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A SYNOPTIC CLIMATOLOGY FOR THE EMERGENCE AND FLIGHT OF THE MOUNTAIN PINE BEETLE (*DENDROCTONUS PONDEROSAE* HOPKINS) IN THE CENTRAL-INTERIOR OF BRITISH COLUMBIA.

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1. INTRODUCTION

This paper reports on the first stage of an investigation into the role of the atmosphere, and its interaction with complex topography, in describing landscape level movements of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in British Columbia. The mountain pine beetle has been present in the forests of British Columbia for millenia, and plays an important role in the natural life cycle of lodgepole pine (Pinus *contorta* var. *latifolia*) forests. Under normal climatic conditions, the mountain pine beetle is a univoltine species that kills its host in the process of breeding. Therefore, movement must be undertaken each generation. Climate change, and a shift in natural stand conditions that have resulted from forest management practices, have contributed to populations reaching epidemic levels in recent years. The beetle population in British Columbia has been increasing over the past decade, and has doubled yearly in the last several years. During the summers of 2001 and 2002, both the rate of spread and the attack intensity have increased, such that the current infestation now stretches across an area of 4.2 million hectares (BC Ministry of Forests, 2003).

During outbreaks, populations exist at the landscape level as a result of local population growth, and both within-stand and long range dispersal (see Figure 1). The dynamics of local patch growth and proliferation near existing infestations are largely the result of short-range movements under the canopy. These movements occur in relation to various host tree, stand and site characteristics, as well as weather conditions and behaviour modifying chemicals (Fig. 1a). Development of new infestations at distant locations is a result of long range transport, possibly above the canopy (Fig. 1b). The movements of mountain pine beetle and other scolytids associated with pheromone seeking activities within the forest canopy has received considerable attention (e.g. Chapman, 1967; Gray et al., 1972; Byers, 1988; Safranyik et al., 1989; Safranyik et al., 1993; and Byers, 2000). Movements above the canopy, while recognized by many of these authors as being a potentially important component to landscape level patterns of infestation, especially in epidemic years, has been largely ignored. This multi-staged project is concerned exclusively with wind-borne transport above the canopy, and does not concern itself explicitly with the question of the causation and behavioural aspects of these movements.

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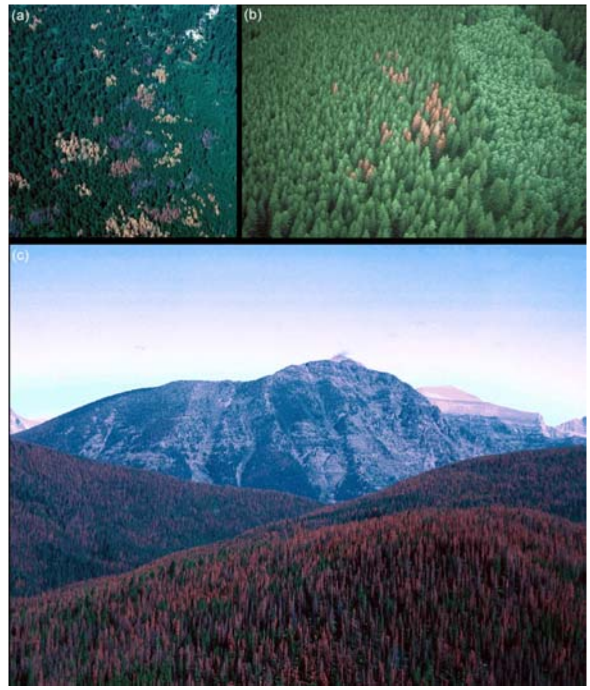


Figure 1. Patterns and Levels of Infestation: Examples of mountain pine beetle infestation showing (a) patch growth within stand over three consecutive years (Ciesla, 2001a); (b) establishment of new patches through between stand movements (McGregor, 2001); and (c) patch proliferation at the landscape level (Ciesla, 2001b).

