Vol. 32: 13–23, 2006 | CLIMATE RESEARCH Clim Res | Published August 10

Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada

K. Stahl[1,*], R. D. Moore[1,2], I. G. McKendry[1]

[1]Department of Geography and [2]Department of Forest Resources Management, The University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z2, Canada

ABSTRACT: A recent epidemic of mountain pine beetles (MPB) has caused mortality in extensive stands of pine trees in British Columbia, Canada. The epidemic has been attributed, in part, to the recent warming trend in winter in western Canada, as MPB experience mortality during extreme cold spells. This study aimed to clarify the roles of synoptic-scale circulation and large-scale climate modes in these recent trends. Potential cold-mortality events were identified by comparing recorded daily minimum air temperatures with experimentally determined critical thresholds. Annual event frequency has declined over past decades, and between 1998 and 2001 temperatures did not reach the 100% MPB mortality thresholds at the stations analysed. Event frequencies depended on the phase of the teleconnection indices. In particular, after the shift to a predominantly positive phase of the Pacific Decadal Oscillation (PDO) following 1976, cold-mortality events occurred mainly during strongly negative Arctic Oscillation (AO) years. The dominant synoptic-scale circulation pattern causing widespread low temperatures is Arctic Outbreak, although other circulation types can be important, depending on location. The frequencies of these cold circulation types varied with the teleconnection indices. In addition, the conditional probability of temperatures cold enough to cause MPB mortality for a given synoptic type varies with the teleconnection phase, particularly for the Pacific North America circulation pattern and PDO.

KEY WORDS: Mountain pine beetle · Synoptic climatology · Teleconnections · Air temperature · British Columbia · El Niño–Southern Oscillation · Pacific Decadal Oscillation · Arctic Oscillation

1. INTRODUCTION

Forest insects are the most important agents of disturbance in North American forests and they are particularly responsive to climate change (Logan et al. 2003). British Columbia (BC) is currently experiencing an outbreak of mountain pine beetle (MPB) *Dendroctonus ponderosae*, which, as of summer 2005, has affected about 7×10^6 ha of mainly lodgepole pine *Pinus contorta* var. *latifolia* stands in southern and central BC (Fig. 1) and is producing significant economic and ecological impacts. Outbreaks require both an adequate population of susceptible pine trees (typically aged between 80 and 160 yr) and favourable climatic conditions. Due to fire suppression and forest management practices in the past few decades, there is currently no shortage of susceptible host trees in most of BC (Ministry of Forests, BC 2003).

The life cycle of the MPB is strongly influenced by temperature (Bentz et al. 1991, Logan & Powell 2001, Powell & Logan 2005), and temperature-controlled synchronicity of the life cycle is a key to the successful strategy of mass attack defining epidemic outbreaks. Other climatic influences on MPB habitat suitability are related to stress of the host trees and winter mortality associated with low temperatures. Safranyik et al. (1975) developed a climatic-suitability index based on climate norms, which includes components based on a threshold number of degree days (heat accumulation) over both annual and seasonal time scales, a lack of

*Email: kstahl@geog.ubc.ca

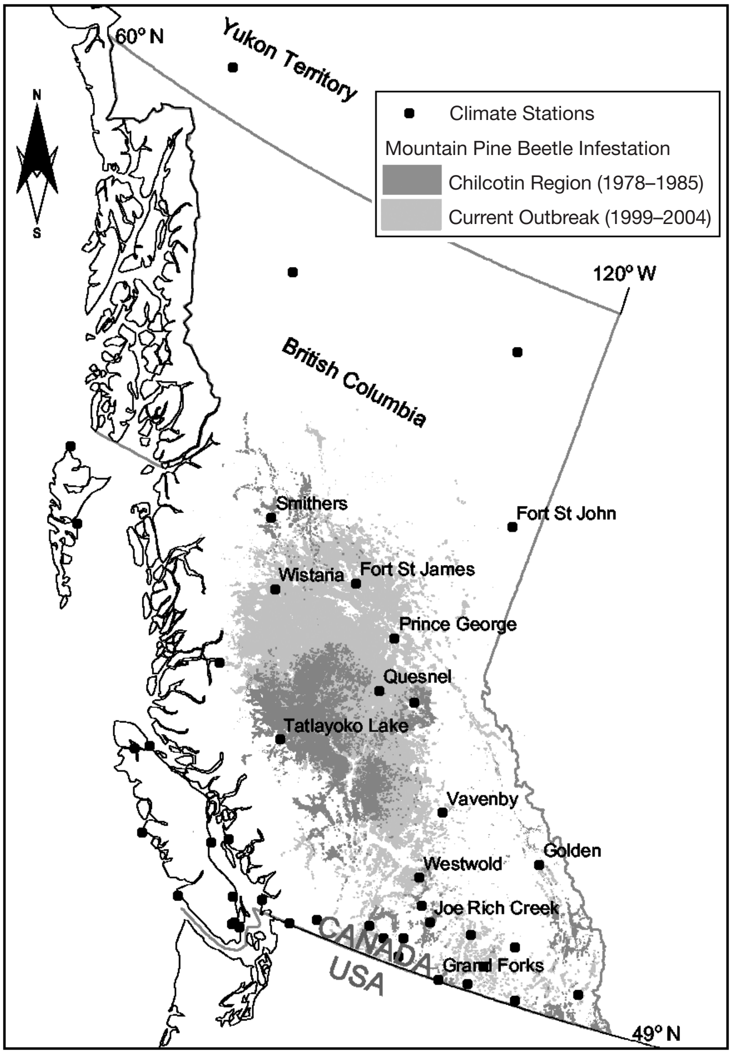

Fig. 1. Study area with location of climate stations and extent of recent and historic mountain pine beetle (MPB) outbreaks (data source: Taylor & Erickson 2003)

extreme low temperatures that cause mortality in winter, relatively high temperatures during flight time, and an index of drought, which stresses host trees and makes them vulnerable to attack. Analysis of recent trends in the climatic suitability index, as well as the effects of future climate warming scenarios, suggests that climate warming has caused and will continue to promote northward and eastward expansion of the MPB range within western Canada (Carroll et al. 2004).

