

Investigation into mountain pine beetle above-canopy dispersion using weather radar and an atmospheric dispersion model

Bruce Ainslie · Peter L. Jackson

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Abstract Above-canopy, wind-assisted mountain pine beetle (MPB) dispersion in British Columbia (BC) is examined during the summer 2005 beetle emergence period. Above-canopy dispersion is simulated by the HYSPLIT atmospheric dispersion model using back trajectories started from locations identified by clear-air returns from the Prince George BC weather radar station. The dispersion calculations are carried out over the 10 days showing the highest intensity of clear-air returns from the 2005 emergence season. The Weather Research and Forecast (WRF) model is used to simulate the meteorological conditions during each of the 10 emergence days. Cumulative clear-air returns throughout each emergence day are used to estimate the distribution of beetle emergence times and atmospheric residence times. Evaluation of the WRF model output is presented using both surface and upper air observations. Evaluation of the HYSPLIT model is performed through a comparison of the vertical distribution of MPB observed in a previous study. A secondary HYSPLIT evaluation is performed using

aerial surveys taken during the following summer (2006), which identify the previous years' beetle-infested regions. Beetle flight distances from the time of beetle emergence to the time of peak clear-air returns are calculated for each trajectory, and the distribution of all flight distances is presented. The mean back trajectory distance is 20.2 km with a standard deviation of 13.6 km. These values represent the MPB flight distance during half of the beetle atmospheric residence time, and typical daily wind-assisted dispersion distances would be expected to be roughly double this value. Mean beetle residence time in the atmosphere over the 10 emergence events is found to be 3.2 h.

Keywords Mountain pine beetle · Dispersion · Trajectory analysis · Weather Radar

1 Introduction

In Western Canada, the mountain pine beetle (MPB), *Dendroctonus ponderosae*, Hopk., a native insect to the forests of western North America, finds its northerly range restricted by climate—specifically by the mean -40°C isotherm of the minimum annual temperature (Safranyik and Linton 1998). Consequently, populations in western Canada have historically been restricted to the southern half of British

B. Ainslie (✉) · P. L. Jackson
Natural Resources and Environmental Studies Institute,
Environmental Science and Engineering Program,
University of Northern BC, 3333, University Way,
Prince George, BC V2N 4Z9, Canada
e-mail: ainslie@unbc.ca

P. L. Jackson
e-mail: peterj@unbc.ca

Columbia (BC) and southwestern Alberta. A noticeable shift in climatically suitable MPB habitat has been observed in the past decade and has led to an expansion of populations both northward and toward higher elevations (Carroll et al. 2004; Taylor et al. 2006). In BC, this expansion of climatically suitable habitat, along with changing natural stand conditions, aided by forest management practices, has contributed to MPB populations reaching unprecedented epidemic levels in recent years—as of 2008, an area of 14.5 million hectares in the interior of BC is affected, and the epidemic has spread into Northern province of Alberta (British Columbia Ministry of Forests 2009). Thus, there is great interest in understanding how MPB infestations evolve and in identification of at-risk forest stands (Aukema et al. 2006; Aukema et al. 2008). The goal of this research is to use observations and an atmospheric dispersion model in this regard.

MPB disperse by flight over a relatively well-defined period during which maturation of new adults, emergence and flight occur. The onset of the emergence and flight period is generally preceded by warm, dry weather, typically mid-July to early August in BC, and occurs over a 7- to 10-day period (Safranyik et al. 1999). With flying speeds of only up to 2 m s^{-1} , and unless aided by wind, within-canopy MPB dispersal is limited to only a few kilometers (Rudinsky 1963). While such below-canopy host-finding movement has received considerable attention (e.g., Chapman 1962; Gray et al. 1972; Byers 1988; Byers 2000; Safranyik et al. 1989; Safranyik et al. 1992; Turchin and Thoeny 1993), above-canopy long-range dispersion has only recently been directly studied (Jackson et al. 2008) (hereafter referred to as J08). In that study, the authors document beetle emergence and beetle above-canopy flight using field measurements, direct in-situ (via aircraft capture) observation and clear sky returns from a weather radar. Their research supports earlier finding that suggest fair-weather convection provides a mechanism for lofting beetles above the forest canopy, and they speculate about the effectiveness of above-canopy winds in dispersing beetles over long distances (Safranyik et al. 1989; Furniss and Furniss 1972). In this paper, we use the J08-observed clear-air radar returns to initialize a series of back trajectories in order to study MPB above-canopy flight behavior.

To perform the back-trajectory calculations, trajectory starting locations as well as MPB travel times are needed. A number of difficulties present themselves in the application of a back-trajectory analysis using the weather radar. These issues are commonly encountered in the analysis of wind-assisted dispersion of migrants (typically birds and insects):

- Typically, the dispersion problem does not involve a single migrant but a population of migrants. Furthermore, migrant emergence is not expected to occur as a single event but will show some temporal dependence. Likewise, migrant emergence location likely shows some spatial variability.
- Given migrant emergence rates and emergence regions likely vary in both space and time, observations of a migrant population at a fixed time represent the superposition of individual migrants having dispersed from a range of unknown locations and over a range of emergence times.
- Instead of having observations from dedicated monitoring stations, other indirect means are often used for migrant detection.
- Due to possibility of self-powered flight, migrant dispersion cannot always be treated as that of a passive tracer.

A number of different approaches have been used to address these difficulties. For example, Ritchie and Rochester (2001) calculate likely emergence regions for mosquitoes potentially carrying Japanese encephalitis (JE) into northern Australia over three monsoon seasons. They associate receptor sites with epicenters of JE outbreaks; to account for uncertainty in flight start times, they use an ensemble of 1,000 back trajectories having a range of starting elevations (100–300 m) and flight durations (0–11 h) to map potential mosquito source regions.

Bejaran et al. (2008) estimate possible source regions for a February 2005 mosquito outbreak in Buenos Aires that coincided with a strong wind event. They use the time of the first detection of mosquitoes in the city to launch a series of back trajectories starting from the Buenos Aires airport. Uncertainty in flight start times is handled by initiating back trajectories at hourly intervals starting before and continuing until after the first mosquito detection time. They infer the location of the

outbreak source region by noting that all trajectories arriving during the peak detection times pass over a lowland flood-prone landscape upwind of the city. Furthermore, up until 10 days prior to the Buenos Aires outbreak, this region had been experiencing a drought, after which a substantial rainfall occurred. The 10-day time interval is consistent with the hatching and maturation period of floodwater mosquitoes.