2. WORKING HYPOTHESIS

Whether the movement of mountain pine beetle by passive transport above the canopy is a behavioural process, or a random meteorological occurrence, we hypothesize that the fundamental relationships determining where mountain pine beetle move and fallout are governed by the interaction of the atmosphere with terrain features. The nature of this interaction is highly dependant upon the synoptic conditions that exist during the emergence and flight period. We further hypothesize that above canopy movements would occur more frequently during epidemic years, and regardless of the population conditions, have both a higher probability of occurring and greater potential of leading to successful re-colonization during periods of peak emergence. Consequently, the purpose of the current investigation is to identify and describe the large-scale (synoptic) weather pattern, or patterns, that exist during peak emergence periods.

3. PATTERNS AND TIMING OF EMERGENCE

Synchrony of adult emergence is required for a successful mass attack strategy to overwhelm the defensive mechanisms of host trees. Under optimal conditions, there is an appropriately timed, compressed flight period. However, the exact timing of emergence in any particular year varies with geographic location and fluctuations in regional climate and weather, and no uniform dates for these events exist. Still, general patterns of emergence have been observed through extensive field studies.

In British Columbia, emergence typically occurs between mid-July and mid-August. Emergence proceeds slowly and erratically for about 20 days, during which time 5-10% of beetles emerge. Then there is a period of rapid emergence over 7 to 10 days when approximately 50% of the total population emerges. During this rapid emergence, there are often two distinct periods of increasing daily temperature, or heating cycles, each with individual emergence maxima. Emergence begins when ambient temperatures reach about 16˚C, and increases with temperature up to about 30˚C, above which both hourly and daily emergence rates begin to decline. Safranyik and Linton (1993) observed that emergence tended to peak when the average daily temperature was higher than 20˚C for at least three consecutive days. Gray et al. (1972) found that ideal conditions for peak attack occurred on days when the daily maximum temperature remained within optimal limits (25 to 30˚C). Under such conditions, emergence activity began when temperatures rose above 20˚C, and ceased in the afternoon at about the same threshold temperature; with the peak emergence occurring between 11:00 am and 2:00 pm. In a controlled environment free of light and temperature fluctuations, Watson (1970) found that beetles exhibited a diurnal rhythm consistent with field observations, were the majority of emergence occurs between 9:00 am and 3:00 pm.

4. SYNOPTIC CLIMATOLOGY

Using the principles of synoptic climatology (Yarnal, 1993), a synoptic composite valid for the British Columbia Central-Interior was constructed to characterize the atmospheric conditions during all periods of peak emergence and flight in the region. A synoptic composite can be viewed as a climatology based on events, rather than means over some period of time, and are typically average pressure maps of specific situations. While a case study can isolate mechanisms which are important for an individual event, the compositing of a large number of cases into one data set can identify processes common to most such events. In the absence of sufficient historical emergence data, temperature was used as an environmental surrogate for emergence activity. Global atmospheric circulation data utilized in this analysis were obtained from model output of the NCEP/NCAR Reanalysis Project (Kalnay et al., 1996). Reanalysis data are available every 6 hours on 17 standard pressure levels at a 2.5 degree resolution from 1948 until present. Surface weather data from the Prince George Airport located on the central-interior plateau at 53°33′N and 122°41′W, was used to establish the relationship between the surface environment and the regional atmospheric circulation field.

