Modelling of Mountain Pine Beetle Transport and Dispersion using Atmospheric Models

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Abstract

The mountain pine beetle population in the British Columbia central interior has reached epidemic proportions. Mountain pine beetles move actively through flight over a few kilometers within a stand, and passively through advection by the wind, within and above a forest canopy. Passive dispersal is likely responsible for between-stand and landscape-scale spread of the population. A strategy for the testing and use of atmospheric numerical models to predict the passive movement of mountain pine beetles is described. Preliminary synoptic climatology results indicate that typical weather patterns associated with weather conducive to mountain pine beetle flight are similar to average summertime conditions, except the surface high pressure ridge influencing the weather over BC is stronger than normal. An atmospheric simulation of a situation conducive to mountain pine beetle emergence and flight showed that the above canopy winds and temperatures had considerable spatial and temporal variability, indicating that treating the atmosphere simplistically as a "constant" in mountain pine beetle population models may not lead to satisfactory results.

Introduction

The mountain pine beetle, *Dendroctonus ponderosae*, Hopkins is the most important bark beetle in western North America. Currently, the mountain pine beetle has reached epidemic proportions in five Forest Districts in central British Columbia (BC) (Vanderhoof, Nadina, Quesnel, Central Cariboo, and Fort St. James), with approximately four million hectares and 108 million m³ of timber affected. The mountain pine beetle issue will remain important given that large tracts of land in central and southern BC are occupied by its principal host, lodgepole pine, *Pinus contorta* var. *latifolia*. The mountain pine beetle's range has been limited climatically to minimum annual temperatures warmer than -40 ˚C; however, the range may be expanding due climate change which has occurred and will continue (Safranyik et al. 1975; Thomson and Shrimpton 1984; Carroll et al. 2004)

Newly hatched mountain pine beetles emerge from host trees in mid to late summer when air temperatures reach 18°C with a peak of flight activity at 25°C (Anhold and Jenkins 1987), and seek new hosts. The onset of emergence and flight is generally preceded by warm, dry weather with the emergence in a region normally occurring over a 7 to 10 day period (Safranyik et al. 1999). It has been suggested

(Furniss and Furniss 1972; Safranyik et al. 1989) that convection during fair weather conditions typical of emergence and flight may carry some beetles above the forest canopy to be carried over long distances. In an experiment using unbaited traps at various heights within the canopy, Safranyik et al. (1992) inferred that 2.4% of the beetles were above the canopy. Gray et al. (1972) suggest that a fraction of the population may either be incapable of responding to secondary attractants or require flight exercise before responding, so may act as pioneers by dispersing to more distant areas. Thus, mountain pine beetle spread to new hosts in two ways: actively by flight within a stand or between stands over distances less than 2 km; and passively by advection due to the mean wind field above the forest canopy and turbulent eddies, which may transport beetles over longer distances (perhaps up to 100 km assuming a 25 km/h wind and a four hour flight period). In both dispersal modes, for the mountain pine beetle to successfully attack a host tree and therefore spread the epidemic, they must attack at densities sufficient to overcome tree resistance, which is about 35 beetles per m^2 of bark surface (Raffa and Berryman 1983).

As an outbreak becomes an epidemic, the increase in mountain pine beetle population levels leads to more competition for suitable hosts within a stand; thus, a greater number of beetles dispersing passively above the canopy. This acts as a positive feedback mechanism, allowing rapid spread of mountain pine beetle over great distances from one year to the next. During passive transport, spatial and temporal variability in both the mean wind field and in turbulent eddies are critically important in determining both where the mountain pine beetle will move and how they are dispersed. Since mountain pine beetles typically fly during periods of high temperature that tend to occur under slack synoptic conditions, it is hypothesized that terrain-induced thermal circulations (i.e., mountain/valley circulations, anabatic and katabatic flows), as well as steering of the synoptic wind by terrain features, will be important. Terrain features and their interaction with atmospheric circulations and habitat should determine mountain pine beetle fallout zones. The successful establishment of beetles in a fallout zone would then depend on the presence of susceptible hosts, and whether or not there is sufficient density of the beetles to kill the new hosts.

This project focuses on modelling the passive transport of mountain pine beetles by wind at the landscape scale. In the past, several modelling or analysis approaches have been used to study mountain pine beetle spread based on stand susceptibility (e.g., Raffa and Berryman 1986; Mitchell and Priesler 1991; Logan and Bentz 1999; Safranyik et al. 1999; Byers 2000; Shore et al. 2000; Fall et al. 2004), none of which have incorporated a realistic representation of the atmosphere. The approach here uses well-tested atmospheric numerical models in an application that has been used for similar phenomena: for example, to study the spread of *Peronospora tabacina* spores (Yao et al. 1997), and to study movement and dispersion of air pollutants (numerous studies). This paper will provide an overview of the project and a summary of the early results from six months into the three-year research program.

Objectives

The overall research is organized around four sequential sub-projects, each with a defining objective:
1) Identify synoptic weather patterns (i.e., large-scale weather patterns) present during periods of mountain pine beetle dispersal;
2) Identify fundamental relationships between terrain features, atmospheric flows, host species and mountain pine beetle fallout zones;
3) Assess the value-added potential for physics-based meteorological and dispersion models to estimate mountain pine beetle dispersal between one year and the next; and
4) Assess the use of high-resolution real-time meteorological and particle dispersion models to provide improved estimates of current and future mountain pine beetle dispersal.