Russell et al. (1998) use weather radar returns in order to identify purple martin (*Progne subis*) emergence regions (roosts) over eastern United States. Their analysis involves examining morning radar images for distinctive annuli created by the simultaneous and omnidirectional morning departure of martins from their roost. Roost locations were assumed to lie at the center of each annuli, but no ground truthing was undertaken to confirm the predicted roost locations or that purple martins were the main cause of the clear-air returns.

Wood et al. (2006) use a vertical-looking insect-monitoring radar to detect nocturnal moth migrations over southern Britain. While primarily interested in the meteorological controls on insect atmospheric layering, they use a back-trajectory model, driven by UK Meteorological Office's numerical weather prediction model to calculate likely emergence regions. All trajectories are forced to remain at 300 above ground level (agl), and they assume that all of the radar-observed moths began their flight at sunset. Also, no corrections are made to account for the self-powered moths' flight speed.

Gauthreaux et al. (2006) use weather radar returns in a back-trajectory analysis of bird migrations around Gulf of Mexico. From radar images taken from a number of stations, they determine the longitude along the northern Gulf coast showing the highest concentration of arriving migrants. They use these longitudes to launch back trajectories using the NCEP (National Center for Environmental Prediction) GDAS (Global Data Assimilation System) meteorological fields at an 80-km grid spacing. Back trajectories are launched at three elevations (500, 1,000 and 2,500 m agl) based on the observed altitudinal distribution of arriving trans-Gulf migrants. The exact flight duration or migrant source regions are not central to their analysis, which is concerned with the orientation of back trajectories with respect to the prevailing wind direction and

whether trans-Gulf migrants act as passive tracers or compensate for atmospheric winds in order to follow a fixed route. As a result, they rely on previous studies to show that Central and South America are the likely migrant emergence regions and to fix the emergence times as the evening preceding the migrant detection. All of their back trajectories are fixed at 24 h.

In this research, our objective is to characterize MPB above-canopy, wind-assisted dispersion through estimates of average beetle atmospheric residence times and the distribution of beetle flight distances. To accomplish this, we perform a time series analysis on radar clear-air returns caused by MPB above-canopy dispersion (as identified through the J08 aerial capture). Using starting locations and estimates of MPB emergence times, both inferred from the radar clear-air returns, we couple meso-scale model output from the Weather Research and Forecasting (WRF) model with the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model to launch a series of back trajectories. This allows us to calculate the distribution of typical MPB flight distances and atmospheric residence times. Furthermore, we constrain the back-trajectory calculations so as to prevent the MPB trajectories from rising into uncharacteristically cold environments. In order to gain confidence in our results, we perform various model validations: we compare the WRF output with both surface and upper air observations; we compare the vertical distribution of trajectory end-points with the vertical distribution of MPB captured during one of the J08 aerial sampling days, and we use the back trajectories to estimate MPB emergence regions, which we compare with aerial surveys of MPB-killed regions.

2 Material and Methods

Based on the J08 field sampling, aerial sampling and radar analysis, the 2005 emergence period was identified to occur between July 11 and August 4th. Within this period, J08 subjectively classified 10 days as having high radar intensities stemming from MPB returns. In the present research, these 10 emergence days (July 11, 17, 21, 22, 25, 26, 27 and August 3, 4, 5) have been used for the back-trajectory calculations. For each emergence day, calculating back trajectories entailed running the WRF meso-scale atmospheric

model, analyzing radar images and running the HYSPLIT dispersion model.

2.1 Meteorological datasets

To assist in the running and evaluation of the WRF model, three meteorological datasets were used. First, WRF was initialized using the NARR high-resolution (32 km), high-frequency (3 h) reanalysis (Mesinger et al. 2006). For each modeled day, the 1200Z NARR field was used to initialize WRF and the subsequent 5 3-h fields (1500, 1800, 2100, 0000, 0300 Z) used to update the lateral boundaries of the WRF model. Next, hourly observations, observed between 04:00 and 19:00 (PST) at the Environment Canada weather station located at the Prince George airport (YXS:53.892°N and 122.6749°W), were used to evaluate the WRF model output on each of the 10 emergence days. Finally, the 0000Z (16:00 PST) soundings taken at the Prince George aerological station (ZXS:53.900°N and 122.800°W) were also used in model evaluation.

2.2 Radar images

Data from Environment Canada's Doppler Weather Radar (XPG:53.6130°N latitude, 122.9544°W longitude) located approximately 35 km southwest of Prince George, BC, were used to determine MPB back-trajectory starting points and MPB emergence and deposition rates. The radar station is located on a volcanic plug at an elevation of 1,128 m above sea level, approximately 325 m above the surrounding terrain. The XPG radar is a 250 kW C band radar that transmits from 5,450 to 5,825 MHz from a 5.5 m antenna with a nominal beam width of 1.1 degrees and pulse length of 2 μ s. The C band wavelength of 5 cm is optimized to detect hydrometeors, which are similar in size to mountain pine beetles. The radar configuration results in a pulse length in radial distance of about 600 m, with azimuthal beam spread away from the radar. At 50 km from the radar, the radius of the cone sampled by the radar is 450 m. The radar data used in the analysis are from a nominal 0.5 degree elevation angle plan position indicator (PPI) scan. Since the emitted radar beam also curves to partially follow the curvature of the earth due to temperature changes with height in the atmosphere, the radar beam is at the following approximate

heights above the radar: 200 m at 20 km distance, 500 m at 40 km distance, 800 m at 60 km distance, 1,100 m at 80 km distance and 1,500 m at 100 km distance.

J08 identify two distinct peaks in clear-air returns over the typical diurnal cycle: a daylight one extending between 09:00 and 17:00 PST and a weaker and lower altitude nighttime one between 20:00 and 06:00 PST. They associate the nighttime cycle with nocturnal insects flying in a shallow and stable nocturnal boundary layer and the day-time cycle with MPB flight. Based on these observations, and in order to include only MPB returns in the back-trajectory analysis, only radar data images between 09:00 and 19:00 (PST) were analyzed on each of the 10 modeling days. Images were available at 10-min intervals and consisted of a digital file containing a matrix of 480×480 integers (pixels). The corresponding spatial resolution of each pixel was 500 m.

2.3 Aerial forest damage surveys

The 2006 aerial forest damage surveys of recent MPB-infected areas ('red counts'), conducted by the BC Ministry of Forests, were used to evaluate the back-trajectory calculations. These surveys were conducted from fixed wing aircraft flown at relatively high elevations above the forest canopy between July and September 2006 and map those areas where trees were killed by MPB during the previous year (and therefore identify areas of new MPB emergence in 2005). Dating of tree-kill is based on the color of the tree foliage, which turns from yellow to bright red after attack before fading as foliage is shed. The aerial surveys are divided by forest districts, and for each district, polygons associated with MPB attack are recorded. The polygons are categorized into 1 of 5 classes depending on the percent of trees within the polygon that have been recently killed: very severe (>50% killed), severe (31–51%), moderate (11–30%), light (1–10%) and trace (<1%) (British Columbia Ministry of Forests 2000).

