Atmospheric Mercury in Vermont and New England:
Measurement of deposition, surface exchanges and assimilation in terrestrial ecosystems

Final Project Report – Executive Summary – 1/16/2009

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Executive Summary

Atmospheric mercury research began at the Underhill, Vermont Air Quality Site in 1992 sponsored by EPA and NOAA. The site, hosted by the University of Vermont Proctor Maple Research Center and the Vermont Monitoring Cooperative became a focus for research on the atmospheric chemistry, deposition and ecosystem cycling of mercury in New England. A community of mercury researchers from Vermont and New England contributed to and made effective use of the first decade of wet deposition measurements and ecosystem studies focused on Underhill and the Lake Champlain Basin. In 2003, these researchers worked together to set goals for the second decade of atmospheric mercury research at Underhill that began with this project.

The primary objectives of this project were to 1) continue year-round monitoring of mercury wet-deposition in the Lake Champlain Basin; 2) establish measurements of speciated (GEM, RGM, HGP) ambient atmospheric mercury; 3) conduct measurements of surface-atmosphere exchanges of gaseous elemental mercury (GEM) over a New England forest; and 4) evaluate possible pathways for assimilation of atmospheric mercury into the biota of terrestrial ecosystems of the region. The project investigators established collaborations and institutional support from a variety of partners to augment the core EPA-ORD funding provided by this project. The additional support allowed us to achieve the majority of objectives set forth by the group and to facilitate information transfer between this core project and related mercury research (Figure 1). The original project scope was reduced due to a Congressional EPA budget rescission that resulted in the elimination of funding for the final 2 years of the project. Below we briefly summarize the major results of EPA-ORD funded atmospheric mercury research from 2004 through 2008.

The revised project scope was broken down into the following subprojects:

- Long-term record of event-based precipitation mercury concentration and deposition at Underhill, VT
- Initial Characterization of precipitation methyl-mercury concentration and deposition
- Characterization of ambient atmospheric mercury speciation and concentrations (GEM, RGM, and HGP) and identification of potential sources
- Identification of source regions and meteorological conditions giving rise to elevated wet and dry mercury deposition
- Initial measurements of GEM exchanges over a forest canopy
- Mercury assimilation in a terrestrial food web
- Coordination with national, regional, and state mercury research

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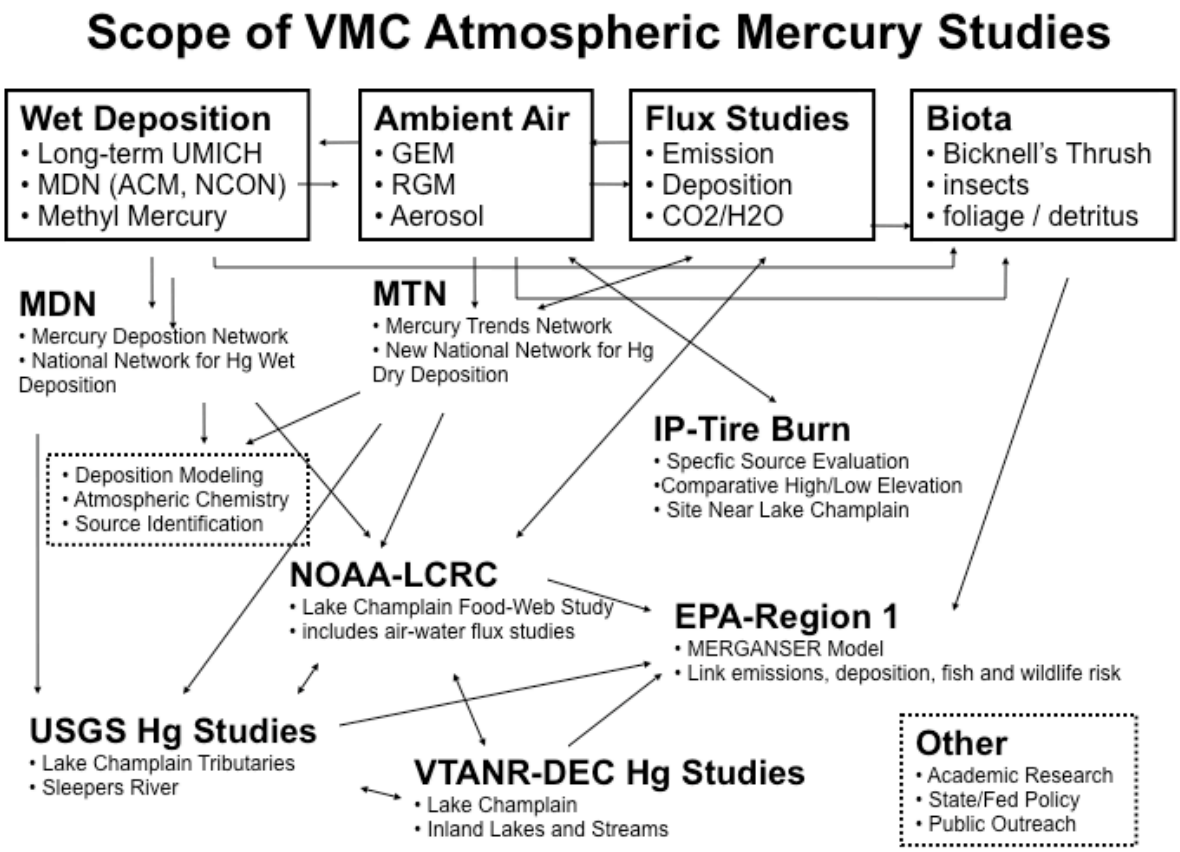

Figure 1. Scope of atmospheric mercury studies coordinated by the Vermont Monitoring Cooperative (VMC) centered on the core EPA-ORD funded atmospheric mercury project (top row of boxes).

Long-term record of event-based precipitation mercury and identification of potential mercury wet-deposition sources

Event-based wet deposition sampling at Underhill, VT was continued for the project duration and continues uninterrupted, maintaining the longest, continuous record of event-based atmospheric mercury deposition *in the world.* We conducted an intensive comparison of collector systems and protocols used for the measurement of mercury in precipitation. The results of this study were used to transition the long-term record at Underhill from the University of Michigan Air Quality Laboratory protocol (deployed from December 1992 through December 2006) to the national NADP-MDN network protocol (deployed at the site since 2004). This project provided a complete 2 calendar-year overlap between the records using different collectors, protocols, and laboratories (Figure 2). Wet-deposition measurements are currently being supported by a grant from NOAA through the Lake Champlain Research Consortium and now follow the NADP-MDN network protocol using event-based sampling.

