

On Calculating Source Regions Using a Non-Diffusive Lagrangian Trajectory Model

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Abstract

This paper examines the use of backward-in-time Lagrangian trajectory simulations to explore source regions associated with atmospheric tracer substances. A non-diffusive trajectory model consisting of a spatially varied ensemble of 30 members (BAM-30) is compared to a Lagrangian stochastic model (BLSM) using 50,000 particles. The goal is to explore whether the simpler model can provide useful source location information. Three cases were chosen for examination, all of which occurred during a significant rainfall event during June 2005 over southern Alberta, Canada. For both models, particles were released at 0000 UTC on the selected days, within a cylinder having a height of 3000 m and radius of 100 km centered on Lethbridge, Alberta. Particles were then back-tracked for 336 hr. Results show that, even though particles became separated by very large distances (on the order of thousands of km) after sufficient time had elapsed, the BAM-30 particles were generally contained within the main “cloud” of BLSM particles. This suggests the BAM-30 method could provide useful source information. We conclude that, for large source regions, such as vapor sources, a relatively simple trajectory ensemble model could provide valuable information. In all three cases, the use of a single trajectory would not have provided sufficient results.

1. Introduction

Backward-in-time trajectory models (often simply called back trajectory models) are commonly used in the atmospheric research community to explore source regions associated with the transport of trace substances. These sources can include available moisture for synoptic storm events (e.g., Brimelow and Reuter 2005), airborne pollution (e.g., Angevine et al. 2006), agricultural diseases (e.g., Krupa et al. 2006), and insects such as mosquitoes (Richie and Rochester 2001). In most cases relatively simple single trajectory models, which incorporate only synoptic scale horizontal and vertical advection, are used to calculate source regions. In these models the trajectory of a particle that passes over a receptor is calculated based on the mean wind. The upwind history of this trajectory thus defines the potential source region of tracer material to the receptor. These models traditionally use a single trajectory to define a source region. For example, Reiff et al. (1998) calculated trajectories for an African dust plume using such a method. However, the transport of material in a column of air over the receptor may be poorly represented by a single mean trajectory. Vertical wind shear causes passive tracers at different heights to be advected from different directions and at different speeds. In addition, turbulent processes cannot be fully represented by a single trajectory.

Multiple simulations in the form of an ensemble of trajectories may provide improvement over a single trajectory (e.g., Draxler 2003). The ensemble technique in its current usage is indicated by Toth (2001) as “ensemble techniques involve the perturbation of the initial conditions (and possibly the model) to an extent representative of initial (or model) uncertainties.” Ensemble prediction techniques are used by the Canadian Meteorological Center (CMC) to produce some weather forecasts. There are a number of approaches toward choosing an ensemble technique. An application outlined by Stohl (1998) assumes that the starting trajectory position is not always exactly known because of uncertainties in source height and model terrain versus actual terrain heights. Although the initial trajectory position error may be rather small, subsequent position errors can quickly become large in divergent flows. The potential trajectory divergence may be accounted for by slightly varying the initial starting position of different trajectories (Merrill et al. 1985).

Another approach, outlined by Kahl (1996), consists of generating a trajectory ensemble by adding a random perturbation to each wind component. Draxler (2003) devised a technique for generating ensemble trajectories whereby the ensemble member is generated at several different heights from the same location, and during calculation the horizontal grid is offset by an amount determined by the user.

While ensemble trajectory models, based on the mean flow field, should provide a more realistic simulation of atmospheric transport than single trajectory models, they still neglect the turbulent dispersion process. Without incorporating dispersion algorithms, no trajectory model can truly mimic atmospheric transport, and truly quantify a potential source region. Lagrangian stochastic (LS) models are a type of trajectory model that incorporate turbulent diffusion. These models simulate dispersion by mimicking thousands of trajectories, each with a stochastic component that yields a unique trajectory. The advantage of an LS model, compared with mean-trajectory models, is a more complete representation of atmospheric transport. While a mean-trajectory model can provide a qualitative estimate of an upstream source region, an LS model can provide the quantitative link (i.e., the relationship between concentration in the source region and a later concentration at a receptor). Backward-in-time Lagrangian stochastic (BLS) models (e.g., Flesch et al. 1995) are often used to identify the source of a pollutant or to estimate emissions from multiple potential sites where measurements are available from a relatively few receptors. Stohl (2002) recommended replacing mean-trajectory calculations by simulations using an LS model.

