The occurrence of rare but significant severe weather events associated with elevated mixed-layer (EML) air in the northeastern United States is investigated herein. A total of 447 convective event days with one or more significant severe weather report [where significant is defined as hail 2 in. (5.1 cm) in diameter or greater, a convective gust of 65 kt (33 m s$^{-1}$) or greater, and/or a tornado of F2 or greater intensity] were identified from 1970 through 2006 during the warm season (1 May–30 September). Of these, 34 event days (7.6%) were associated with identifiable EML air in regional rawinsondes preceding the event. Taken with two other noteworthy events in 1953 and 1969, a total of 36 significant severe weather events associated with EML air were studied via composite and trajectory analysis. Though a small percentage of the total, these 36 events compose a noteworthy list of historically significant derechos and tornadic events to affect the northeastern United States. It is demonstrated that plumes of EML air emanating from the Intermountain West in subsiding, anticyclonically curved flows can reinforce the capping inversion and maintain the integrity of the EML across the central United States over a few days. The EML plume can ultimately become entrained into a moderately fast westerly to northwesterly midtropospheric flow allowing for the plume’s advection into the northeastern United States. Resultant thermodynamic conditions in the convective storm environment are similar to those more typically observed closer to the EML source region in the Great Plains of the United States. In addition to composite and trajectory analysis, two case studies are employed to demonstrate salient and evolutionary aspects of the EML in such events. A lapse rate tendency equation is explored to put EML advection in context with other processes affecting lapse rate.

1. Introduction

During late spring and summer, it is common downstream of major mountain ranges to find evidence of displaced hot, dry, and deeply mixed boundary layer air that has moved with the prevailing horizontal flow over areas of lower terrain. Such an example is revealed in the juxtaposed soundings in Fig. 1, where the surface-based mixed layer extending upward to 450 mb at Albuquerque, New Mexico (station elevation 1620 m), has advected in a quasi-conservative manner to Dodge City, Kansas (station elevation 790 m), with nearly dry-adiabatic lapse rates present in the 700–450-mb layer. The horizontal advection of deeply mixed boundary layer air off the elevated terrain is manifest as an elevated mixed layer (EML; Carlson and Ludlam 1968) and is a readily identified feature by convective forecasters dating back to the conceptual “type 1” (or “loaded gun”) sounding as described by Fawbush and Miller (1954). The base of the EML lies atop an interface of strong static stability (the “capping” inversion), which, given a moist local boundary layer, creates convective inhibition for surface lifted parcels and allows for a strong buildup of convective available potential energy (CAPE), potentially prior to the initiation of deep moist convection. The EML is a
contributor to the well-known climatological maximum in severe weather occurrence across the Great Plains of the United States and has been studied for its high frequency there (Carlson et al. 1983; Lanicci and Warner 1991; Lanicci and Warner 1997).

The frequency of significant severe weather [SIG SVR, defined by the occurrence of hail ≥ 2 in. (5.1 cm) in diameter, convective wind gusts ≥ 65 kt (33 m s⁻¹), and/or tornadoes of ≥ F2 intensity] over the northeastern United States (NEUS) is an order of magnitude less than across the central and southern Great Plains (Concannon et al. 2000; Doswell et al. 2005)—a more northern latitude and the absence of rich low-level moisture associated with parcel trajectories from the Gulf of Mexico are important factors. In addition, the decreased frequency of the EML as a function of increased distance from the Intermountain West (Farrell and Carlson 1989) limits the ability to generate similarly large CAPE values across the eastern United States (Doswell and Bosart 2001). Likewise, operational experience suggests that the absence of steep midlevel lapse rates is a primary limiting factor for SIG SVR in the northeastern United States. While EML formation is well understood, the subsequent movement, evolution, and eventual destruction of the “EML plume” (defined as the horizontal extent of the EML) have received less attention.

Though rare, the intrusion of EML air and its influence on severe weather in the northeastern United States has been documented. Johns and Dorr (1996) examined 22 tornado episodes in eastern New York and New England from 1950 to 1991 and found evidence of modified EML air in three violent tornado cases occurring in westerly to northwesterly midlevel flow regimes. Farrell and Carlson (1989) documented the role of an EML in the generation of unusually large CAPE values, contributing to the severity of the 31 May 1985 tornado outbreak in the upper Ohio Valley. The same study showed a 4-yr climatology of the “lid” (i.e., the capping inversion below the EML base), which indicated the occasional intrusion of the EML into the northeastern United States during the warm season (on the order of 1 day month⁻¹), and a relative maxima of the lid across the Great Plains. These studies were limited insofar as 1) they solely focused on tornadoes and not derechos or large hail events and 2) they were performed prior to high-powered compositing techniques afforded by modern reanalysis datasets.

The motivation for this work was to catalog SIG SVR events, of any type, with an EML present in the northeastern United States. Furthermore, the goal was to then use composite and trajectory techniques to better understand the large-scale conditions and physical processes favorable for the unusually long downstream transport of the EML from the Intermountain West to the northeastern United States. We believe this knowledge will provide forecasters with a framework to better anticipate EML-associated SIG SVR events, leading to improved forecasts, warnings, and call-to-action statements commensurate with the threat posed to life and property.

The remainder of this paper is organized as follows. In section 2, we present a lapse rate tendency equation, including a physical interpretation and scale analysis. Section 3 explains the observational and severe weather report data utilized for the composite and trajectory analyses, which follow in section 4. Individual case studies are shown in section 5. Finally, in section 6, a concluding summary and ideas for future work are presented. (The supplemental information referred to in this paper consists of an HTML page that contains additional text, images, and loops. This information may be downloaded in compressed format from the URL given on the title page of this paper.)