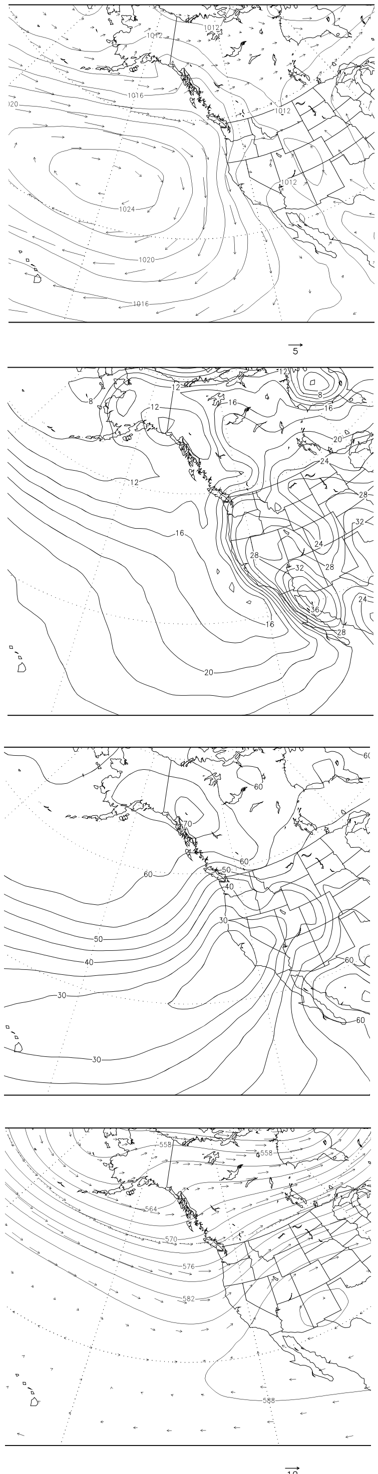
4.1 July-August Climatology

The regional summer climatology of British Columbia is depicted in the 55-year average NCEP Reanalysis fields in Figure 2. The surface pressure pattern is characterized by relatively low pressure over the Great Central Plains (Continental Low) with a warm thermal low centred over California, a high pressure centre dominating the northeast Pacific (the Pacific High), and a ridge of high pressure extending from the Pacific High into British Columbia. The slack pressure gradient and orientation of the isobars implies a weak westerly regional wind over much of BC. However, station records show that southerlies are most common due to steering of the flow by the mountains that flank the central-interior plateau. Aloft, British Columbia lies in the belt of the westerlies. Thermal instability mixes the stronger winds aloft down to near the surface, resulting in an increased frequency of daytime winds with a westerly component, with winds increasing late in the afternoon when the surface temperature reaches a maximum. In the southern region of the province, temperature increases sharply with decreasing latitude, while across the central-interior plateau, temperature increases more strongly eastward. Skies are generally free of cloud, but cloudiness increases with increasing latitude, particularly in the northwest corner of the province. Station records show that precipitation is generally low, with stations in the west at the extreme edge of the rain shadow of the Coastal Mountains being the driest, and the precipitation amount gradually increasing eastward. Thunderstorms are also relatively infrequent, typically occurring 5 days per summer in the west, and 20 days per summer in the eastern part of the region.

4.2 Composites for Peak Emergence

The environmental criteria adopted for identifying potential periods of peak emergences was a daily maximum temperature that remained within the optimal temperature range (25-30°C) for more than four consecutive days. A total of 92 heating cycles were identified. Of these 92 heat cycles, 71 or 77% occurred during the months of July and August and were typically 4-5 days in length. Only 5 of the surrogate days for peak emergence had precipitation; all of which had less than 1 mm/day.

Synoptic composites were constructed by averaging the daily reanalysis fields corresponding to the third day of each of the identified heating cycles falling in July, or August. The composite surface pressure pattern was similar to climatology, but exhibited stronger ridging of the Pacific High into BC. The upper level ridge was also more pronounced, and was centred over central British Columbia. An anomaly map was constructed by subtracting the composite from climatology, and the statistical significance of the composite was tested at the 95% level, using a Students's t-test. The results are shown