An advantage of using the simpler mean-trajectory models is the ease of computation and relatively small computing resources required. These models are available for download and use on a personal computer. In contrast, the LS model often requires significant computational time which may not be readily available to some potential users.

The aim of this paper is to explore whether the simple backward mean-trajectory model (BAM) can be useful for identifying potential source regions, specifically moisture sources. As a basis for determining the reliability of the BAM method, it was qualitatively compared to a backward Lagrangian stochastic model (BLSM). This study forms part of a larger project dealing with potential moisture sources for rain storms which caused severe flooding over southern Alberta.

2. Method

The BAM and BLSM trajectory calculations are based on the Canadian Meteorological Centre's Global Environmental Multiscale (GEM) model (Cote et al. 1997). Trajectories calculated with the BAM include only the effect of mean wind advection on motion. The BLSM includes the effect of turbulence when calculating trajectories, using a zeroth-order Langevin model MLDP-0 (D'Amours and Malo 2004). In this model, an ensemble of trajectories is calculated, with each member having different random displacement sequences to mimic the effect of turbulence. Vertical dispersion is based on a diffusion coefficient that is a function of the gradient Richardson number. Horizontal dispersion is related to the variance and timescale of wind fluctuations, empirically based on wind analysis errors (D'Amours and Pagé 2001). Particles that escape the model domain cannot

re-enter and are no longer tracked. The BLSM method is assumed to represent the true parcel trajectories within the limits of the GEM model (Batchelder 2006).

As mentioned in the Introduction, this study forms part of a larger investigation of severe flooding events over southern Alberta during June 2005. The city of Lethbridge, Alberta (YQL; 112.8 W, 49.6 N, elevation 929 m; Fig. 1), received about 270 mm of rain during this month. Most of the rainfall occurred before 20 June with only trace amounts of precipitation between 20 June and 25 June. Back trajectories calculations for three cases were performed to explore potential source regions corresponding to heavy rainfalls and dry conditions. The release times of the three cases chosen for analysis were: Case-1, 0000 UTC 22 June 2005; Case-2, 0000 UTC 7 June 2005; and Case-3, 0000 UTC 18 June 2005. The case of 22 June was associated with no rainfall while last two cases of 7 and 18 June were associated with heavy rainfall occurrences. Since the rainfall occurred over a region, a release area around Lethbridge, rather than a single point, was chosen. The BLSM method consisted of releasing 50 000 tracer particles (hereafter referred to simply as particles) within a cylinder of radius 100 km and height 3000 m AGL centered on Lethbridge. For a quantitative assessment of source concentrations, significantly more than 50 000 particles would most likely be necessary. All particles were released at one time (0000 UTC), in a Gaussian distribution in the horizontal, and evenly distributed in the vertical from the surface to 3000 m AGL. The height of the cylinder was chosen to roughly correspond to the layer in which most of the rainfall from Alberta storms could be typically expected (Reuter and Nguyen 1993). Particles were back-tracked for a period of 336 hr (14 days). An example of calculated particle positions using the BLSM is shown in Fig. 1a. The BAM ensemble method consisted of releasing 30 particles (BAM-30). Horizontal releases were at 5 locations: Lethbridge and 100 km north, east, south, and west of Lethbridge. Vertical releases were at 6 levels for each location: 500, 1000, 1500, 2000, 2500, and 3000 m AGL. As with the BLSM method, these particles were back-tracked for 336 hr (see example in Fig. 1b). In addition, the trajectory for a single particle (BAM-1) released at 1500 m over Lethbridge was tracked (see the example in Fig. 1b).