While it is widely believed that milder winter weather in recent years has contributed to the magnitude of the current MPB outbreak in BC (Anon 2003), no research appears to have examined in detail the changes in winter climatology that could have led to decreased cold-mortality. However, several studies have examined general trends in winter temperature and its links to large-scale circulation patterns. Etkin (1991) found positive trends in the winter temperatures over northwestern Canada for 1977–1988, which he attributed to a strengthened Aleutian Low and increased advection of warm air masses from the Pacific. Bonsal et al. (2001) found that positive temperature trends in the interior of BC were strongest for the lower percentiles of the daily-minimum-temperature distribution. Along the west coast, significant positive trends also occurred in the higher percentiles. This reduction in the number of extremely cold days corresponds to a decrease in the frequency, duration and intensity of cold spells in western Canada, and an increase in the number and length of warm spells (Shabbar & Bonsal 2003). Shabbar & Bonsal (2004) revealed significant differences between the warm and cold phases of the El Niño–Southern Oscillation (ENSO) with respect to the frequency of winter cold spells, the frequency of winter warm spells, and the duration of winter warm spells. The Arctic Oscillation (AO) has a weaker influence on western Canada, but there are some noticeable differences between the phases in the frequency of warm spells along the border between BC and Alberta and in the duration of cold spells in northeastern BC (Shabbar & Bonsal 2004).

In this study we examined whether and how recent trends in winter temperature in western Canada may have translated into changes in winter climatic favourability for MPB, which overwinter under the bark of pine trees. Since they cannot escape low temperatures, they produce anti-freeze in order to avoid the lethal freezing of body tissue, a phenomenon called cold-hardening. In BC, a temperature of –40°C is commonly used to define mortality thresholds for assessing climatic suitability (Safranyik et al. 1975, Carroll et al. 2004). Experimental studies have demonstrated that less extreme temperatures can produce mortality, particularly in the early stage of cold-hardening in autumn and later in spring, when higher temperatures may trigger a feeding response (Wygant 1937, Bentz & Mullins 1999). The seasonal pattern and level of cold-hardening may vary from year to year (Bentz & Mullins 1999). Further evidence for seasonally varying cold-mortality thresholds is illustrated by the cold spells in the autumns of 1984 and 1985, which appeared to stop a major MPB outbreak in the Chilcotin region (Fig. 1) that began in the late 1970s. A cold spell in late October involved air temperatures of –25 to –29°C (Moore et al. 2005). The Canadian Forest Service (http://mpb.cfs.nrcan.gc.ca/biology/introduction_e.html) hence claims that 'a winter low of −40°C or a sudden cold snap in early autumn or late spring of −25°C would reduce MPB populations enough to end the outbreak.'

In addition, we examined the linkages between potential winter-mortality events and large-scale climate modes such as ENSO, AO and the Pacific Decadal Oscillation (PDO), and how these linkages are facilitated by changes in the frequency and characteristics of the synoptic-scale atmospheric circulation patterns that were associated with extreme cold spells. The following specific hypotheses were tested: (1) the frequencies of synoptic types associated with potential MPB cold-mortality change with phase of climate indices, and (2) the temperatures and therefore the probability of a potential mortality event for a given synoptic type vary with the dominant large-scale climate phase. As both the geographic range and the dynamics of many insect populations are controlled by the occurrence of lethal cold spells, the objective in examining such linkages is not only to improve the understanding of the climatic factors contributing to cold spells, but also to explore the potential for predicting future impacts on the biosphere resulting from changes in atmospheric circulation.

2. DATA AND METHODS

2.1. Identification of potential cold-mortality events

Daily air temperature data were compiled for stations within the Environment Canada network that had relatively complete records for 1948–2003. A total of 44 stations (including 2 just across the border in the Yukon Territory) having less than 5 yr of missing data were retained for analysis. The stations are distributed

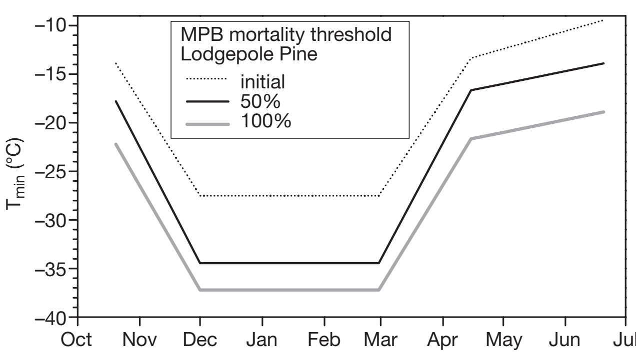

Fig. 2. *Dendroctonus ponderosea*. Cold-mortality thresholds for mountain pine beetles (MPB) (adapted from Wygant 1942); linear interpolation between Wygant's threshold values for Lodgepole pine for 20 November, 1 December, 1 March, 15 April and 20 June

unevenly through the province, with a higher density in southern BC (Fig. 1).

At each station, days were classified as having potential for winter mortality if the minimum temperature was less than the thresholds for initial, 50% or 100% cold-mortality for that date, as determined by Wygant (1942; Fig. 2). Spatial and temporal patterns and trends of these 'potential cold-mortality days' were then analysed. The cold-mortality curves reflect the higher vulnerability of MPB in autumn and spring, which was also found in laboratory experiments by Bentz & Mullins (1999). To our knowledge, no such experimental studies exist for MPB in the area of the current outbreak in BC. Therefore, the assumed cold-tolerance is considered a best-guess scenario. An important caveat is that temperatures in the phloem (the inner bark of a tree, and MPB winter habitat) may not be as extreme as air temperatures (Bolstad et al. 1997) due to lag times associated with heat conduction and the insulating effects of snow cover over the lower portion of a tree trunk. Therefore, the occurrence of air temperatures below the given thresholds will not guarantee mortality.