Methods

The synoptic weather pattern determines the atmospheric background conditions in which mountain pine beetles emerge and move. It is useful to define the weather patterns associated with typical mountain pine beetle episodes before modelling or further work is undertaken. In order to do this, the standard synoptic climatology technique of compositing is employed. This essentially involves finding average weather map patterns (and their standard deviations) associated with different periods in the mountain pine beetle outbreak based on historical information on when mountain pine beetles emerged and the period over which they are in flight. Since these data are not readily available, we have instead used a "Heating Cycle" as a surrogate. We define a "Heating Cycle" as at least four consecutive days in which the maximum temperature is over 20 °C but less than 30 °C, focussing on July and August, since these conditions represent environmental conditions conducive to emergence and flight. We used day three of the sequence for the synoptic climatology.

Weather data for this work comes from the NCAR/NCEP Reanalysis Project (Kalnay et al. 1996) that provides archived gridded meteorological fields every 6 hours on the standard pressure levels at 2.5-degree horizontal resolution from 1948 until the present time.

We hypothesize that fundamental relationships determining where mountain pine beetles move passively and fallout are governed by the interaction of the atmosphere with terrain features (in combination with forest conditions and mountain pine beetle behaviour). The atmosphere is known to exhibit complex interactions with terrain, especially in hot weather, e.g., mountain/valley circulations, anabatic/katabatic flows (up-slope/down-slope winds), lake/land breezes, all of which are flow circulations that reverse between day and night. In addition, during the summer, the planetary boundary layer above the forest canopy evolves considerably during a day – increasing turbulence and growing in depth from only tens of meters overnight up to 2 km or so in depth by late afternoon. Wind speeds increase and directions normally turn clockwise with increasing height above the surface, and this is affected dramatically by the diurnal evolution of the planetary boundary layer that also influences stability and turbulent eddies above the forest canopy. In order to explore these relationships, a mesoscale atmospheric modelling approach using the CSU RAMS (Pielke et al. 1992, http://www.atmet.com) model for meteorological prediction, and the HYPACT lagrangian particle dispersion model (Turner and Hurst 2001; http://www.atmet.com) that uses the RAMS mean wind fields to advect and disperse particles, will be used. RAMS is a mesoscale atmospheric numerical model that is very flexible and is able to use a variety of numerical, boundary condition and parameterization schemes. It can run with nested grids in order to achieve high spatial resolution (e.g., 25 m vertical, 500 m horizontal resolution in the atmosphere) for research applications. RAMS is a finite difference model that solves the partial differential equations governing fluid flow and thermodynamics on a 3-D grid. As such, it is a state-of-the-art, physics-based approach to modelling weather at high spatial resolution. In this first stage of the modelling work, the models will be used in an idealized mode, with simplified terrain of various types (i.e., a domain with a hill, a domain with a valley, combination of hill/valley, large lake, etc.) and idealized meteorological conditions (based on the results from the first study). Mountain pine beetles will be treated as passive tracers and advected/dispersed using RAMS/HYPACT to discover the pattern of their dispersion under different idealized landscapes. This will result in generalized conclusions concerning the nature of the interaction between the atmosphere during typical periods of mountain pine beetle dispersion, and terrain features, leading to different patterns of mountain pine beetle attack at the landscape scale.

In order to assess the value-added potential for physics-based meteorological and dispersion models to estimate mountain pine beetle dispersal between one year and the next, RAMS/HYPACT will be used in a realistic hindcast mode in several case-studies of past mountain pine beetle spread. The idea is to utilize the database of known mountain pine beetle infestations (e.g., http://www.pfc.forestry.ca/entomology/mpb/historical/index_e.html) and use RAMS/HYPACT to simulate a number of those years in order to see whether the approach can successfully simulate past dispersion. Meteorological information needed to

initialize and nudge RAMS will be obtained from the NCEP Reanalysis Project for the time of mountain pine beetle emergence and flight. Validation data will come from the various reports documenting the current mountain pine beetle epidemic (e.g., web site above and Wood and Unger 1996; and the detailed maps produced by BC Ministry of Forests). Statistical and graphical comparisons will be made between the modelled and observed pattern of mountain pine beetle spread in order to assess the success of the method.

If it can be demonstrated that the approach can be used successfully to simulate past mountain pine beetle dispersal, then an assessment and recommendations will be made on the use of these models to provide improved estimates of current and future mountain pine beetle dispersal.

Early Results and Discussion

Synoptic Climatology

As a surrogate for mountain pine beetle emergence and flight dates, we have defined a "heating cycle" as at least four consecutive days with the daily maximum temperature between 20° and 30°C. We use day three of the sequence for the synoptic climatology. The annual distribution of heating cycles by month, is given in Figure 1, while Figure 2 shows the distribution of heating cycle lengths for Prince George, BC.

It can be seen that most heating cycles occur in July and August, but can occur as early as April and as late as October (Fig. 1). Most are less than 6 days in length, but can last as long as 24 days (Fig. 2). Since mountain pine beetle are not biologically capable of emergence and flight (depending on the year) until the end of June (Thomson and Shrimpton 1984), and most flight activity typically occurs during July and August (Thomson and Shrimpton 1984), we focus on these two months.

