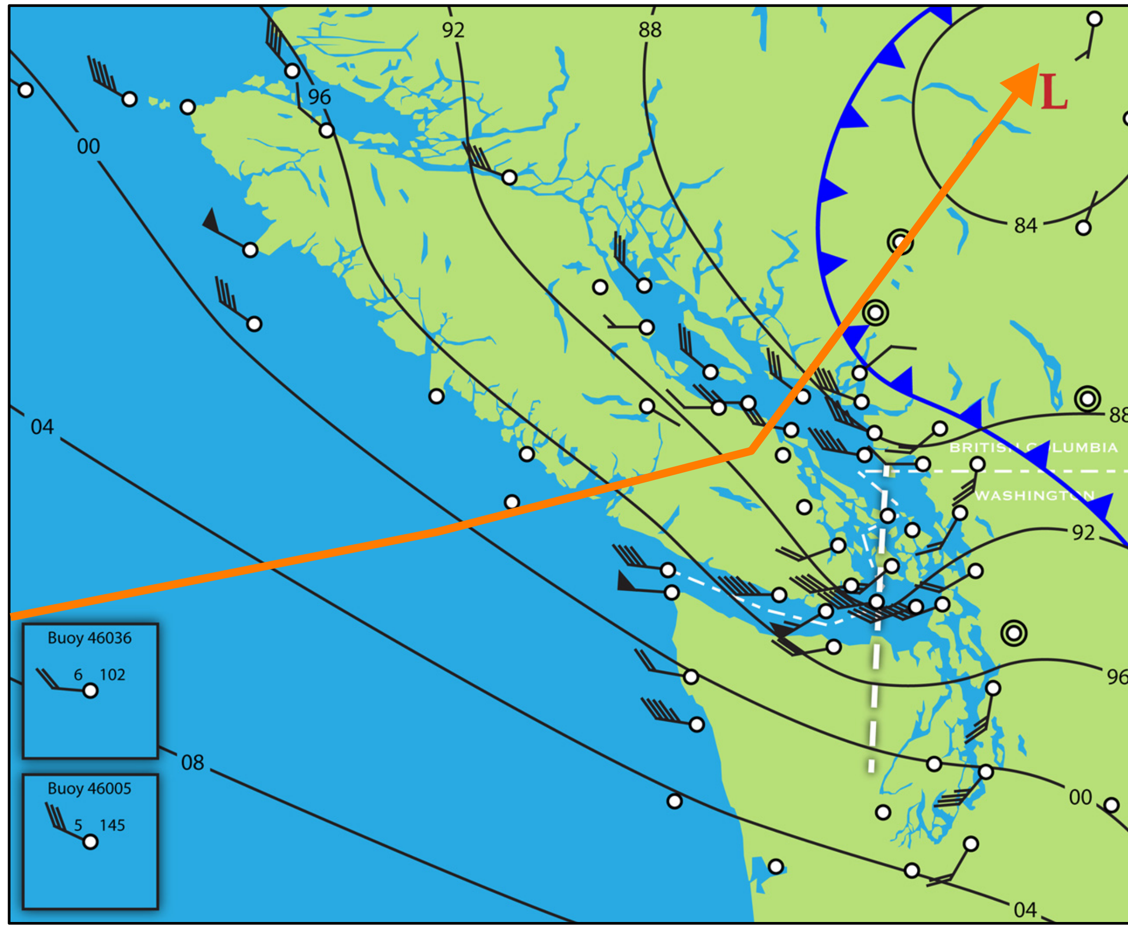
- 97.6 kPa low tracks across *southern* Vancouver Island
- East to east-northeast pressure slope ahead of low supports E winds at the study stations
  - Save at stations affected by the warm sector (e.g. CYXX)
- Secondary cold front behind low tracks through the region, bringing W winds

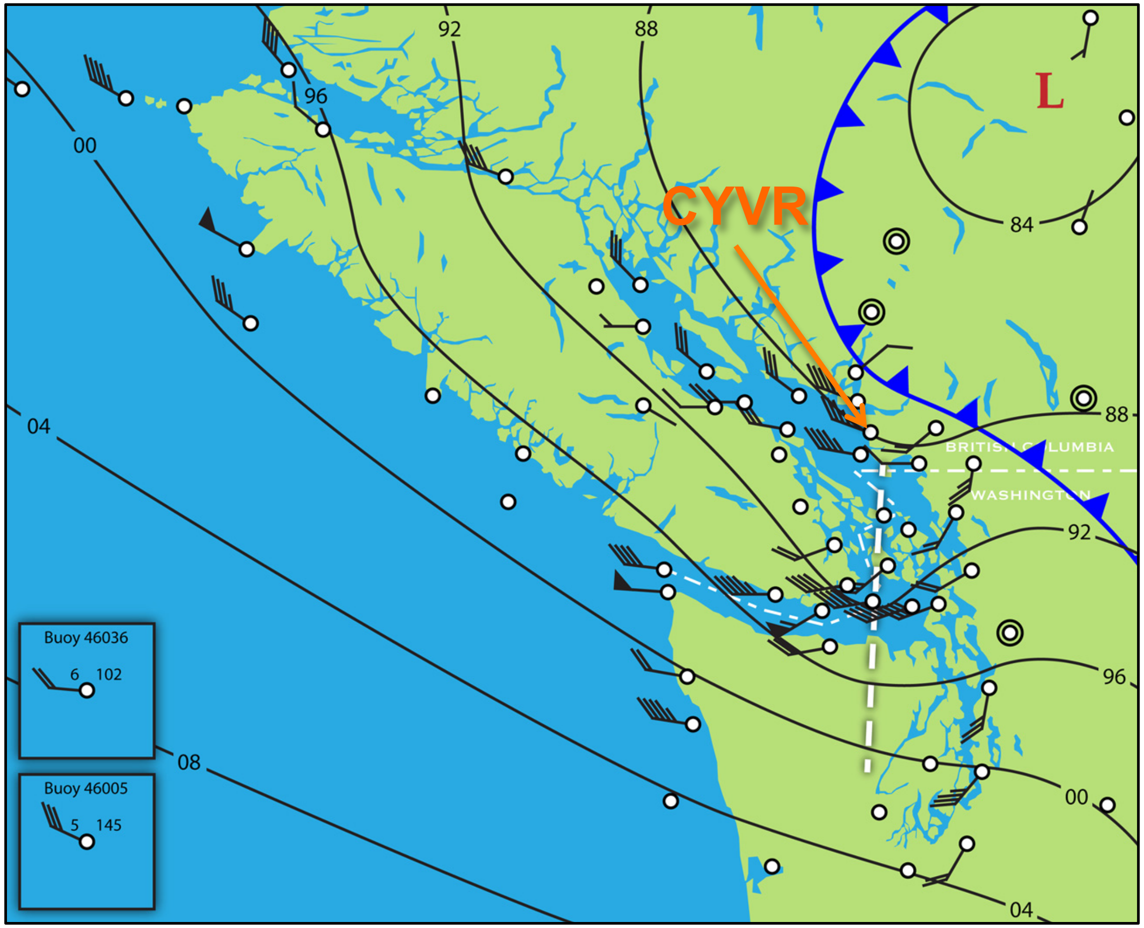


1100 UTC 15 Dec 2006

Meteorology of Southwest BC Windstorms

Mesoscale Analysis

- Peak winds arrive during the passage of the secondary cold front, long after the low has made landfall and moved inland
  - Exception is CYXX where peak winds occurred in the leading warm sector in a fashion typical of a southeaster
- Southwesterly pressure slope supportive of W to NW winds down the Georgia Strait