2. Lapse rate tendency equation

a. Physical interpretation

The change in lapse rate as a result of downstream advection of the EML depicted in Fig. 1 is important in establishing the thermodynamic conditions needed for significant CAPE and large vertical parcel accelerations within severe thunderstorms. It is useful to have a theoretical framework for the local rate of change of lapse rate \( \frac{\partial \theta}{\partial t} \) to understand the relevant physical processes.
before proceeding to the observational study. The lapse rate tendency equation is

\[ \frac{\partial \gamma}{\partial t} = \frac{1}{c_p} \frac{\partial Q}{\partial z} - \mathbf{V} \cdot \nabla \gamma - w \frac{\partial \gamma}{\partial z} + \frac{\partial \mathbf{V}}{\partial z} \cdot \nabla_h T + \frac{\partial w}{\partial z} (\Gamma_d - \gamma), \]  

where \( Q \) is the diabatic heating rate, \( \mathbf{V} \) is the horizontal wind, \( w \) is the vertical velocity, \( \Gamma_d \) is the dry adiabatic lapse rate, and \( c_p \) is the specific heat at constant pressure. [See the appendix for the derivation of Eq. (1).] The terms on the right-hand side of Eq. (1), from left to right (and correspondingly illustrated in Fig. 2), are as follows. Term A is the diabatic heating term. For example, a decrease (increase) in diabatic heating with height yields a steepening (lessening) lapse rate. Terms B and C are the horizontal and vertical lapse rate advection terms, respectively. Term D is the differential temperature advection term, which must be due to the ageostrophic part of the wind (since \( \frac{\partial \mathbf{V}}{\partial z} \cdot \nabla_h T = 0 \)). For instance, a steepening (lessening) of the lapse rate would occur within a thermally indirect (direct) circulation. Finally, term E is the vertical stretching term, which is modulated by the instantaneous departure of the environmental lapse rate from the dry-adiabatic value. If the environmental lapse rate is less than dry adiabatic, an increase (decrease) in upward (downward) vertical motion with height will lead to a steepening lapse rate.

b. Scale analysis

One can make assumptions as to the order of magnitude of terms in Eq. (1) for synoptic-scale motion away from fronts, jets, and areas of deep moist convection, as shown in Table 1. Since the undisturbed EML plume is isolated from boundary layer processes and largely void of moist thermodynamic processes, diabatic heating was
Table 1. Estimation of variables and terms in the lapse rate tendency equation, based on the synoptic-scale analysis described in section 2.

<table>
<thead>
<tr>
<th>Variable/Term</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_hT</td>
</tr>
<tr>
<td>$</td>
<td>V_h$</td>
</tr>
<tr>
<td>$</td>
<td>V</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$10^{-6}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

Term A: $(1/c_p)(\partial Q/\partial z)$
Term B: $\mathbf{V} \cdot \mathbf{V}_h \gamma$
Term C: $w(\partial \gamma/\partial z)$
Term D: $(\partial \mathbf{V}/\partial z) \cdot \mathbf{V}_h T$
Term E: $(\partial \omega/\partial z)(\Gamma_d - \gamma)$

Estimated from studies of zonally averaged radiative heating rates in midlatitudes (e.g., Peixoto and Oort 1992), which are typically found to be on the order of $1$ K (1 day)$^{-1}$. In the absence of convective overturning, the diabatic heating term is typically quite small at $10^{-9}$ K m$^{-1}$ s$^{-1}$. Synoptic-scale wind fields and thermodynamic conditions in weakly baroclinic environments typifying warm season conditions across the central and eastern United States are estimated from observational work, such as Portis and Lamb (1988) for vertical motion, and readily observed horizontal wind and temperature gradients, which were assessed from constant pressure analyses.

Based on the synoptic scaling in Table 1, the horizontal advection of lapse rate is 1–2 orders of magnitude greater than the other terms. A long downstream transport of the EML plume is plausible when the other terms are small. Although $\gamma$ is not conserved, synoptic conditions exist that allow for the horizontal advection of the lapse rate to dominate over the other physical processes in Eq. (1); these patterns are described through composite and trajectory analysis in section 4.

The nonadvective terms in Eq. (1) help explain changes to the EML plume that normally prevent the EML from persisting long enough to reach the northeastern United States. For instance, a midtropospheric diabatic heating maximum (e.g., resulting from the latent heat of condensation $L$ within deep moist convection) would decrease the lapse rate below the maximum, having a deleterious effect on the EML plume. One can roughly consider these effects within an area of thunderstorms using a latent heat of condensation term from the first law of thermodynamics $Ldw_w$, where $w_w$ is the saturation mixing ratio. Taking $L$ as a constant and assuming development of a deep updraft over $\sim 20$ min yields the following estimate of the diabatic heating term:

$$\frac{\partial \gamma}{\partial t} = \frac{L}{c_p} \frac{\partial (dw_w)}{\partial t}$$

$$= \frac{2.5 \times 10^6 \text{ J kg}^{-1}}{1004 \text{ J kg}^{-1} \text{ K}^{-1} \left(10^3 \text{ m}\right)} \left(-10^{-2} \text{ kg kg}^{-1}\right)$$

$$= -2.5 \times 10^{-6} \text{ K m}^{-1} \text{ s}^{-1},$$

which equates to a decrease in the lapse rate of $-9$ K km$^{-1}$ h$^{-1}$. While Eq. (2) ignores the counteracting effect of vertical advection of the lapse rate, it is clear that deep moist convection quickly eradicates any portion of the EML it processes, likely producing a trend to moist adiabatic in the layer. Likewise, whenever differential ageostrophic temperature advection is positive—as would typically occur downstream of an amplifying baroclinic wave, secondary circulation of a jet entrance region, or frontogenetic circulation—lapse rates decrease with time. Since the EML will often become entrained in an increasingly baroclinic environment over time, differential ageostrophic temperature advection can potentially become large and lead to erosion of the EML plume.

The vertical advection and stretching terms are negligible within the EML plume as these terms are numerically small as $\gamma$ approaches $\Gamma_d$. However, at the EML base, the vertical stretching term is important for cap removal during the convective initiation process when vertical velocity increases with height. Conversely, near midlevel anticyclones, subsidence increasing with height at the capping inversion interface contributes to a strengthening of the inversion, which has implications for the maintenance of the EML plume over time, as elaborated upon in section 4.

3. Data and methodology

a. Severe weather report and sounding databases

The Storm Prediction Center (SPC) severe weather database was systematically searched from 1 May through 30 September from 1970 to 2006 using the SVR PLOT software program (Hart 1993) for reports over New England, New York, New Jersey, Pennsylvania, and small portions of adjacent states (Fig. 3). As shown in Table 2, a total of 30 617 severe weather reports were found (an average of 827 per warm season). Of these, only 929 reports (3%) met our SIG SVR criteria over 447 individual event days. Importantly, these 3% account for a majority of the total severe weather fatalities (57.3%) and injuries (61.8%).

For the SIG SVR report days, regional rawinsonde data were utilized to search for the presence of an EML. An “EML sounding” was classified using the following criteria:
1) an elevated (not surface-based) environmental lapse rate greater than or equal to 8.0°C/km through a depth of 200 mb or greater and
2) an increase in the environmental relative humidity with height from a relative minimum at the bottom of the layer of steep lapse rate, as defined above, through the depth of the steep lapse rate layer.