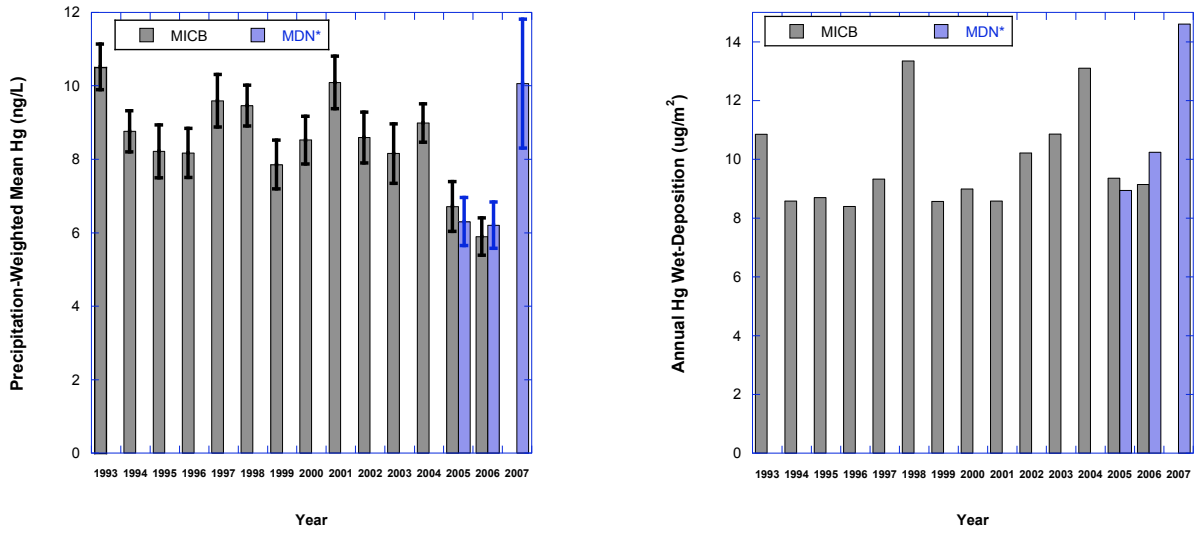

Figure 2. (Left) Annual precipitation-weighted mean Hg concentrations at Underhill, VT as determined by the MICB collector operating the UMAQL protocol with analysis at UMAQL (1993-2006) and the MDN ACM collector operating the MDN event protocol with analysis at Frontier Geosciences (2005-2007). MDN raw concentration values were adjusted by a factor of 1.22 (MDN*) as established by a 1-year collector comparison study. This factor compensates for different collector and sample train performance as well as a persistent laboratory bias. (Right) Annual wet-deposition of Hg at Underhill, VT as determined by the MICB (1993-2006) and the MDN ACM (2005-2007) collectors. The MDN deposition values were calculated from the corrected MDN concentrations and precipitation recorded by the NWS rain gage.

Analysis of the first decade of results obtained with the MICB sampler was conducted by Keeler et al. (2005) and reported in a special issue of the journal *Ecotoxicology*. This analysis demonstrated a strong seasonal pattern to both mercury concentrations and deposition with the highest deposition occurring during the warm season (late spring through early fall) at the peak of terrestrial and aquatic biological activity. Studies of air-mass back trajectories associated with the highest mercury wet-deposition events suggested sources to the west through south were primarily responsible the largest deposition fluxes.

Annual mercury wet deposition averaged 10.1 ug/m^2 from 1993-2007 with a precipitation-weighted mean concentration of 8.5 ng/L and average precipitation rate of 120 cm/year. There was considerable year-to-year variation in precipitation, mercury concentration (Figure 2), and mercury deposition (Figure 2). Variations in climate (precipitation amount and atmospheric circulation – frequency of storms in air with favored trajectories) explain much of the year-to-year variation in mercury deposition at Underhill, VT.

There were major national (45%) and regional (54%) reductions of estimated mercury emissions during the period of observation. However, neither wet deposition nor the concentration of mercury in precipitation at Underhill declined in response to these reductions. Mercury deposition and concentration at Underhill were correlated with precipitation amount. Deposition was strongly seasonal and event driven with 44% of annual deposition occurring from June through August in conjunction with specific high-deposition events. Analysis of NOAA HYSPLIT model backward air mass trajectories indicated that likely source regions for high deposition events and the majority of

annual deposition were located to the south and west in areas with high densities of coal-fired electric generating units (EGUs) (Figure 3). In contrast to estimated total mercury emissions, estimated EGU emissions have been flat during the period of observation. Variation in precipitation amounts at Underhill and along transport paths appear to be responsible for much of the year-to-year variation in mercury wet deposition at Underhill, VT.

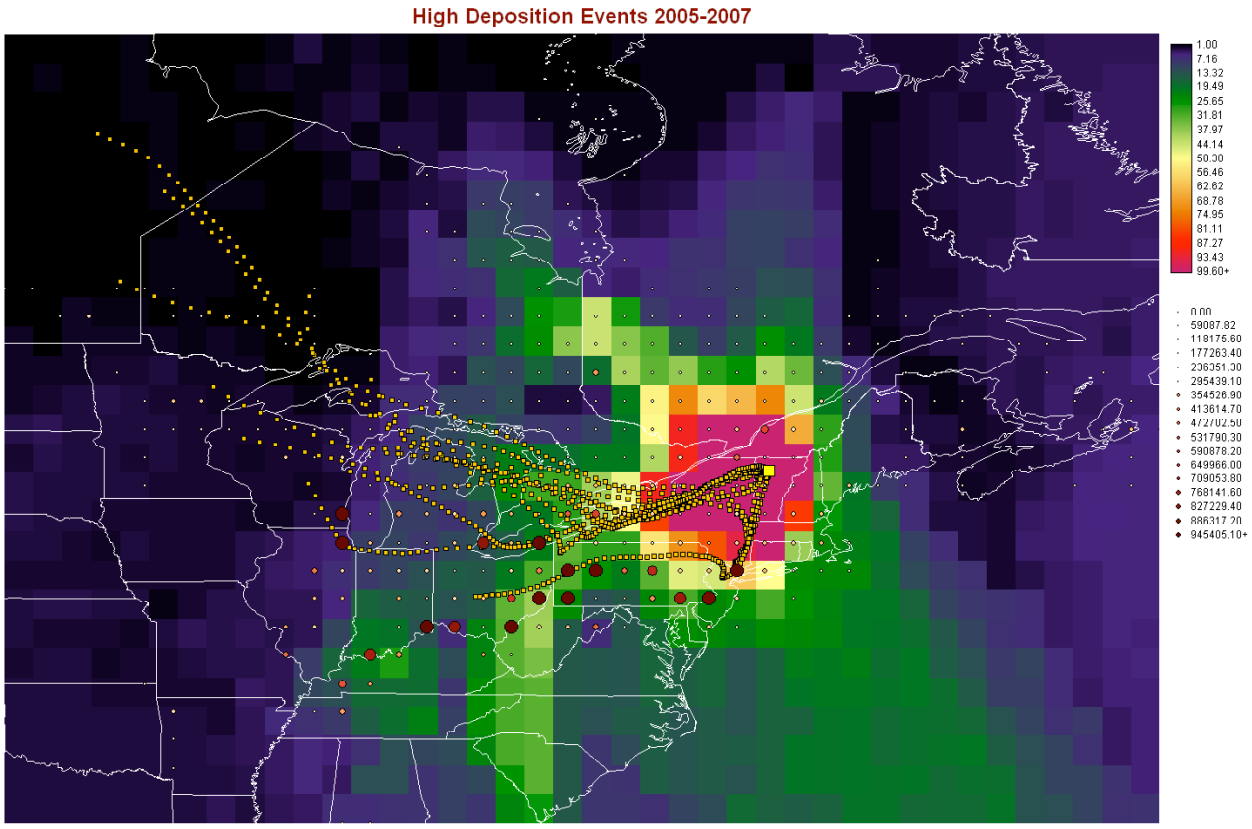

Figure 3. Mercury emissions sampled by air masses reaching Underhill, VT (large yellow square) during "High" deposition type precipitation events 2005-2007 (see text). The frequency of trajectory endpoints falling in a grid cell is shown by the color shading of the grid cells, illustrating the region of potential mercury sources. Overlaid on the grid are circles indicating (by color and size) the annual emissions from each grid cell (g/y). The grid cells with both a high frequency of trajectory crossing and high mercury emissions are the most likely sources for the mercury in wet deposition at Underhill, Vt. Overlaid in small yellow squares are the hourly (72-hours) HYSPLIT backward trajectory endpoints associated with precipitating periods during the event with collection ending on 7/17/2007. This single event provided the highest fraction of annual deposition of any event collected in the 15-year record. Major mercury emissions sources in NJ, central and western PA, OH, and possibly even IL contributed to this extreme event.