(a) MSLP

(b) Tmx

(c) RH

(d) 500 hPa

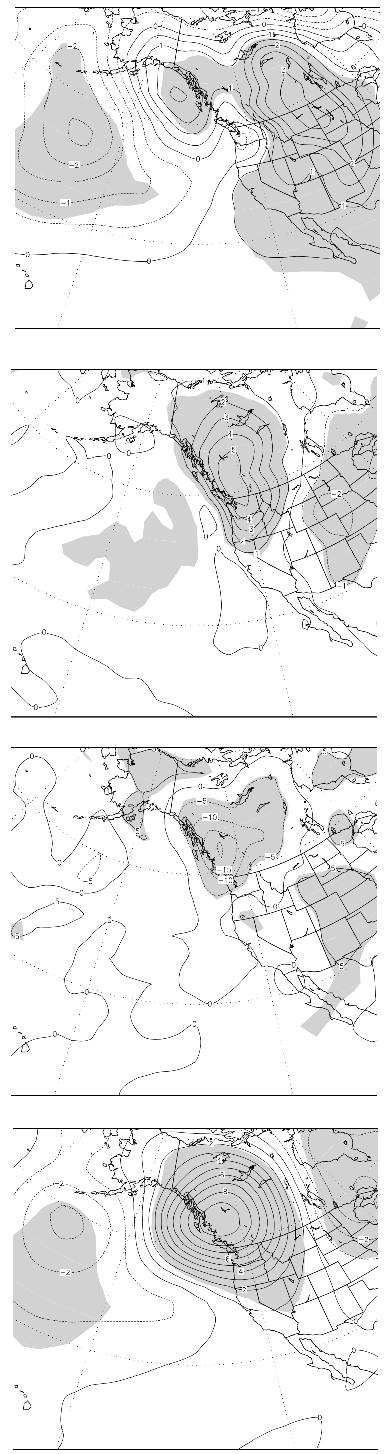


Figure 2. Regional Climatology: Average daily NCEP Reanalysis fields for July-August (1948-2002): (a) mean sea-level pressure (hPa) and 925 hPa winds (m/s); (b) near surface 00 UTC air temperature (°C); (c) 700 hPa relative humidity (%); and height of 500 hPa pressure surface (dm) and winds (m/s).

Figure 3. Peak Emergence Anomalies: Deviation of NCEP Reanalysis fields from July-August climatology (see Fig. 2) during peak emergence surrogate days, and statistical significance of composite anomaly at the 95% level (shaded region).

in Figure 3. On average, pressure was 1-3 hPa higher than normal over most of the western continent, and slightly lower than normal over the Northeast Pacific. Aloft, the 500 hPa heights over most of BC were 8 dm higher than normal for the period. Temperatures over most of BC were 5 °C higher than the climatology and the relative humidity is 15% lower than normal, an indication of the prevalence of clear skies and dry conditions that exist during the period of peak emergence and flight. The complex pattern in the mean sea-level pressure anomaly indicates that periods of peak emergence are characterized by an evolution in the synoptic conditions.

4.3 Synoptic Evolution

To examine the evolution in the synoptic conditions surrounding the period of peak emergence, individual composites for Day ± N (for N=1..3) were constructed and animated. The evolution of the synoptic conditions is depicted in the daily time series of the composite reanalysis fields shown in Figure 4 for the grid cell nearest to Prince George. The lower plot shows the evolution of the near-surface daily maximum temperature (using the temperature at 00 UTC as a surrogate for the day-time maximum), and daily mean sea-level pressure. The upper plot shows the evolution of the daily 500 hPa height field and the daily surface lifted index (a measure of atmospheric stability). During summer in the Central-Interior, the occurrence of low but rising barometric pressure is generally an indication of fair-weather moving into the region, and would correspond to the onset of the flight window. The increased solar radiation contributes to intense surface heating and increasing air temperatures, that is accompanied by a building of an upper level ridge to the west. The animation shows temperatures continue to warm as the upper level ridge intensifies and moves eastward. The end of the heating cycle is typically triggered by the passage of low pressure systems from the west that are steered northward around the surface ridge. A trough of low pressure extending southward from the surface low gradually approaches British Columbia from the north, eventually bringing a shift in wind direction and cooler air. Surface pressure begins to fall as the trough approaches, and during this period temperatures continue to increase due to an intensification of the south-north pressure gradient temporarily increasing the advection of southerly warm air into the region.