2.2. Synoptic-scale circulation types

Each day of the study period was assigned to 1 of 13 synoptic circulation types from an existing catalogue (Stahl et al. 2006). The catalogue was derived by classifying daily circulation patterns using Synoptic Typer 2.2, an application developed by the Australian Bureau of Meteorology (Dahni 2004). Data from the NCEP Reanalysis Project (Kalnay et al. 1996) were used to construct daily grids of mean sea level pressure (MSLP) for a 20 × 10 grid that covers the North Pacific and BC from 157.5 to 110.0° W and 40 to 60° N (grid cells of 2.5°) for 1948–2003. These grids were subjected to a principal component analysis (PCA) followed by an unsupervised *k*-means cluster analysis on the scores of the retained components (Dahni & Ebert 1998). Merging the daily time series of synoptic types and potential cold-mortality days allows identification of the specific atmospheric circulation situations associated with potential MPB cold-mortality events. Fig. 3 shows composite MSLP patterns for those synoptic types from the catalogue that are relevant to this study.

2.3. Large-scale climate indices

The dominant modes of atmosphere–ocean variability relevant to western North America include the ENSO (commonly indexed by the Southern Oscillation Index, SOI), the PDO, the Pacific North American pat-

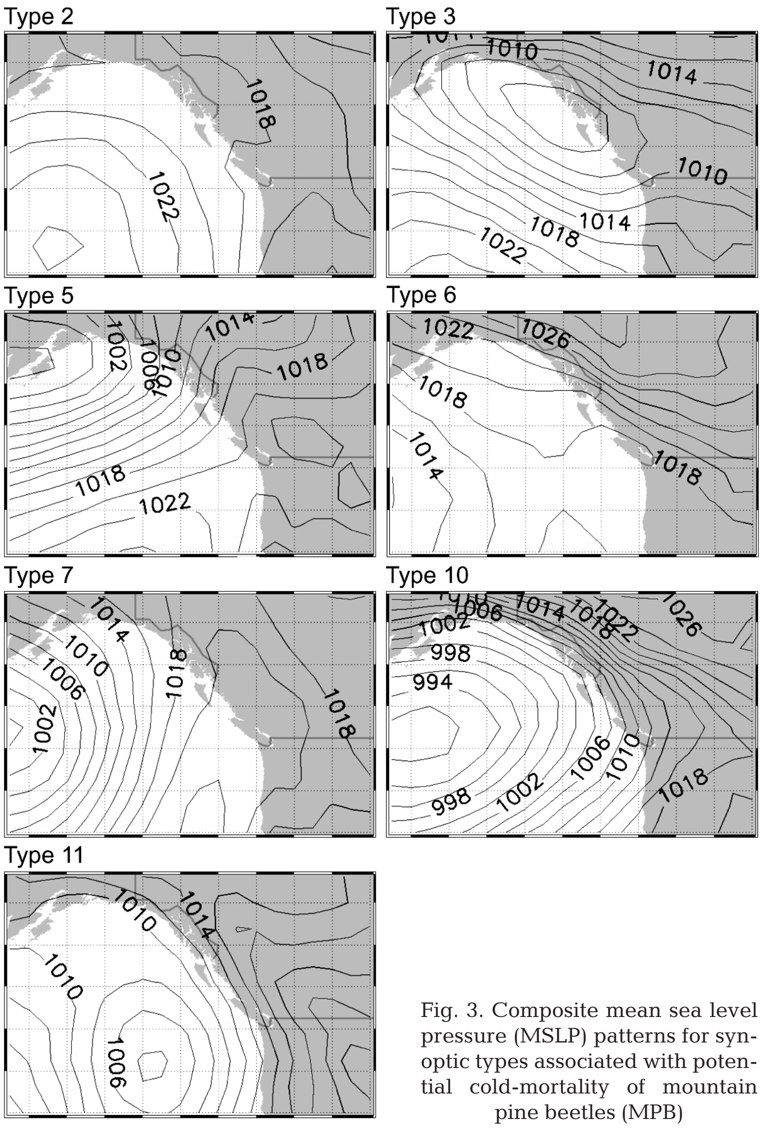

Fig. 3. Composite mean sea level pressure (MSLP) patterns for synoptic types associated with potential cold-mortality of mountain pine beetles (MPB)

tern (PNA) and the AO. El Niño and La Niña winters were defined by the preceding May to November SOI according to Redmond's (2005) classification. Positive/negative PDO winters were defined by the December–February (DJF) mean of the PDO index (>0.5/<–0.5). Similar thresholds were applied to DJF averages of PNA and AO indices to define positive and negative years. For presentation and analysis, the DJF winter season from December 1948 to February 1949 is assigned to 1949, and so on.

Inter-annual variations in ENSO, PDO, AO and PNA indices are shown in Fig. 4. Major El Niño events occurred in 1982/83, 1987/88, 1992/93 and 1997/98. The PDO is manifested by El Niño-like changes (regime shifts) in the sea surface temperature (SST) distribution over the tropical and north Pacific that are evident at decadal time scales (Mantua et al. 1997). The warm (positive) phase of the PDO is characterised by below-normal SSTs in the central and western north Pacific and unusually warm SSTs along the west coast of North America. The cold (negative) phase produces the reverse distribution. Shifts in the preferred states occurred in approximately 1922, 1947 and 1977 (Mantua et al. 1997). The PDO is strongly linked to atmospheric circulation over North America and the North Pacific as commonly expressed by the PNA pattern. Negative values of the PNA index are associated with a weak Aleutian Low pressure, while positive values are associated with a strong Aleutian Low (Wallace & Gutzler 1981). Positive values of the PNA index tend to be associated with the warm (positive) phase of PDO (e.g. 1977–1988) and El Niño events.

The AO is associated with fluctuations in the strength of the winter stratospheric polar jet. Its index is computed as the time series of scores for the leading-mode principal component of SLP poleward of 20° N. A positive AO index value generally indicates negative and positive SLP anomalies in the Arctic and mid-latitudes, respectively, and relatively strong 55° N (surface) westerlies; a negative index value indicates the opposite pressure anomalies and weaker westerly flow (Thompson & Wallace 1998).