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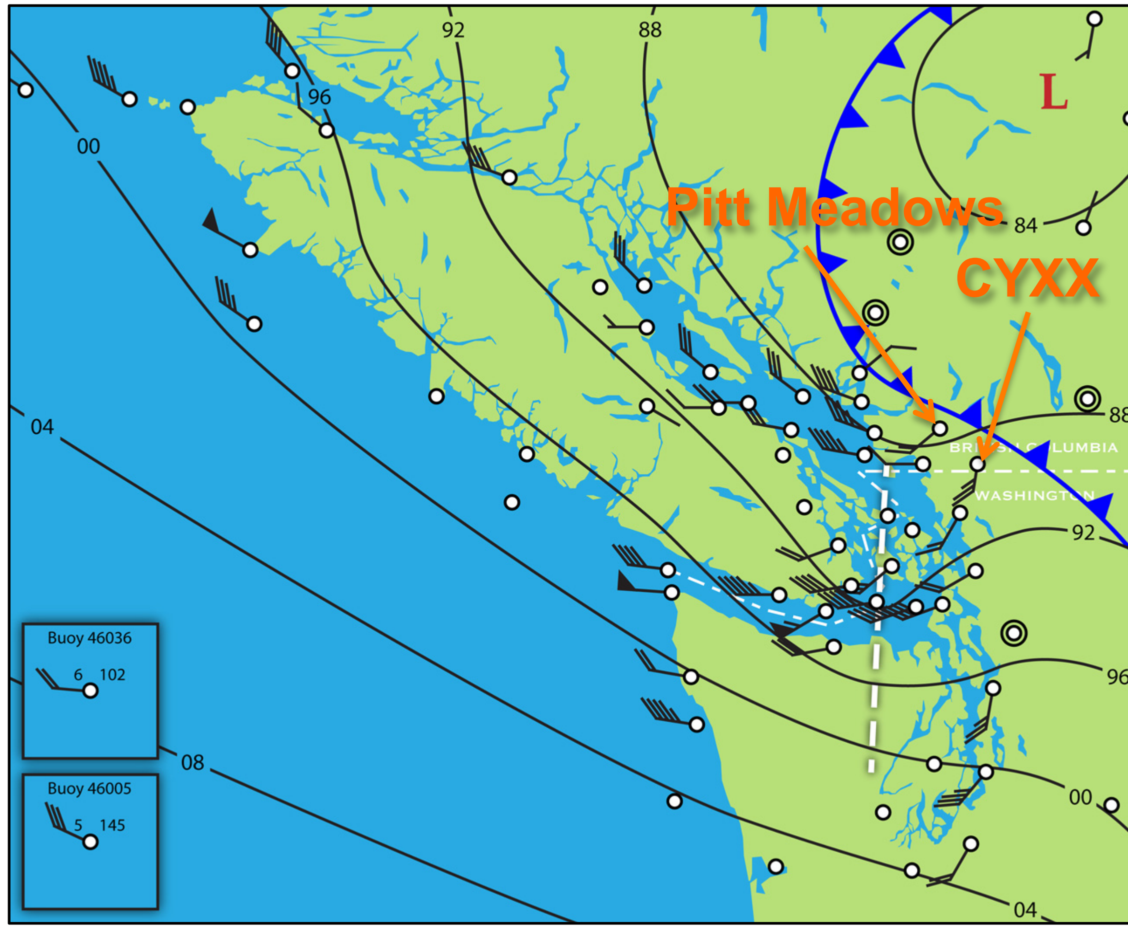
Meteorology of Southwest BC Windstorms

Mesoscale Analysis

- The full strength of the overwater W winds did not penetrate far inland due to turbulent drag
- This is different from southeasters, which tend to affect the Lower Mainland more uniformly