The normal climatology of mean sea level pressure (MSLP) for all days in July and August from 1968-1996 is shown in Figure 3.
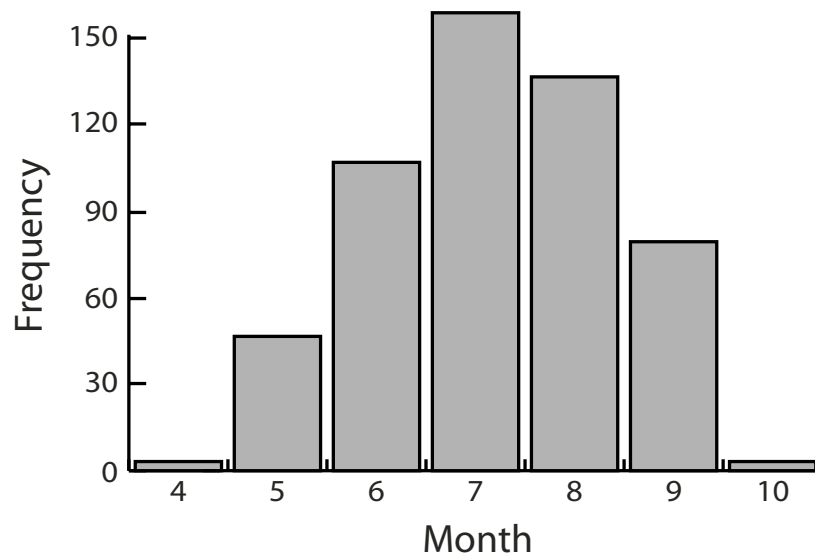

Figure 1. Distribution of heating cycles by month for Prince George between 1943 and 2002. There are an average of 8.9 cycles per year.
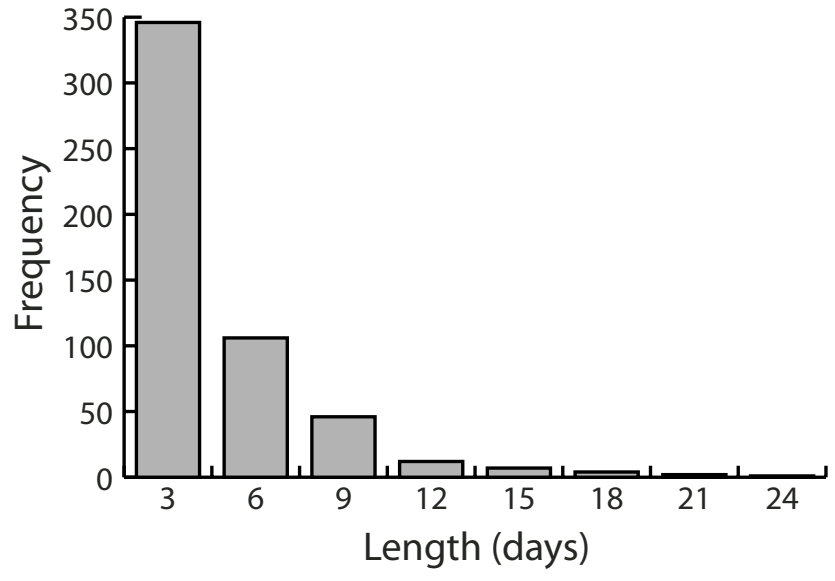
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Figure 2. Distribution of heating cycle length for Prince George between 1943 and 2002. The average length is 5.6 days.
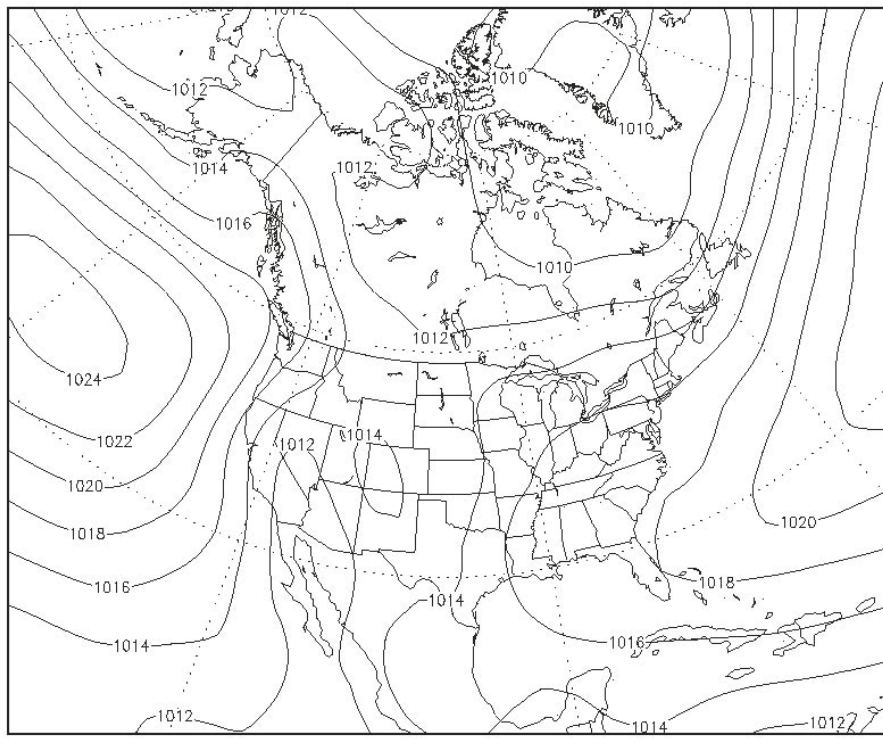

Figure 3. July-August Mean Sea Level Pressure Climatology (1968-1996) based on 1978 days of data. Contours are in hPa.