The lapse rate criteria were arrived at subjectively, based on an initial inspection of soundings from several candidate cases. While the ultimate choice is arbitrary, we believe marginal or questionable EML events were reasonably eliminated from consideration based on these values. Additionally, the temporal and spatial resolutions of the rawinsonde network are such that some subjectivity was necessary in determining if the EML was present at the location of SIG SVR; nearby soundings were often convectively contaminated by 0000 UTC. In those cases, lapse rate evolution patterns from available reanalysis datasets (described in section 3b) were consulted to help determine the continuity of the EML into the area of interest.

This procedure yielded 34 SIG SVR event days from 1970 to 2006 (7.6% of the significant severe event day total) associated with EML soundings, with a total of 189 SIG SVR reports (20.3% of the 929 reports). Significant hail reports were found at a disproportionately high percentage within the EML subset at 35.9%, while significant tornadoes occurred at percentages close to the EML report subtotal at 19.2%. We suspect significant wind reports are underrepresented, since a measured gust of ≥65 kt is required (as opposed to “wind damage” reports that might have occurred owing to significant wind).

To add perspective on the importance of the EML cases (including nonquantified significant wind events), the authors tallied all fatalities and injuries due to severe weather of any magnitude on the EML event days (Table 2). Although the EML event day reports accounted for only 0.1% of all severe weather reports in the northeastern United States, 109 fatalities (52.9% of the total) and 1451 injuries (45% of the total) occurred, placing great importance on accurate forecasts of EML-related severe weather events.

In addition to the systematically determined 34 EML event days, the authors utilized an SPC online publication concerning historic derechos to discover an additional EML-associated event in 1969. Also, we would be remiss not to include the 9 June 1953 Worcester, Massachusetts, tornado as part of the dataset because of our a priori knowledge of the case, its destructive impact, and its 74-km track. While these two earlier events were not part of the systematic detection scheme applied to the 1970–2006 period, associated soundings met our required criteria and increased the available sample to 36 events for the composite and trajectory analyses. Tables 3 and 4 give summary descriptions of the EML-associated SIG SVR events used in this study.
Using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global reanalysis dataset (Kalnay et al. 1996), we constructed composite analyses of 700-mb heights, temperatures, 700–500-mb lapse rates, the four-layer lifted index, and the sea level pressure, as well as their 1968–96 climatological anomalies, for the 36 EML event days and 413 non-EML SIG SVR days. The composites were created using straight averages on the native georeferenced grid. Combining events in this way yields a certain degree of spatial smoothing in the composites and is one reason individual case studies are also

### Table 3. EML-associated SIG SVR events over the northeastern United States (1970–2006, plus two earlier events). SIG SVR reports refer to the number of reports available in Storm Data. The third column (fatalities/injuries) references the total number of weather-related fatalities and injuries associated with the event, respectively. EML soundings refer to soundings meeting EML criteria preceding the event. Midlevel flow refers to mean wind direction in the midtroposphere during the event. (Storm Data publications are available online at http://www7.ncdc.noaa.gov/IPS/sd/sd.html.)