2.4 Methods

Two major difficulties arise when using radar returns to calculate MPB flight characteristics. First, while it is easy to determine the location and elevation of the clear-air returns (which have been identified as MPB

in J08) from any given image, the time at which these observed MPB began their flights is not known, and thus, the MPB travel time, needed to constrain the back-trajectory calculations, is unknown. Secondly, MPB emergence likely occurs throughout the day, so that at any given time, the observed returns likely arise from beetles emitted at various times throughout the day, and it is not possible to distinguish those returns from beetles recently entering the boundary layer from those emitted hours earlier.

We use a two-part approach to surmount these difficulties. First, we look at the time series of total beetle counts observed on the radar, throughout each emergence day, to estimate the temporal nature of the emergence. Next, we use this temporal dependence to develop a distribution of emergence times, which we randomly assign to each clear-air return. This then allows us to calculate a back trajectory for each clear-air return. Contouring the calculated back-trajectory end-points gives us an estimate of local MPB infestation regions, which we use to evaluate our model by comparing the contoured regions with the following summer's red-count fields.

2.5 Radar Image analysis

For each emergence day, a total of 61 radar images, at 10-min intervals, were analyzed over the 10-h 09:00–19:00 PST analysis period. For each image, pixels associated with clear-air returns, along with the return intensity, were identified. In each image, return intensities are given between 0 and 65 dBZ at 2.5 dBZ intervals and stored as integer values. While return intensities are measured in dBZ, they are also reported as rainfall rates (mm/hr) where an empirical relationship has been used to relate radar-return intensity to number of hydrometeors within the sampled volume. For the present analysis, we assume that the relationship between radar-return strength and MPB density is similar to the radar/rainfall relationship so that the observed rainfall rates are proportional to the actual MPB densities. Coordinates for each return were determined based on the 500-m image resolution, the radar location, radar elevation and the curvature-corrected PPI distance–elevation relationship. For each image, we define the total intensity-weighted MPB count as the sum, over all returns, of the detected rainfall rate. In Fig. 1, MPB clear-air returns from July 21 2200Z

are shown along with a series of range rings at 20-km intervals, cross-hairs and the region's major rivers. The colorbar gives the rainfall rate in mm/h, which, again, we assumed to be proportional to beetle densities.

On half of the modeling days (July 11, 17, 22, 27 and August 3), coherent features, likely convective precipitation, appear during part of the daily analysis period. These features tend to appear later in the day as localized areas of high intensity, progressively moving returns across a great depth of the atmosphere. This is in contrast with the MPB returns that have lower but more uniform return intensities and are clustered around the radar due to their lower altitudes. The high-intensity, fast-moving features were filtered from the radar images if: the intensities were greater than a set threshold; at locations where modeled WRF temperatures were below 11°C; and locations further than a fixed distance from the radar. The intensity and distance thresholds were determined through visual observation of each radar image and varied between model days. The 11°C threshold was based on the J08 aerial sampling data that did not find beetles at elevations where the temperature was colder than 11°C.

In order to estimate beetle emergence times, we assume that the time rate of change of beetles ($\dot{N}$), within the volume swept out by the radar beam, is equal to the average surface emissions flux ($\dot{E}$) of beetles into this volume less the average surface deposition flux ($\dot{D}$) out of this volume. We further assume that the temporal dependencies for the emission and deposition fluxes are everywhere the same, and so the $\dot{E}$ and $\dot{D}$ can be expressed as the product of a function with only a spatial dependence and another with only a temporal dependence:

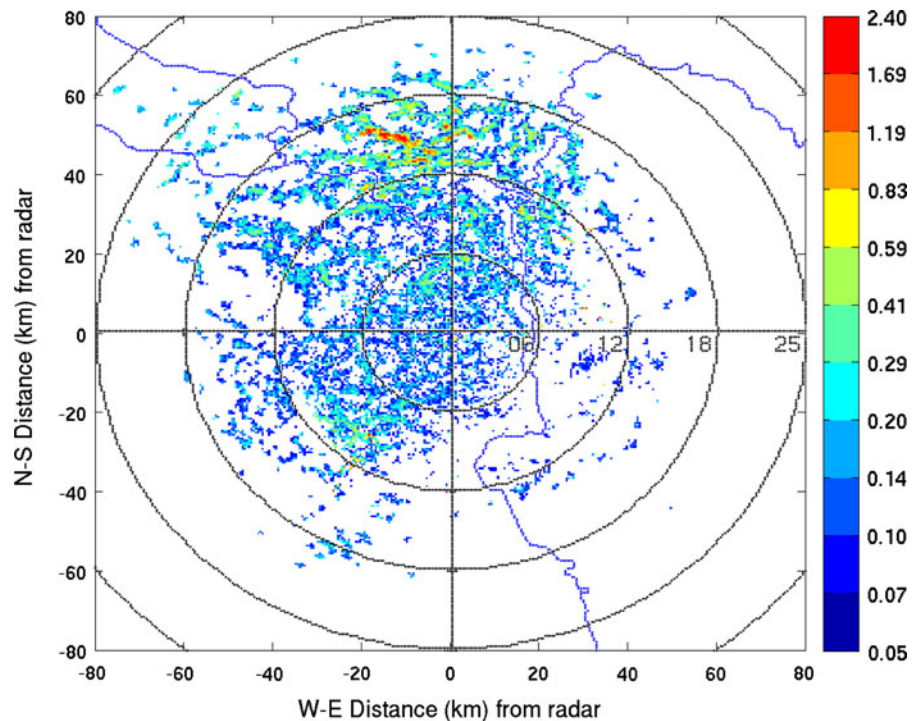
$$\begin{aligned}\dot{E} &= e(x, y) \cdot \varepsilon(t) \quad \text{and} \\ \dot{D} &= d(x, y) \cdot \delta(t)\end{aligned}\tag{1}$$

thus

$$\begin{aligned}\dot{N} &= \iint_A (\dot{E} - \dot{D}) dA \\ &= \iint_A (e(x, y) \cdot \varepsilon(t)) dA - \iint_A (d(x, y) \cdot \delta(t)) dA\end{aligned}\tag{2}$$