Initial characterization of precipitation methyl mercury

As has been observed elsewhere, trace amounts of methyl mercury (range 0.07-3.93%, mean 1.2% of total mercury) are present in precipitation sampled at Underhill, VT. The source of methyl mercury in precipitation is not clearly established and may be varied, but the majority seems quite likely to be the result of aqueous phase methylation of non-particle bound Hg^{2+} (Hammerschmidt et al. 2007). With the exclusion of two outliers (the top 2 high deposition events for total mercury 11.7%

and 7.9% of annual deposition during the methyl mercury sampling period 2005-2007), methyl mercury concentration was positively linearly correlated with total mercury concentration ($r^2 = 0.40$, $p = 0.0005$). This correlation is consistent with Hammerschmidt et al.'s (2007) hypothesis. A provisional estimate of the annual deposition of methyl mercury is 76.5 – 162 ng/m^2/y (central estimate 116 ng/m^2/y) derived by multiplying the monthly volume-weighted mean methyl mercury concentrations by the average monthly precipitation and propagating uncertainties. This flux represents a significant delivery of methyl mercury to terrestrial and aquatic ecosystems in the region.

Characterization of ambient atmospheric mercury speciation and identification of potential sources

Earlier modeling studies indicated that RGM deposition could be nearly equal in magnitude to the wet deposition flux of Hg (Miller et al. 2005). At the outset of this project, there were few measurements of RGM levels in the US (e.g. Lindberg and Stratton 1998) and none in rural northern New England. The Vermont Agency of Natural Resources Air Pollution Control Division (VTANR-APCD) funded the acquisition of a Tekran 1130 RGM module for use with the Tekran 2537A as part of this project. The Tekran 1130 RGM module was deployed with the Tekran 2537A with inlets on the top of the forest canopy observation tower in 2004. This tower was destroyed in a severe storm in the winter of 2004 and equipment was repaired and relocated to the Underhill Air Quality site in the spring of 2005. We acquired and deployed an 1135 particulate mercury module in 2005. We also conducted one short-term deployment of a second system provide by USEPA Region1 at Shoreham, VT, allowing paired observations at a lake-level and mid-elevation site. These measurements were designed to characterize GEM, RGM, and HGP levels in terms of their diurnal, seasonal and spatial variation in the region. The measurements provided necessary information for dry-deposition modeling as well as the opportunity for analysis of potential mercury sources using air-mass back-trajectory methods.

Because of concerns about the comparability of measurements made from the differing inlet locations and heights from 2004 to 2005, the climatology of speciated mercury is presented based on measurements made from the longer record at the Air Quality Site. Measurements are reported from the period May 2005 through June 2008. GEM measurements were made every 5 minutes during the RGM and HGP 2-hour accumulation periods. GEM concentrations presented below are 2-hour averages of the 5-minute observations to be consistent with the 2-hour average concentrations represented by the RGM and HGP measurements.

GEM concentrations ranged from 0.81 to 5.58 ng/m^3 with a period average of 1.45 ng/m^3. RGM concentrations ranged from 0 to 132.5 pg/m^3 with a period average of 3.56 pg/m^3. HGP sampling spanned only 44% of the RGM measurement period due to the later acquisition date of the 1135 module, deployment at Shoreham, VT, and minor problems with the module. HGP ranged from 0 to 121 pg/m^3 with a period average of 11.50 pg/m^3.

The observed concentrations of all three species were dependent on meteorological conditions but in different ways for RGM and HGP than for GEM. There were significant differences in concentrations based on surface wetness state (dry, moist, or wet), time of year, time of day, and in response to different atmospheric conditions. These variations are described in detail in the full report. Of particular note were the correlation of RGM concentrations with relative humidity, the correlation of HGP concentrations with water-vapor mixing ratio, and the tendency for GEM concentrations to rise after first insolation of a moist surface at dawn or after precipitation. The dependence of RGM concentrations on RH may reflect the tendency for that species to be readily scavenged by moist

aerosols at moderate RH. The dependence of HGP on the water vapor mixing ratio may relate to HGP source regions and accompanying seasonal variations in water vapor.

The concentrations of the three mercury species exhibited strong seasonal patterns that were slightly out of phase with each other (Figure). GEM concentrations peak in winter and spring with an early fall minimum, HGP concentrations peak in late winter and RGM concentrations peak in spring (Figure 4). The wintertime peak in HGP may be due, in part, to increased local combustion for home heating. However, trajectory analysis (discussed below) also indicates major out-of-region sources contribute to the observed HGP signal. The spring peak in RGM is likely due to a combination of factors including favored trajectories over major EGU RGM sources and relatively low atmospheric moisture levels at a time when leaves are off of trees along the favored trajectories. As soon as leaves emerge in late spring and early summer, the surface area for dry-deposition removal along the transport pathway increases by a factor of 3 to 4. Atmospheric moisture and relative humidity increase as well, allowing more scavenging by particles and ultimately cloud and rain droplets. As discussed above, summer is the time of peak observed concentrations of Hg in precipitation. The patterns described here suggest more of the ionic mercury in the atmosphere is partitioned into the liquid phase during the summer months.

RGM and HGP concentrations exhibited two distinct temporal patterns that we interpret as driven by either 1) atmospheric mixing processes in conjunction with the balance between deposition and formation reactions and 2) regional transport episodes (Figure 5). The relatively long and continuous record of high-temporal resolution measurements permits unique analysis opportunities for understanding the atmospheric chemistry and regional transport of mercury. These analyses are discussed in detail in the full report. One example of these types of analyses is summarized here.

We adapted existing methods of potential source contribution analysis in order to make full use of the extensive data collected during this study. Our approach, continuous potential source contribution analysis (CPSCA) was developed to take advantage of the very large number of samples produced by semi-continuous high-time resolution analyzers (5-minute to hourly or 2-hour samples) for pollutants such as fine particles, O_3, SO_2, NO_X, and mercury. In addition to the increased number of samples provided by semi-continuous analyzers, each sample can be directly associated with a specific air-mass back trajectory as back-trajectories rarely differ significantly over the course of such short sample durations.

In the data set considered here there are 8,296 2-hour samples from a 26-month period. A 72-hour air-mass back-trajectory with hourly end-points reported was calculated using the NOAA HYSPLIT model with vertical mixing for the center of each 2-hour sample period. There were 588,285 trajectory end points that could each be associated with a concentration measurement at the receptor (Underhill, VT). Because all samples were used, and because the samples were nearly continuous and evenly spaced in time, multiple trajectories "sampled" or "represented" 2/3 of North America and the eastern Atlantic Ocean.