<table>
<thead>
<tr>
<th>Date</th>
<th>SIG SVR Reports</th>
<th>Fatalities/ injuries</th>
<th>EML sounding IDs</th>
<th>Midlevel flow</th>
<th>Event comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Jun 1953</td>
<td>3</td>
<td>94/1288</td>
<td>Hempstead, NY (NY9)</td>
<td>W</td>
<td>F4 Worcester, MA, tornado</td>
</tr>
<tr>
<td>4 Jul 1969</td>
<td>N/A</td>
<td>0/0</td>
<td>Dayton, OH (DAY); Green Bay, WI (GRB)</td>
<td>NW</td>
<td>Western PA derecho</td>
</tr>
<tr>
<td>28 Aug 1973</td>
<td>5</td>
<td>4/37</td>
<td>ALB; Buffalo, NY (BUF); Washington, DC (IAD); Pittsburgh, PA (PIT)</td>
<td>NW</td>
<td>F4 West Stockbridge, MA, tornado</td>
</tr>
<tr>
<td>31 Aug 1973</td>
<td>4</td>
<td>0/0</td>
<td>IAD; John F. Kennedy International Airport, New York, NY (JFK); PIT</td>
<td>NW</td>
<td>F2 tornado in CT</td>
</tr>
<tr>
<td>4 Jul 1974</td>
<td>1</td>
<td>0/0</td>
<td>ALB</td>
<td>NW</td>
<td>2.00-in. hail in VT</td>
</tr>
<tr>
<td>11 Jul 1976</td>
<td>6</td>
<td>2/24</td>
<td>Flint, MI (FNT); Huntington, WV (HTS)</td>
<td>NW</td>
<td>F3 tornado in PA</td>
</tr>
<tr>
<td>10 Jul 1978</td>
<td>1</td>
<td>0/0</td>
<td>DAY; Salem, IL (SLO)</td>
<td>NW</td>
<td>2.00-in. hail in PA</td>
</tr>
<tr>
<td>5 Jul 1980</td>
<td>1</td>
<td>0/0</td>
<td>DAY, HTS, SLO</td>
<td>NW</td>
<td>4.00-in. hail in PA</td>
</tr>
<tr>
<td>8 Jul 1980</td>
<td>1</td>
<td>0/0</td>
<td>DAY, FNT, SLO</td>
<td>NWW</td>
<td>F2 tornado in western PA</td>
</tr>
<tr>
<td>31 May 1985</td>
<td>29</td>
<td>75/851</td>
<td>DAY, SLO</td>
<td>W</td>
<td>F4-F5 PA tornado outbreak</td>
</tr>
<tr>
<td>24 Jun 1985</td>
<td>12</td>
<td>0/1</td>
<td>Wallops Island, VA (WAL)</td>
<td>NW</td>
<td>Multiple 2.75-in. hail reports in PA</td>
</tr>
<tr>
<td>9 Jul 1985</td>
<td>2</td>
<td>0/0</td>
<td>BUF, DAY, HTS, PIT</td>
<td>NW</td>
<td>Multiple 2.00-in. hail reports in PA</td>
</tr>
<tr>
<td>28 Aug 1988</td>
<td>3</td>
<td>1/3</td>
<td>ALB</td>
<td>WSW</td>
<td>F2 tornado in PA; 2.5-in. hail and 70 mi h⁻¹ wind gust in VT</td>
</tr>
<tr>
<td>10 Jul 1989</td>
<td>12</td>
<td>1/153</td>
<td>FNT, IAD, PIT</td>
<td>NW</td>
<td>F4 tornado in CT</td>
</tr>
<tr>
<td>30 May 1991</td>
<td>1</td>
<td>0/0</td>
<td>ALB, FNT</td>
<td>NW</td>
<td>2.75-in. hail in NY</td>
</tr>
<tr>
<td>28 Jun 1991</td>
<td>2</td>
<td>0/0</td>
<td>Portland, ME (PWM)</td>
<td>NW</td>
<td>2.75-in. hail in ME</td>
</tr>
<tr>
<td>7 Jul 1991</td>
<td>2</td>
<td>0/14</td>
<td>DAY, FNT, HTS</td>
<td>WNW</td>
<td>Southern Great Lakes derecho</td>
</tr>
<tr>
<td>10 Jul 1993</td>
<td>2</td>
<td>0/26</td>
<td>Atlantic City, NJ (ACY); PIT</td>
<td>WNW</td>
<td>79 mi h⁻¹ wind gust in NY; 2.00-in. hail in CT</td>
</tr>
<tr>
<td>29 May 1995</td>
<td>6</td>
<td>3/30</td>
<td>Gray, ME (GYX); Upton, NY (OKX)</td>
<td>WSW</td>
<td>F4 Great Barrington tornado</td>
</tr>
<tr>
<td>19 Jun 1995</td>
<td>1</td>
<td>0/0</td>
<td>BUF; GYX; Maniwaki, QC (WMW)</td>
<td>NW</td>
<td>3.00-in. hail in ME</td>
</tr>
<tr>
<td>20 Jun 1995</td>
<td>6</td>
<td>0/0</td>
<td>ALB, BUF, WMW</td>
<td>NW</td>
<td>2.75-in. hail in CT</td>
</tr>
<tr>
<td>13 Jul 1995</td>
<td>1</td>
<td>0/0</td>
<td>DAY; Detroit, MI (DTX)</td>
<td>NW</td>
<td>Derecho across OH–western PA</td>
</tr>
<tr>
<td>15 Jul 1995</td>
<td>5</td>
<td>5/11</td>
<td>BUF; Sterling, VA (LWX); OKX; PIT</td>
<td>NW</td>
<td>Adirondacks derecho</td>
</tr>
<tr>
<td>15 Aug 1996</td>
<td>1</td>
<td>0/0</td>
<td>BUF; PIT</td>
<td>SW</td>
<td>2.75-in. hail in PA</td>
</tr>
<tr>
<td>18 Aug 1996</td>
<td>1</td>
<td>0/0</td>
<td>GYX</td>
<td>NW</td>
<td>2.00-in. hail in ME</td>
</tr>
<tr>
<td>31 May 1998</td>
<td>27</td>
<td>4/132</td>
<td>LWX, PIT</td>
<td>W</td>
<td>F3 Mechanicville tornado</td>
</tr>
<tr>
<td>24 Aug 1998</td>
<td>2</td>
<td>0/0</td>
<td>ALB, OKX</td>
<td>W</td>
<td>2.75-in. hail in NH</td>
</tr>
<tr>
<td>7 Sep 1998</td>
<td>12</td>
<td>6/79</td>
<td>BUF, OKX</td>
<td>WNW</td>
<td>Labor Day derecho</td>
</tr>
<tr>
<td>7 Jun 1999</td>
<td>2</td>
<td>0/2</td>
<td>BUF, OKX</td>
<td>W</td>
<td>90 mi h⁻¹ wind gust in NY</td>
</tr>
<tr>
<td>5 Jul 1999</td>
<td>6</td>
<td>1/5</td>
<td>WMW; Yarmouth, NS (YQI)</td>
<td>WNW</td>
<td>Canadian and northern New England derecho</td>
</tr>
<tr>
<td>6 Jul 1999</td>
<td>10</td>
<td>4/4</td>
<td>PIT, WAL</td>
<td>W</td>
<td>100 mi h⁻¹ gust in NY; 2.75-in. hail in MA</td>
</tr>
<tr>
<td>20 Jun 2001</td>
<td>5</td>
<td>0/0</td>
<td>ALB, GYX</td>
<td>W</td>
<td>2.75-in. hail in NY</td>
</tr>
<tr>
<td>31 May 2002</td>
<td>6</td>
<td>1/64</td>
<td>Chatham, MA (CHH); LWX</td>
<td>NW</td>
<td>Significant wind and significant hail</td>
</tr>
<tr>
<td>24 May 2004</td>
<td>5</td>
<td>0/1</td>
<td>LWX, PIT</td>
<td>WNW</td>
<td>90 mi h⁻¹ wind gust and 3-in. hail in NY</td>
</tr>
<tr>
<td>22 Jul 2005</td>
<td>1</td>
<td>0/0</td>
<td>OKX</td>
<td>NW</td>
<td>2-in. hail in VT</td>
</tr>
<tr>
<td>18 Jul 2006</td>
<td>8</td>
<td>2/14</td>
<td>ALB, CHH, OKX</td>
<td>W</td>
<td>2.75-in.hail in ME; 75 mi h⁻¹ wind gust in PA</td>
</tr>
</tbody>
</table>

* The total fatalities and injuries for the period are 203 and 2739, respectively.
shown later in the paper. That said, the composite analyses are useful in drawing out common meteorological features across the range of EML-related SIG SVR events.

For each SIG SVR event day, the date and time of the first severe weather report was determined. The global reanalysis data are available at 6-hourly subsynoptic time steps (0000, 0600, 1200, and 1800 UTC), and the closest time step before the first report for each event was utilized in the composite (defined as $t = t_0$). Additional composites were generated at 6-h time increments working backward from the event in time through 5 days (i.e., $t_0 - 6$ h, $t_0 - 12$ h, ..., $t_0 - 120$ h).

The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess 1997, 1998) was utilized to produce backward Lagrangian trajectories based upon the global reanalysis dataset for each of the 36 EML events. Backward Lagrangian trajectories were generated at 250 m AGL, and every 1 km from 1 to 6 km AGL for a duration of 96 h. A series of low- to midtropospheric trajectories were run to assess the airflow characteristics at different levels and also to account for the variability in the EML plume height. The starting point for each generated backward trajectory corresponded to the location (latitude–longitude pair) of the first SIG SVR report, with the starting time rounded to the nearest hour. Finally, two brief case studies are presented using archival sources of surface and upper-air data.