where A is the surface footprint of the PPI scan. If we let

Fig. 1 Location and intensities of clear-air returns from the July 21 2200Z radar image. Color scale is in mm/h, which we assume is proportional to beetle density. Also shown are the 20, 40, 60, 80 and parts of the 100 km range rings, east–west and north–south cross-hairs and outlines of the Nechako and Fraser rivers. Numbers beside the range rings give PPI elevation in 100s of feet



$$\bar{e} = \frac{1}{A} \iint_A e(x, y) dA \quad \text{and} \quad (3)$$

$$\bar{d} = \frac{1}{A} \iint_A d(x, y) dA$$

then

$$N(t) = A \cdot \bar{e} \int_0^t \varepsilon(s) ds - A \cdot \bar{d} \int_0^t \delta(s) ds \quad (4)$$

where we set the constant of integration arising in Eq. 4 to 0 by requiring the number of MPB within the PPI scan to be zero at time $t = 0$. This can be accomplished by setting $t = 0$ to be before the days' emergence period begins. If we assume that on a given day, the beetle emergence flux equals the beetle deposition flux over the radar footprint (A), then:

$$A \cdot \bar{e} = A \cdot \bar{d} = k \quad (5)$$

so that

$$N(t) = k \left[\int_0^t \varepsilon(s) ds - \int_0^t \delta(s) ds \right] \quad (6)$$

Now, individual MPB emergence is likely sensitive to many factors (like beetle biological maturity,

sensitivity to temperature, ease at which a beetle can emerge from a tree), so it is reasonable to expect $\varepsilon(t)$ follows a Gaussian distribution. Similarly, individual beetle deposition is likely sensitive to various factors including individual beetle fitness, beetle proximity to suitable host trees so that $\delta(t)$ likely follows a Gaussian model too.

To simplify matters, we assume that both the emissions and deposition Gaussian have the same variance (σ) but have different means (μ and $\mu + \tau$):

$$N(t) = k \left[\int_0^t N(\mu, \sigma) ds - \int_0^t N(\mu + \tau, \sigma) ds \right] \quad (7)$$

where the difference between means (τ) represents the mean beetle atmospheric residence time.

To make use of these relationships, for each emergence day, we plot total intensity-weighted MPB counts ($N(t)$ in Eq. 7), from all 61 radar images, as a function of time. We then model this time series as the difference between two cumulative normal distributions having different means but the same variance. This modeling process involves fitting three parameters: μ , τ and a scale factor (k in Eq. 7).

While $\varepsilon(t)$ gives us the distribution of MPB emergence times, needed for the back-trajectory

modeling, we still do not know how to assign these emergence times to each clear-air return. Instead, we use $\varepsilon(t)$ to randomly assign beetle emergence times to each clear-air return in a given radar image. While emergence time assignments will overestimate the true emergence time for some returns (and hence likely lead to an estimated emergence location too far upwind) it should also underestimate emergence times at a similar number of returns (leading to estimated emergence locations too far downwind). It is hoped that through this random emergence assignment, the predicted distribution of MPB travel distances will be an accurate and unbiased estimate of the true distribution.

The random assignment of beetle emergence times from $\varepsilon(t)$ was subject to two conditions:

- Emergence times had to be at least 10 min (the time interval at which the meteorological fields were saved) prior to the radar observation times. For example, if the time of peak intensity-weighted counts was 2000Z, then all of the randomly chosen emergence times had to occur on or before 1950Z. This constraint was chosen to allow HYSPLIT to integrate the back trajectories for at least 1 time step.
- Emergence times could not occur earlier than the time of peak intensity-weighted counts less the mean residence time (τ). For example, for a 2000Z peak emergence time and a τ of 4.167 h, emergence times could not occur earlier than 1550Z. This constraint was imposed in order avoid sampling too far into the tails of $\varepsilon(t)$ and getting unrealistic early emergence times or unrealistically long flight times.

Finally, by assuming that $\dot{E} = e(x, y) \cdot \varepsilon(t)$, it follows that by knowing $\varepsilon(t)$ then the clear-air returns from any individual image should be sufficient to estimate $e(x, y)$ (via the back-trajectory calculations). However, at the time of the earliest returns, the planetary boundary layer (PBL) is still relatively shallow, so only clear-air returns close to the radar site are visible in the PPI scans. Hence, back trajectories based on these returns will estimate $e(x, y)$ only over a limited area around the radar. By choosing an image later in the day, when the PBL is deeper and hence the PPI scans detect beetles further from the radar station, we should expect to recover $e(x, y)$ over a greater area. The drawback of

using images from a later time is that the PPI scans will record returns from beetles having a wider range of emergence times, and hence, the estimate of $e(x, y)$ will have more uncertainty. Thus, there is a trade-off to be made: clear-air returns from earlier in the day limit the possible combinations of beetle emergence times leading to a sharper estimate of $e(x, y)$ but only over a region immediately surrounding the radar, while clear-air returns taken later in the day will allow for an estimate of $e(x, y)$ over a larger area but at the cost of more uncertainty. As a compromise, for each modeling day, we chose the hour with highest intensity-weighted counts for the random assignment of emergence times.

2.6 Atmospheric modeling

To provide 3-D wind fields for the back-trajectory calculations, the Weather Research and Forecasting (WRF) meso-scale model (version 3.1) was used to simulate meteorological condition over the XPG weather radar on each of the 10 emergence days. The WRF modeling setup consisted of 3 nested domains at 32, 8 and 2 km grid spacing centered over the weather radar (Fig. 2). The outer domain had 60×61 gridcells, the middle domain 77×81 and the inner domain 97×101 . Model output was saved at 10-min intervals to coincide with radar image times.

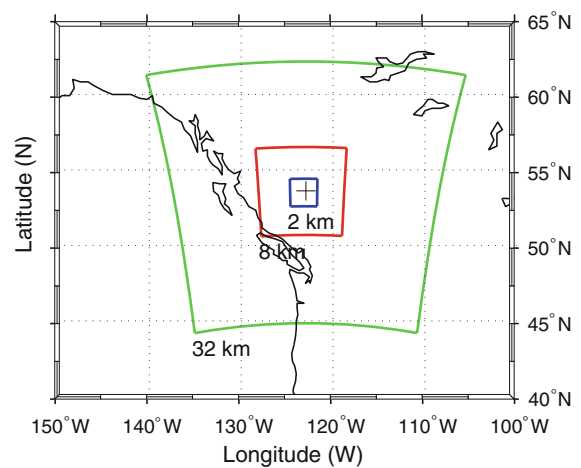


Fig. 2 WRF outer (32), middle (8) and inner (2 km) computational domains. Also shown is the XPG radar site as a + sign

On each emergence day, WRF was initialized at 1200Z (04:00 PST) giving 5 h for the model fields to spin-up before the 09:00 PST analysis start time. All WRF simulations were 15 h long, ending at 19:00 PST. All model grids had 28 vertical levels (which used an hydrostatic pressure coordinate with model top at 10 kPa) and 5 soil levels. The main physics options used included: weak analysis nudging for winds, temperature and humidity outside of the boundary layer; the Dudhia shortwave radiation scheme (Dudhia 1989); the YSU boundary layer scheme (Noh et al. 2003); and the Kain-Fritsch convective parametrization (Kain 2004).