The weather pattern is characterized by a "Pacific High" pressure center dominating the northeast Pacific, with a ridge of high pressure extending eastward from the High across southern BC. The orientation of the isobars implies a westerly regional wind at the surface over much of central BC. The windrose diagram for all days in July shown in Figure 4, which depicts the wind frequency by speed class and direction, shows that winds frequently come from the west, but southerlies are most common due to steering of the flow by the mountains that flank the central interior plateau.

The average MSLP pattern during day 3 of the 105 heating cycles that occured between 1968 and 1996 (Fig. 5) shows a somewhat similar pattern as the average over all days, with the difference between the two patterns shown in Figure 6.
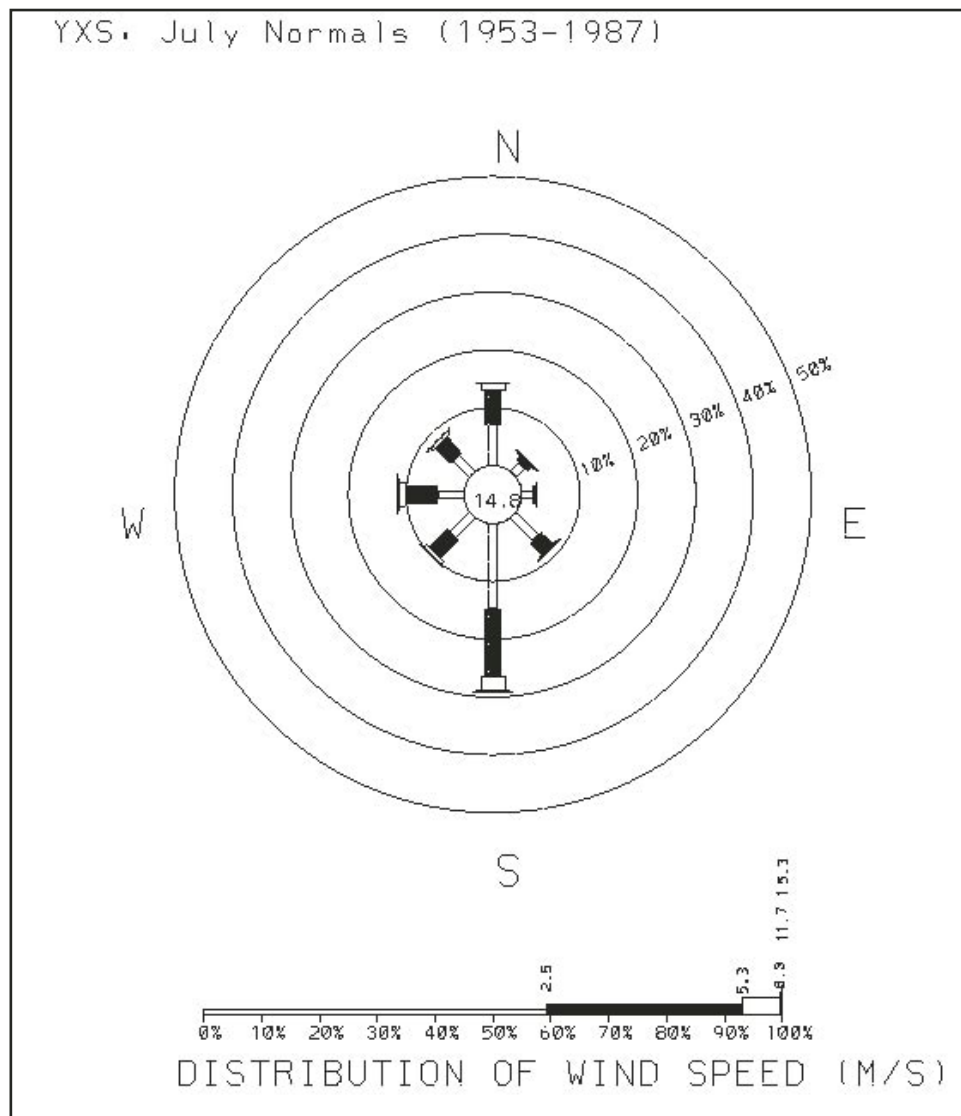