According to the results of this synoptic climatology, the occurrence of high and falling pressure is accompanied by favourable temperatures and increasing instability for a period of typically 4 days. Peak emergence occurs in the centre of a 4-day period of falling pressure, while the centre of the 500 hPa ridge is directly above the region. If the composite criteria adopted for this study is an accurate prediction for the timing of peak emergence, a consequence is that peak emergence will occur during a period of relative maximum instability in the lower atmosphere, as can be seen from the slightly negative values of the composite surface lifted index. Aloft, emergence would begin with the 500 hPa ridge to the west under a northwesterly flow, with the peak occurring as the ridge line passes over the region, and the tail of the peak emergence period occurring with a ridge to the east under a southwesterly flow. An examination of the thermally driven landscape circulations that develop under the above conditions, is the subject of an ongoing study.

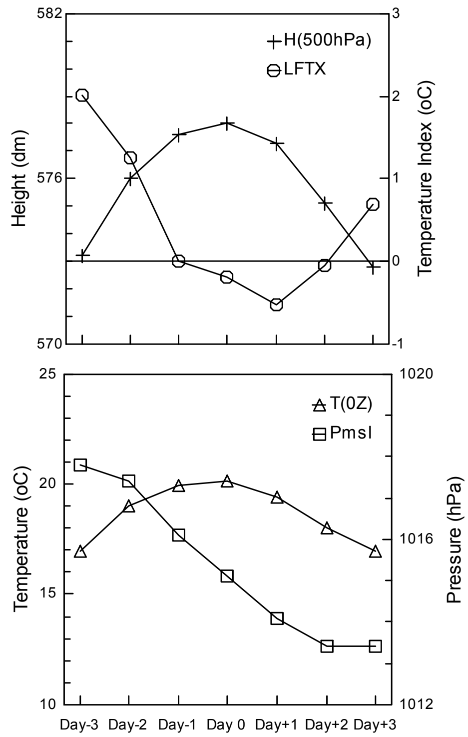


Figure 4. Composite Evolution: Daily evolution of NCEP fields in Fig. 2, shown for the reanalysis grid cell nearest Prince George. (a) Surface lifted index (°C) and height of 500 hPa pressure level (dm). (b) Near surface afternoon temperature (°C) and mean sea-level pressure (hPa). Time-series is centred on day-3 of each of the heating cycles for peak emergence.

5.0 COMPARISON TO ACTUAL EMERGENCE

To corroborate the evolution of the synoptic conditions relative to the timing of peak emergence, trends during historical emergence events documented in the scientific literature, and emergence monitoring conducted by forest licensees, are currently being analysed. An example of the observed trends during a recent emergence event monitored near Carp Lake, approximately 100 km northeast of Prince George, is shown in Figure 5. The timing of peak emergence (July 30) was estimated on the basis of a weekly sampling interval which was staggered in time between various monitoring locations, and is believed to be accurate to within 1-2 days.

The observed trends are similar to the synoptic evolution of the composite in Figure 4. The heating cycle is characterized by four days of consecutive warming. Peak emergence coincides with the centre of the 500 hPa ridge being over the region and continuous drop in station pressure on the order of 5 hPa per day. Temperature reaches a maximum as the pressure reaches a minimum value, at which time the atmosphere is most unstable. The magnitude of the changes during an actual event are much larger and less smooth than in the composite time-series. It should be noted that the reanalysis data represent an average value for a large spatial volume, and are therefore typically lower than measured surface values. Actual temperatures and station pressure recorded at the Prince George Airport are shown in Figure 5c for comparison. The daily maximum temperature and station pressure at the airport closely follow the trends in the reanalysis data, providing an additional justification of the appropriateness of using this global data set, and supports the synoptic climatology approach adopted in this analysis.