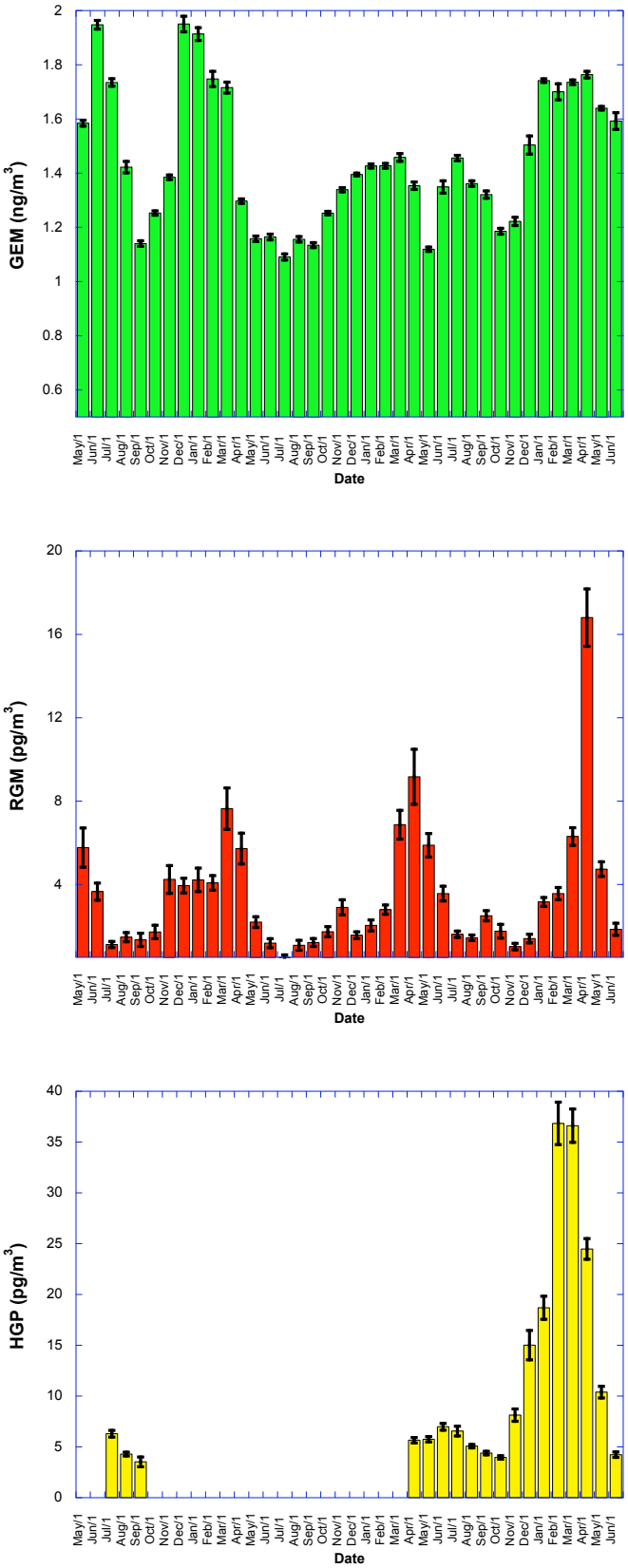

Figure 4. Time series of monthly average concentrations with standard errors for GEM (top), RGM (middle), and HGP (bottom) starting in May of 2005 and ending June 2008. GEM concentrations peak in winter and spring, HGP concentrations peak in late winter and RGM concentrations peak in spring.

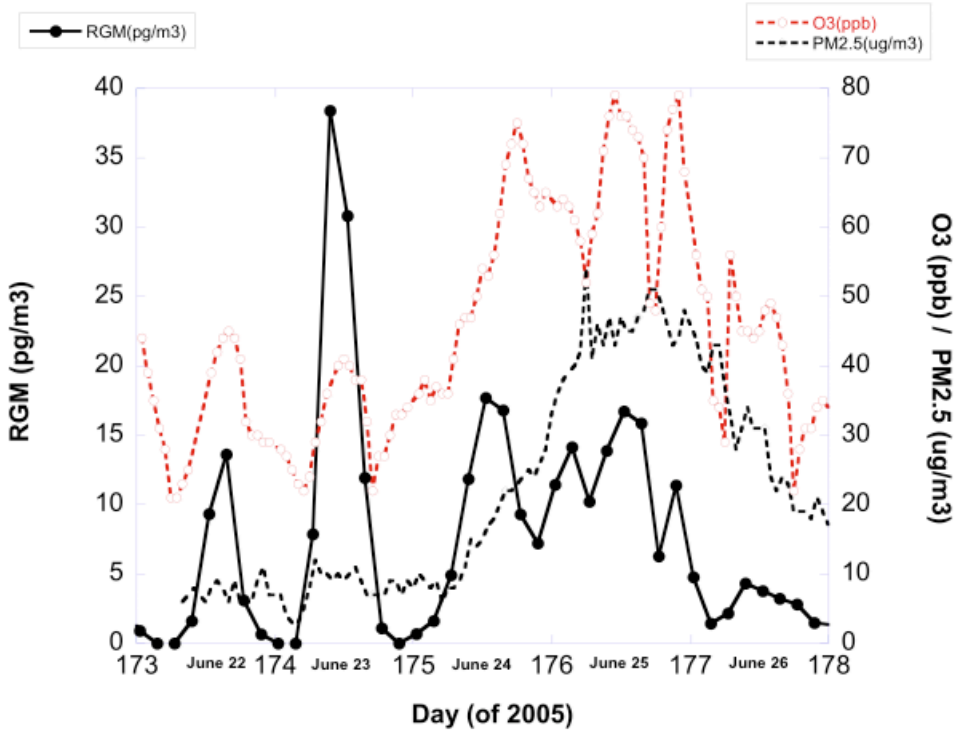

Figure 5. Example of the two primary temporal patterns of RGM and HGP (RGM only shown here). On June 22nd and 23rd, the strong diurnal cycle with concentrations returning to near zero a night suggest that dry-deposition processes outpace replenishment via production reactions or mixing of upper-level air during conditions of low atmospheric mixing at night. During the day, mixing (and/or production processes) outpace the deposition rate and allow surface air concentrations to increase. Ozone and PM levels are moderate on these two days and O_3 follows the same pattern as RGM for the same reasons. The record from June 24th through June 26th illustrates a typical regional transport episode with O_3, and RGM rising together and PM increases lagging slightly. The transport-event signature is the maintenance of moderate to high concentrations overnight. The daytime peaking during a transport event likely indicates additional production during those hours due to photochemistry or the mixing down to the surface of higher concentrations being transported at higher levels in the atmosphere.

The CPSC map for the average RGM at Underhill indicates potential major sources in a corridor from Tennessee through West Virginia and Pennsylvania (Figure 6). Important sources are also indicated in New Jersey and Southern New York. A potential significant source is indicated as far away as northeast Texas. A major potential marine source region is indicated in the western Atlantic Ocean east of Cape Cod. A less significant marine source is indicated from the region of Hudson Bay. Speciated mercury emissions data provided by Mark Cohen of NOAA-ARL representing 1999 emissions inventories for the US and Canada were used to determine the spatial and emissions magnitude correspondence with receptor concentrations associated with a given potential source location. Incinerator (municipal waste and medical) emissions, which are known to have been reduced dramatically since 1999, were excluded to avoid confounding the analysis.

There was an excellent spatial correspondence between emissions source locations and intensity and the potential source areas for a given average RGM concentration at the receptor (Figure 6). The different densities and intensities of sources appear clearly related to the average RGM

concentration arriving at the receptor attributable to a given source field. It is noteworthy that very large and very distant sources (NE Texas, base-metal smelter in Manitoba are indicated as potential sources by the CPSC map for mean RGM concentration. Additional CPSC maps shown in the full report (FR-sec3a-AmbHgSpec-2009-01-16.pdf) further serve to pinpoint the contribution of specific sources to the highest concentration events or "plume hits".

CPSC maps were prepared for HGP and GEM and identify the different spatial distribution and intensities of anthropogenic HGP and GEM emissions. These analyses demonstrate that out-of-region and even very distant sources are significant contributors to the mercury burdens in New England's terrestrial and aquatic ecosystems. These observations and source identification analyses will assist the air-quality modeling community in improving emissions transport models. Air-quality planners will make use of the information to target specific sources for emissions reductions.