Figure 4. Windrose diagram for Prince George in July, based on data from 1953 - 1987. The direction is that from which the wind is blowing, the radial distance represents the frequency, and the variable width rose arms represent different speed classes (from .3 to 2.5 m/s, from 2.6 to 5.3 m/s, etc.).
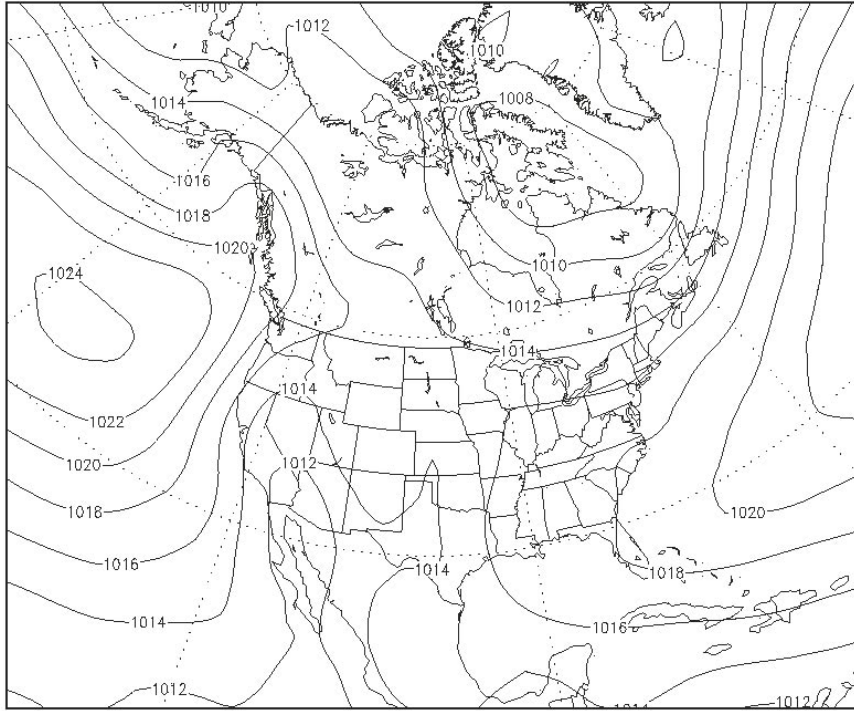
Figure 5. July-August heating cycle Mean Sea Level Pressure Climatology (1968-1996) based on 105 days. Contours are in hPa.
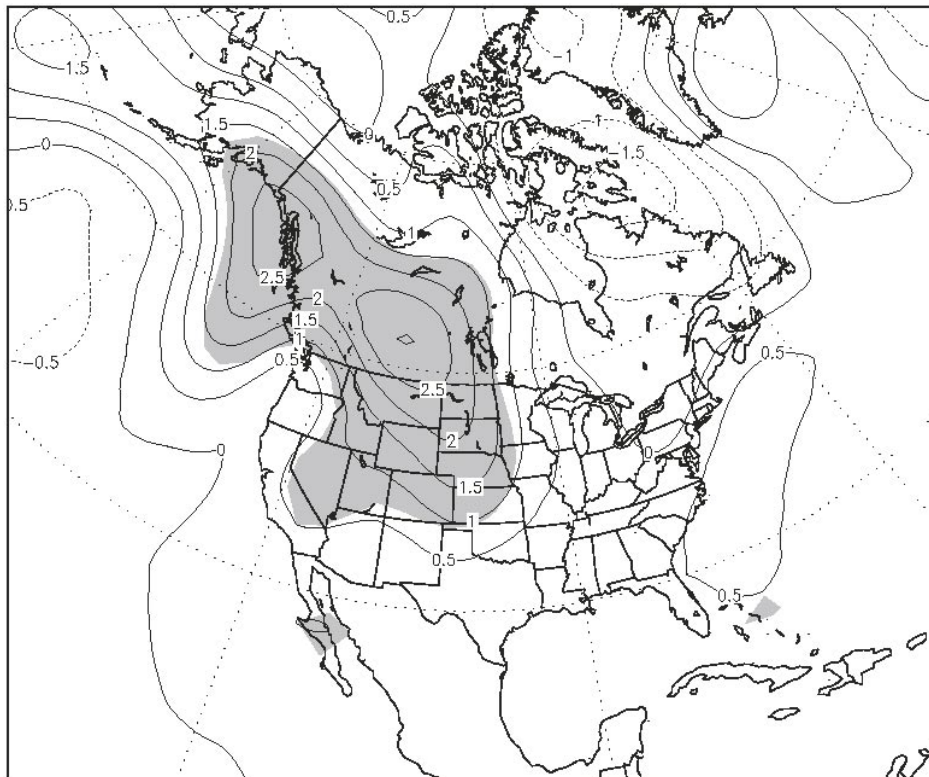

Figure 6. July-August heating cycle Mean Sea Level Pressure anomaly (i.e., Figure 4 minus Figure 5). Areas of statistically significant differences at the 99% level are shaded. Contours are in hPa.

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While the pattern and orientation of the isobars over BC on heating cycle days is quite similar to the mean pattern during those months, the MSLP is on average in excess of 2 hPa higher on heating cycle days than it is on all days combined. This indicates stronger surface ridging during the heating cycle days that would contribute to the higher temperatures.

A diurnal variation in windspeed during the above heating cycle days is evident in Figure 7.