2.4. Hypothesis testing

Spearman's (r_S), rank correlation coefficient was used to test for the existence of time trends in the frequency of days each year having potential cold-mortality conditions. This test does not require normality, can accommodate non-linear trends, and has similar power to the Mann-Kendal test (Yue et al. 2002). Significance of the trend at each station was assessed at $\alpha = 0.05$.

χ^2 tests of independence were used to examine the following null hypotheses: (1) the frequencies of synoptic types associated with potential cold-kill events are independent of teleconnection phase; (2) the frequency of potential cold-kill events is independent of teleconnection phase; and (3) the frequency of potential cold-kill events for a given synoptic circulation type is independent of teleconnection phase. In conducting the χ^2 tests, each day within the winter half-year (October–March) was classified on the basis of (1) whether or not the minimum temperature fell below a mortality threshold, (2) the synoptic type of that day and (3) the teleconnection phase for that winter.

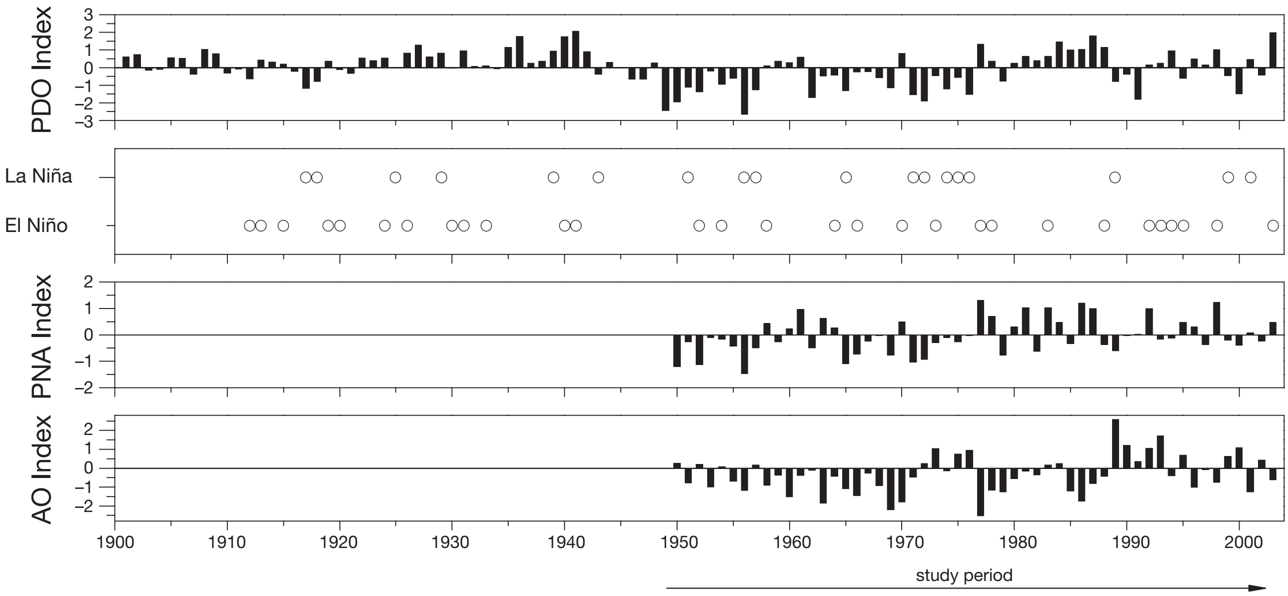

Fig. 4. Time series of teleconnection phases and indices. PDO: Pacific Decadal Oscillation; PNA: Pacific North American pattern; AO: Arctic Oscillation

χ^2 tests were conducted by cross-tabulating the numbers of days falling into different categories. As the synoptic types as well as the potential cold-mortality days are serially correlated and the teleconnection-index categories are clustered by year, the χ^2 statistic is inflated (Altham 1979, Brier 1980). Unfortunately, there appears to be no commonly accepted method to correct for these violations of the χ^2 test in tables larger than 2×2. Therefore, we used a rigorous significance level of $\alpha = 0.001$ to help account for the possibility of inflation.

The winter half year (October–March) is a slightly shorter season than defined by the Wygant curves for MPB mortality. However, our main interest was in the extreme cold days in winter. In addition, the surface climate associated with the 13 synoptic types differs for summer and winter and an extension too far into the spring might have confounded the response.

3. RESULTS

3.1. Occurrence and distribution of potential cold-mortality events

The highest frequency of potential cold-mortality days occurs in the northeast of BC (and at the 2 Yukon stations), where continental arctic air masses dominate in winter (Fig. 5). At those locations, on average >10 d yr^{-1} are colder than the 100% cold-mortality threshold and more than 30 d yr^{-1} are colder than the 50% and initial-mortality thresholds. In central BC, temperatures colder than the 100% cold-mortality threshold are rare (1 to 2 d yr^{-1}), and even days with temperatures colder than the 50% and initial-mortality thresholds are, on average, infrequent. Stations on the BC coast, as well as low-elevation stations in southern BC, never experience temperatures colder than any of the thresholds. The 2 stations closest to the northernmost extent of the MPB infestation, Smithers in the west and Fort St John in the east, only have respective averages of 1.3 and 5.6 d yr^{-1} with temperatures colder than the 50% cold-mortality threshold.

At no climate station within or near the area influenced by the current outbreak do potential 100% cold-mortality temperatures occur every year, and only northeast of the outbreak, at Fort St John, do temperatures fall below the 50% cold-mortality temperatures almost every winter (Fig. 6). In central BC, runs of years with and without potential cold-mortality are common. A particularly long period with regular cold-kill conditions occurred from the beginning of the study period until 1957. After that, shorter spells of 2 to 4 yr occurred regularly every 5 to 10 yr. Few 50% cold-mortality days and no 100% cold-mortality days have occurred since 1998.