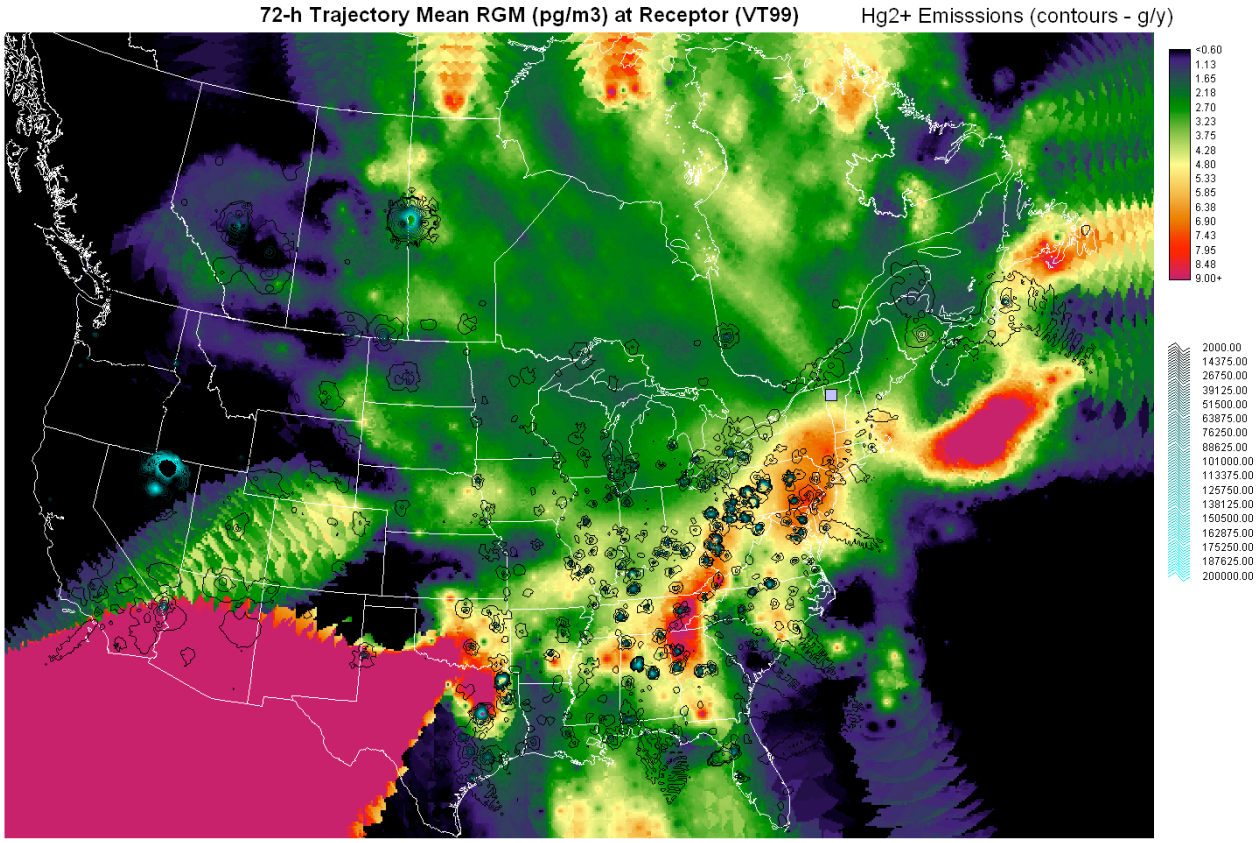

Figure 6. Overlay of 1999 US and Canada Hg^{2+} emissions (courtesy of Mark Cohen, NOAA-ARL) on the CPSC map for mean RGM at Underhill, VT. Emissions (g/y) are contoured with light blue indicating the highest emission rates. *SPECIAL NOTE: this report reflects work in progress. As this material is revised for publication figures will be improved. We plan to mask these figures at a specific value of number of trajectory endpoints per grid cell. This will eliminate the visual artifacts such as the large red area extending from western Texas where only a few trajectories endpoints were located (see Figure12 in Final Report section 3a). The analysis discussed in this report ignores or discounts these artifacts. Please try to not be distracted by them. We did not have time to remake all the figures by the report submission deadline.*

Several potential "natural process[2]" sources are also indicated by the analysis, but cannot be compared with emissions data as the anthropogenic sources can. An example is the significant marine source of RGM in the western Atlantic Ocean east of Cape Cod. High halogen concentrations enhance the production of RGM in the marine boundary layer and this potential source location is consistent with the frequent inflow of Atlantic air into New England.

Measurements of GEM exchanges over a forest canopy

At the outset of the project there was tremendous uncertainty about the magnitude and the mechanisms governing net-gaseous Hg assimilation by forest canopies (Miller 2002, Lindberg et al. 1998). The most widely used inferential model for GEM deposition at the time (Lindberg et al. 1992) did not represent the known bi-directional nature of the GEM flux. It was clear from limited direct observations that at times GEM deposits and at times it is emitted from the forest canopy (Lindberg et al. 1998). It was also impossible to reconcile the large GEM fluxes implied by the Lindberg et al. (1992) model with the much smaller fluxes indicated by measurements of leaf-assimilated Hg (see Miller 2002, 2005). It appeared likely that Hg deposition/emission is governed by a compensation point, an ambient concentration above which deposition occurs and below which emission occurs (Hansen et al. 1995). Direct measurements of atmosphere-forest exchanges of GEM were needed to resolve this discrepancy, identify a potential field compensation point and to help elucidate the physical and physiological processes regulating GEM deposition or emission.

Direct, micrometeorological measurements of atmosphere-canopy exchanges of GEM were made using the modified Bowen-ratio method (Lindberg et al. 2002, Lindberg and Meyers 2001, Lee et al. 2000). Briefly, this method involves measuring the concentration gradient of mercury-vapor above the surface while concurrently measuring the gradient of either temperature (Lee et al. 2000) or water-vapor (Lindberg et al. 2002) and the turbulent flux of sensible or latent heat over the same height interval. The turbulent transfer coefficient derived from, for example, the latent heat flux and the water-vapor gradient is then assumed to apply to mercury vapor (Lindberg and Meyers 2001). The turbulent fluxes of latent and sensible heat were measured using the Bowen-ratio method and confirmed with sensible heat-fluxes measured by the eddy correlation method. The mercury gradient was measured with a Tekran 2537A. The GEM flux measurements were conducted from the VMC forest canopy observation tower at the Proctor Maple Research Center.

Bi-directional fluxes (both emission and deposition) were observed (Figure 7). Net emission and deposition fluxes ranged up to 1000 ng/m^2/h. Deposition was typically observed during the day with high solar fluxes, while emission typically occurred at night or during cloudy periods. Companion measurements of CO_2 and water-vapor exchanges suggested peak deposition values occurred in conjunction with strong photosynthesis (Figure 8).

GEM exchange measurements and their analysis were limited by the rescission of funding for years 4 and 5 of the project and due to the unfortunate collapse of the forest canopy tower in the winter of 2004 which caused a significant delay in the measurement program.

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[2] While there is no proximal anthropogenic source at the location for such "natural process" emissions as marine boundary-layer oxidation of GEM to form RGM, these processes must be understood to be at least partially, if not largely, anthropogenic sources. They convert previously largely anthropogenically emitted GEM to RGM.