Hourly WRF surface temperatures, interpolated to the YXS measuring station, over each analysis period and vertical profiles of WRF-predicted wind speeds and directions, interpolated to the ZXS aerological station, at the 00Z sounding times were used to evaluate the model output.

2.7 HYSPLIT trajectory model

Back trajectories were calculated using the HYSPLIT model driven by the WRF meteorological fields (Draxler and Hess 1997). In the present study, the WRF meteorological fields were used by HYSPLIT to simulate beetle back trajectories around the radar. For each emergence day, the latitudes, longitudes and elevations of each return, observed at the time of peak MPB counts, were extracted and used to initialize the back-trajectory calculations. For each return, multiple back trajectories were initiated using a 10-min time step and ran from the peak observance time to the randomly assigned emergence time. The number of back trajectories started from each radar return was proportional to the return's rainfall rate and ranged from 1 to 34.

The aerial sampling of J08 did not find MPB at elevations where temperatures were less than 11°C suggesting that MPB were not acting as passive particles but were actively limiting their maximum altitude through a change in flight behavior. These findings are consistent with studies that found insects riding thermals in such a way as to maintain an approximately constant altitude (Geerts and Miao 2005). As a result, the HYSPLIT model was adjusted so that if the temperature along any trajectory drops below 11°C, a new vertical elevation is found:

$$Z_{\text{new}} = Z_{\text{old}} + (1.0 - Z_{\text{old}})/10 \quad (8)$$

where Z_{new} is the new elevation and Z_{old} is the existing elevation. These Z -values are in sigma units (1.0 model surface and 0.0 model top), and the change given in Eq. 8 is equal to 10% of the difference between the current sigma level and ground. At a typical elevation of 500 m agl, this represents a change of 53 m.

On each emergence day, the HYSPLIT-predicted latitudes and longitudes at the end of each back trajectory were gridded at a 5,000-m resolution over a 360×240 km region centered over the radar station. This field is an estimate of that part of $e(x, y)$ as seen by the radar given the day's meteorology and was used for model evaluation with the red-count fields. The HYSPLIT-predicted elevations at the trajectory end-points were also gridded onto a 50-m resolution grid extending from 0 to 2500m agl. For the July 26 event, this distribution was compared with the July 26 vertical MPB distribution observed in the J08 aerial capture.

2.8 Gridding recent MPB-infected areas

The 2006 aerial forest damage surveys from the 5 forest districts surrounding the radar station were used to evaluate the back trajectory-calculated MPB emergence locations. For each forest district, polygons associated with very severe (V), severe (S), moderate (M) and light (L) attacks were identified. Next, MPB attack severity rates were gridded onto the same 360×240 km domain as for the HYSPLIT-predicted emergence locations. For each polygon, red-count values in all grid cells overlapping the polygon were incremented by a factor equal to the mid-point of each class' mortality severity scale: 75 for the very severe class, 40.5 for severe, 20.5 for moderate, 5.5 for light and 0.5 for the trace class. Both the back trajectory and red-count gridded fields were normalized by the total number of back trajectories and red counts, respectively.

2.9 Statistical evaluation of back-trajectory areas and red count areas

Contingency tables, commonly used to evaluate precipitation forecasts, were used to compare the HYSPLIT-predicted MPB emergence regions with

the red-count fields. For each field, each gridcell was assigned a binary value depending on whether the value of the gridcell was above or below the 50th percentile. The choice of 50th percentile as a threshold for discriminating between emergence and no emergence (or red count/no red count), while arbitrary, was found to provide a reasonable means of ranking the accuracy of the emergence days. Specifically, we found that the red-count field was less smooth than the back-trajectory field so that a high threshold choice lead to a contingency table with very few red-count hits. On the other hand, a low threshold choice lead to a contingency table with almost all gridcells having back-trajectory hits. The 50th percentile provided a reasonable compromise between these two extremes.

We then used odds ratio to quantify the association between the two 50th percentile fields (Stephenson 2000). This ratio is the product of the number of concordant gridcells (those gridcells either above the 50th percentile for both fields or below the 50th percentile for both) to the product of the number of discordant cells (gridcells either above the 50th percentile in one field but not the other or vice versa). While this single ratio cannot completely describe the level of agreement between the two fields and while there are numerous other metrics useful for measuring contingency agreement, we are most interested in assessing the relative accuracy of each day's prediction as opposed to establishing absolute agreement levels.

3 Results and discussion

3.1 WRF model output

In general, the WRF model does a good job at reproducing the stagnant conditions that occur for most of the emergence events: the mean 04:00–19:00 PST WRF 2m temperatures at the YXS location are 17.6°C compared to the observed mean of 17.9°C; the mean WRF-simulated 10 m wind speed of 7.1 km/h is close to the observed mean value of 6.1 km/h; and the WRF mean upper air wind speed, averaged between 0 and 2,000 m agl over the ZXS aerological station and at the time of the 0000Z sounding, is very close to the mean observed value (16.1–15.9 km/h). However, model accuracy varies

between events and the 10 m, and upper air wind results, broken down by emergence event, are given in Table 1. The WRF root mean square error (RMSE) for 10 m wind speed varies from a low of 3.1 km/h (July 21) to a high of 7.4 km/h (July 21) with an overall RMSE of 5.1 km/h. Mean absolute errors in 10 m wind direction vary from a high of 83° (August 4) to a low of 12° (August 3). Part of the reason for the high August 4 wind direction errors likely stems from the very low winds speeds observed that day (mean of 4.4 km/h). Overall, the mean MAE of 54° seems large, but part of this problem likely arises from the generally low wind speeds over the emergence events. The upper air RMSE wind speed errors are generally larger and vary from a low of 3.1 km/h (August 3) to a high of 14.6 (July 25) with an overall mean of 8.3 km/h. The July 25th event also produces the largest discrepancy in wind direction with a MAE of 81°. Both July 26th and August 3rd have MAE errors of less than 20°, and the overall upper air wind direction MAE is 50°.