The number of potential cold-mortality days per year has decreased over the study period, especially since 1957. Rank correlations r_S were negative for all records in BC. Trends were significant for 7 out of the 17 climate records across BC for temperatures below the 50% mortality threshold: Golden (r_S = –0.43, p = 0.001), Quesnel (r_S = –0.37, p = 0.005),

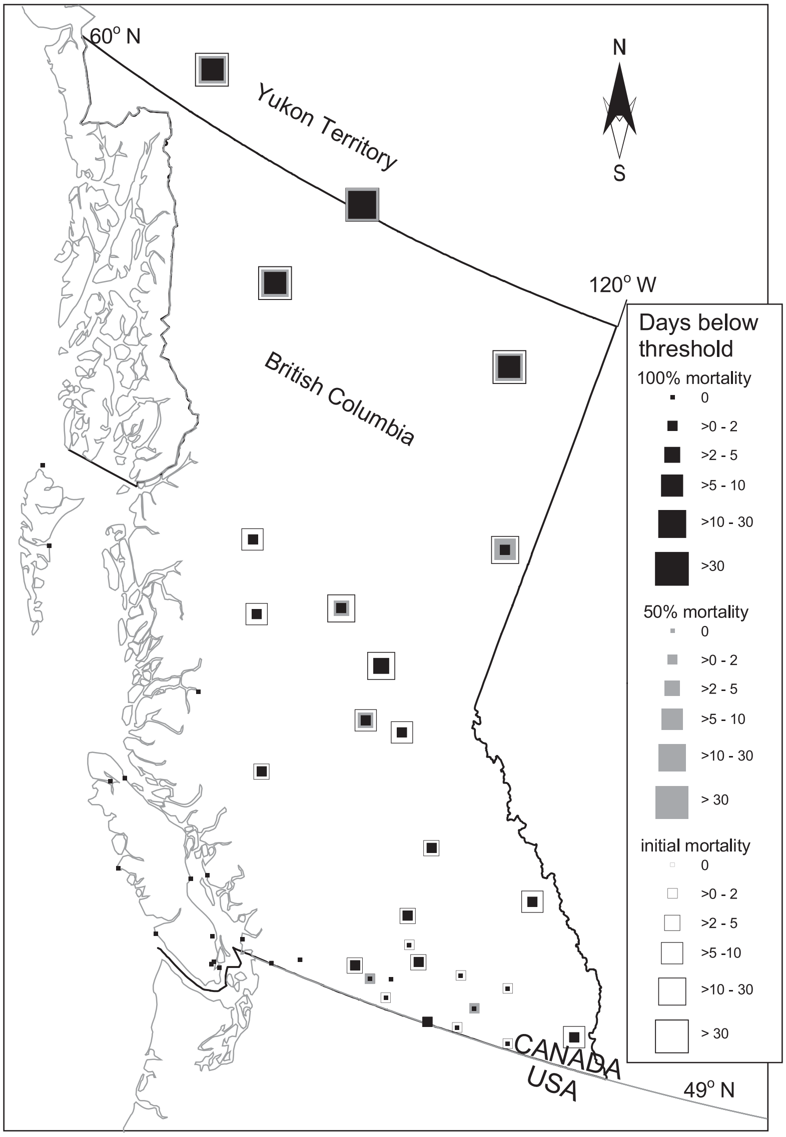

Fig. 5. Spatial distribution of the mean number of potential mountain pine beetle (MPB) cold-mortality days per year

3.2. Relation between cold-mortality events and synoptic scale circulation patterns

Potential cold-mortality events across BC are most frequently associated with the Type 6 circulation pattern (Table 1). This pattern (Fig. 3) is characteristic of an 'Arctic Outbreak' situation in which high pressure dominates in the northeast, low pressure prevails offshore to the southwest and isobars are aligned parallel to the BC coast. As a result, cold interior Arctic air flows coastward through mountain passes and valleys causing low temperatures across BC. In northern BC, Types 2, 3, and 10 also frequently produce temperatures below the mortality threshold. The isobars of Types 3 and 10 indicate a northeasterly flow of Arctic air into northern BC, and these types often precede or succeed Type 6. Types 2, 5 and 7 are additional important cold-weather situations in central BC. Type 2 represents generally high pressure over the Pacific, and Type 5 is characterized by a continental ridge reaching into interior BC from the south; in Type 7 the ridge is shifted westward. In southern BC, where cold-mortality days are generally rare, Type 11 plays a role. This type has a somewhat weaker ridge over the interior.

Types 3, 5 and 6 tend to occur more frequently than other 'cold' types, averaging about 20 d yr^{-1}. Frequencies of many of the 'cold' types exhibit substantial interannual variability, particularly Types 3 and 5; Type 6 has lower year-to-year variability.

Prince George (r_S = −0.33, p = 0.013), Fort Nelson (r_S = −0.32, p = 0.018), Fort St John (r_S = −0.31, p = 0.021), Joe Rich Creek (r_S = −0.28, p = 0.037) and Grand Forks (r_S = −0.27, p = 0.049). In addition to the overall tendency to decreasing frequency of cold-mortality events, results for Quesnel and other stations suggest that autumn and spring temperatures, in particular, have reached the mortality threshold less often over time. Through the 1950s, cold-mortality events occurred as early as late October (~Day 300) and as late as March (~Day 80). Since then, only 2 cold-mortality events occurred in October or November (1984 and 1985), with the rest occurring from December to February.

3.3. Frequency of 'cold' synoptic types in relation to large-scale climate indices

The frequencies of different synoptic types depended on several of the large-scale indices (Table 2). Of the types that are associated with potential cold-mortality events, frequencies of Types 2, 3 and 10 have significant associations with ENSO, PDO and PNA. The frequencies of Type 6 change with the combined ENSO/PDO phase and with PNA phase. Only Type 3 frequencies change significantly with AO phase. While cold Types 2, 3, 5 and 6 were less (more) frequent in positive (negative) PDO winters, Types 7 and 10 were more (less) frequent in positive (negative) PDO win-