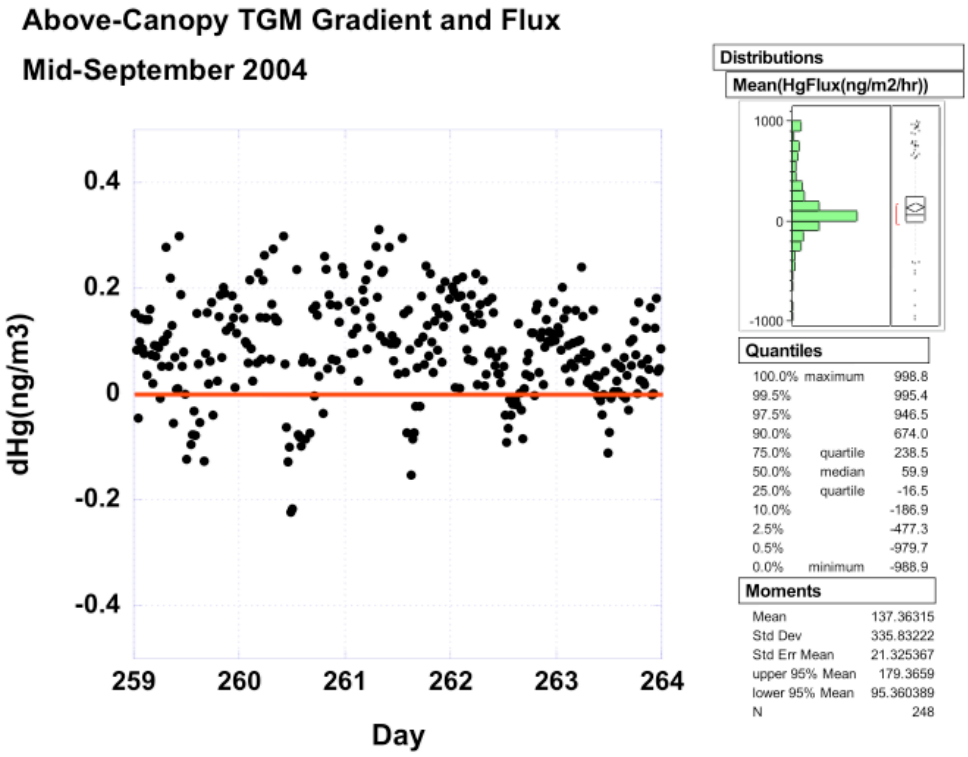

Figure 7. (Left) Example of diurnal and multi-day pattern of above-canopy mercury gradient. Positive values indicate emission of GEM and negative values indicated deposition to the forest canopy. (Right) Frequency distribution of fluxes.

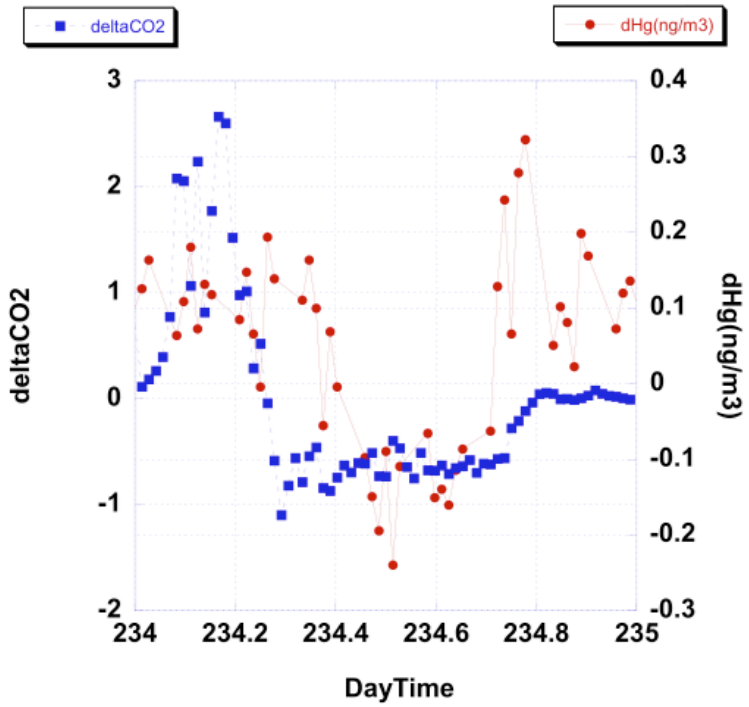

Figure 8. Example diurnal cycle of GEM and CO_2 gradients measured above the forest canopy. GEM deposition is indicated by the negative GEM gradients (red). GEM deposition is strongest at mid-day during intense photosynthesis (indicated by the strong negative CO_2 gradient - blue).

Mercury assimilation in a terrestrial food-web

Methylmercury (MeHg), the bioavailable form of mercury (Hg), is a neurotoxin with well-documented, adverse impacts on natural systems and wildlife populations. Most investigations of Hg bioaccumulation and biomagnification in the northeastern U.S. have focused on freshwater aquatic ecosystems, where conditions promoting methylation are common and Hg concentrations in upper trophic level consumers may be high (e.g., Bank et al. 2005, 2007; Chen et al. 2005; Evers et al. 2005; Yates et al. 2005). Research has increasingly demonstrated that Hg impairs reproductive performance, lifetime productivity, growth and development, behavior, motor skills, and survivorship in aquatic birds and other wildlife (Wolfe et al. 1998; Evers 2004, 2008; Scheuhammer et al. 2007). Despite the recent documentation of elevated Hg exposure in terrestrial biota (summary in Driscoll et al. 2007), relatively little is known about pathways for Hg uptake and transfer in upland ecosystems, or about Hg risk thresholds for terrestrial organisms.

In montane areas of northeastern North America, anthropogenic Hg deposition is 2-5 X higher than in surrounding low elevation areas (Miller et al. 2005). Although mechanisms that drive methylation in montane forests are poorly understood, Hg has recently been documented to bioaccumulate in montane fauna of the Northeast (Bank et al. 2005, Rimmer et al. 2005, Evers and Duron 2008). Bicknell's Tthrush *(Catharus bicknelli)*, in particular, has been shown to exhibit elevated Hg blood and feather concentrations among all age and sex classes across its breeding range (Rimmer et al. 2005). Understanding of Hg burdens in this species and in other components of its food web could contribute to species-specific and ecosystem-based conservation planning.

As part of long-term demographic research on montane forest bird populations in the northeastern U.S., we investigated the bioaccumulation and trophic transfer of Hg on Stratton Mountain (43° 05' N, 72° 55' W) in southern Vermont. From late May through late July in 2004-2006, we sampled discrete compartments in the terrestrial food web, using an established study site between 1075-1180 m elevation. To reflect a range of trophic levels, we sampled foliage, leaf litter, folivorous and carnivorous arthropods, a terrestrial salamander, an insectivorous passerine bird, two carnivorous raptors, and an omnivorous rodent. Salamanders, birds and rodents were sampled across a study area of c. 25 ha between 1075-1180 m elevation, while we collected foliage, leaf litter and arthropod samples at two sites 50 m apart at 1100 m elevation. Samples were analyzed at the Texas A&M University Trace Element Research Laboratory (TERL) by element-specific cold vapor atomic absorption.

Overall, Hg concentrations showed a pattern of biomagnification at successive trophic levels in the montane forest food web (Figure 9). Mercury concentrations increased from autotrophic organisms to herbivores < detritivores < omnivores < carnivores. Within the carnivores studied, raptors had higher blood mercury concentrations than their songbird prey. The Hg concentration in the blood of the study focal species Bicknell's thrush varied over the course of the summer. Upon arrival on the breeding ground Bicknell's thrush blood Hg increased above the levels carried over from the wintering grounds (Figure 10). By mid-June Bicknell's thrush blood Hg levels began a decline that continued through the end of observations (Figure 10).