### 4. Synoptic composite and trajectory analyses

#### a. Composite analysis

Several salient synoptic signals are apparent in the composite analyses, with distinctions between the EML and non-EML composites. We focus our discussion at 700 mb because it is embedded within the EML. The mean 700-mb heights for the EML composites (Figs. 4a, 4c, and 4e) reveal a ridge axis extending from the western Atlantic Ocean westward across the southeastern and south-central United States, with a northward extension of the ridge into the mid-Mississippi and Tennessee River valleys. The mean ridge is comparatively stronger and displaced farther northward compared to the non-EML composite (Figs. 4b, 4d, and 4f), with stronger anticyclonic curvature in the height field downstream of the Rockies in the EML composite at $t_0 - 48$ h (Fig. 4a) and $t_0 - 24$ h (Fig. 4c). Likewise, a positive geopotential height anomaly builds to near 36 m across the Ohio Valley and southern Great Lakes region between $t_0 - 48$ h (Fig. 4a) and $t_0 - 24$ h (Fig. 4c) in the EML composite, and then flattens in response to a low-amplitude mean short-wave trough and associated negative height anomalies moving eastward across the Great Lakes at $t_0$ (Fig. 4e). The negative height anomaly over the northern Great Lakes suggests the prevalence of an embedded short-wave trough in the EML events, which is presumably providing the synoptic-scale ascent for cap removal and convective initiation. The northward displacement of the ridge and the approaching trough are important contributors to the relatively strong belt of westerly geostrophic flow that develops in the mean across the northeastern United States at $t_0$ (Fig. 4e). The temporal evolution of the non-EML mean height and height anomaly composite is different, showing the development of a more highly amplified mean 700-mb trough and stronger negative geopotential height anomaly field ($-27$ to $-30$ m) across the upper Mississippi Valley into the Great Lakes region (Figs. 4d and 4f) with southwesterly geostrophic flow across the northeastern United States at $t_0$ (Fig. 4f).

### Table 4. Written excerpts from Storm Data for several EML events.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Jul 1989</td>
<td>F4 tornado</td>
<td>This major tornado . . . touched down in Hamden, CT. As many as 350 homes and over 40 businesses were destroyed, resulting in many hundreds of people being displaced. Damage estimates in Hamden alone exceeded 100 million dollars.</td>
</tr>
<tr>
<td>28 Jun 1991</td>
<td>Giant hail</td>
<td>Extensive damage was reported in Calais, ME at (23 UTC) when tennis ball to baseball size hail fell. Cars were dented by the hail and their windows blown out. A car dealership had 55 cars damaged with damage estimated at $135,000. Total damage to cars and homes in Calais was estimated at several hundred thousand dollars.</td>
</tr>
<tr>
<td>20 Jun 1995</td>
<td>Giant hail</td>
<td>Baseball-size hail lasted for up to 20 min in Deep River, CT causing hundreds of thousands of dollars in damage. The hailstones broke hundreds of windows in buildings and automobiles, tore holes in roofs, dented siding and automobiles, and ruined gardens. Some automobiles were totaled.</td>
</tr>
<tr>
<td>15 Jul 1995</td>
<td>Derecho</td>
<td>One of the most devastating severe weather outbreaks to hit eastern New York . . . occurred on the morning of July 15th. Extensive tree damage occurred across the area with the Adirondacks being the hardest hit. Damage estimates . . . indicated that some 900,000 acres of forest were damaged with 125,000 acres of timber in the Adirondack Park sustaining moderate to severe damage. The timber damage (was) estimated at 1 billion board feet with an estimated value of $204 million. Five deaths and eleven injuries occurred with this event.</td>
</tr>
</tbody>
</table>
FIG. 4. Composite analyses of the mean 700-mb geopotential height (solid contours) and 700-mb height anomaly (shaded) (vs 1968–96 climatology) based on the NCEP–NCAR reanalysis dataset for (left) all EML events and (right) all SIG SVR non-EML events. Here, \( t_0 \) corresponds to the 6-hourly subsynoptic time step preceding the first significant severe weather report for each of \( n \) events listed. Composites valid at (a),(b) \( t_0 - 48 \) h, (c),(d) \( t_0 - 24 \) h, and (e),(f) \( t_0 \). The contour intervals are 15 and 3 m for the mean geopotential height and height anomaly analyses, respectively.
The positive height anomaly (of 9–15 m) to the south and east is significantly weaker. There also exists a persistent, negative height anomaly (on the order of 10 m) corresponding to a slightly stronger mean West Coast trough axis in the EML composite, which likely aids in the ejection of the EML plume from the Intermountain West; the non-EML composite shows a ridge across the central Rockies.

The advective nature of the EML is evident in the associated temporal evolution of the 700-mb temperature anomaly field. A positive anomaly maxima moves from the central plains at $t_0 - 48$ h (Fig. 5a), elongating...
FIG. 6. Composite 700–500-mb mean lapse rate for all 36 EML events based on NCEP–NCAR global reanalysis data at (a) $t = t_0 - 48\,\text{h}$, (b) $t = t_0 - 24\,\text{h}$, and (c) $t = t_0$. Solid lines represent $g$ with a contour interval of 0.5°C km$^{-1}$. Shading represents the 700–500-mb lapse rate anomaly in tenths of °C km$^{-1}$ based on 1971–2000 climatological values. The contour interval for the lapse rate anomaly is 0.2°C km$^{-1}$. 
across the Great Lakes region at $t_o - 24$ h (Fig. 5c), and then into the northeastern United States as it becomes entrained in the strong west-northwest flow downstream of the Great Lakes mean short-wave trough at $t_o$ (Fig. 5e). Temperature anomalies at 700 mb of +3°C to +3.5°C exist across New York, Pennsylvania, and far western New England at $t_o$ (Fig. 5e). In the non-EML composite (Figs. 5b, 5d, and 5f), the zonal positive temperature anomaly with connection back to the Rockies is absent, and the anomaly field is of a lower magnitude (Fig. 5b), on the order of +1°C. This is likely the result of synoptic-scale warm advection downstream of the mean trough position, with a similar magnitude negative temperature anomaly upstream of the mean trough axis over the north-central United States and south-central Canada at $t_o$ (Fig. 5f).

Fig. 7. Composite mean four-layer best lifted index (shaded every 0.5°C) and sea level pressure (isobars every 2 mb) for (a) EML and (b) non-EML events, and $t_o$ is defined as in Fig. 4.