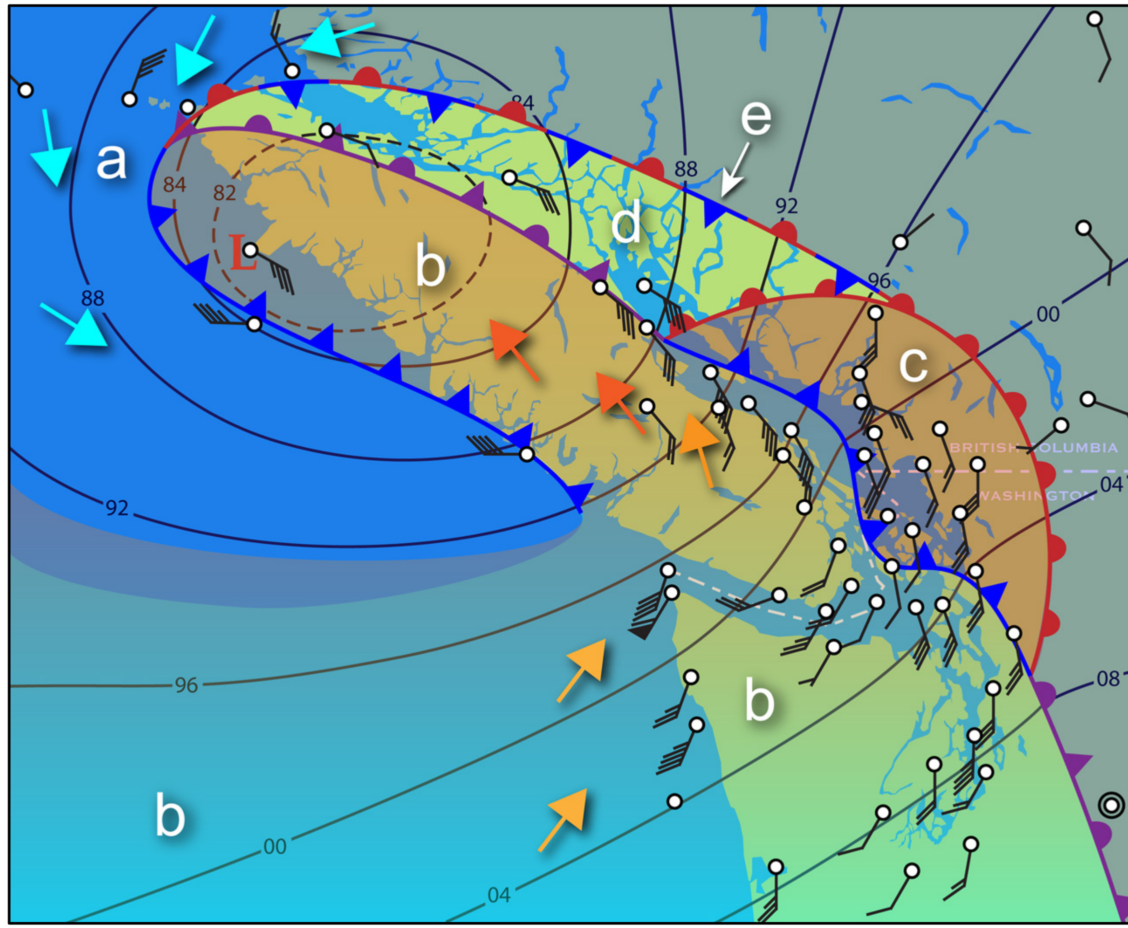


1100 UTC 15 Dec 2006

Meteorology of Southwest BC Windstorms

Mesoscale Analysis

- Conceptual model of a landfalling ETC with a strong secondary cold front
- Continental-polar air sourced from the BC interior (a)
- New cold front essentially transforms the old cold sector into a de-facto warm sector (Bjerknes and Solberg 1922) (b)



Meteorology of Southwest BC Windstorms

Windstorm Conceptual Model for Study Region

Modifying the four-step conceptual model of Mass and Dotson (2010):

Stage	Key Conditions / Features
1: Pre-landfall	• Low well offshore, deepening • Cold surface layer emplaced • Gradually escalating winds (E to SE)
2: Landfall	• Rising central pressure • Weakening pressure gradients around core • Peak winds for southeasters
3: Bent-back trough or post-landfall	• Bent-back front closest approach • Weakening winds for southeasters • Peak winds for westerly windstorms
4: Termination	• Weakening low well inland • Slowing winds (SW to W)

Meteorology of Southwest BC Windstorms

Key Conclusions

- Storm track is an important determiner of peak wind direction
- For southeasters, peak winds tend to occur at the time of landfall
- For westerly windstorms, peak winds tend to occur after the low has moved inland and passed to the east
- Secondary cold fronts can develop when cold continental-polar air wraps around an incoming low
  - The most intense winds are sometimes associated with these fronts, especially during westerly windstorms
  - Hanukkah Eve Storm can be considered the archetypical example

Tree-Related Damage to the BC Hydro Distribution Grid

Background

Knowledge Gaps: Power Outages

- Research focused on the vicinity of southwest BC is limited:
  - Taylor and Neale (2007) used threshold analysis on BC Hydro data for Victoria
  - Guggenmoos (2011) used approaches that included a Weibull fit on Puget Sound Energy data
  - Hirata (2011) used logistic regression on a spatial outage dataset from BC Hydro with a focus on the Lower Mainland's North Shore

- These studies by and large did not use an independent storms approach

- Nor did they look at outages on an hour-by-hour basis

Tree-Related Distribution Grid Outages

Methods

- Hourly and Special observations from Environment Canada for stations in southwest BC, including:
  - Vancouver (CYVR)
  - Abbotsford (CYXX)

- Power outage dataset from BC Hydro covering the period October 2005 to August 2009, including:
  - Time of outage
  - Outage type (e.g. forced, planned)
  - Cause of outage (e.g. tree/branch, wildlife)
  - Location information (circuit number, equipment ID, lat/long)
  - Number of customers affected

Tree-Related Distribution Grid Outages

Methods

- For the Oct 2005 to Aug 2009 period:

- Manually determined all independent storms with a peak wind of >40 km h^{-1} (22 knots) at either CYVR or CYXX
  - Isolated 119 events

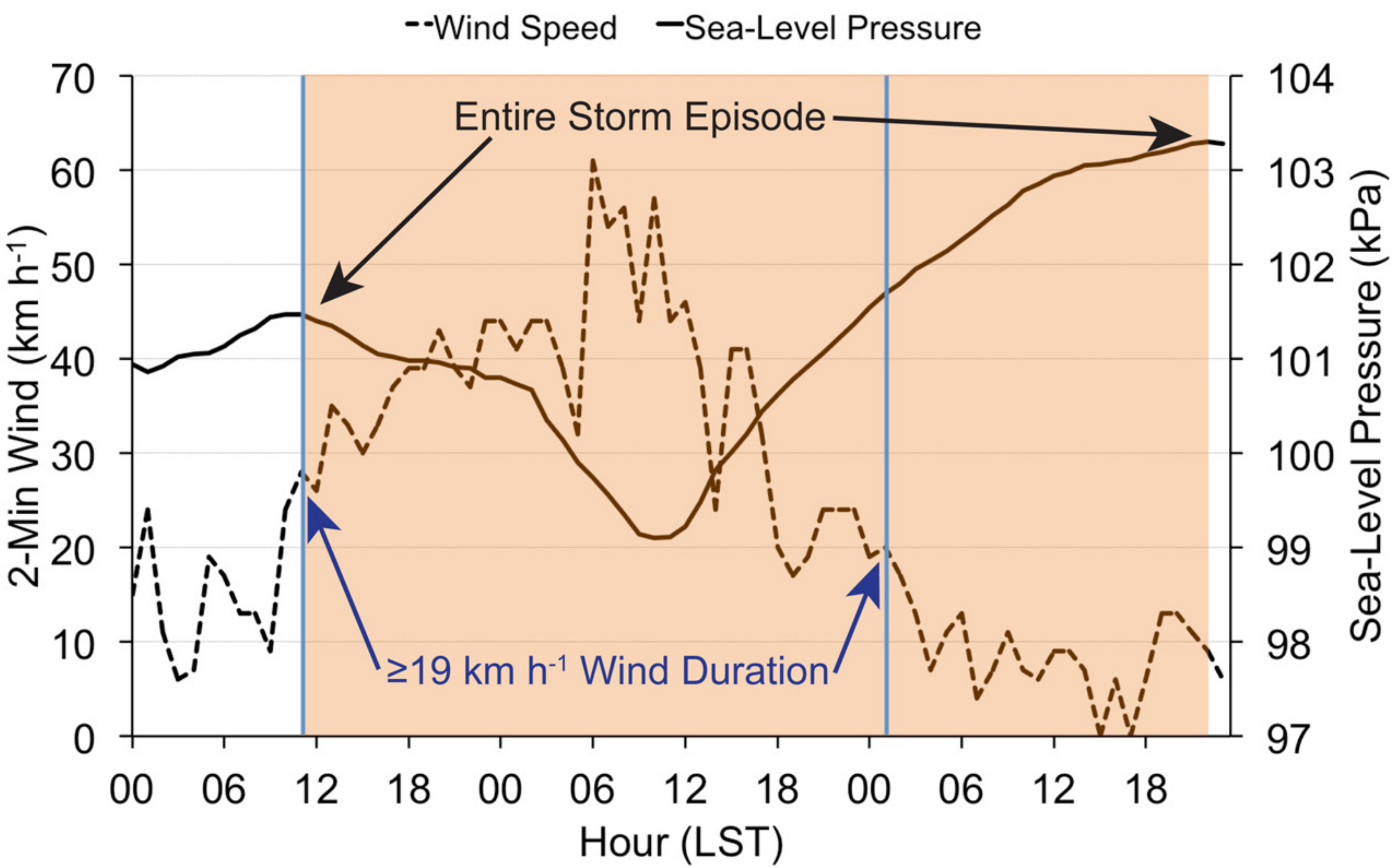
- Wind duration was bounded by the first and last observation of ≥19 km h^{-1} (10 knots, 80^{th} percentile) within the pressure fall and rise phase of a given storm