3. Results

a. Case-1 (release time $t = 0000$ UTC 22 June 2005)

The animation sequence of BLSM, BAM-30 and BAM-1 calculated particle positions is shown in Fig. 2. Selected frames from the animation at 72-hr intervals are shown in Fig. 3. At $t=72$ hrs (Fig. 3a) both the BLSM and BAM-30 were indicating a strong flow of particles from the southwest of Lethbridge (YQL) with an elongated source region stretching across the northwestern U.S., through the desert area, and to the southwest of California. As a subjective assessment we might say the BAM-30 particles were still all contained within the “cloud” of BLSM particles. The BAM-30 could have provided useful source region information. The BAM-1 particle would have indicated an area to the southwest of Lethbridge as the preferred source location. By $t=144$ hr (Fig. 3b) the main BLSM source region stretched across the eastern Pacific from near the equator to the Gulf of Alaska. The BAM-30 outlined a similar broad source region whereas the single particle alone becomes of little use by this time. At $t=216$ hr (Fig. 3c) the western coast of North America and the eastern Pacific were the main source regions as indicated by both BLSM

and BAM-30. The BAM-30 would have been useful for identifying sources as far afield as Mexico and into the Gulf of Alaska. At $t=288$ hr (Fig. 3d) the spread of particles was very large, with the eastern Pacific from near the equator to the Gulf of Alaska being the favored area. In the broadest sense the BAM-30 also indicated this source area. Possibly as important, however, is the indication that the middle and eastern parts of North America would not have been source regions.

b. Case-2 (release time $t = 0000$ UTC 07 June 2005)

The animation sequence for Case-2 is shown in Fig. 4. At $t=72$ hr (Fig. 5a) the BAM-30 particles generally followed a similar path to the BLSM particles with one group arriving from northeast of Lethbridge and a second group moving in from the southwest. The BAM-1 particle was traced back to the northeast. The BLSM particles showed more dispersion especially to the southwest. The BAM particles were still all contained within the “cloud” of BLSM particles. For a user mainly concerned with a fairly broad source region—such as determining where moisture may originate to feed a rain storm (e.g., Brimelow and Reuter 2005)—the BAM-30 method could provide very useful information. Obviously, the single particle BAM-1 cannot identify two separate source regions. By $t=144$ hr (Fig. 5b) the BLSM showed dispersion over a wide area with one section generally over the mid-western U.S., a second significant section over the eastern Pacific, and a third section that had moved over the Canadian Arctic. The BAM-30 particles were still contained within the BLSM cloud with the areas over the mid-western U.S. and the Arctic corresponding fairly well. However, the BAM-30 did not show particles over the Pacific. By $t=216$ hr (Fig. 5c) the BLSM dispersed the particles over a large portion of eastern North America and the eastern Pacific. There were still indications of more concentrated areas of particles over the mid-western U.S., Ontario/Quebec, the eastern Arctic, and a zone across the eastern Pacific. The BAM-30 had only one particle outside of the BLSM cloud (over Oregon) and still showed a tendency for particles to be located within the higher concentrated areas of BLSM particles. By $t=288$ hr (Fig. 5d) the BLSM particles were spread over most of North America with the exceptions tending to be Alaska and the southwestern U.S. At this time it appeared the BAM-30 would provide very limited source information. However, it does indicate the southwestern U.S. likely would not have been a source.

c. Case-3 (release time $t = 0000$ UTC 18 June 2005)

The animation sequence for Case-3 is shown in Fig. 6. At $t=72$ hr (Fig. 7a) the BLSM had been tracking most of the particles to the southwest and southeast of Lethbridge to cover a large portion of the southwestern U.S. and the northern plains of the U.S. The BAM-30 showed a similar distribution while the BAM-1 particle moved with the group to the southeast. There was an arm of both BLSM and BAM-30 particles over extreme southern Manitoba. All of the BAM-30 particles were still contained within the cloud of BLSM particles. At $t=144$ hr (Fig. 7b) the main source regions indicated by the both the BLSM and BAM-30 were concentrated over the western U.S. and the eastern Pacific with a smaller area over Hudson Bay. The cloud of BLSM particles still contained all the BAM-30 particles. The BAM-1 particle was now over Washington. At $t=216$ hr (Fig. 7c) the

BLSM had generally three broad regions; one over the eastern Pacific and Gulf of Alaska, a second over the northern U.S. and southern Canadian prairies, and a third over Hudson Bay. The BAM-30 concentrated most of the particles over the Pacific with only a few over Hudson Bay. The broad region over the northern U.S. and southern Canadian prairies is missed by the BAM-30. There was also no indication by the BAM-30 of particles over the Gulf of Mexico as shown by the BLSM. By t=288 hr (Fig. 7d) the BLSM dispersed particles over much of the Pacific, across central Canada, and over Hudson Bay. There was also a noticeable collection of particles over Texas and over the Gulf of Alaska. The BAM-30 only captured the Pacific source region and would have provided little help in identifying the sources over the southeastern U.S. and Gulf of Alaska.