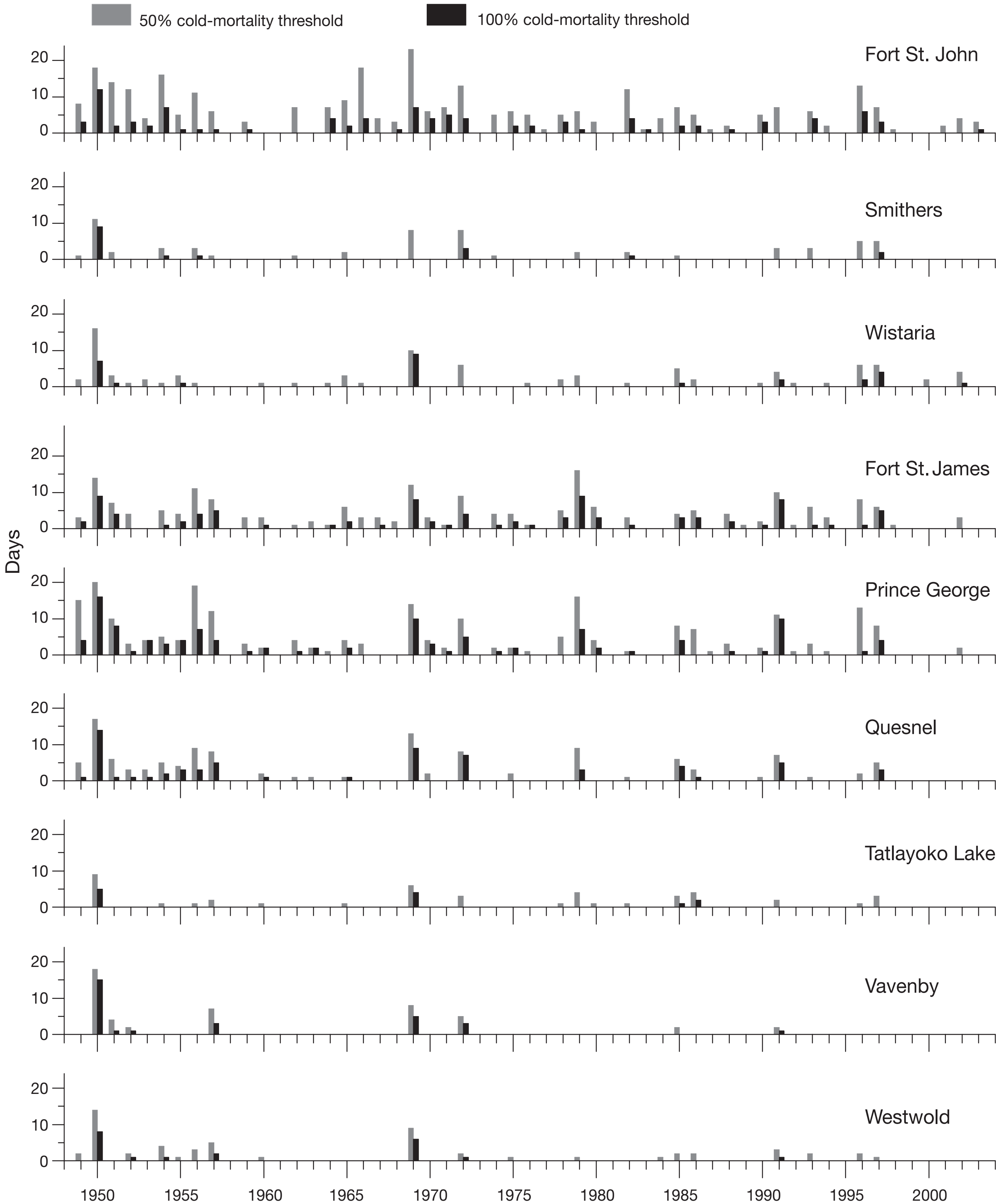

Fig. 6. Time series of annual number of potential mountain pine beetle (MPB) cold-mortality days at selected stations within and bordering the area affected by the current MPB outbreak

ters. Type 3 shows the largest changes: ca. 4% (3 to 4 d) more or less per winter. The directions of the changes in synoptic-type frequencies were similar for certain phases of ENSO, PDO, and PNA, and hence consistent with the known association of PDO with frequent El Niño events and PNA pattern occurrence.

3.4. Frequency of cold-mortality events in relation to large-scale climate indices

The frequent cold-mortality events in the beginning of the study period (1949/50) coincided with the strongest negative PDO winters in recent history (Fig. 3). Similarly, the cold-mortality events in 1969, 1972, 1979 and 1991 occurred together with strongly negative PDO indices. The latter 2 yr present negative PDO index winters after the general shift to a predominantly positive PDO phase. Events that appeared to stop the MPB outbreak in the Chilcotin region in 1984/85 occurred during years with positive PDO but negative AO index. All components of the climatic-suitability index, except that for cold-mortality, showed favourable conditions for MPB during those years. Therefore, cold-mortality during those autumn cold spells appears to be the most probable cause for the reduction of the population below epidemic level (Moore et al. 2005).

The χ^2 tests indicate significant associations between the frequency of potential mortality events and large-scale index phases for all teleconnection patterns considered for all 8 stations except for Fort St John and Tatlayoko Lake, where cold-day frequencies do not change significantly with ENSO and AO, respectively (Table 3). When the analysis was conducted for each synoptic type, statistically significant ($p \leq 0.001$) differences in the frequencies of cold-mortality days were found for a few types only. They are most consistent for Type 6 changes with PDO, ENSO and PNA phases. Frequencies of cold-mortality days during other circulation types show less consistent significant changes.

Fig. 7 shows the relative frequency of a Type 6 day having temperatures below the 50% cold-mortality threshold in the different phases of PDO and ENSO. The probability for temperatures that could cause MPB cold-mortality to occur on a Type 6 day is therefore highest during negative PDO winters and La Niña or neutral ENSO years. On the other hand, the probabilities for a Type 6 day to have temperatures below the cold-mortality threshold are particularly low at all stations during El Niño winters and neutral PDO years.