- Wind duration is the range of time in which all outages were counted
  - Allowed two extra hours at each end to account for spatial variation in wind across the Lower Mainland

Tree-Related Distribution Grid Outages

Methods

11-13 November 2007 Windstorm at CYVR



Tree-Related Distribution Grid Outages

Methods

Line Faults

- For the purposes of this analysis, a line fault is when any tree or branch impacts a line
- May not result in an outage, though most do
- Line faults not associated with an outage still have to be dealt with by line crews (e.g. removal of a branch hanging from wires)

Tree-Related Distribution Grid Outages
Methods

Study Region

- 50 km radius of CYVR (dark red)
- Excludes Vancouver Island, some Gulf Islands and Washington State
- 491 individual distribution circuits

Tree-Related Distribution Grid Outages

Methods

- For the Oct 2005 to Aug 2009 period:
- Isolated all tree-related line faults within a 50 km radius of CYVR
  - Returned 2146 incidents for the 119 storms
- Used this data to build linear and Poisson regression models
- Poisson regression is preferred because line-faults is count data (Zhou et al. 2006)

Tree-Related Distribution Grid Outages

Results

All Storms (n=119)

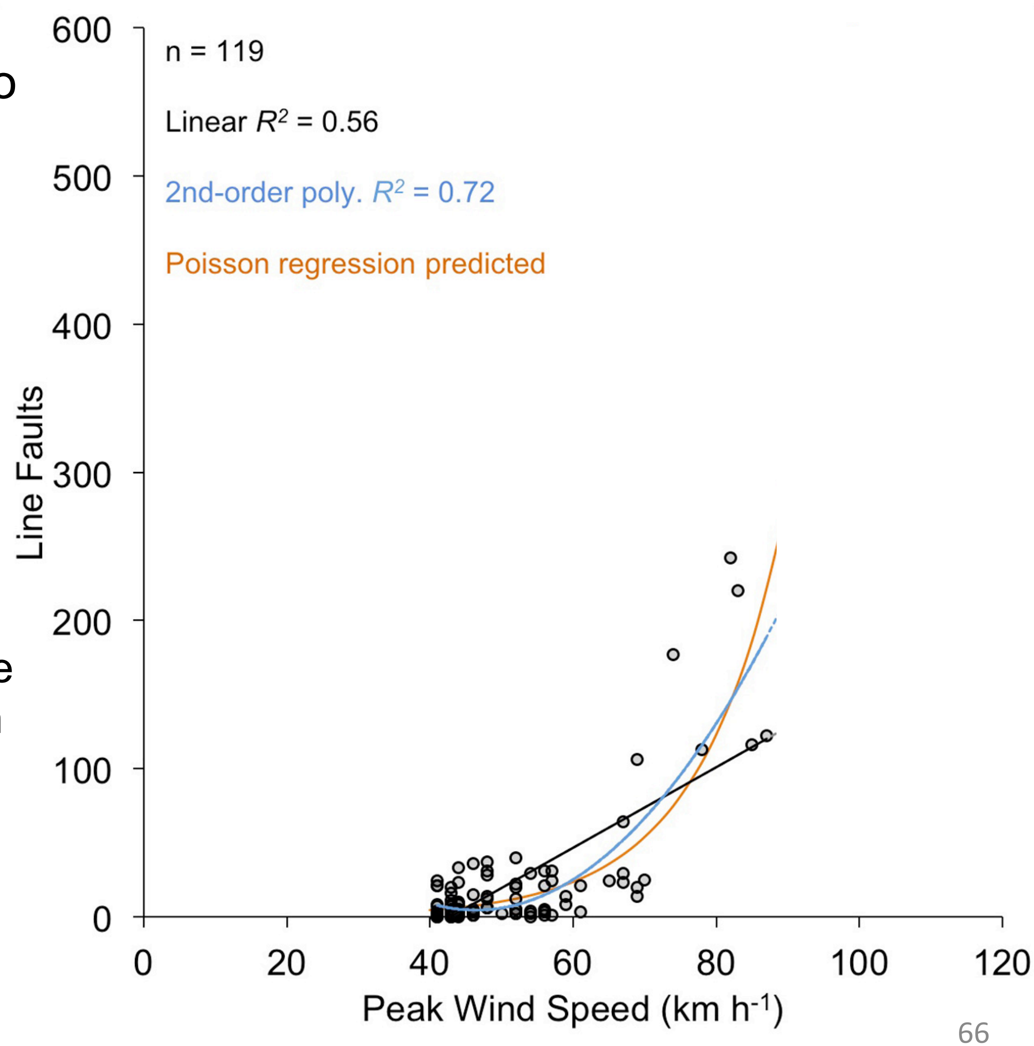
Variable	wnddir	maxwnd	maxgst	strmpcpn	linefalt	uniquelf	custo
maxwnd	0.04						
maxgst	-0.17	0.90					
strmpcpn	-0.29	0.12	0.19				
linefalt	-0.14	**0.75**	**0.75**	0.19			
uniquelf	-0.15	**0.80**	**0.81**	0.25	0.93		
custo	-0.13	**0.73**	**0.73**	0.13	0.85	0.80	
stormdur	0.01	0.09	0.13	0.26	0.21	0.18	0.18