3.2 Intensity-weighted rainfall rates

For most of the 10 events, the time series of intensity-weighted total rainfall rates was very well captured by Eq. 7. Notable exceptions were July 27 and August 4, which both had extensive organized convective activity throughout parts of the analysis period that proved difficult to filter out. Figure 3a and b show time series of raw (+) and filtered (o) total intensity-weighted rainfall rates. For both days, the raw signal is much larger than the resulting filtered signal, and in order to show the fitted ε , δ and N curves, the vertical scales have not been scaled to show the maximum raw rainfall rates (28678 and 22867 for July 27 and August 4). For the July 27 case, the $N(t)$ curve fits the filtered signal until about 2300Z, whereas for the August 4 case, the filtered signal is not very well modeled by Eq. 7. On three of the other events (July 17, July 22 and July 25), convection is seen but starts late in the afternoon, and the filtered signal is well modeled by Eq. 7 past the peak intensity rainfall rate. Figure 3c shows such a case where $N(t)$ fits the filtered rainfall until about 2000Z on the 22nd of July. For the remaining 5 days, only minor filtering of the radar signal was needed, and Eq. 7 provides a good fit to the observed rainfall rate. Figure 3d shows the July 21 event where the

Table 1 Summary of 10 m and upper air modeled wind speed and direction errors for each of the 10 modeled emergence events along with overall average

Date	Surface		Upper air	
	RMSE Speed (km/h)	MAE Dir (Deg.)	RMSE Speed (km/h)	MAE Dir (Deg.)
July 11	7.4	62	9.9	56
July 17	6.0	56	5.8	30
July 21	3.1	39	9.3	71
July 22	5.5	41	5.5	67
July 25	4.4	75	14.6	81
July 26	4.6	76	6.5	12
July 27	4.3	60	9.6	28
August 3	5.3	12	3.1	17
August 4	4.4	83	7.9	38
August 5	5.0	29	8.3	45
All events	5.1	54	8.3	50

The 10-m errors are based on the observed and modeled winds at the YXS measuring station between 04:00 and 19:00 PST of each event. The upper air statistics are based on the 0–2,000 m winds observed at the ZXS aerological station for the 0000Z sounding taken each day

observed weighted rainfall rate is well fit by $N(t)$ throughout the analysis period.

3.3 Back trajectories

A total of 211,933 back-trajectory calculations were performed for the 10 events. The breakdown by individual event is given in Table 2 and ranges from as few as 5,096 (July 22) to 41,579 (July 11). Figure 4 shows the vertical distribution of trajectory end-points

for the July 26 event along with the observed July 26 vertical distribution from the J08 the aerial capture. This event was chosen for comparison because of the large number of beetles captured on that aerial sampling day. Both the trajectory end-point and aerial capture counts have been normalized by their respective maximum values. The HYPPLIT-predicted vertical distribution generally puts beetles at a higher level than the observed distribution, especially between 900 and 1,350 m asl. Both distributions

Fig. 3 Raw (+) and filtered ('o') total intensity-weighted rainfall rate as a function time during the July 27 (a), August 4 (b), July 22 (c) and July 21 emergence events. Also shown is the fitted emissions curve ($\varepsilon(t)$: triangles) and deposition curve ($\delta(t)$: squares) and the difference between the cumulative sum of ε and δ ($N(t)$: solid line)

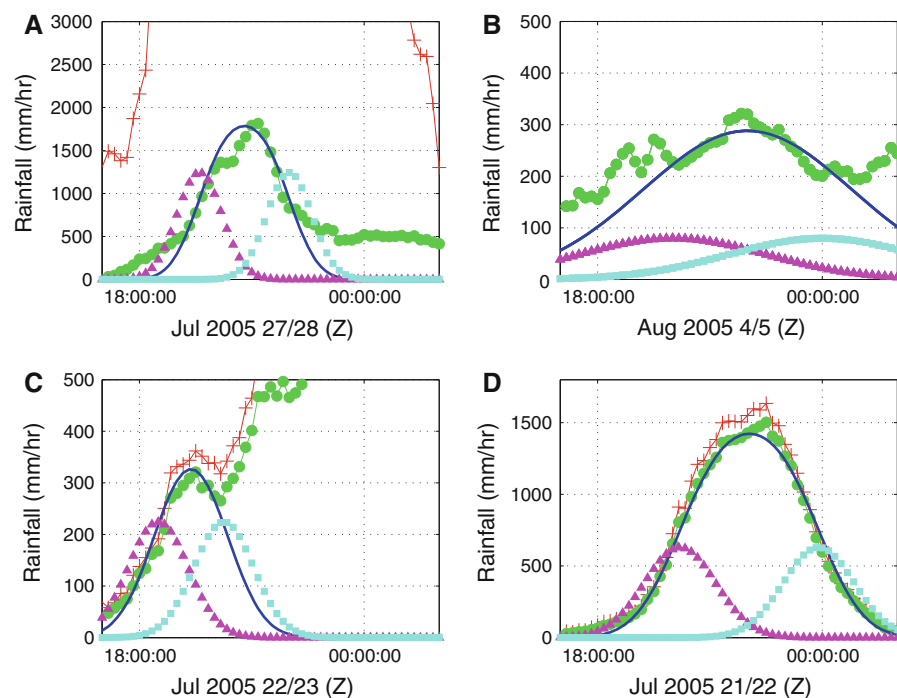
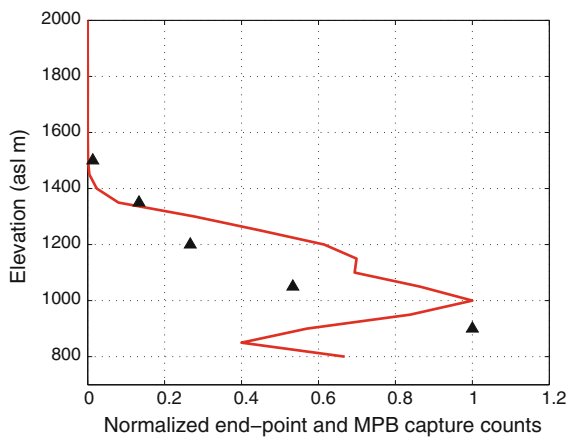