Across the Great Lakes region at $t_o - 24$ h (Fig. 5c), and then into the northeastern United States as it becomes entrained in the strong west-northwest flow downstream of the Great Lakes mean short-wave trough at $t_o$ (Fig. 5e). Temperature anomalies at 700 mb of +3°C to +3.5°C exist across New York, Pennsylvania, and far western New England at $t_o$ (Fig. 5e). In the non-EML composite (Figs. 5b, 5d, and 5f), the zonal positive temperature anomaly with connection back to the Rockies is absent, and the anomaly field is of a lower magnitude (Fig. 5b), on the order of +1°C. This is likely the result of synoptic-scale warm advection downstream of the mean trough position, with a similar magnitude negative temperature anomaly upstream of the mean trough axis over the north-central United States and south-central Canada at $t_o$ (Fig. 5f).

Time series loops showing the evolution of these and additional fields are available online as part of the supplemental information to this article (http://dx.doi.org/10.1175/2010WAF2222363.s1).

Looking specifically at 700–500-mb lapse rates, at $t_o - 48$ h, a plume of steep lapse rates extends from Colorado northeastward across the central plains into the upper Mississippi Valley (Fig. 6a). The EML composite mean value of the 700–500-mb lapse rate is on the order of 7.5°C–8.0°C km$^{-1}$, with anomalies on the order of +1°C km$^{-1}$. At $t_o - 24$ h (Fig. 6b), the EML plume has become elongated and extends eastward across the Great Lakes region. Finally, at $t_o$ (Fig. 6c), the EML plume extends across the southern half of New York, Pennsylvania, and into southern New England. It appears the short-wave trough axis at 700 mb (Fig. 5e) has suppressed the EML plume slightly southward and eastward in the mean at $t_o$. Consistent with Farrell and Carlson (1989), the occurrence of SIG SVR was frequently on the poleward edge of the EML plume for individual events in the dataset (not shown). The correspondence is good between the positive 700-mb temperature anomaly and the positive lapse rate anomaly. This suggests that the 700-mb thermal ridge axis and its associated anomalies can serve as a proxy for the general location of the EML plume and can cue the forecaster to its possible existence.

The sea level pressure field at $t_o$ is similar in the EML and non-EML composites (Fig. 7), which further points to the relevance of what is occurring aloft in the EML layer. The composite mean best low-level lifted index at $t_o$ (Fig. 7) shows greater potential instability in the EML composite (Fig. 7a).

b. Trajectory analysis

For discussion purposes, we focus our attention on the backward trajectories starting at 3 km AGL, which generally corresponded to the lower to middle portion of the EML. While individual trajectories exhibit a large variance, it is apparent that many of the 36 trajectories exhibit neutral to anticyclonic curvature across the plains and Midwest (Fig. 8a), consistent with the anomalously strong mean 700-mb ridge over the Tennessee Valley. None of the trajectories approach from the south; most originate or cross the Intermountain West, consistent with the paths of the 700-mb temperature anomaly and 700–500-mb lapse rate composites.
FIG. 8. Backward 3-km AGL trajectories taken from the location of the first significant severe weather report (marked by circles) rounded to the nearest hour for (a) each of the 36 EML events and (b) a subset of 10 trajectories exhibiting three-quarter or greater anticyclonic loops along their path. Each trajectory’s duration is 96 h.
Interestingly, backward trajectories in 10 of the 36 events exhibited at least a three-fourths anticyclonic loop en route to the SIG SVR starting location. This subset of events is shown separately in Fig. 8b. Some of these events originate east of the Front Range, though it is noteworthy that backward trajectories from 4 to 5 km AGL often originated from the Intermountain West. Of the 10 events, 9 were associated with subsidence (descending air parcel trajectories) in the period 12–36 h prior to the event (not shown).

A 3-km AGL backward trajectory time–height analysis was developed from the 36 individual EML events (Fig. 9). After \( t_o - 51 \) h, the mean trajectory (top line in Fig. 9) begins subsiding, persisting until roughly 14 h before the event. Mean instantaneous vertical motion (Fig. 9, bottom line) is approximately \( 1 \mu \text{b s}^{-1} \), consistent with the magnitude of synoptic-scale vertical velocities. Fourteen hours before the first significant severe report, the mean instantaneous vertical velocity reverses sign, showing ascent, and reaches roughly \( -1 \mu \text{b s}^{-1} \) at \( t_o - 3 \) h. The box-and-whisker analysis of 6-h pressure change following the trajectory motion, \( (Dp/Dt)_{\text{6h}} \), shows consistency in this pattern for the majority of trajectory members, revealing persistent subsidence 1–2 days prior to the event, followed by ascent as trajectories approach the time and location of the first SIG SVR report. The period of ascent is short in duration, but almost certain near \( t_o \).

Consistent with the lapse rate tendency in Eq. (1), mean subsidence from \( t_o - 51 \) to \(-14 \) h likely strengthens the capping inversion at the base of the EML [through differential downward vertical motion, in term E of Eq. (1)]. A strong cap and large-scale subsidence would generally not be conducive for widespread deep moist convection, which would otherwise have a deleterious impact on the EML plume. Thereafter, the rising motion in the hours prior to the first SIG SVR report is consistent with the lift necessary for weakening the cap and a necessary ingredient for deep moist convection (Doswell 1987). There is also consistency between the time series of vertical motion and the composite analyses. In the composite 700-mb analysis, there existed anticyclonic curvature in the flow, contributing to downward motion east of the Rockies, until such time that the parcel is entrained in a rising airstream in advance of the mean short-wave trough translating eastward across the Great Lakes region.

Given the paucity of EML significant severe weather episodes over the northeastern United States, we hypothesize that both horizontal advection and downward vertical motion within the EML plume are essential factors for EML maintenance and transport over large distances.
Furthermore, the timing of large-scale ascent is important in lessening convective inhibition and ultimately in the release of the instability over the northeastern United States. Mesoscale features might also be expected to play an important role, but were beyond the scope of this research.

5. Case studies


On 28 August 1973, three significant tornadoes occurred in eastern New York and western Massachusetts with a supercell thunderstorm that developed in the Adirondack Mountains of New York. The storm tracked south-southeastward, producing a nearly continuous 350-km swath of severe weather before weakening over Long Island Sound. An F4 tornado was responsible for three deaths and 36 injuries when it struck a truck stop in West Stockbridge, Massachusetts, near 1740 UTC, with an additional fatality at a nearby house. At least two other severe thunderstorms affected eastern New England with large hail, damaging winds, and isolated tornadoes.