- Pearson correlations between eight variables
  - Peak wind (maxwind)
  - Peak gust (maxgust)
  - Wind direction (windir)
  - Storm total precipitation (strmpcpn)
  - Storm duration (stormdur)
  - Total Line Faults (linefalt)
  - Independent circuits hit (uniquelf)
  - Customers out (custo)

Tree-Related Distribution Grid Outages

Independent Storm Peak Wind and Line Faults

- Linear and polynomial regression show a moderate to moderately strong relationship (respectively)
  - Poisson regression uses maximum likelihood and not least-squares
  - A maximum likelihood approach does not offer a convenient means of assessing model strength like a coefficient-of-determination

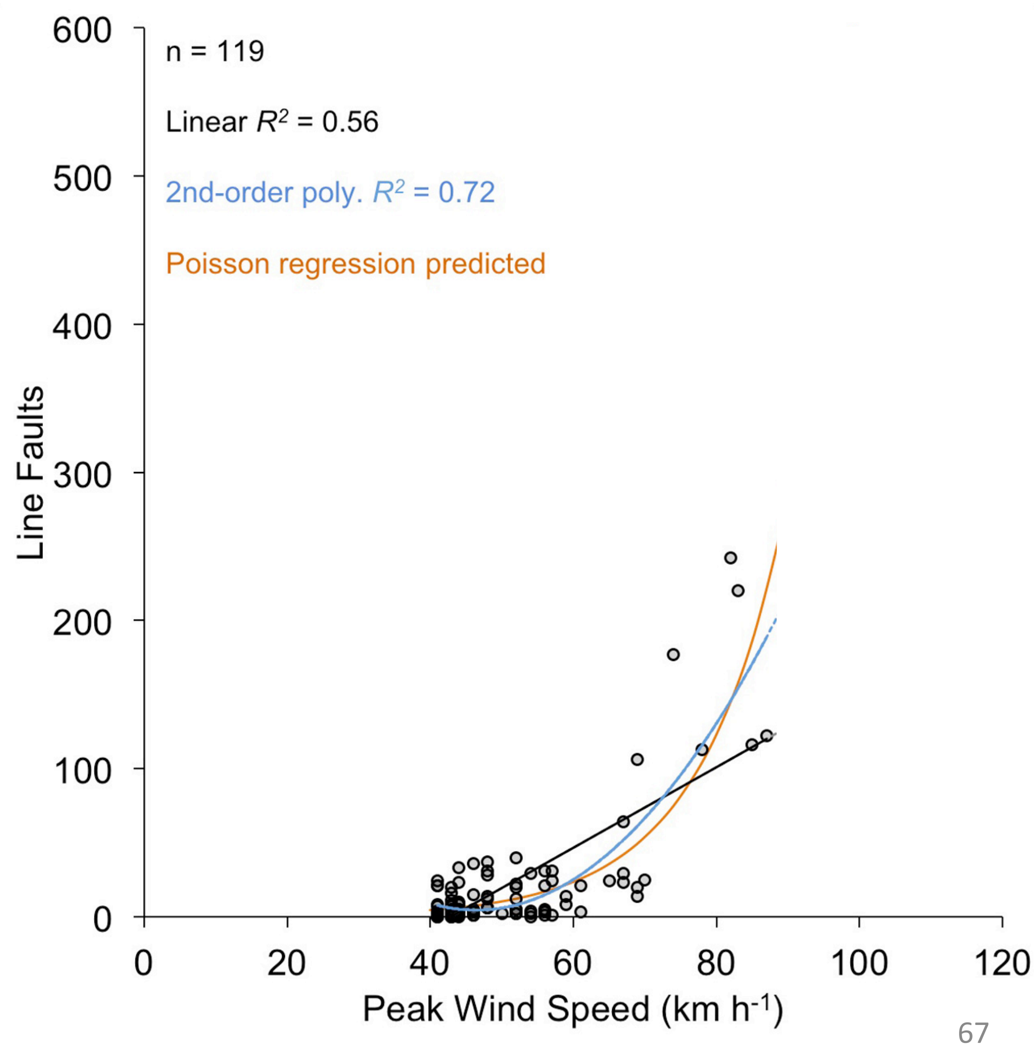


Tree-Related Distribution Grid Outages

Independent Storm Peak Wind and Line Faults

- The Poisson regression predicted (and the polynomial best-fit) suggest that damage to the power grid increases exponentially with wind speed

- An exponential increase in damage has been reported in other studies (e.g. Guggenmoos 2011)



Tree-Related Distribution Grid Outages

Independent Storm Peak Wind and Line Faults

- Multivariate Poisson regression models were also created using combinations of

  i. peak gust;
  ii. peak wind direction;
  iii. storm total rainfall; and
  iv. storm duration

- Shown at the left are the AICs for these models
  - Lower AICs indicate a stronger model
- The strongest is highlighted in bold

Model Variables	AIC
Null: line faults with no predictor variables	5180
Peak wind	1787
Peak wind, wind direction	1599
Peak wind, storm duration	1658
Peak wind, storm total precipitation	1657
Peak wind, storm total precipitation, storm duration	1576
Peak wind, wind direction, storm total precipitation	1509
Peak wind, wind direction, storm total precipitation, storm duration	1466
Peak wind, wind direction type and wind interactions	1550
Peak wind, wind direction type, storm total precipitation and wind interactions	1488
Peak wind, wind direction type, storm total precipitation, storm duration and wind interactions	1417
Peak gust	1577
Peak wind, peak gust	1567
Peak wind, peak gust, wind direction	1495
Peak wind, peak gust, storm duration	1511
Peak wind, peak gust, storm total precipitation	1435
Peak wind, peak gust, wind direction, storm duration	1461
Peak wind, peak gust, wind direction, storm duration, storm total precipitation	1376
Peak wind, peak gust, wind direction type, and wind interactions	1358
Peak wind, peak gust, wind direction type, storm duration and wind interactions	1323
Peak wind, peak gust, wind direction type, storm total precipitation and wind interactions	1289
Peak wind, peak gust, wind direction type, storm total precipitation, storm duration and wind interactions	**1273**
Storm total precipitation	4919
Storm total precipitation, wind type and interactions	4689
Storm duration	4773

Tree-Related Distribution Grid Outages

Independent Storm Peak Wind and Line Faults

- Taking peak gust out of consideration:
- Adding peak wind direction, to peak wind (orange) results in the most model improvement
- Storm duration and storm total precipitation (blue) add some additional improvement
  - Not as strong as simply adding wind direction
- Including all basic variables (black) makes the strongest model