4. Summary and discussion

In this paper, we explored the usefulness of a relatively simple non-diffuse Lagrangian model (BAM) for calculating back trajectories to determine potential source regions of tracer substances. We compared these trajectories to those calculated using a Lagrangian stochastic model (BLSM). Three cases were examined which occurred during June 2005 in southern Alberta. Particles were released within a cylinder centered over Lethbridge, Alberta. A study by Batchelder (2006) showed that results using a BLSM method were superior to those using a non-diffusion model for determining oceanic source areas. With this in mind, we used particle locations calculated from a BLSM as our set of “observations.” Using the BAM, a single particle trajectory and an ensemble of 30 trajectories were compared to BLSM calculated trajectories. The results of our empirical study indicate a single particle trajectory would hardly have been sufficient to determine potential source regions in any of the three cases examined. Particles within a fluid element can become separated by large distances after a relatively short length of time. An ensemble of 30 particle trajectories (BAM-30) with release locations varied in the horizontal and vertical showed a significant improvement over a single particle trajectory. The ensemble technique provided useful information for determining potential synoptic scale source regions. The BAM-30 particles were generally contained within the main “cloud” of BLSM particle locations to about 144 hr. After 144 hr a significant number of BAM-30 particles were outside the main BLSM cloud. We conclude that the BAM-30 method could be very useful, for example, to locate source regions for atmospheric moisture feeding synoptic-scale rain storms. An advantage of the BAM method is its simplicity and ease of computations which can be done quickly on a personal computer. However, we suggest that the BAM would not provide adequate results when attempting to locate relatively minor source areas.

Operational forecasters are frequently faced with the task of assessing where airflows may originate from. Knowing the source region is important, for example, in determining the amount of water vapor that may be available to feed rain or snow storms. Numerical model forecasts can underestimate amounts in heavy precipitation events in Alberta (Dupilka and Reuter 2004). To issue snowfall warnings in Alberta (amounts > 10 cm per 12 hr) it is imperative to estimate the amount of water vapor available for snow formation. Dupilka and Reuter (2004) demonstrated the use of downwind sounding data to predict maximum snowfall amounts. In Alberta, available water vapor for major storms generally comes from two sources: the Pacific Ocean and the Gulf of Mexico. Brimelow and Reuter

(2005) examined trajectories associated with three extreme rainfall events that caused significant flooding in central Alberta. From operational experience, flows that originate relatively unimpeded from the Gulf of Mexico carry larger amounts of moisture than those originating from the Pacific which lose moisture due to fallout when crossing the Rocky Mountains. Therefore, it is critical for the Alberta forecaster to have a tool to help assess source regions for vapor feeding into storms. A traditional tool used by forecasters is satellite loops which show the flow of cloud and water vapor. The forecaster could benefit greatly by having access to an additional tool to depict the likely trajectory of moist air. It is here that trajectory models, which run quickly and easily, can provide a possible tool to help determine such trajectories. In addition, such models can allow the forecaster to easily vary input parameters to determine the effect on the trajectories. An ensemble trajectory model would meet the stringent time constraints of an operational venue. Tools should be readily available that make it easy to do postmortems on events (Stuart et al. 2006). The use of a relatively simple ensemble trajectory model could provide invaluable information for forecasters to assess air flow trajectories and see how they became incorporated into a storm. This could also be used as a training tool for new forecasters.