Table 2 Summary of back-trajectory calculations on each of the 10 emergence days

Date	Trajectories	00Z Upper Air Wind		μ	τ	Odds ratio	Half-distance
	Number	Direction	Speed (km/h)	(Z)	(h)	–	(km)
July 11	41579	134	13.0	2018	3.60	0.92	9.8
July 17	20216	213	23.5	1848	1.60	0.93	18.9
July 21	27546	144	8.0	2012	3.70	0.76	15.5
July 22	5096	283	6.1	1830	1.75	0.83	7.8
July 25	30445	49	8.5	2000	4.25	0.85	31.2
July 26	13102	274	21.3	1827	4.70	0.61	22.0
July 27	35474	279	25.9	1936	2.40	1.16	21.8
August 3	20430	169	19.6	2021	3.80	1.40	30.6
August 4	5925	161	20.9	2000	4.00	0.95	25.6
August 5	12120	347	10.3	2118	2.30	0.98	20.0
Average	21193	216	15.7	1945	3.2	–	20.2

**Fig. 4** Vertical distribution of normalized trajectory end-points (curve) and normalized MPB aerial capture counts (triangles) taken from J08

show no beetles above 1,500 m asl. The HYSPLIT-based distribution produces a maximum beetle count at 900 m asl, whereas the observed maximum count is at 1,000 m asl.

The final method for evaluating the back-trajectory calculations involves the comparison of back-trajectory end-points with the following summer's red-count aerial surveys. The back-trajectory contoured area represents the likely MPB emergence regions. Areas within the red-count contours represent forested regions with high recent tree mortality as observed from the following summer's aerial survey. Thus, we expect a strong correspondence between contoured back-trajectory end-point locations and

red-count areas, although the relationship need not be linear. Note that the back-trajectory contoured area will only overlap with a small part of the red-count field (which covers the entire province). For each of the 10 modeled days, the spatial extent of the back-trajectory end-points (i.e. the footprint) is determined by the spatial extent of the radar returns, the estimated MPB residence time, the mean wind speed and mean wind direction. MPB-infested regions lying outside of this footprint, while potentially significant emergence regions, will not produce flight trajectories that pass over the radar. As a result, only red-count values within the back-trajectory footprint are considered in the model comparison.

Figures 5 and 6 show the back-trajectory-calculated emergence regions along with the contoured red-count field for the August 3rd and July 26th events. In both plots, the fields have been normalized by the total number of trajectories and red counts, respectively. Both fields have been contoured at the 50th percentile. For clarity of presentation, solid color-filled contouring has been used for red-count field. In addition, the back-trajectory footprint has been plotted. It is over this region that the contingency table has been calculated. Finally, the mean wind direction over the lower 1,100 m based on 00Z sounding is indicated. These 2 days show reasonable agreement (odds ratio of 1.50 and 1.16, respectively) and have 00Z wind directions from the south (169°) and west (279°).

In Fig. 5, there is large overlap between the red-count and back-trajectory contoured areas and to

lesser extent between the red-count and back-trajectory free areas. While there are mismatch areas (back-trajectory free locations overlapping red-count areas and vice-versa), these are smaller in size. The most notable mismatch is the area extending due west of the radar for about 100 km. There, there is an absence of red counts (at least above the 50% threshold), whereas the back-trajectory calculations identify this as a significant emergence region. The odds ratio for this day is 1.40 which is above 1.0 (significant at the 95th percentile) suggesting non-random (but small) association between the two fields. The southerly wind directions (169°) on this day sends the back trajectories over the large red-count regions south of the radar and likely helps in the agreement.

On the other hand, in Fig. 6, the red-count/back-trajectory overlap is smaller, and the areas of mismatch larger. The general orientation of the back-trajectory footprint and 50th percentile are east–west (dominant 00Z wind direction was 279°), which overlaps with the largely red-count-free region due west of the radar. The low odds ratio of 0.61 suggests there is no association between the two fields.

Table 2 lists the dominant 00Z wind direction and odds ratio for each of the 10 emergence days. In general, the agreement between the back trajectory and red-count fields is poor with only the July 27 and

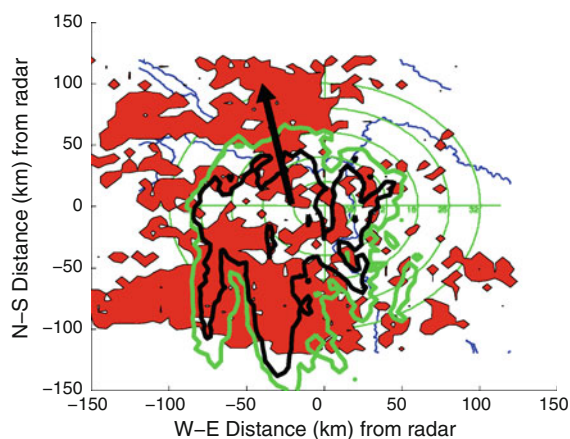


Fig. 5 Contour of the 50th percentile August 3 back-trajectory end-point concentrations (*inner thick black line*) and 2006 red-count concentrations (*solid red contour*) at the 50th percentile. Also shown is the back-trajectory footprint (*outer thick green line*), mean wind direction (*black arrow*) over the lower 1,100 m taken from the August 4 00Z sounding, radar range rings (*thin lines*) and major rivers

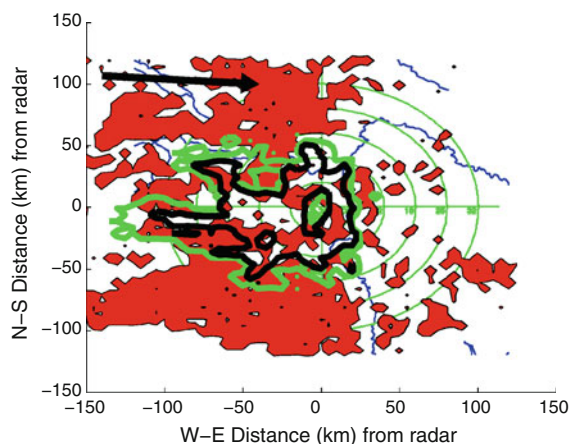


Fig. 6 Same as for Fig. 5 except for July 27

August 3 events showing odds ratios above 1.0. Additionally, only the August 3rd event is significant at the 95th percentile.