The within-season changes in Bicknell's thrush blood Hg levels were consistent with a diet switch from the more abundant Hg rich prey of the detrital-based food-web dominant in early summer to a relatively lower Hg content prey of the foliage-based food web that was relatively more abundant in mid to late summer (Figure 11). There were significant year effects in different ecosystem compartments indicating a possible connection between atmospheric Hg deposition, detrital-layer Hg

concentrations, arthropod Hg concentrations, and passerine blood Hg levels. This project has accomplished possibly the first extensive characterization of mercury in a terrestrial food web.

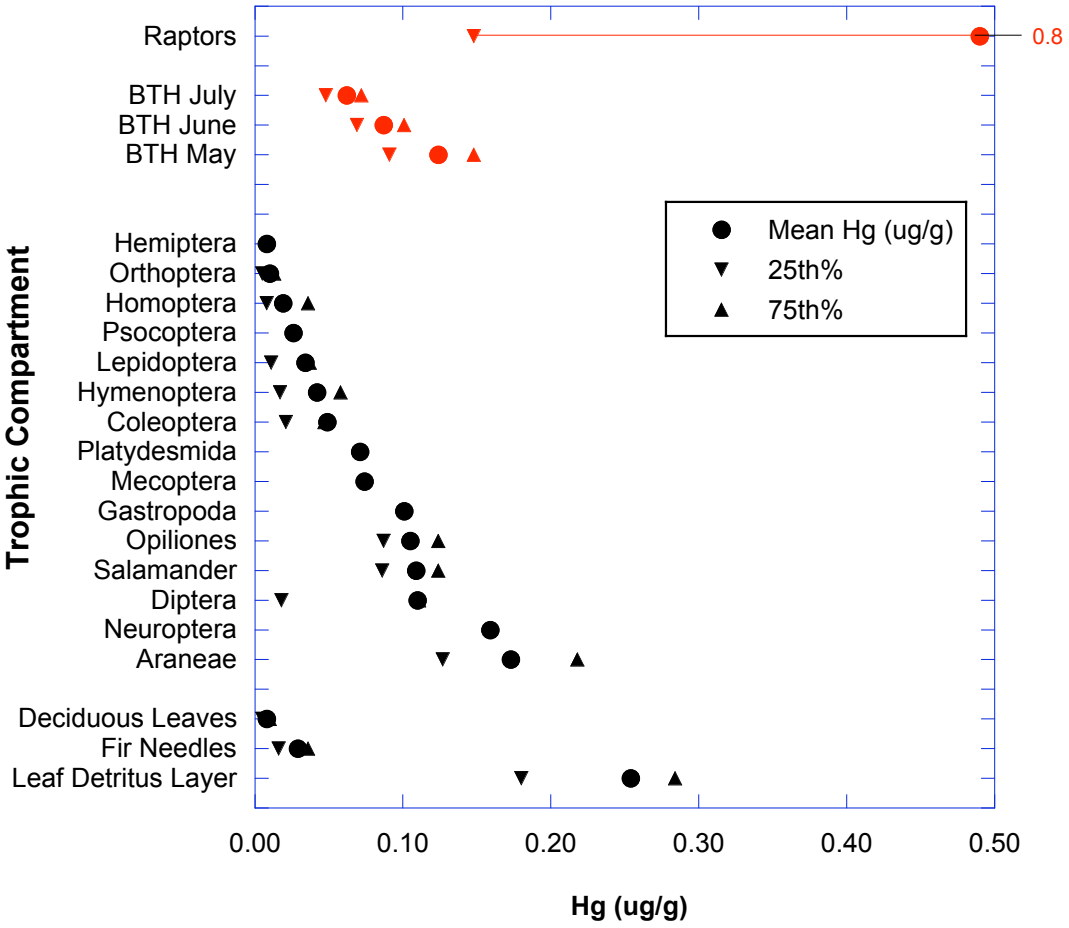

Figure 9. Mean, 25th, and 75th percentile Hg concentrations for leaf litter and biota sampled on Stratton Mountain, Vermont in 2004-2007. BTH = Bicknell's thrush, the focal species of this study.

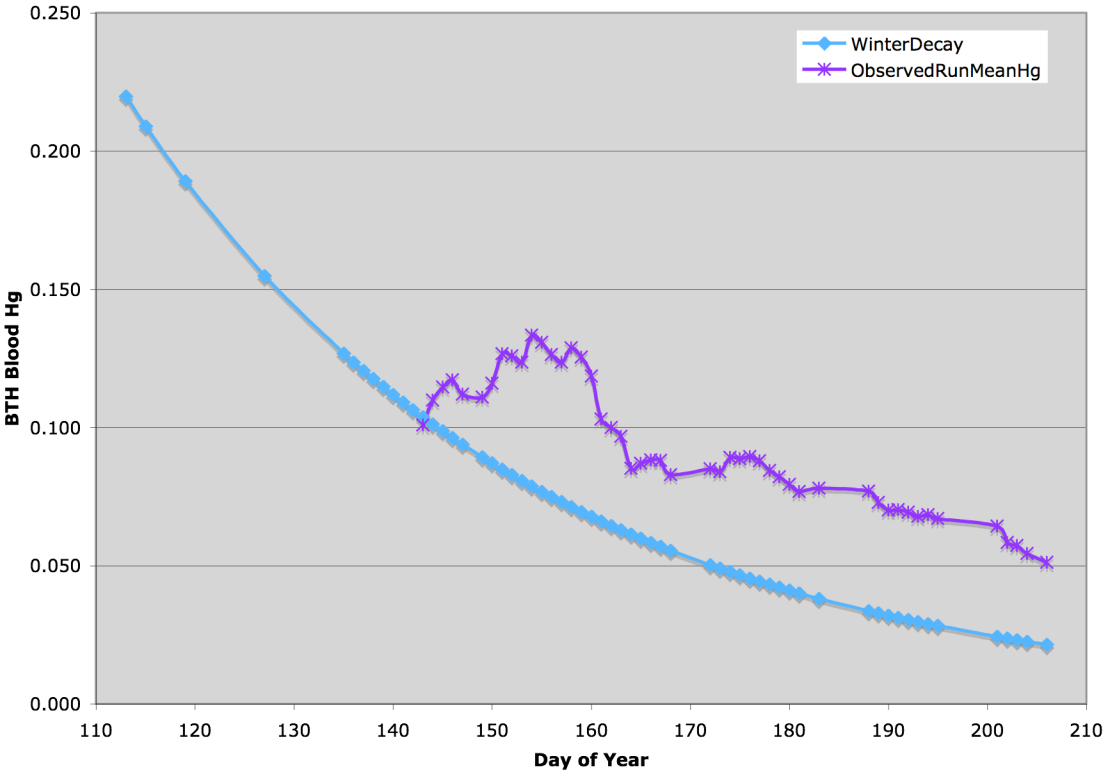

Figure 10. Exponential decay model (light blue) of the dissipation of wintering ground Hg burden and observations (purple) of Hg blood concentrations (ug/g) on the breeding ground in Bicknell's thrush. Due to the fluctuations in number of birds captured and sampled daily, the observed blood levels are presented as the 10-day moving average. Bicknell's thrush blood Hg initially increased after reaching the breeding ground. A decline in blood Hg levels began about mid-June.