In conclusion, the use of back trajectory models might be a useful component in an operational setting for quantitative precipitation forecasting (QPF). For this it is essential to have a trajectory model that can be run easily and quickly. As a final note we suggest that source regions determined by the use of trajectory models should be viewed in a *probabilistic* rather than a *deterministic* manner. In other words, due to uncertainties of physical processes in the atmosphere when calculating trajectories, the best we should say is that there exist certain calculated locations that are more likely to be sources than others. This notion eliminates the use of a single calculated trajectory as a useful tool for determining a source location and demands the use of multiple particle trajectories.

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FIGURES

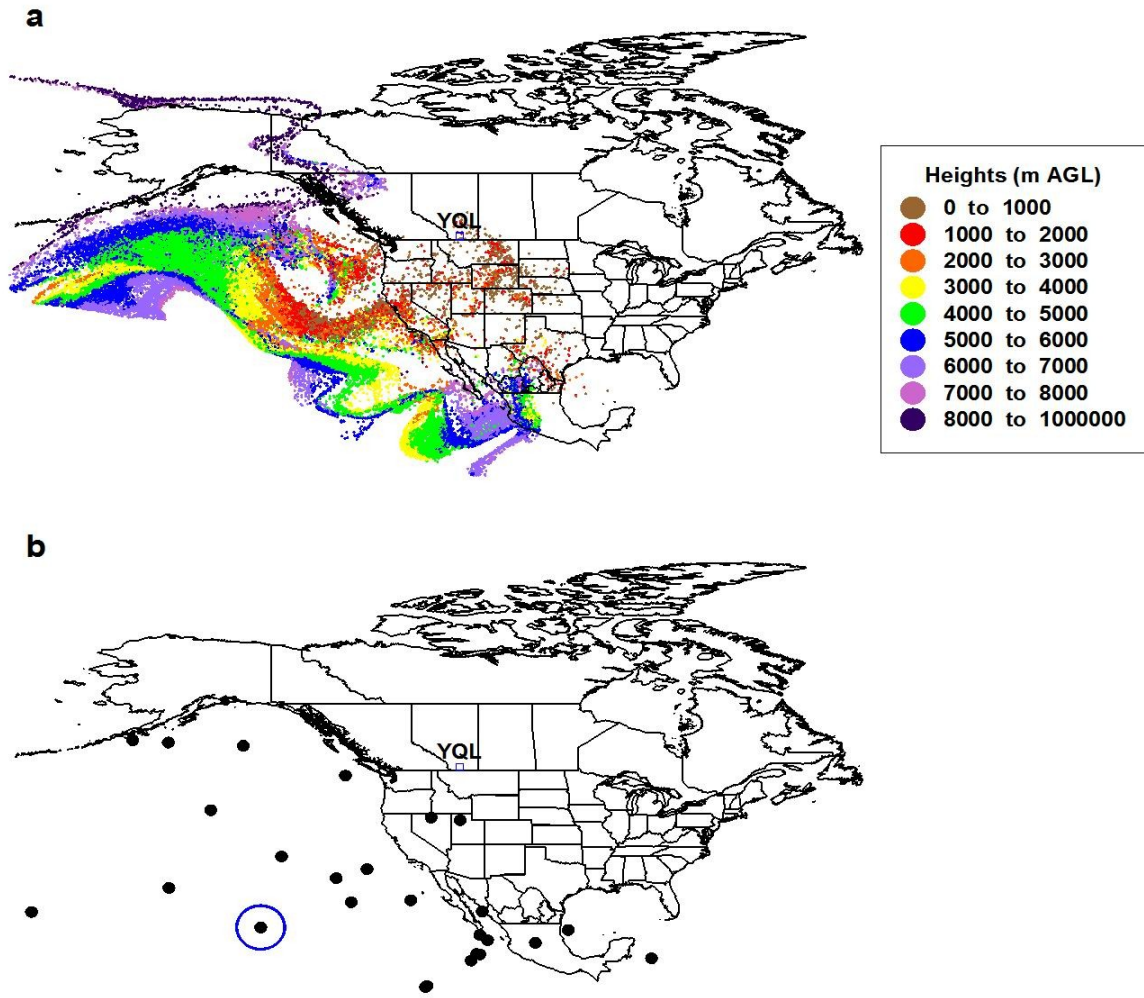


Fig. 1. An example of a) BLSM (small colored dots) and b) BAM (large black dots) calculated particle positions. Images in a) and b) are overlaid in following animation sequences. BLSM particles are color coded in height intervals (m AGL) to enhance the visual effects of such phenomena as deformation due to stretching and wrapping along shear boundaries. The single particle BAM-1 is outlined by a blue circle.