As solar radiation heats the surface, this destabilizes the lower atmosphere by warming the air near the ground (Fig. 8). This creates rising plumes of warm air that mix the stronger winds aloft down to near the surface. Since the maximum air temperatures are reached in the late afternoon (Fig. 8) this accounts for the increase in wind speeds at this time.
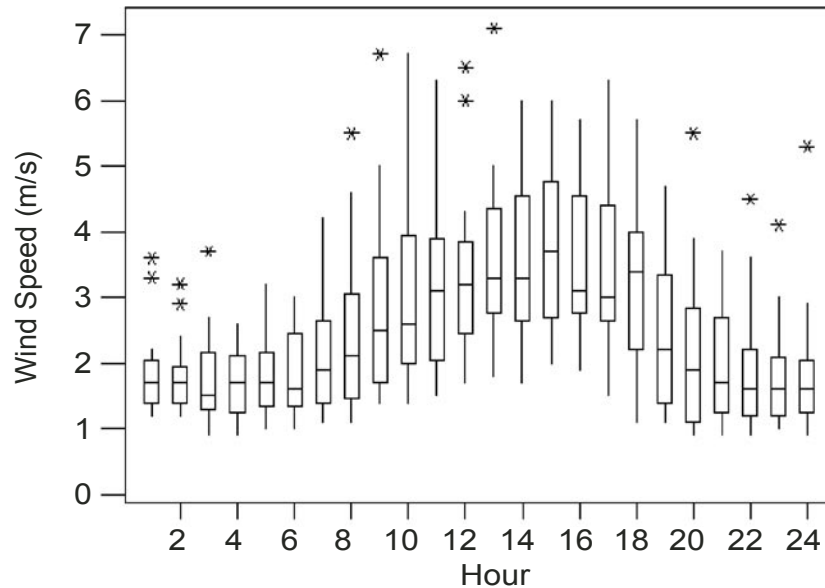

Figure 7. Box and whisker plot showing the distribution of wind speed by hour at Prince George during day 3 of 105 heating cycles. The box indicates the interquartile range, the line in the center of the box is the median, the "whisker" extends from the upper and lower quartile to the highest and lowest value, unless there are outliers that are indicated by asterisks.
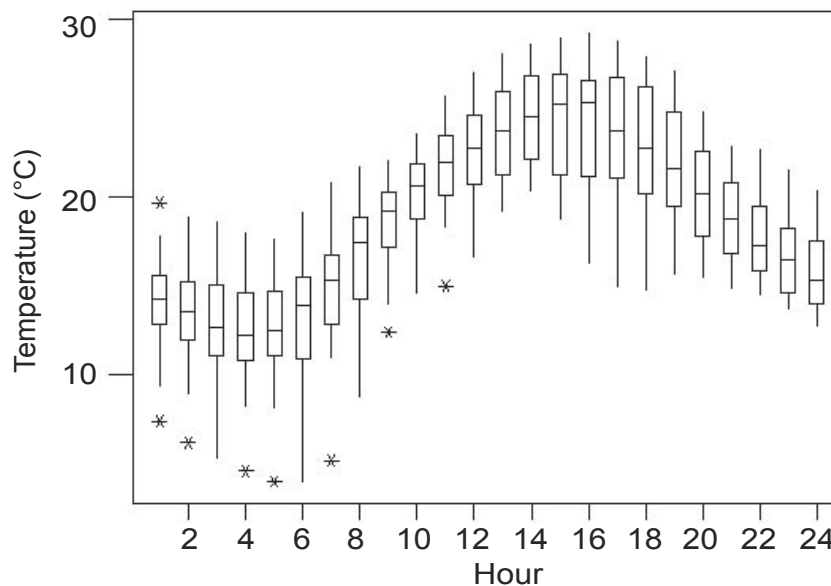

