**Precipitation events associated with terrain-generated convergence in the Mohawk and Hudson River valleys of New York**

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**ABSTRACT**

The unique terrain in eastern New York State plays a pivotal role in both the warm and cold season weather of the region. The west to east Mohawk and north to south Hudson River valleys intersect in the Capital Region of New York, and can result in localized flow channeling and boundary layer convergence. Several previous case studies have documented the important role of Mohawk–Hudson convergence (MHC) in modulating the low-level wind profile in cases of warm-season severe weather. However, a comprehensive, composite and case study analysis of these events, which pose a significant challenge to forecasters, has not been previously published.

 Composite analysis shows that warm-season MHC precipitation events are characterized by weak warm-air advection and low-level geostrophic southwesterly flow that advects low-level, warm, moist air up the Hudson River valley and westerly flow down the Mohawk River valley, leading to increased instability. Cold-season MHC events are characterized by weak cold-air advection from low-level geostrophic northwesterly flow which allows for surface flow to be channeled westerly down the Mohawk Valley and northerly down the Hudson Valley. If low-level moisture persists after the passage of a strong northeast cyclone, the channeled low-level flow can lead to boundary layer convergence at the junction of the river valleys.

While most MHC events do not produce significant sensible weather, they can occasionally produce hazardous weather conditions if they occur with little warning and/or during peak travel times. Cold MHC precipitation can result in persistent moderate to heavy snow in the wake of a departing cyclone, whereas warm MHC cases often initiate an unexpected thunderstorm close to Albany International Airport.

**1. Introduction**

 Channeled flow occurs when orographic features, such as breaks in mountain barriers or valleys through complex terrain, act to change the local wind direction and/or speed. Frequently, this phenomenon reveals itself as a recurring area of surface wind observations that differ systematically from surrounding observations and/or the geostrophic wind direction, and which occur only under certain specific synoptic conditions. As will be shown, the flow in the Capital Region of New York state, where the Mohawk and Hudson River valleys intersect (Fig. 1), meets each of these characteristics for channeled flow.

 There are four main mechanisms described in Whiteman and Doran (1993) that have been identified as creating channeled flow. The first mechanism, thermal forcing, results from the diurnal cycle of heating in complex terrain, which causes up-valley winds during the day and down-valley winds during the night. The second mechanism is downward momentum transport as a result of vertical turbulent mixing by gravity waves and/or friction. This process generates in-valley winds that are of a similar direction as the ambient flow. The third mechanism is forced channeling, in which the wind is channeled by the valley walls creating a flow up or down the valley axis depending on the direction of the geostrophic wind. Lastly, the fourth mechanism for channeled flow, pressure driven channeling, is driven by small differences in pressure along the valley’s length.

Topography plays a role in mesoscale weather events in river valleys around the United States and around the world. In post-cold front environments in the Puget Sound, topography is responsible for spatial variations in the precipitation climatology in the Seattle region associated with mesoscale convergence events (Mass and Clifford 1981). The important effects of topography were also investigated in Zhong (2008) where the presence of topography can lead to thermally and dynamically induced mesoscale wind fields in the Owens Valley of California. Complex terrain can also influence climatological surface winds due to channeling effects as in the case of the topography of Northwest Utah (Jeglum and Hoch 2016). In eastern North America river valleys such as the St. Lawrence River Valley experience channeled flow which contributes significantly to the weather in the vicinity of Montreal, Canada (Razy 2011). The St. Lawrence River Valley in eastern Canada alters the surface wind enhancing convergence which contributes to locally higher precipitation amounts typically do to pressure driven channeling. This sometimes occurs as transitioning tropical cyclones establish a synoptic-scale pressure gradient in the valley (Milrad 2012). River valleys can offer a mix of complex flow regimes and topographic layout leading to mesoscale forcing. Channeled flow via the mechanisms above has been shown to occur even in very shallow river valleys. For example, Gross and Wippermann (1987) documented channeled flow in Germany’s Rhine Valley, where the valley walls only extended to 500 m in height.

The Hudson Valley is a broad and shallow river valley oriented north-south direction, stretching from near Glens Falls, New York to New York City. The Mohawk Valley is fairly narrow compared to the Hudson River valley and is oriented from west to east stretching from Rome, NY to Albany, NY. As shown in Figure 1, these two valleys intersect in the vicinity of Albany, NY. In the Capital Region, the valleys are approximately 500 m deep and approximately 60 km across, truly fitting the definition of a broad, shallow river valley. This intersection can alter the wind flow in such a way that leads to locally strong surface convergence (known as Mohawk–Hudson convergence (MHC)), unpredicted and significant precipitation events, and even severe weather.