< Insert Animation >

Fig. 2. Case-1 animation sequence of BLSM (small colored dots), BAM-30 (large black dots), and BAM-1 (large yellow dot with a black outline). Animation frames show particles positions at 3-hr intervals backward from the initial release time. Individual frames are titled as follows: initial release time, case number, frame number-animation date/time. The first frame is 3 hr after release time. The animation runs for 336 hr (14 days).

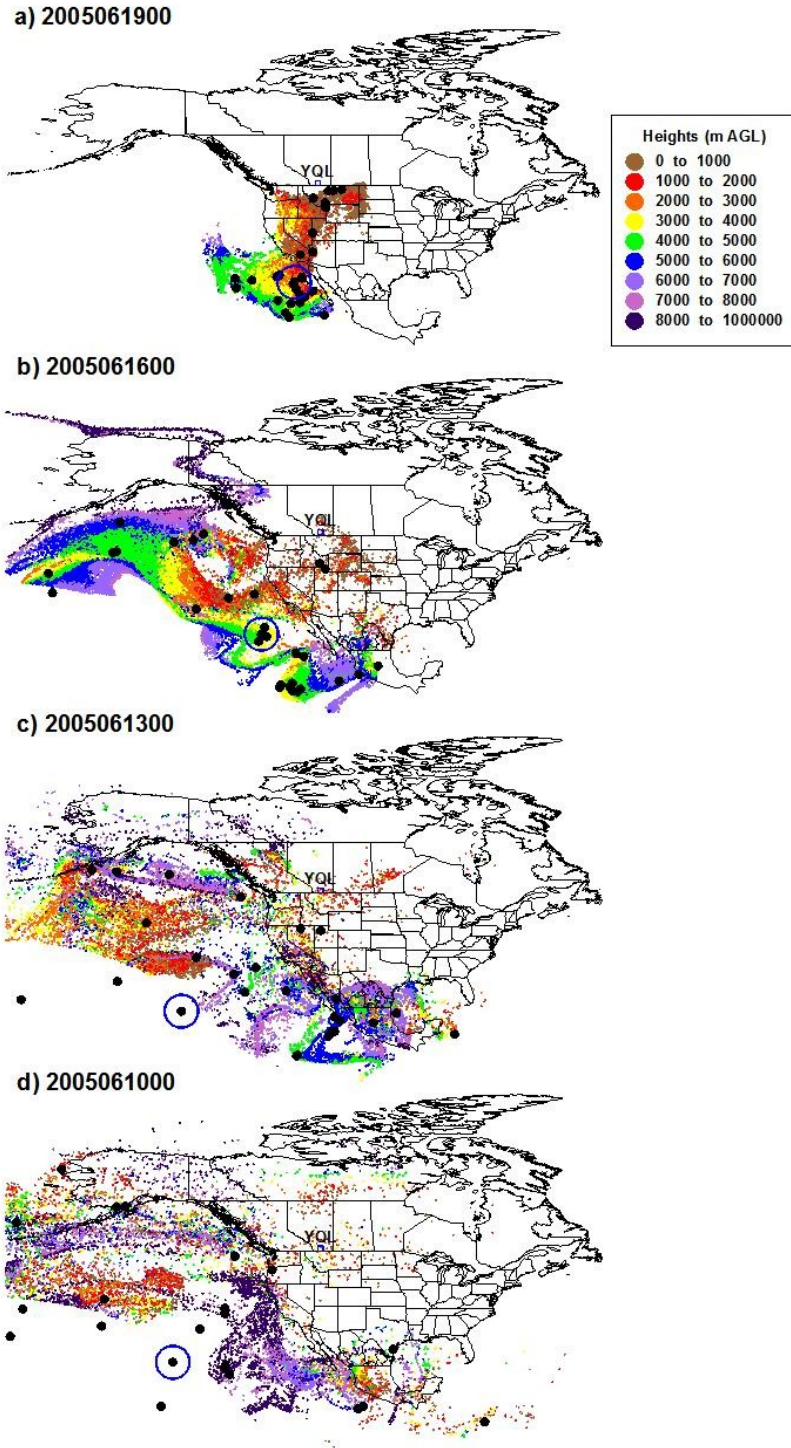
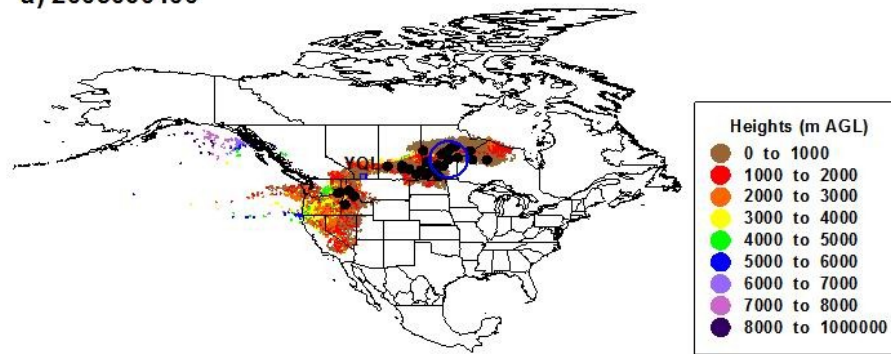