Model Variables	AIC
Null: line faults with no predictor variables	5180
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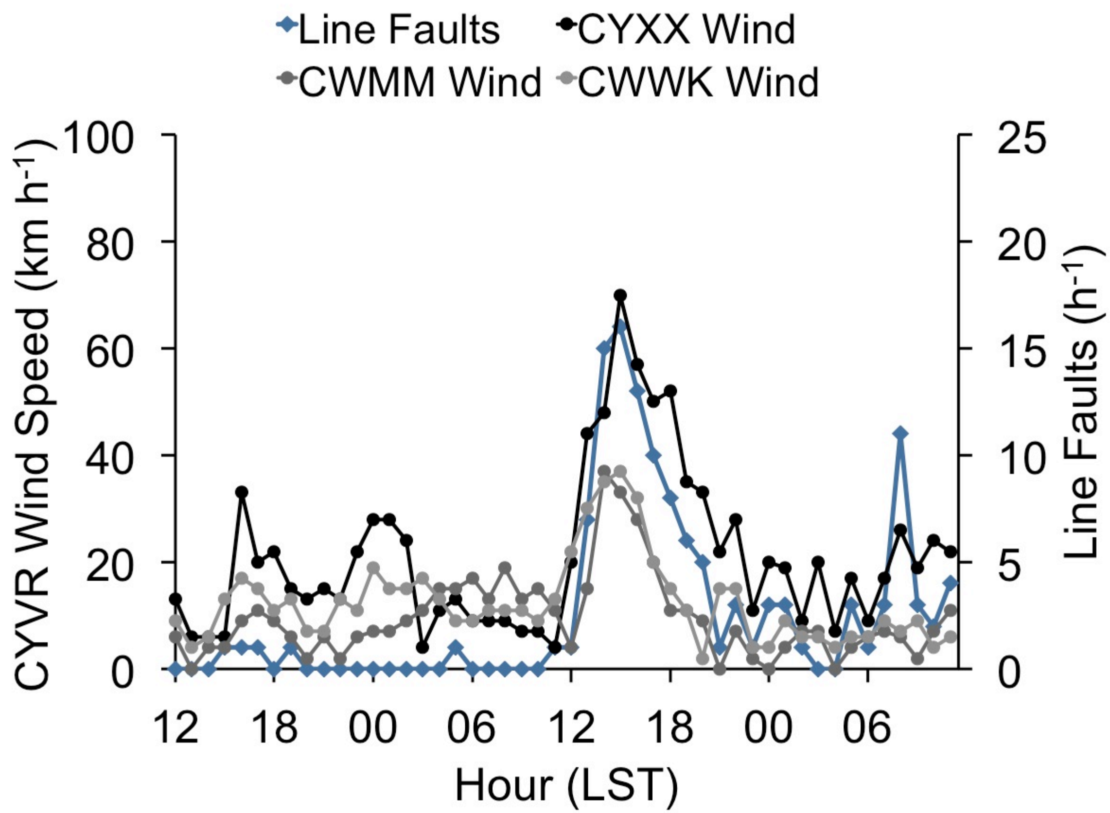
Tree-Related Distribution Grid Outages

Results: Hourly Analysis

- Comparing the total number of line faults over the previous hour (blue) to the hourly 2-min wind observation (black/gray)
  - CYXX = Abbotsford
  - CWMM = Pitt Meadows
  - CWWK = White Rock

- Looking specifically at CYXX, there is a clear relationship during this severe southeasterly windstorm

11-12 Dec 2006 Southeasterly Windstorm

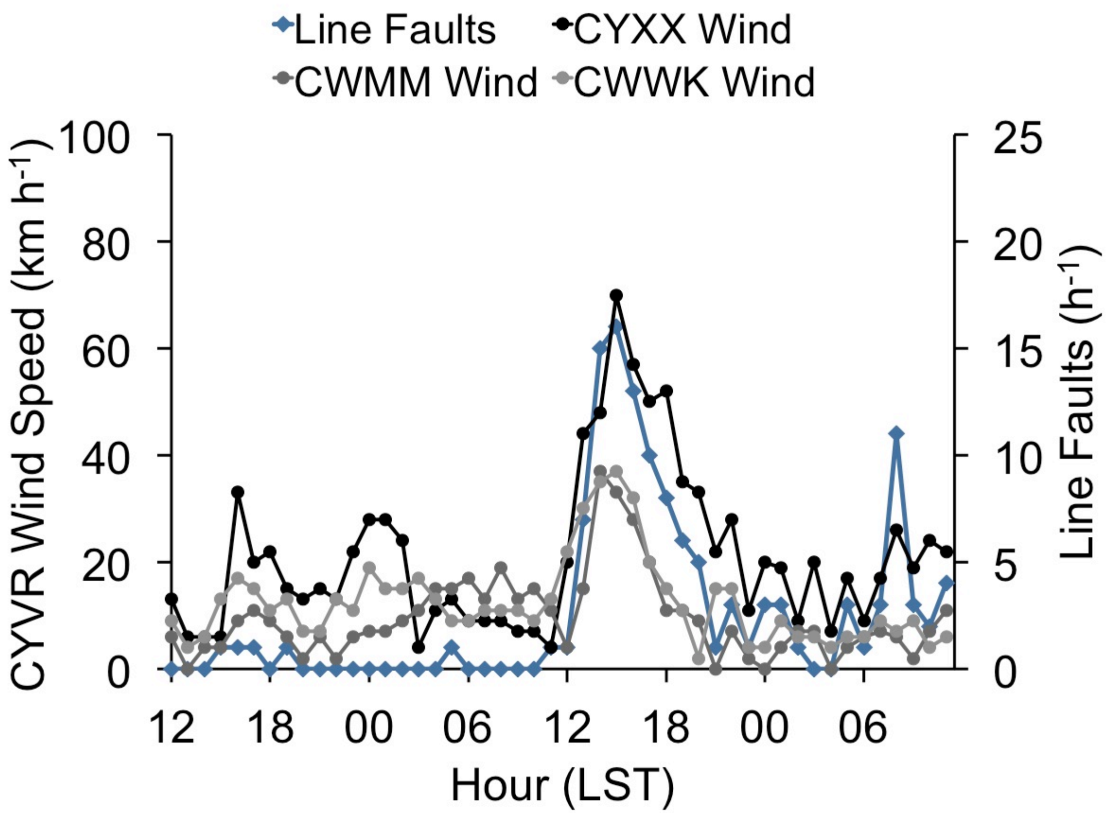


Tree-Related Distribution Grid Outages

Hourly Analysis

- Linear regression between hourly line faults and hourly 2-min wind speed during the main surge of wind (1200-2200 LST) has an R^2 of 0.82 with a positive slope