At 1200 UTC 28 August, a 700-mb anticyclone was centered over southeastern Ohio with a ridge axis extending northward across eastern Ontario. A plume of 700–500-mb lapse rates of 8°C km⁻¹ or greater was present in an arc from Colorado northeastward to southwestern Ontario, and then southeastward into the Ohio Valley (Fig. 10). A 96-h backward trajectory analysis (Fig. 11) revealed that the EML likely originated over the Mexican Plateau and was advected northeastward around the midtropospheric ridge, finally turning south-eastward over the Great Lakes before reaching Albany.
New York (ALB), at 1200 UTC 28 August. The progression of the EML plume is evident in observed soundings analyzed at 24-h intervals (Figs. 12a–d) near the trajectory. Note that the plume exhibited minimal change in character despite being advected nearly 3500 km, as evidenced by the nearly dry-adiabatic lapse rates in the 800–500-mb layer on the 1200 UTC 28 August ALB sounding (Fig. 12d). The steepest lapse rates do not necessarily conform to common fixed layers (e.g., 700–500 mb), highlighting the importance of examining soundings.

Figures 13a–d shows the chronological progression of the EML plume via the 700-mb temperature anomaly maximum as it “breaks off” from the source region of the high plains of Texas and elevated terrain of New Mexico and is advected into the northeastern United States over 96 h. At 1200 UTC 28 August (Fig. 13d), the 700-mb temperature anomaly maximum shifted southward into the mid-Atlantic states as a thermal trough over Quebec embedded in midtropospheric northwest flow translated southeastward. The short-wave trough was likely responsible for providing the necessary ascent for cap removal and initiation of deep moist convection. Note also that the convection occurred on the northern fringe of the EML, as has been found in similar events (e.g., Farrell and Carlson 1989).

The 1200 UTC 28 August ALB sounding was modified using the 2000 UTC 28 August surface temperature of 31°C and dewpoint of 21°C, to better approximate the thermodynamic environment close to the occurrence of the F4 tornado (Fig. 14). The 900–700-mb layer was
modified slightly to account for assumptive cooling aided by ascent associated with the approaching 700-mb thermal trough shown in Fig. 13d. The modified sounding revealed a potentially unstable environment with 100-mb mean-mixed CAPE [convective inhibition (CIN)] of approximately 2750 ($\pm$60) $J kg^{-1}$. The strong instability combined with northwesterly surface to 6-km vertical shear values of approximately 25 m $s^{-1}$ and weak low-level linear forcing allowed for long-lived, isolated supercells.

b. Northern New England and southern Quebec derecho: 5 July 1999

A significant nocturnal derecho affected far northern New England and southern Quebec during the early morning hours of 5 July 1999, resulting in two fatalities and several injuries, as well as considerable destruction of property and forest (Mainville 1999). The derecho began as a cluster of thunderstorms over North Dakota early on 4 July 1999 and subsequently grew upscale while traveling over 2000 km, finally weakening over coastal Maine early in the morning on 5 July 1999 (Fig. 15).

The 0000 UTC 5 July rawinsonde plot at 700 mb revealed a strong midtropospheric anticyclone centered over Kentucky along with anomalously warm temperatures ($+13^\circ$ to $+15^\circ C$) as far north as southern Ontario and Quebec (Fig. 16). A nearly continuous plume of anomalously steep midtropospheric lapse rates extended from the northeastern United States westward to the Intermountain West. The midtropospheric trajectory suggests the source region of the EML was the southwestern United States, and the EML was then advected northeastward over a period of 96 h (Fig. 17). Observed soundings were again examined at 24-h intervals near the trajectory to verify the presence of the EML (Figs. 18a–d). The 0000 UTC 5 July rawinsonde at Maniwaki, Quebec (Fig. 18d), confirmed the presence of an EML in the region with near-dry-adiabatic lapse rates and...
increasing relative humidity with height in the 700–500-mb layer. This rawinsonde conveniently serves as a “near proximity” sounding, as the derecho passed over the site approximately 5 h after the rawinsonde was launched. The presence of the EML and the associated capping inversion allowed for an unusual buildup of boundary layer moisture (surface dewpoints near 23°–24°C with surface $\theta_e$ values in excess of 350 K), which in turn aided in unusually strong instability prior to the passage of the derecho. The combination of 45 kt of surface-to-6-km wind shear and surface-based CAPE values near 3500 J kg$^{-1}$ allowed for the maintenance of the derecho as it entered Quebec and northernmost New England. Once the mesoscale convective system became organized, strong low-level ascent along the leading edge of the existing cold pool allowed parcels to reach the level of free convection, within a deep, unidirectional flow regime strongly favoring forward propagation (Corfidi 2003). Organized convection would not ordinarily be expected in an area with 700-mb temperatures in excess of 13°C (owing to a strong cap). However, a subtle shortwave trough embedded in the midtropospheric northwest flow (not shown) likely provided sufficient ascent and the resultant cooling within the inversion layer to sustain incipient deep convection. The 1200 UTC 5 May Maniwaki sounding (not shown) indicated an observed 700-mb temperature of +8.4°C, 5.2°C cooler than the observed 700-mb temperature just 12 h earlier. The advection of the EML plume is also evident in 700-mb temperature anomalies of +2–3 standard deviations, denoting the location of the EML plume as it moved around the northern periphery of the midlevel ridge (Figs. 19a–d).

![FIG. 14. The 1200 UTC 28 Aug ALB sounding modified using 2000 UTC 28 Aug temperature and dewpoint from the surface observation at ALB. Mixed-layer CAPE and CIN are shaded.](image14)

![FIG. 15. Area affected by the 4–5 Jul 1999 derecho (scalloped line) with isochrones of the leading edge gust front at 3-h intervals (curved lines). Crosses indicate locations of wind damage or estimated wind gusts above severe limits (25 m s$^{-1}$ or higher). (Analysis provided by B. Johns.)](image15)
6. Summary and future work

a. Summary

The authors catalogued warm season SIG SVR reports in the northeastern United States from 1970 to 2006. Events were categorized as either being associated with or not associated with EML air based on an examination of regional soundings. The 7.6% of SIG SVR event days associated with an EML disproportionately accounted for 52.9% of the fatalities and 45% of the injuries over the study period and was composed of historically important severe weather events in the region.