MHC events often happen with very little warning and can have significant societal impacts. Cold MHC can create moderate snowfall and additional accumulation of snow on the tail of nor’easters, prolonging the plowing and salting of roads. Often times, these isolated light to moderate snowfall events can extend periods of instrument flight rules (IFR), or even low instrument flight rules (LIFR), conditions at Albany International Airport. Warm MHC events can also quickly disrupt operations at Albany International Airport as discrete convective cells can suddenly develop. Channeled, southerly flow up the Hudson River Valley can add to the surface instability and increase the vertical wind shear, which can rapidly turn discrete cells severe and even influence supercell and mesoscale convective system development (Markowski and Dotzek 2011). The channeled flow is also known to affect the formation of tornadic supercells as topographic influences have been examined in cases such as the Duanesburg (Tang et al. 2016), Mechanicville (LaPenta 2005), and Great Barrington (Bosart 2006) tornadoes.

MHC events only occur under specific atmospheric conditions. In years past these events were difficult to predict, often without warning. Part of the reason these events are difficult to predict is the fact that sometimes it appears as if MHC will happen and then doesn’t. Through analysis of a composite of past events we are able to pinpoint synoptic scale patterns favorable for MHC events.

**2. Data and methodology**

*a. Case selection*

All MHC cases were chosen based on radar analysis of KENX base reflectivity to locate isolated precipitation events within a 16 km (10 miles) radius of Albany International Airport. This is the radius at which a thunderstorm would be reported in the vicinity by the ASOS for the warm cases. Evidence for boundaries such as fronts, troughs, and/or cold pools from ongoing convection were identified from surface and upper air analyses, and radar. Cases in which precipitation was directly initiated by these features were discarded.

For the warm season MHC events, every event was analyzed in which lightning was reported within 16 km (10 miles) of Albany International Airport (KALB) fitting the definition of a thunderstorm in the vicinity (VCTS) on the METARs. MHC convection in these cases had to reach a minimum of 30 dBZ. Cases were also verified by looking for a nose of increased, surface based convective available potential energy (SBCAPE) being advected up the Hudson River Valley using the Storm Prediction Centers mesoscale analysis. There was a subset of 17 warm-season events in which convection was initiated as the result of other mechanisms (e.g., prefrontal trough, cold pool dynamics, etc.), but were enhanced by MHC. As this paper seeks to analyze only clear MHC events, so cases which showed enhancement of convection, rather than initiation of convection by MHC were not included. In total, 19 warm cases were identified and information about each case can be found in Table 1.

For the cold season MHC events any case in which a surface low tracked west of the 40°N, and 70°W benchmark were analyzed, this is because lows tracking further east of this benchmark nearly always have no impact to the Capital Region. These events were examined to make sure no lake-effect, or lake-enhanced, snow took place and that the cases occurred independent of synoptic-scale forced precipitation. In total, 12 cold cases were identified and information about each case can be found in Table 2.

*b. Data*

 Surface observations were obtained from the Iowa State Archive and radar data was obtained from the National Centers for Environmental Information. Warm and cold-season MHC composites were created using 0.5° Climate Forecast Systems Reanalysis (CFSR) (Saha et al. 2010). The composite was centered on the time of maximum reflectivity of each MHC event. Composite soundings were made centered on Albany International Airport. Although the resolution of the CFSR doesn’t allow us to resolve MHC and channeled flow, we are only using the composite analysis for identifying synoptic-scale features leading to MHC. The 2 January 2008 case study uses the 13-km resolution Rapid Update Cycle (RUC) model initialized at 1200 UTC 2 January 2008.

**3. Results**

*a. MHC warm cases*

In figure 2a composite mean sea level pressure shows a generally weak surface cyclone located over southern Quebec during the time of peak reflectivity of the warm MHC event. Another interesting point is the weak pressure gradient associated with this surface cyclone. This surface cyclone would induce weak southwesterly geostrophic flow over New York and New England.