6.0 IMPLICATIONS FOR FUTURE ANALYSIS

As any investigator of mountain pine beetle movements within the forest canopy can attest, winds are generally light and highly variable during the period of emergence and flight. However, the wind both within and above the forest canopy is related to the wind aloft in the free atmosphere where the flow is considerably more regular and predictable. Understanding the relationship between the synoptic atmospheric circulation and the surface environment can help bring a sense of order to the observed variability of winds within and above the forest canopy. The current study will establish the relationship between the synoptic wind field and the above canopy wind field during conditions under which beetles take flight for conditions at a single point, namely the Prince George Airport. The use of mesoscale atmospheric models, that can simulate the transfer of momentum from the air aloft down toward the surface, while incorporating terrain effects, will allow the results of this investigation to be extrapolated at a much higher spatial resolution than could be attained by surface measurements alone.

The fact that the synoptic evolution surrounding the period of peak emergence is accompanied by a developing and propagating upper level ridge further highlights the importance of determining whether this mode of transport is behavioural, or the result of random meteorological interactions during the highly convective period of emergence and flight. For instance, if flight above the canopy is behavioural, it may occur at a particular point within the emergence window corresponding to one particular regional flow pattern. The current numerical simulation of the July 28, 2003 Carp Lake event, and the ongoing theoretical simulations aimed at determining the fundamental relationships between historical mountain pine beetle movement patterns and topography, may provide further guidance on this issue.

This improved understanding of the nature of the variation in wind speed and direction, particularly during peak emergence period, can be exploited to estimate probabilistic pathways (ensemble trajectories) of mountain pine beetle above the canopy, and will be the subject of future investigations by the authors. It is anticipated that by incorporating this above canopy component into current population models, this work will contribute to a better understanding of past and future redistributions of the mountain pine beetle population.

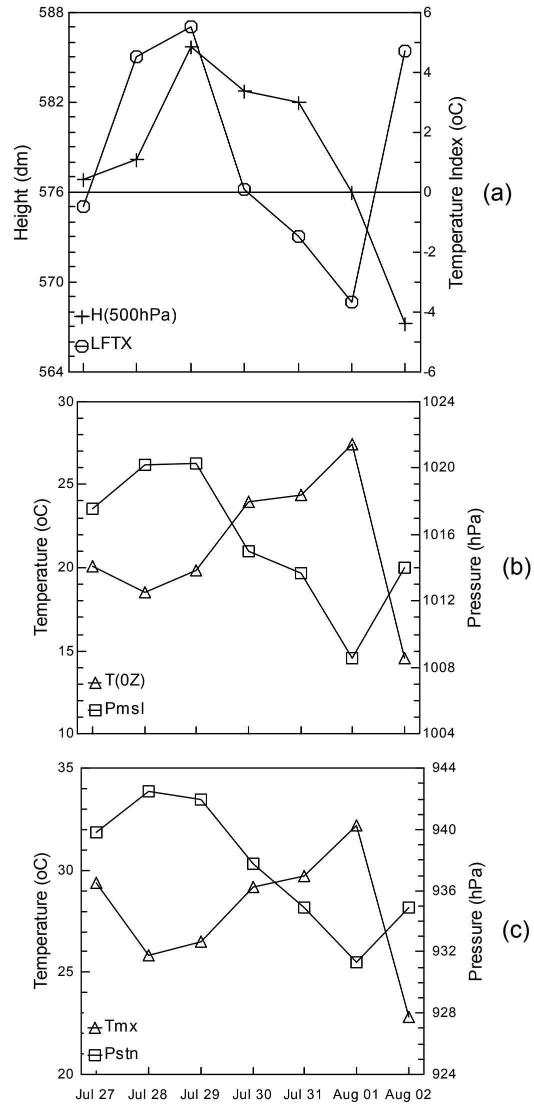


Figure 5. Composite Validation: Observed synoptic evolution during a peak emergence event near Carp Lake approximately 100 km north east of Prince George. Top two plots are reanalysis fields (see Fig.4) and bottom plot shows the daily maximum temperature and daily mean station pressure as measured at the Prince George Airport (675 m). Time-series is centred on the best-estimate of the peak in emergence (July 30, 2003).

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