Table 1. Percentage of mountain pine beetle (MPB) cold-mortality events (based on 50% threshold) associated with different synoptic types at a selection of stations: arranged from north to south in British Columbia. Freq.: mean frequency of events per year

Station	Freq.	Synoptic type (%)							
		2	3	5	6	7	10	11	Other
Fort St John	5.7	8.7	15.1	4.8	44.1	2.3	18.0	2.9	4.2
Smithers	1.1	12.9	4.8	9.7	54.8	11.3	0.0	1.6	4.8
Fort St James	3.7	13.4	2.5	8.0	47.3	7.5	10.0	6.0	5.5
Wistaria	1.7	14.3	5.5	7.7	54.9	5.5	6.6	3.3	2.2
Prince George	4.3	12.4	3.4	12.8	44.4	8.5	9.0	5.6	3.8
Quesnel	2.3	13.6	0.8	15.2	43.2	9.6	8.0	5.6	4.0
Tatlayoko Lake	0.8	13.6	0.0	13.6	43.2	4.5	9.1	11.4	4.5
Vavenby	0.9	22.9	0.0	12.5	37.5	10.4	0.0	10.4	6.3
Golden	1.2	13.6	0.0	21.2	33.3	6.1	4.5	13.6	7.6
Grand Forks	0.2	9.1	0.0	9.1	18.2	0.0	0.0	45.5	18.2

4. DISCUSSION

It is not surprising that synoptic circulation Type 6, representing Arctic Outbreak conditions, was the weather type most frequently responsible for potential cold-mortality events throughout BC. More interesting is the finding that interannual variations in the frequencies of 'cold types', and also the frequency of extremely low temperatures during the cold types, are significantly associated with different phases of large-scale ocean–atmosphere teleconnections, including ENSO, PNA and PDO. For many stations the frequencies of the synoptic types associated with potential cold-mortality events were shown to be lower in the neutral and positive phases of PDO, which have dominated since the occurrence of a major regime shift in 1976/77. Furthermore, the conditional probability of having a day with temperatures colder than the cold-mortality threshold, given the occurrence of a 'cold' synoptic type, was generally lower in neutral and positive phases of PDO. Therefore, the net effect is that the dominance of neutral and positive phases of PDO since 1977 has been associated with less-frequent and less-severe cold spells, hence favouring MPB expansion. The PDO shift therefore appears to provide a reasonable proximal explanation for the more favourable

Table 2. Results of χ^2 tests (p-values) for synoptic-type frequencies during different climate index phases ($p \leq 0.001$ in **bold**)

Type	PDO	ENSO	ENSO/PDO	PNA	AO
2	**<0.001**	0.006	**0.001**	**<0.001**	0.378
3	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
5	0.936	0.252	0.016	0.021	0.178
6	0.082	0.007	**<0.001**	**<0.001**	0.069
7	0.941	0.682	0.050	0.079	0.046
10	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.004
11	0.256	0.012	0.012	0.125	0.003

Table 3. Results of χ^2 tests for potential mountain pine beetle (MPB) cold-mortality day frequency during different climate index phases. Data are probabilities associated with the null hypothesis; only results for types with significant differences for at least 1 index are shown ($p \leq 0.001$ in **bold**)

Location	Type	Index			
		PDO	ENSO	PNA	AO
Fort St John	All	**<0.001**	0.03	**<0.001**	**<0.001**
	2	0.042	0.185	**0.001**	0.47
	3	0.005	0.573	**0.001**	0.042
	6	**<0.001**	0.275	0.093	0.006
	10	0.008	0.143	**<0.001**	0.226
Smithers	All	**<0.001**	**0.001**	**<0.001**	**0.001**
	6	**<0.001**	0.005	**<0.001**	0.045
Fort St James	All	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	5	**<0.001**	0.177	**<0.001**	0.232
	6	**<0.001**	**0.001**	0.024	0.003
Wistaria	All	**<0.001**	**<0.001**	**0.001**	**<0.001**
	5	0.005	0.581	**<0.001**	0.164
Prince George	All	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	5	**<0.001**	0.019	**<0.001**	0.011
	6	**<0.001**	**<0.001**	0.002	**<0.001**
Quesnel	All	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	2	**<0.001**	0.33	0.05	0.232
	5	**<0.001**	0.222	**<0.001**	0.088
	6	**<0.001**	**0.001**	**<0.001**	0.044
Tatlayoko Lake	All	**<0.001**	**<0.001**	**<0.001**	0.007
Vavenby	All	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	6	**<0.001**	0.027	**<0.001**	0.12

winter climate. However, it is possible that the PDO shift is itself only one manifestation of a larger-scale climate phenomenon such as global warming.

One apparently contradictory observation to the link between PDO and winter climatic favourability is the occurrence of cold-mortality events in the autumns of 1984 and 1985, which stopped the major outbreak of MPB in the Chilcotin region that began in the late 1970s. These cold-mortality events occurred in years with positive winter PDO indices (1985 and 1986) and thus appear to be anomalies in the general trend within that region to less-frequent cold-mortality following the 1976/77 climate shift. One possible explanation for this apparent anomaly is that the AO index was highly negative in 1985 and 1986 (Fig. 3), suggesting that interactions among these large-scale indices need to be considered. For example, Budikova (2005) found negative temperature anomalies for negative PDO winters in the western USA and for negative AO index winters in northern central USA (Budikova 2005). Anomalies were stronger and spread from the northwest to central USA when PDO and AO were in phase. However, occurrence of negative AO indices does not appear to be sufficient in all cases to over-ride the effects of positive PDO phases, as illustrated by the lack of potential cold-mortality events in the winter of 1976/77.

Results presented herein are consistent with previous studies describing linkages between synoptic circulation, climate variability and surface climates in BC (e.g. Bonsal et al. 2001, Shabbar & Bonsal 2004, Stahl et al. 2006). In particular, the reduced frequency of cold-mortality events during El Niño and positive PDO winters is consistent with proposed dynamical mechanisms in which a deepening of the Aleutian Low, an amplification and eastward displacement of the Canadian Ridge, and a northward displaced polar jet stream inhibit the outflow of cold Arctic air over BC. The results further illustrate the role of systematic within-type variability as identified by Stahl et al. (2006). Not only do different phases of the major indices (particularly PDO) change the frequency of particular synoptic patterns across the BC region, but they are also associated with changes in the weather (in this case, cold spells) experienced within particular weather types.