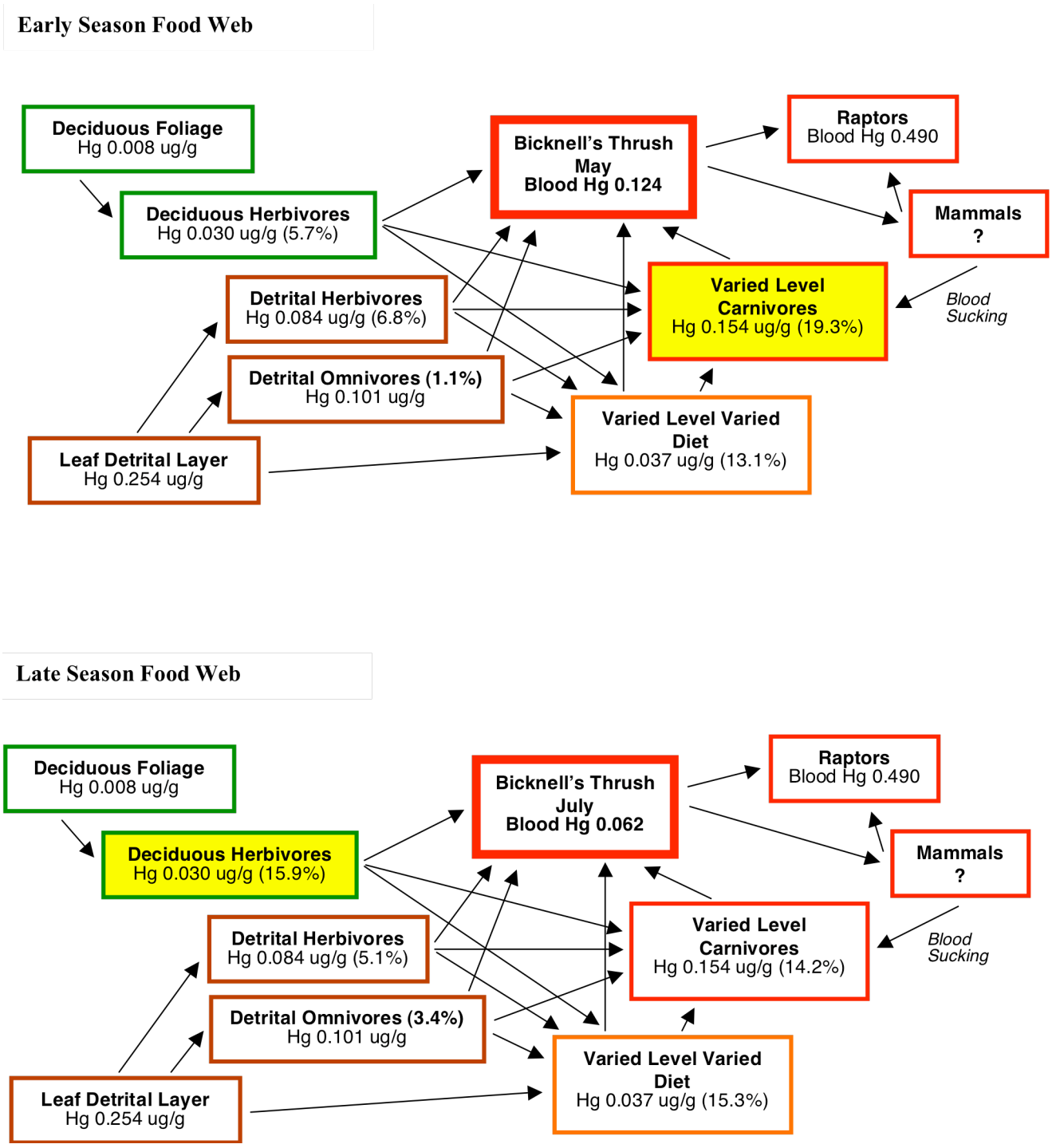

Figure 11. Shifts in food web structure from early to late summer in a montane ecosystem. The relative abundance of different arthropod feeding guilds (as percents in parentheses) and each compartment's mean Hg level are indicated. Food items from a detrital-based food web dominate the early season, while a canopy-based food web oranisms increase in relative importance during the late summer season. Bicknell's Thrush (red) is the focal species in this study.

Coordination with national, regional, and state mercury research

The project personnel successfully coordinated with other mercury research efforts at local, regional and national levels. We used the new Hg information from the Underhill site and this project to estimate mercury deposition not only to the forested watersheds of Vermont, but also specifically to Lake Champlain in collaboration with researchers supported by the NOAA funded, Lake Champlain Research Consortium. More broadly, Drs. Miller and Keeler participated in the Northeast Mercury Research Group, a regional research group funded by the USDA Forest service (www.briloon.org/mercury). The three-way, west-east (WA-VT), precipitation mercury collector intercomparison was a collaboration designed to inform the national MDN program on potential improvements to collector design as well as to facilitate Underhill's transition from the UMAQL to the MDN system.

Observations and analyses of mercury concentrations and fluxes at Underhill are providing benefits to several mercury research groups working to model emissions-transport-deposition cycles at regional, national and global scales. The results of our trend analysis (no trend detected) for wet deposition and our source identification efforts for wet and dry deposition have informed state, regional, national, and international air-quality planning bodies about the identity of sources contributing mercury to the biologically sensitive New England region. Our pioneering assessment of mercury in a terrestrial food-web has highlighted the need for expanded consideration of the risks posed by atmospheric mercury deposition to terrestrial environments.

Dr. Miller participated in the technical working group designing protocols and operations standards for the proposed MTN (Mercury Trends Network), a new mercury dry deposition network being established by NADP. Dr. Miller provided detailed information on our operating procedures and data management process for use in developing the network SOP. Underhill served as demonstration site for the network and we hosted a field trip for NADP personnel to observe our operations in 2007. The Underhill site was one of the initial four sites funded by EPA-OAR-CAMD for start-up of the network in January of 2008.

Scientific communication and public outreach

In addition to the research coordination activities described above project personnel made numerous presentations about project activities and results at regional and national meetings. Dr. Miller produced a public-outreach overview document describing mercury research activities at Underhill in conjunction with the VMC. Interviews were granted to print and radio media to convey project results to the public. Several peer-reviewed scientific publications were prepared, accepted and published that made use of project data. Additional manuscripts are currently being prepared for submission by the project team. The final results of the project (which are the subjects of these manuscripts) will be presented at national meetings and communicated to the air-quality management community.

Organization of the Final Report and document file names

Section 0 – **Executive Summary** – "FR-sec0-ExecSum-2009-01-16.pdf"

Section 1 – **Introduction** – "FR-sec1-Introduction-2009-01-16.pdf"

Section 2a – **Event-Based Wet Deposition** – "FR-sec2a-Event-Wet-2009-01-16.pdf"

Section 2b – **Collector Comparison Manuscript** – "FR-sec2b-Collector-Comparison-2009-01-16.pdf"

Section 2c – **Long-Term Wet Deposition Manuscript** – "FR-sec2c-Long-Term-Record-2009-01-16.pdf"

Section 3a – **Ambient Air Mercury Speciation Studies** – "FR-sec3a-AmbHgSpec-2009-01-16.pdf"

Section 3b – **Shorham, VT Short-term Study** – "FR-sec3b-Shoreham-2009-01-16.pdf"

Section 4 – **GEM Flux Measurements** – "FR-sec4-GEMFlux-2009-01-16.pdf"

Section 5 – **Terrestrial Food-Web Study** – "FR-sec5-Food-Web-2009-01-16.pdf"

Section 6 – **Additional Project Activities** – "FR-sec6-EndSections-2009-01-16.pdf"

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