Figure 8. Box and whisker plot showing the distribution of temperature by hour at Prince George during day 3 of 105 heating cycles.
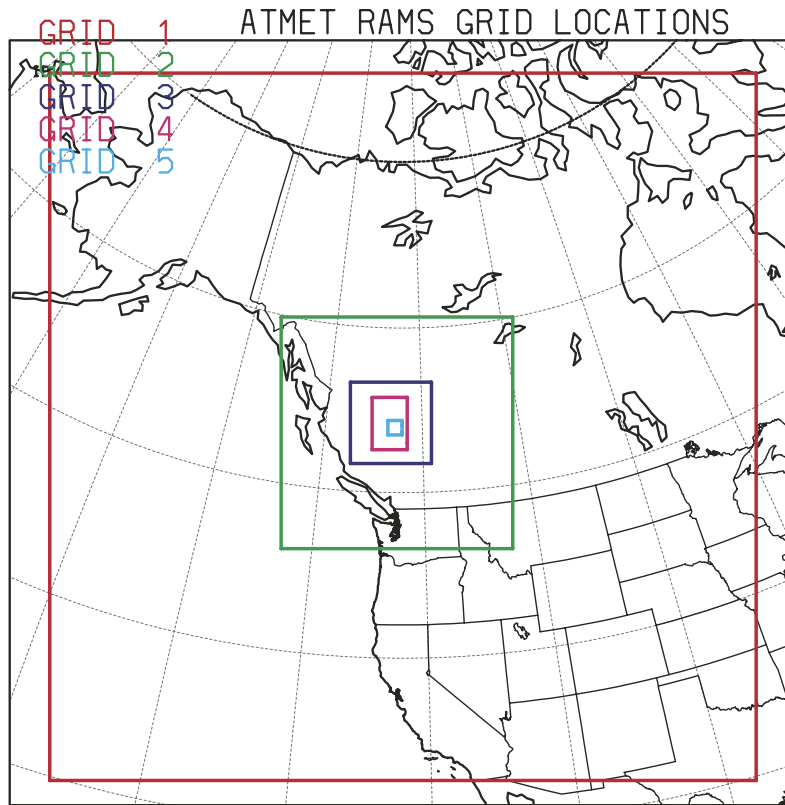
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Figure 9. RAMS nested grid locations. Grid 1 (largest) has horizontal grid points 81 km apart. Grids 2, 3, 4 and 5 have horizontal grid points 27, 9, 3 and 1 km apart respectively. All grids have 30 levels in the vertical with 25 m resolution near the surface, stretching to 1000 m resolution in the upper atmosphere.
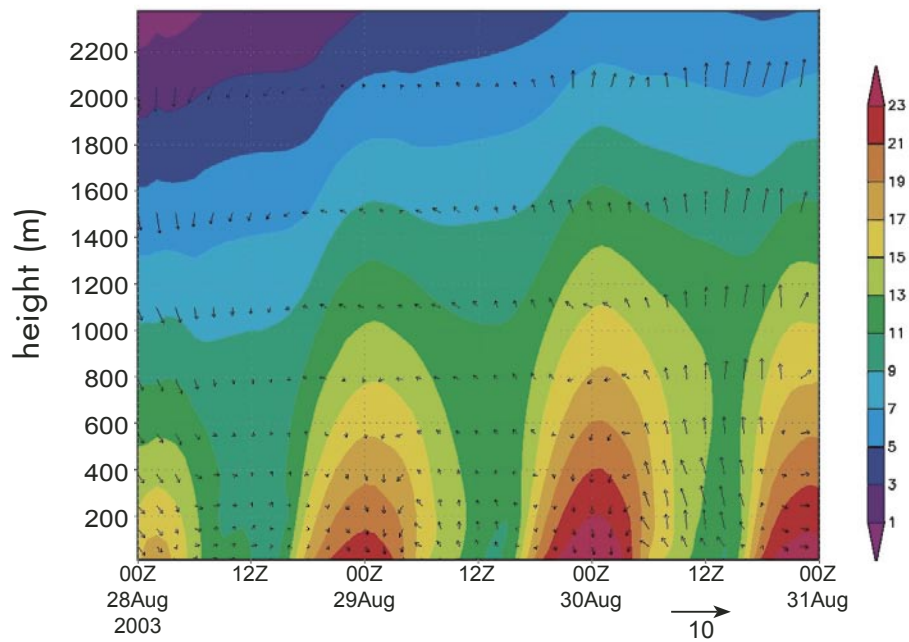

Figure 10. RAMS simulated height - time cross section from 17:00 PDT August 27 to 17:00 PDT August 30, 2003. Temperature (C) is displayed in colour fill, and horizontal wind is shown as vectors. Time on the x-axis is in UTC (UTC is 7 hours ahead of PDT).

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Modelling Example

As a first step in modelling mountain pine beetle dispersion, we have conducted an atmospheric simulation, using RAMS of a heating cycle that occured between 17:00 PDT August 27, 2003 and 17:00 PDT August 30, 2003. In configuring the model, we have used five nested horizontal grids (at 81, 27, 9, 3, and 1 km horizontal spacing) as shown in Figure 9. All horizontal grids used the same 30 vertical levels that were spaced 25 m apart near the ground, gradually stretching to 1000 m in the upper atmosphere. The model was initialized and nudged using model output from the NCAR/NCEP Reanalysis 2.5 degree gridded model output to represent the weather processes occuring at scales larger than the domain of grid 1 (Fig. 9).

The results showed great spatial and temporal variability in the wind and temperature fields, especially within the lowest 2 km of the atmosphere over the time of the simulation. Figure 10, showing a height-time cross-section of simulated winds and temperatures for this time period over Prince George, indicates the range of temperature and wind conditions which mountain pine beetles are exposed to during a typical flight period. The 19°C isotherm may delineate the time during the day and maximum altitude of potential mountain pine beetle flight during this time period.

Figure 11 shows a comparison of observed and simulated temperatures at Prince George for this time period. The model generally over-predicts the temperature by a few degrees, although the timing of the maximum and minimum is quite good.