It appears that MPB spreading in central and southern BC will not be subject to winter-season climatic limitations if current large-scale conditions and trends prevail in the future. Future climate scenarios predict that frequencies of cold air outbreaks in the 21st century will decline by 50 to 100% compared with late 20th century conditions (Vavrus et al. 2006). One approach to estimating the effects of future climatic change on MPB population viability in BC is to exam-

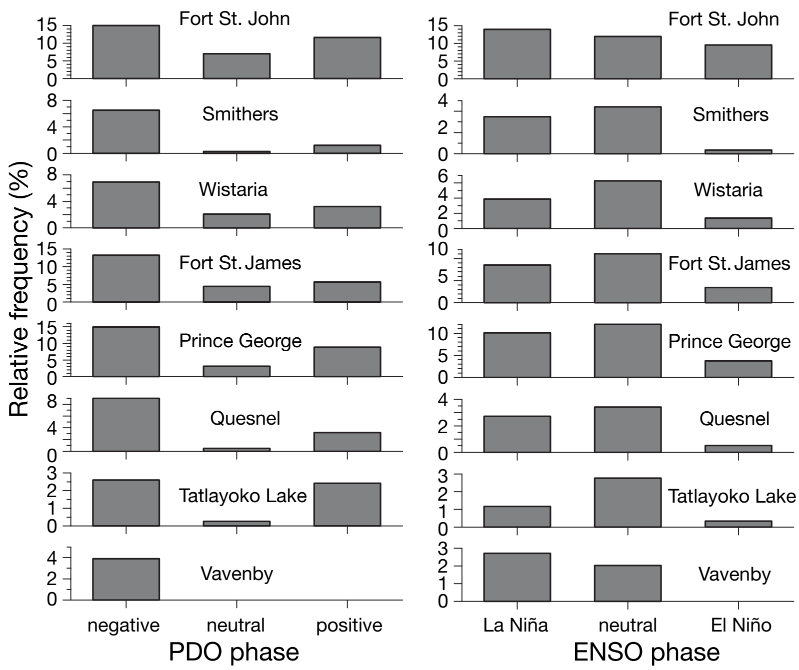

Fig. 7. Relative frequency of mountain pine beetle (MPB) cold-mortality days during circulation Type 6 at selected stations for the different index phases

ine the changes in GCM-predicted frequencies of the cold synoptic types, particularly Type 6. Unfortunately, an attempt to apply this approach using the Canadian second-generation coupled global climate model (CGCM2) was abandoned, because the GCM was found to underestimate the frequencies of Types 3 and 6 in the control run compared with observed frequencies based on analysis of NCEP MSLP fields (McKendry et al. 2006). The MSLP patterns of Types 3 and 6 are particularly difficult to model as they depend on the unique topographic barrier of the Canadian Cordillera, which is not well resolved by CGCM2.

This study has examined only 1 of the 5 climatic factors identified by Safranyik et al. (1975) and Carroll et al. (2004) as affecting MPB (i.e. severe cold). The selection of the cold-mortality criterion for this investigation is justified by a study of the climatic conditions of historic MPB outbreaks across BC, which identified temporal variations of this factor as one of the major controls (Moore et al. 2005). In terms of MPB climatic favourability indices, further research is needed on MPB biology and population dynamics to define more precisely the climatic thresholds for expansion. The threshold for cold-mortality of the MPB used in this study was largely based on one set of experiments (Wygant 1937) and on the threshold of –40°C used in the climatic-range studies (Carroll et al. 2004). Another important consideration for interpreting these analyses is that most of the climate stations are located at relatively low elevations, and thus may not be representative of conditions at the elevations of lodgepole pine stands that are vulnerable to MPB infestation. Unfortunately, simple extrapolation using standard lapse rates may not provide accurate temperature estimates at higher elevations, because the extreme cold conditions that cause MPB mortality are typically associated with temperature inversions and cold-air ponding. In addition, approaches are required for predicting the effects of microclimatic variability on temperatures within the phloem, similar to those developed for Idaho and Utah (Bolstad et al. 1997).

5. CONCLUSIONS

The current MPB infestation in BC has developed coincident with an amelioration of the winter climate, characterised by a low incidence of cold spells that may cause high mortality in the MPB population. This pattern is consistent with changes in circulation associated with a shift to a positive phase of the PDO beginning in 1977. It appears that the PDO shift may also have been implicated in the major Chilcotin outbreak, which ended following consecutive cold spells in the autumns of 1984 and 1985. The association between decreased winter cold-mortality and the dominance of neutral and positive phases of PDO suggests that, unless there is a shift back to dominance by the negative phase of PDO (which was the case prior to about 1922 and between about 1947 and 1976), winter climatic conditions are unlikely to limit the spreading of MPB throughout central BC. The situation for the northeast of the province is less clear based on historic trends, although the latter do suggest an increased frequency of favourable winter conditions in recent years. Now that MPB have become established east of the Rocky Mountains both in the south (near Banff, Alberta) and the north (Chetwynd), further research should focus on the climatology of cold spells over the boreal forest zones to assess the potential for MPB spread to eastern North America. Linkages established between the major climate indices, especially PDO, and the incidence of cold spells in BC suggest that there is some potential for seasonal forecasts of the probability of MPB infestations (and their spreading) based on the increasing predictability of both ENSO and PDO phases. However, interactions between these modes and the Arctic Oscillation may be important in some years and require further study.

Acknowledgements. Financial support from the Government of Canada's Climate Change Impacts and Adaptation Program via Grant A676 is gratefully acknowledged, as are funds from NSERC Discovery Grants to R.D.M. and I.G.M. A. Carroll, S. Taylor and B. Aukema of the Canadian Forest Service provided useful advice and access to data on mountain pine beetle infestations. F. Wu assisted with many aspects of data processing in support of this project. D. Hutchinson of Environment Canada assisted with accessing daily climate data from that agency. Comments by 2 anonymous reviewers improved the clarity of this paper.

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Editorial responsibility: Nils Chr. Stenseth, Oslo, Norway

Submitted: November 21, 2005; Accepted: June 17, 2006
Proofs received from author(s): July 19, 2006