Figure 3a shows the composite 1000-hPa wind speed and direction as well as convergence. The composite shows westerly to southwesterly flow across eastern New York State consistent with the results expected from the mean sea level pressure plot. The composite winds in the Hudson Valley are generally less than 4 kts, while winds in the Mohawk Valley are typically slightly stronger, but generally less than 12 kts. The geostrophic flow is generally southwesterly, low level winds are then turned by the topography creating more southerly flow in the Hudson Valley and more westerly winds in the Mohawk Valley. Deceleration of the wind can be seen as the flow enters the Hudson Valley. Large convergence can be seen over southern Connecticut and extreme northern New York.

 At 850-hPa, weak warm air advection in the prefrontal environment occurs during the peaks of these events over most of New York State (Fig. 4a). Focusing on the Eastern region of New York the composite shows weak warm air advection on the order of 0.4 *°*C h-1. Warm air advection to the east and cold air advection to the west is indicative of a cold front approaching the region.

Focusing again on the eastern region of New York weak advection of 500-hPa cyclonic relative vorticity occurs during the warm events (Fig. 5a). Weak cyclonic curvature is seen upstream of the Capital Region, indicative of possible shortwaves in the flow at 500-hPa. A deeper investigation of the cases shows that cases had these shortwaves but they varied greatly in position. The common feature of all of the cases was that there was cyclonic relative vorticity near western New York during all of the cases.

 At 300-hPa (Fig. 6a), a weak jet is located to the northeast of New York State with its maximum over New Brunswick and extending southwest into southern Quebec. The green contours show that most of the upper level divergence is taking place close to the jet streak. A strip of divergence can be seen crossing New York.

The composite sounding (Fig. 7a) for warm MHC cases shows a warm surface temperature around 28 *°*C and surface dew points around 19 *°*C. With a warm, moist surface, the lack of any significant capping inversion, and steep mid-level lapse rates, there is 100 J/kg of CAPE in a deep layer in the composite from the surface to 250-hPa. Surface southwesterly winds around 5 kt veer with height, representative of warm air advection, which was seen in the 850-hPa map.

*b. MHC cold cases*

Cold cases of MHC typically occur typically after the passage of synoptically forced precipitation. The cold case sea-level pressure composite (Fig. 2b) shows that during the peak of cold MHC events a surface cyclone is located just to the east of Cape Cod. Surface geostrophic winds would be from the north, northwest over New York. The composite gradient in sea level pressure is much larger than that of the warm cases.

Winds in the Hudson River valley are northerly while the winds in the Mohawk River valley are more northwesterly (Fig. 3b). The magnitude of the wind varies between 12 ktsin the Mohawk Valley to near 6 kts in the northern Hudson Valley. The magnitude of the wind in the cold cases is larger than that in the warm cases because the departing cyclones in the cold cases are associated with stronger pressure gradients and, therefore, stronger background geostrophic flow. Weak convergence of the 1000-hPa winds are taking place in the Capital Region.

Cold air advection at 850-hPa dominates the region during cold season MHC events (Fig. 4b). The cold air advection in the region is stronger than that in the warm cases. Looking closely at the Capital Region we can see a noticeable minimum in the cold air advection. This is indicative of neutral or slightly warm air advection occurring in the lower levels.

At 500-hPa, a maximum in relative vorticity is located over the Capital Region (Fig. 5b), implying anticyclonic relative vorticity advection beginning upstream of the 500-hPa trough axis at the peak of the MHC event. Approximating the thermal wind as parallel to the thickness contours the Sutcliffe-Trenberth form of the QG omega equation predicts that the Capital region is in an area of downward vertical motion at 500-hPa.

In the 300-hPa composite, a strong 100 kt, jet maximum can be seen well to the south of the New York pushing off the coast of North Carolina (Fig. 6b). Most of the upper level divergence is taking place on the south side of the jet and near the surface cyclone. The Capital Region is not in an area of favored upper level divergence.

The cold MHC composite sounding (Fig. 7b) shows backing through the mid-levels of the atmosphere, consistent with the presence of weak cold air advection. At the lowest levels there is veering of the winds, which is associated with warm air advection. Though the composite can smooth out detailed features of the individual events, the remnants of a weak inversion can be seen around 900-hPa. The sounding is saturated from the surface to 800-hPa and is entirely below 0 *°*C allowing for the growth of dendrites.