A lapse rate tendency equation and scale analysis revealed horizontal advection as a plausible means of long downstream transport of EML air from the Intermountain West into the northeastern United States, with large-scale subsidence maintaining the EML plume and capping inversion en route. A sample of 36 EML events allowed for composite and trajectory analysis and revealed several key synoptic findings: 1) a mean 700-mb anticyclone centered over the Tennessee River valley, north and west of its normal location; 2) a 700-mb trough along the West Coast that results in the ejection of the EML plume northeastward across the Great Plains; 3) anticyclonic flow (or complete trajectory “loops” in some cases) across the plains and upper Mississippi Valley, yielding mean downward motion and limited convection, maintaining the EML plume until it moves downstream of the ridge axis; and 4) a short-wave trough embedded in enhanced and moderately strong west-to-northwest midlevel flow north of the ridge position across the Great Lakes, which ultimately entrains the EML air and contributes to upward motion and convective initiation for the events in the northeastern United States. When compared, the EML and non-EML composites deviated significantly from each other, with the former revealing a

![Figure 16](image1.png)

FIG. 16. As in Fig. 10, but at 0000 UTC 5 Jul 1999.

![Figure 17](image2.png)

FIG. 17. As in Fig. 11 except starting from Maniwaki, QC, at 0000 UTC 5 Jul 1999. Points a–d represent the rawinsonde locations shown in Fig. 18.
west-to-northwest midlevel flow regime, and a stronger 700-mb positive temperature anomaly of \(+3\textdegree-4\textdegree\)C owing to the presence of the EML itself. Synoptic case studies were employed to further elucidate the key findings listed above, consistent with how an operational forecaster would see an individual EML event unfold in sounding, upper-air, and departure from climatology datasets.

There are two main limitations to this study. First, the methodology precluded an examination of null cases; that is, scenarios that could bring an EML plume across the study area but do not result in SIG SVR. A lack of forcing for ascent or dry, cool boundary layer conditions yielding insufficient CAPE could allow EML air to pass the region without development of deep moist convection. Second, it is important to note that the EML alone does not determine the storm mode; the events in this study include historical derecho and tornadic supercell events. However, both modes pose risk to life and property, and one is not necessarily of greater severity than the other. Factors such as the magnitude of the vertical shear and mesoscale boundaries, and the geometry of the upward motion, would also need to be considered to determine storm mode.

b. Future work

We foresee opportunities to pursue this topic further. Most interesting would be a model-based study to quantitatively assess each term of the lapse rate tendency equation in various situations to better understand how the EML evolves over time across the central and eastern United States. Examination of the convective mode in EML environs and null cases would also be topics worthy of future investigations; one could start from the sounding or reanalysis data to systematically catalog all steep lapse rate occurrences as a means of finding null events. Finally, the construction of maximum layer lapse rate maps (e.g., 100–200 mb deep) above the boundary layer not arbitrarily linked to specific pressure levels (e.g., 700–500 mb) would likely show potential EMLs and their boundaries more vividly for forecasters, and such procedures
Acknowledgments. This project stemmed from enlightening early discussions with Jon Finch (NWS DDC) and Bob Johns (SPC), and we are grateful for their insights. Drs. John Gyakum and Eyad Atallah (McGill University) created the lapse rate composites used in Fig. 6 and Bob Johns provided the derecho isochrone analysis used in Fig. 15. The NCEP–NCAR global reanalysis images were provided by the NOAA/ESRL Physical Sciences Division from their Web site (http://www.cdc.noaa.gov/). The NOAA Air Resources Laboratory (ARL) READY website (http://www.arl.noaa.gov/ready.html) was used for the HYSPLIT trajectories. The paper benefited from reviews by Steve Corfidi, Joe Dellicarpini, Walter Drag, Jim Hayes, Andy Nash, Dave Radell, Dave Schultz, Jay Shafer, Paul Sisson, Bob Thompson, and Jeff Waldstreicher. We also thank the three anonymous reviewers for helping to improve the manuscript.

APPENDIX

Lapse Rate Tendency Equation

The lapse rate tendency equation described in section 2 is derived below. Variations of the lapse rate tendency equation derivation below also appear elsewhere (e.g., Air Weather Service 1990; C. Doswell 1987, personal communication).

The environmental lapse rate \( \gamma \) is defined as

\[
\gamma = \frac{\partial T}{\partial z},
\]

where \( T \) is the temperature and \( z \) is the geometric height. The lapse rate tendency \( \partial \gamma / \partial t \) represents the local time rate of change of the environmental lapse rate. Starting from the first law of thermodynamics,

\[
dh = c_p \, dT - \alpha \, dp,
\]

where \( dh \) is the inexact differential denoting an infinitesimal change in heat; \( \alpha \) is the specific volume, or the

Fig. 19. As in Fig. 13, but at (a) 0600 UTC 2 Jul 1999, (b) 0600 UTC 3 Jul 1999, (c) 0600 UTC 4 Jul 1999, and (d) 0600 UTC 5 Jul 1999.
inverse of density (i.e., 1/ρ); cₚ is the specific heat of air at constant pressure; and ρ is the pressure. Dividing both sides of the equation by the inexact differential dt, expanding the total derivative dT/dt, and substituting with the hydrostatic equation dp = −gdz/α yields

\[ \frac{dh}{dt} = c_p \left( \frac{dT}{dt} + \mathbf{V} \cdot \nabla_h T + w \frac{\partial T}{\partial z} \right) + g \frac{dz}{dt}. \]  (A3)

We will define the diabatic heating as dh/dt = Q. Also note that dz/dt is the vertical velocity w. Next, we differentiate with respect to height ∂/∂z and multiply both sides by −1:

\[ -\frac{\partial Q}{\partial z} = c_p \left[ \frac{\partial}{\partial t} \left( \frac{\partial T}{\partial z} \right) + \mathbf{V} \cdot \nabla_h \left( \frac{\partial T}{\partial z} \right) + w \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right) \right] \]  (A4)

\[ -\frac{\partial}{\partial z} \left( \frac{\partial Q}{\partial z} \right) = c_p \left[ \frac{\partial}{\partial t} \left( \frac{\partial T}{\partial z} \right) + \mathbf{V} \cdot \nabla_h \left( \frac{\partial T}{\partial z} \right) + w \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right) \right] \]  (A5)

Rearrangement of terms to solve for the local change in lapse rate ∂γ/∂t yields a lapse rate tendency equation, which is described in section 2:

\[ \frac{\partial \gamma}{\partial t} = \frac{1}{c_p} \left( \frac{\partial Q}{\partial z} \right) - \mathbf{V} \cdot \nabla_h \gamma + w \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right) + \mathbf{V} \cdot \nabla_h T \]  (A6)

REFERENCES