Fig. 3. Case-1 selected times for calculated particles positions of BLSM (small colored dots) and BAM (large black dots) particle positions. These are the same images included in the full animation sequence. Particle positions from release time are shown at a) 72 hr, b) 144 hr, c) 216 hr, and d) 288 hr. The time is shown in the upper left.

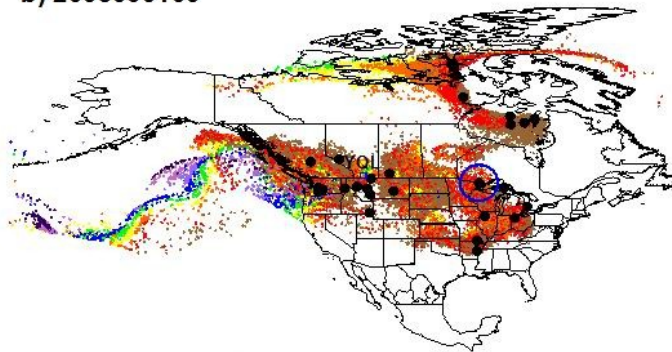
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Fig. 4. As in Fig. 2 except for Case-2.

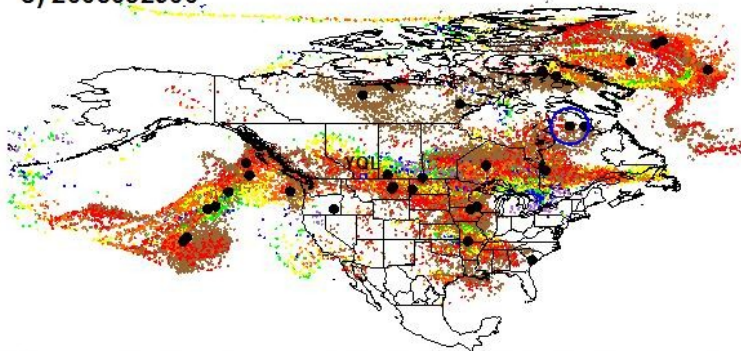
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b) 2005060100