*c. Cold MHC case study: 2 January 2008*

The 2 January 2008 MHC event was particularly significant because of its duration, intensity, and low predictability in the Capital Region. Officially, an additional 0.8 cm of snow was reported at KALB, but weather observers reported more significant accumulation attributed to MHC in various parts of the region, with 12.7 cm more snow reported in Cohoes, NY, on top of the nearly 28 cm produced by the cyclones synoptically forced precipitation field.  The evolution of the event is shown in the radar and surface observation data in figure 8. The event starts as a broad area of precipitation and then organizes into a more band like feature. Cohoes, NY is labeled with a red dot which coincides nicely where the highest reflectivity was being reported. Outside of this narrow band, little or no additional snow accumulations were reported.

At the surface (Fig. 9), much like in the composite, there is an area of low pressure located off the New England coast with a central pressure lower than 1004-hPa. The cyclone tracked slightly west of 40°N, 70°W, which allowed the synoptic scale precipitation field of the cyclone to impact the Capital Region. This cyclone location helped to induce northwesterly geostrophic flow.

On the backside of the storm, there was cold air advection at 850-hPa over most of New York State, as shown in Figure 10. There was actually a small nose of warm air advection located over the Capital Region on the order of 0.4 *°*C h-1.. This could perhaps be caused by the advection of downslope winds off the Eastern Adirondack Mountains or the artificial veering of the winds due to channeling.

 At 500-hPa, most of the cyclonic relative vorticity (Fig. 11) was located in the base of the trough over Northern Mississippi, Alabama and Georgia and into Kentucky, North and South Carolina. This is being advected off the coast of eastern New England where the cyclone was deepening as it moved away from eastern New England. At 1200 UTC Cyclonic vorticity advection was occurring in the Capital Region a few hours after that point we can see the evolution of the MHC event from a broad area of precipitation to a single band (Fig. 8).

A 300-hPa jet maximum of over 165 kts (Fig. 12) was located southeast of eastern New York and western New England. The areas of maximum upper-level divergence were far south of the Capital Region over the Southeast United States. This was very similar to the cold case composite as most of the upper level divergence is taking place on the south side of the jet.

Figure 13 shows the observed sounding from KALB at 1200 UTC 2 January 2008, which is 2 hours before the MHC maximum in reflectivity. Like in the composite case the boundary layer is very moist with temperatures less than 0*°*C. The winds in the observed sounding veer in the lower layers from the surface to around 900-hPa, consistent with low-level warm air advection (Fig. 10). The winds above this level begin to back, which is consistent with the cold air advection through the remainder of the troposphere. Much like what is seen in the composite sounding.

**4. Summary and conclusions**

 The Mohawk and Hudson River valleys as well as the Catskill, Adirondack, Berkshire and Southern Green Mountains play a pivotal role in altering wind flow in the Capital Region. Through composite analysis and a case study, an increased understanding of the synoptic scale setup common to Mohawk-Hudson Convergence (MHC) events will better forecasting abilities for these events.

 The synoptic setup for warm cases of MHC is a broad trough at 300-hPa over the eastern United States. This in part with  weak cyclonic vorticity advection due to an upstream shortwave and weak warm air advection associated with the warm sector of a cyclone are typical of warm season MHC cases. Most importantly, weak geostrophic south or southwesterly winds are channeled westerly in the Mohawk valley and southerly in the Hudson valley supplying unstable air to the greater Capital Region. The winds are typically weak in the pre-frontal environment in the Capital Region and there is little upper level forcing for ascent.

The synoptic setup for cold cases of MHC is a strong jet with a trough over the East Coast with the jet maximum off the coast of North Carolina. Strong cyclonic vorticity advection leads to a deepening of an area of low pressure off the New England coast increasing the surface pressure gradient over eastern New York. This strengthening of the pressure gradient leads to moderate northerly flow in the Hudson valley and northwesterly flow in the Mohawk valley. Cold events are also characterized by a moist boundary layer with warm air advection in the low-levels and drier air with cold advection in the mid-levels. The low level warm air advection suggests rising motion in the lower atmosphere being capped by mid-level descent as a cyclonic relative vorticity maximum moves over the Capital Region. This supports the fact that these cases seem to be bound to the lowest levels of the atmosphere.

 MHC events are hard to predict because of their seemingly innocuous conditions on the large-scale. They can quickly turn into high impact weather events. Slight ascent from the river valleys causing upward vertical motion can lead to thunderstorms and quick bursts of precipitation. Figure 14 shows a checklist for forecasters to help them determine if MHC is probable. Future advances in surface observation such as the New York State mesonet will significantly help the prediction of MHC events as often surface level winds can show convergence before the onset of precipitation.

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