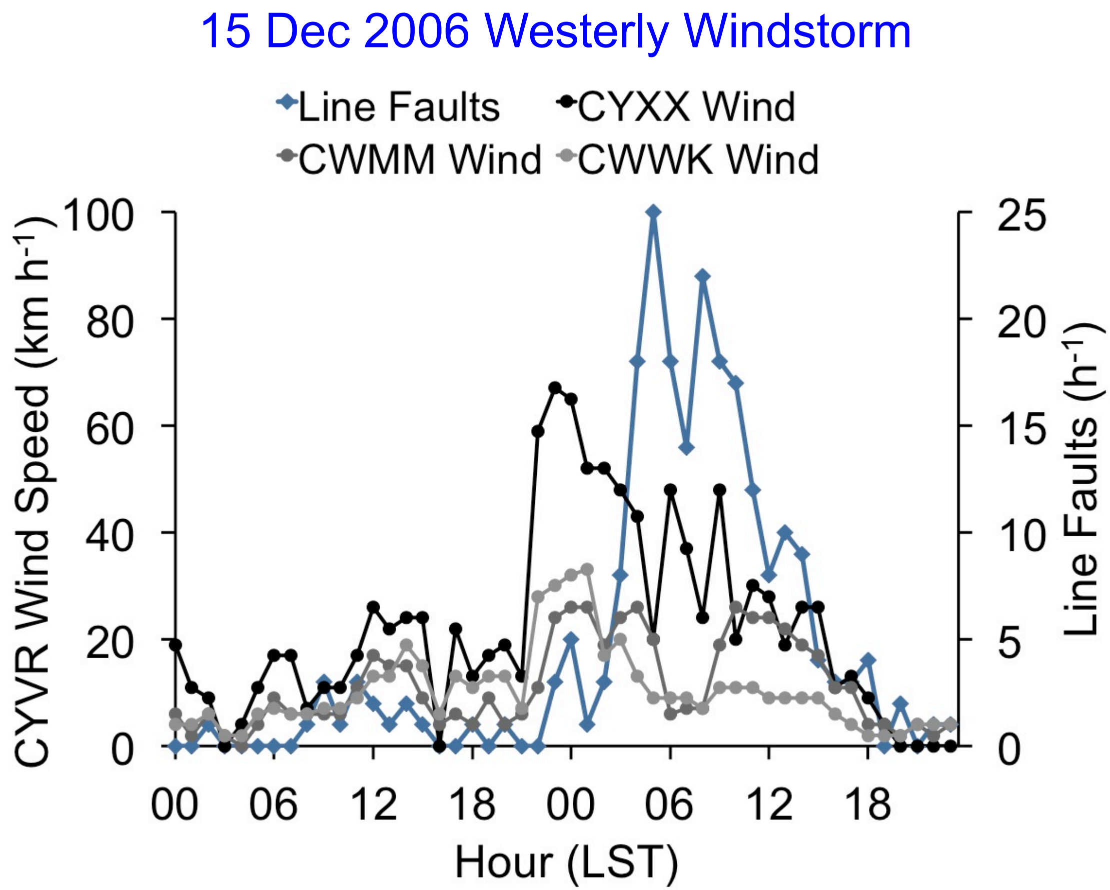
11-12 Dec 2006 Southeasterly Windstorm



Tree-Related Distribution Grid Outages

Hourly Analysis

- For the 15 Dec 2006 westerly windstorm, the relationship is much weaker
- Peak winds occurred well ahead of the spike in outages
- Linear regression has $R^2 = 0.39$ with a *negative* slope

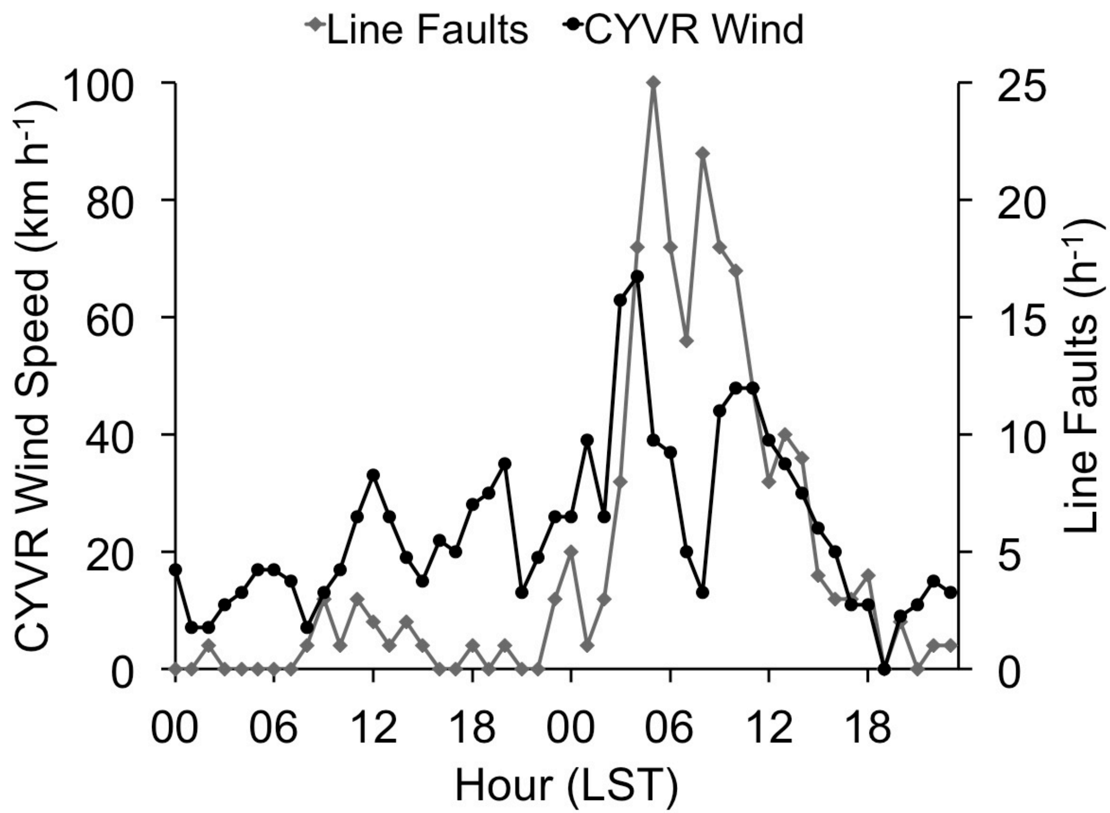


Tree-Related Distribution Grid Outages

Hourly Analysis

- At CYVR, there is a closer correspondence between line faults and wind speed during the 15 Dec 2006 storm
- Linear R^2 is 0.67 with positive slope when using an additional hour of lag (e.g. outages for 0401-0500 are compared to the wind at 0300)
- Lag is important to consider