c) 2005052900



d) 2005052600

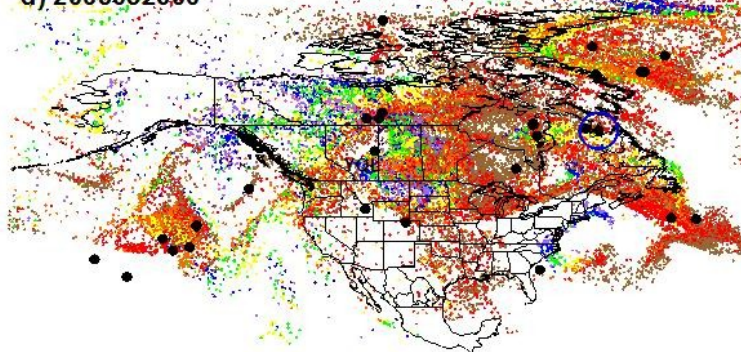
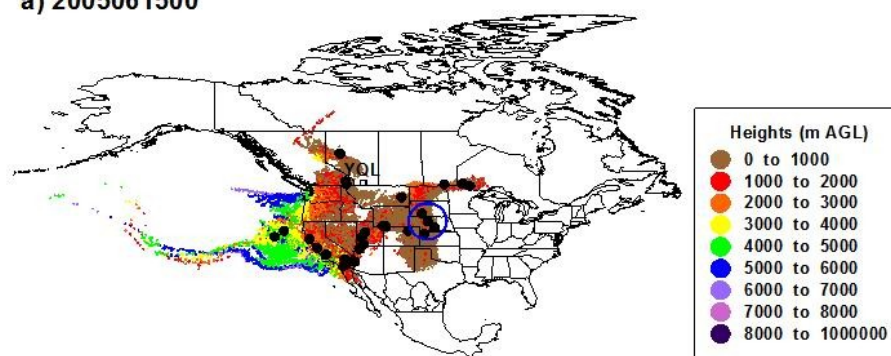


Fig. 5. As in Fig. 3 except for Case-2.

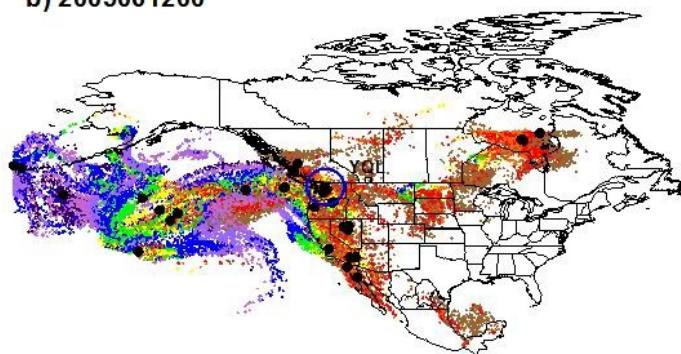
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Fig. 6. As in Fig. 2 except for Case-3.

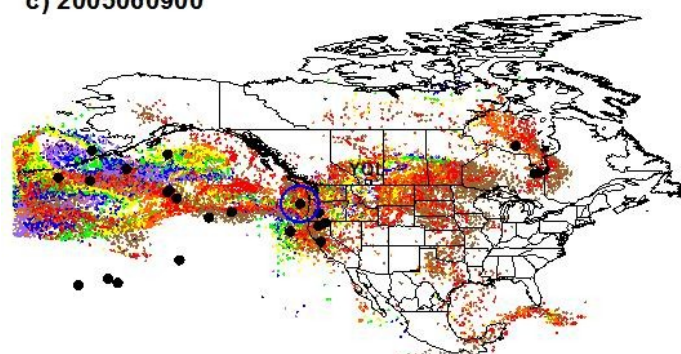
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b) 2005061200



c) 2005060900



d) 2005060600

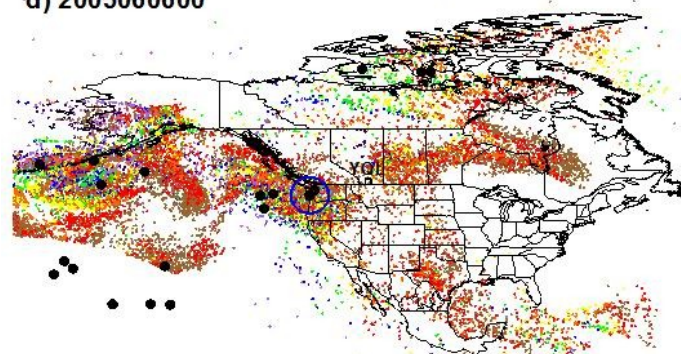


Fig. 7. As in Fig. 3 except for Case-3.