3.4 MPB flight distances

Figure 7 gives the distribution of MPB flight distances over all 211,933 back-trajectory simulations, and Table 2 summarizes the MPB flight characteristics for each of the emergence events. Distances are straight line distances calculated using only the starting and ending locations and are necessarily shorter than the trajectory arc lengths. The distribution gives the distance MPB fly between emergence and the time of peak observation and would likely, on

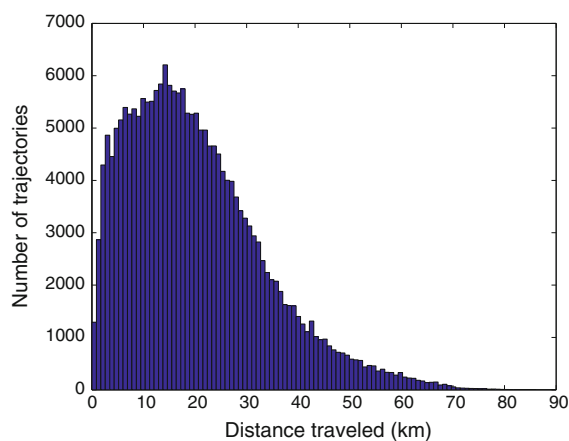


Fig. 7 Distribution of MPB flight half-distances over all 10 events. The actual distances traveled over the full flight would be approximately double those shown

the average, be only half of the total distance traveled during the beetle residence time (τ). The distribution has a mode of 16.5, a mean of 20.2 and median of 18.0 km. If the MPB travel forward from the time of peak observation for another $\tau/2$, then it would be expected that MPB travel, on average, about 40.4 km during a wind-assisted flight.

Mean flight distances on each of the 10 emergence days varies greatly (SD 7.8 km) due to a combination of residence time variability (SD 0.9 h) and wind speed variability (SD 7.3 km/h). Both July 17 and 22 have residence times less than 2.0 h. On both these days, significant convective activity was observed just after the time of peak observation. It is not possible to tell whether this convective activity was interrupting the MPB flights or the methods used to filter out the convective returns has also filtered out some MPB returns. While strong convective activity was also seen on July 25, the calculated residence time is over 4 h.

3.5 Discussion

The orientation of the back trajectories over the 10 modeled days indicates a general east-to-northeast dispersion. Since emergence also occurs on other days, it is difficult to gauge the importance of the non-modeled days of the 2005 emergence period on the distribution of MPB flight distances, residence times and direction of dispersion. A superposition of calculated MPB emergence regions from all days during the 2005 emergence period should improve the agreement with the gridded red-count field.

J08 estimate beetle dispersion between 30 and 110 km/day using simple arguments based on observed mean wind speeds and estimated atmospheric residence times of 4 ± 2 h. Assuming that total daily MPB flight distances are roughly twice the modeled trajectory distances, the present study finds 58% of calculated trajectories are within this range. Hodgkinson (2005) reports that between 1996 and 2001 MPB west of the present study area were dispersing at approximately 65 km/year. Our results show only 17% of back trajectories had half-flight distances equal to or greater than 32.5 km.

MPB flight distances are directly dependent on beetle atmospheric residence times whose estimation is difficult when the radar returns are contaminated with convective precipitation. In this study, the mean

calculated MPB atmospheric residence time is 3.2 h (standard deviation of 1.1 h). On the 5 days that had little or no convective activity (July 11, 21, 26 and August 3 and 5) and for which fitting Eq. 7 to the observations was straight forward, the mean residence time is 3.6 ± 0.9 h. On the 3 days with noticeable convective activity but for which it fitting Eq. 7 was reasonably straight forward up until a few hours past the time of peak radar returns remaining days (July 17, 22, 25), the mean is 2.5 ± 1.5 h. It appears from these three cases that the shorter residence times arise from late afternoon convective activity putting an end to the favorable flying conditions.

Beetle flight times in nature are unknown but have been measured in laboratories using flight mills: Forsse and Solbreck (1985) found 90% of European spruce bark beetles flew for less than 2.5 h (with a maximum of 6.3 h); Atkins (1961) found Douglas fir beetles (*Dendroctonus pseudotsugae* Hopk.) could fly up to 8 h, while the southern pine beetle (*Dendroctonus frontalis* Zimm.) up to 6 h; and Williams and Robertson (2008) found that 6 h of flight for Douglas-fir beetles could be achieved but at the expense of a $\approx 50\%$ decrease in body fat. J08 suggest that beetles undergoing passive transport in the midst of thermal updrafts should expend less energy than beetles on flight mills, while Williams and Robertson (2008) note that flight mill studies might overestimate flight times in nature due to the mill supporting the beetle's body while in flight. Given the range of measured flying times and the difficulty in assessing how laboratory studies simulate natural flying conditions, the methods developed in this paper appear to be both consistent with previous work and present a novel way of determining beetle flying times.

We have used an algorithm, developed to calculate rainfall rates given radar-return intensities, to estimate MPB counts. This should be a reasonable assumption since MPB sizes are comparable to typical hydrometeor sizes, and thus both should scatter radio waves in the Rayleigh regime for the 5 cm weather radar used here.

The back-trajectory-contoured regions and the red-count fields did not show good agreement, and it is difficult to ascertain the cause. Since the back trajectories were over a relatively short time span, errors in the back-trajectory calculations would have limited time to grow although it is known that back-trajectories

calculations are less accurate in the PBL or when they encounter deep convection (Stohl 1998). Using HY-SPLIT to simulate Lagrangian particle dispersion instead of back trajectories may have mitigated some of these problems, although, since so many back trajectories were initiated, it is not obvious how much a difference this would have made, especially given the short integration times. Other potential sources for the discrepancies between the two fields include the small number of days simulate over the total emergence period; the random assignment of emergence times to each pixel, which will lead to (at best) smoothed estimates of MPB emergence regions; and potential biases in the aerial forest health surveys arising from the inclusion of unsuitable habitat or overestimation of mortality due to the high visual perception of red foliage (Aukema et al. 2006).

4 Conclusions

Beetle movement above the canopy, while being recognized as a potentially important component to landscape level patterns of infestation, especially during epidemics, has only recently been directly studied (J08). Presently, there is growing concern that climate change will turn the vast expanses of jack pine (*Pinus banksiana* Lamb.) west of the Canadian Rockies, and lodgepole pine in northern Canada into MPB-suitable habitat (Ayres and Lombardero 2000; Logan et al. 2003; Carroll et al. 2004). Thus, knowledge concerning the ability of MPB to undergo wind-assisted above-canopy dispersion is important in assessing the potential for such an eastward movement.

In this research, we have used statistical analyses of clear-air radar returns and back-trajectory analyses to understand MPB above-canopy dispersion. We characterize this wind-assisted dispersion through beetle atmospheric residence times and the distribution of beetle flight distances. While our results are in general agreement with other studies, they are dependent on number of assumptions and different models with the potential for accumulation of errors along the analysis chain. While we have tried to validate our methods at both the intermediate and final stages of the analysis, it is difficult to ascertain error bounds on the distribution of MPB flight distances and atmospheric residence times.

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