15 Dec 2006 Westerly Windstorm



Tree-Related Distribution Grid Outages

Lag in Hourly Analysis

Time Shift From Wind Observation	CYVR 15 Nov 2006	CYVR 11 Dec 2006	CYVR 15 Dec 2006	CYVR 12 Nov 2007	CYXX 15 Nov 2006	CYXX 11 Dec 2006	CYXX 15 Dec 2006	CYXX 12 Nov 2007	Average of Absolute Values
-2 h	0.05	0.04	0.03	0.01	0.01	0.04	0.20	0.01	0.05
-1 h	0.11	0.00	0.00	0.12	0.01	0.08	0.43	0.00	0.09
0 h	**0.26**	0.06	0.01	0.16	0.44	0.58	0.48	0.21	0.28
+1 h	0.17	0.39	0.16	0.27	**0.71**	**0.82**	0.39	0.36	0.41
+2 h	0.15	**0.68**	**0.67**	0.26	0.33	0.47	0.65	**0.56**	**0.47**
+3 h	0.16	0.56	0.39	**0.32**	0.03	0.34	**0.74**	0.41	0.37
+4 h	0.13	0.37	0.05	0.28	0.06	0.17	0.46	0.05	0.20
n	26	23	8	32	10	10	7	10	

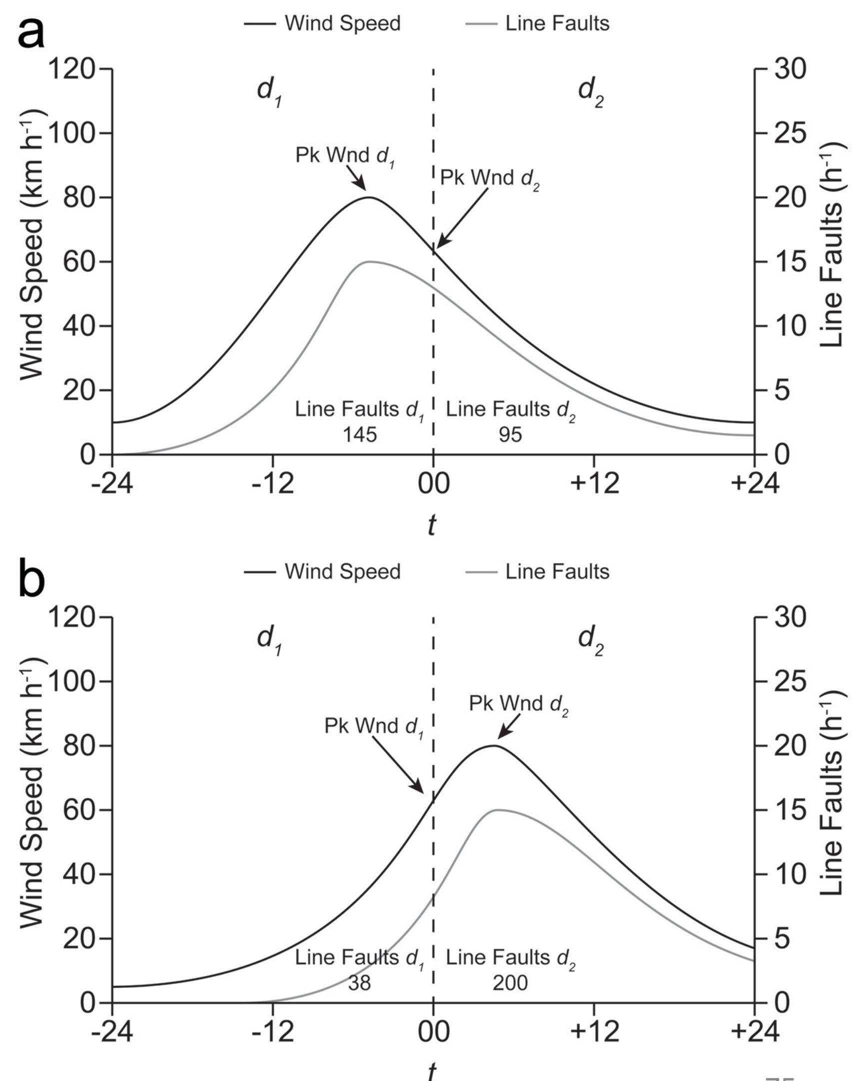
- The relationship between hourly 2-min wind speed and the hourly number of outages tends to be stronger 1-3 h after a given wind observation

- The primary contributor to lag is likely the method of recording outages

Tree-Related Distribution Grid Outages

Lag in Hourly Analysis

- For models that use daily data, lag can cause additional noise
- When a day starts is arbitrary
- Shark-fin shape of curve depicting line-faults (gray) is the result of lag
  - For a given wind speed, there are more outages post-peak wind than pre-peak wind
- Total number of outages for each day changes dramatically—for the same daily peak wind values—when the start of a day is shifted



Tree-Related Distribution Grid Outages

Key Conclusions

- The number of line faults increases exponentially with peak wind speed
- Peak wind and/or gust is the dominant factor in determining number of line faults
- Wind direction is the next most important
- There is a 1-3 h lag between the hourly 2-min wind speed and the hourly number of line faults, perhaps mainly due to the method of reporting outages
  - The lag can confound models that use daily data
  - Independent storms is an better approach that avoids daily data issues

Broad Conclusions

Southwest BC Windstorms and Tree-Related Distribution Grid Damage

- Windstorms are a recurring feature of southwest BC climate
  - Occur on an annual basis
  - Managers have to plan for these events

- Some windstorms can be very strong and cause widespread damage to trees and property, including to the power grid
  - Strong to severe storms occur at intervals ranging from about 3-8 years
  - Catastrophic ~50 yr?

- There is a clear relationship between peak wind speed and the number of tree-related line faults in the Lower Mainland
  - Damage increases exponentially with wind speed

Recommendations

Southwest BC Windstorms and Tree-Related Distribution Grid Damage

- Expand the windstorm climatology to include other regions and also over a longer time period
  - Including focus on variability over long time scales

- Expand the detailed windstorm analyses to include more storms and other regions
  - Continued focus on bent-back fronts
  - Also, examine all potential contributors to peak wind speed (fronts, upper-air conditions, surface pressure gradients, low center positions) and determine when they have a critical role

- Develop regression models to forecast power outages ahead of windstorms
  - There is the potential for using NWP output to predict outages on an hourly to three-hourly basis

Recommendations

Southwest BC Windstorms and Tree-Related Distribution Grid Damage

- Distribution Grid Resiliency:
  - Hardening infrastructure, especially those areas most exposed to southeasterly and westerly wind
  - Effective vegetation plans, including stand-level management along power line right-of-ways (e.g. Mitchell 2000)
  - Having a large inventory of utility poles, transformers and power cables on hand (it may be difficult to get this after a catastrophic windstorm)
  - Training personnel, especially for a catastrophic windstorm (e.g. 12 Oct 1962) that may be outside the experience of most people working at BC Hydro today

Thank You

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