Figure 12 shows the observed and simulated wind speeds at Prince George for the three days. While RAMS increases the wind speed in the late afternoon, it under-predicts the increase compared with the observations. As we make further simulations, we will be refining our modelling strategy to better represent the low-level wind fields.
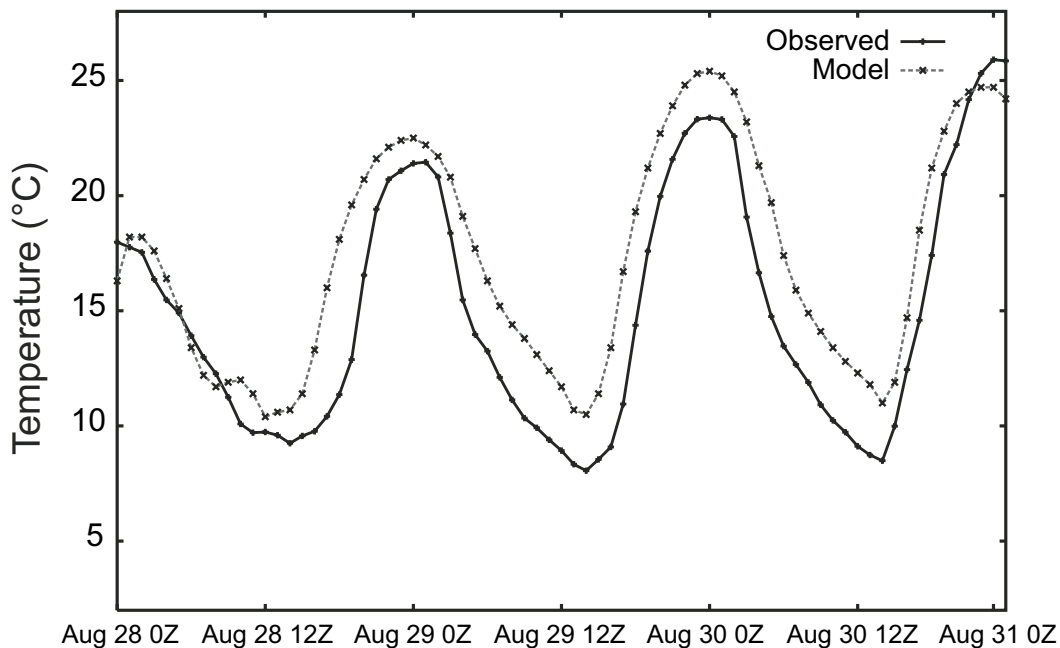

Figure 11. RAMS simulated and observed temperatures at Prince George from 17:00 PDT August 27 to 17:00 PDT August 30, 2003.
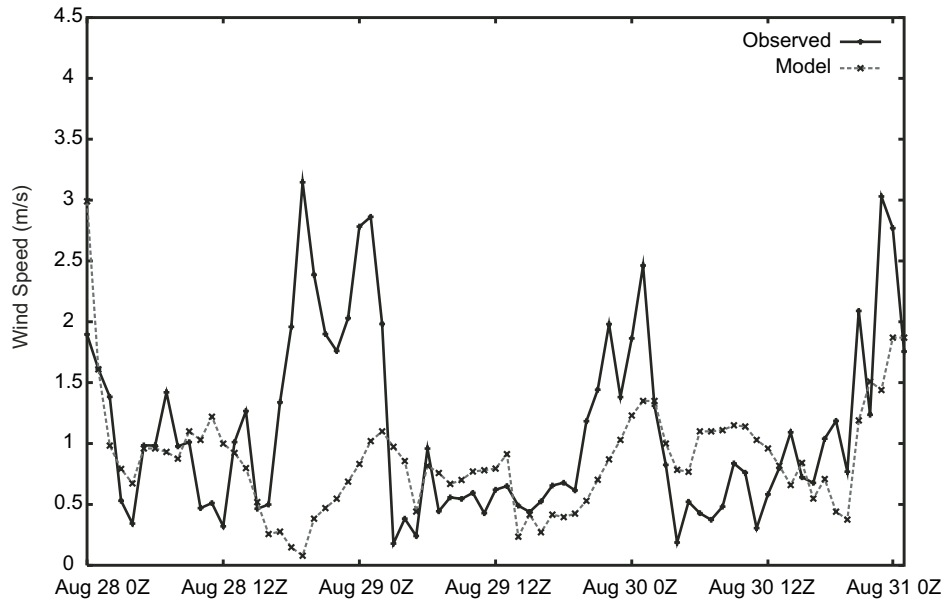
Figure 12. RAMS simulated and observed wind speed at Prince George from 17:00 PDT
August 27 to 17:00 PDT August 30, 2003.

Summary and Conclusions

A strategy to model the passive transport of mountain pine beetles by the atmosphere at the landscape
scale is described. The strategy involves four steps:

- i) identifying typical weather patterns associated with mountain pine beetle flight and dispersal;
- ii) finding fundamental relationships between terrain features, atmospheric flows, host species and mountain pine beetle fallout zones;
- iii) evaluating the potential and efficacy of atmospheric models to estimate mountain pine beetle dispersal between one year and the next; and
- iv) assessing whether use of these techniques in real-time is useful and practical. Early results from step i) (typical weather patterns) and step iii) (atmospheric modelling of a mountain pine beetle dispersal scenario) are presented.

We define a heating cycle as representing temperature conditions in which mountain pine beetles
have been observed to emerge and fly. Using this definition we develop a synoptic climatology, based on
day 3 of the heating cycle that shows the typical weather pattern associated with atmospheric conditions
conducive to mountain pine beetle flight are quite similar to average summertime conditions, except
the surface ridge of high pressure is significantly stronger than normal on the heating cycle days. An
atmospheric simulation nested to 1 km horizontal resolution over a three day heating cycle in August
2003 showed considerable spatial and temporal variability in the above canopy windfield. A preliminary
comparison with observed temperature and wind speeds at Prince George indicates that the model can
simulate the temperature reasonably well, although the wind speed taken directly from the model is
not as close to observed and will need to be improved in subsequent simulations. A more detailed and
comprehensive verification of the wind and temperature fields, as well as atmospheric transport will be
conducted in future work. Nevertheless, the considerable spatial and temporal variability in the above
canopy wind and temperature fields shown in the RAMS simulation indicates that passive atmospheric
transport of mountain pine beetle is complex and probably cannot be well treated simplistically. One

implication of this is that treating the atmosphere as a "constant" in mountain pine beetle population models may not lead to the best results.

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