Identifying Source Regions and the Distribution of Cross-Tropopause Convective Outflow Over North America During the Warm Season

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Abstract We analyzed the interaction between the North American monsoon anticyclone (NAMA) and summertime cross-tropopause convective outflow by applying a trajectory analysis to a climatology of convective overshooting tops (OTs) identified in GOES satellite images, which covers the domain from 29°S to 68°N and from 205 to 1.25°W for the time period of May through September 2013. With this analysis we identified seasonally, geographically, and altitude-dependent variability in NAMA strength and in cross-tropopause convection that control their interaction. We find that the NAMA has the strongest impact on the circulation of convectively influenced air masses in August. Over the entire time period examined the intertropical convergence zone contributes the majority of OTs with a larger fraction of total OTs at 370 K (on average 70%) than at 400 K (on average 52%). During August at 370 K, the convectively influenced air masses within the NAMA circulation, as determined by the trajectory analysis, are primarily sourced from the intertropical convergence zone (monthly average of 66.1%), while at 400 K the Sierra Madres and the Central United States combined constitute the dominant source region (monthly average of 44.1%, compared to 36.6% of the combined Intertropical Convergence Zone regions). When evaluating the impact of cross-tropopause convection on the composition and chemistry of the upper troposphere and lower stratosphere, the effects of the NAMA on both the distribution of convective outflow and the residence time of convectively influenced air masses within the NAMA region must be considered.

Plain Language Summary We analyze the seasonal and regional variability of both the distribution of convection that has reached the lower stratosphere (an exceptional height) over North America from May through September and the subsequent circulation of the air masses that have been influenced by this convection within the large-scale but transient summertime anticyclone over North America. Overshooting convection that has reached the lower stratosphere is identified using infrared and visible satellite imagery. We then simulate the circulation of the convectively influenced air to track its motion throughout the season. We find that the anticyclone has the greatest impact on convectively influenced air masses in August concurrent with a maximum in the frequency of overshooting convection over the study domain. Which regions contribute the most to overshooting convection is dependent on the depth of convection, with both upper and lower levels most impacted by convection from the intertropical convergence zone on average but with the Sierra Madres and the Central United States combined becoming the dominant contributor to convectively influenced air impacting the upper level in August. Convection that penetrates the tropopause has the potential to transport air from the troposphere into the stratosphere and affect its chemical composition.

1. Introduction

The North American Monsoon upper-level anticyclone (NAMA) is a dominant feature of the stratospheric circulation over North America in the summer. It exerts a significant influence on the composition of the upper troposphere and lower stratosphere (UTLS) through its interaction with both meridional isentropic transport and cross-tropopause convective outflow. The NAMA has been shown to facilitate isentropic transport from the tropics to the extratropics along the western edge of the circulation and from the midlatitudes and high latitudes to low latitudes along its eastern edge (Pittman et al., 2007; Ploeger et al., 2013). Further, the role of the NAMA in the circulation of convectively influenced air in the lower stratosphere has been
demonstrated by in situ observations of trace species including water vapor, carbon monoxide, and carbon dioxide in conjunction with trajectory analyses (Gettelman et al., 2004; Li et al., 2005; Pittman et al., 2007; Randel et al., 2012; Ray et al., 2004; Smith et al., 2017; Weinstock et al., 2007) and by modeling studies of water vapor (Ploeger et al., 2013) and of potential vorticity streamers (Kunz et al., 2015). Most importantly, the NAMA is associated with a local boreal summer water vapor maximum and ozone minimum (Ploeger et al., 2013) and of potential vorticity streamers (Kunz et al., 2015). Analysis of water and its heavy isotopologue, HDO, indicates that up to 45% of water vapor in the NAMA may be attributed to convective transport of water—predominantly as ice onto the UTLS, though the convective source may not be entirely local (Hanisco et al., 2007; Randel et al., 2012).

Cross-tropopause convection provides a means of rapidly transporting boundary layer air into the lower stratosphere, thus by-passing the dominant global-scale troposphere-to-stratosphere transport mechanism associated with the Brewer-Dobson circulation in which air ascends slowly across the tropical tropopause and then moves poleward and descends. Observational and modeling studies indicate that convective overshooting moistens the lower stratosphere through the lofting of ice crystals into the stratosphere, which then subsequently sublimate (Corti et al., 2008; de Reus et al., 2009; Hanisco et al., 2007; Hassim & Lane, 2010; Hegglin et al., 2004; Homeyer, 2014; Homeyer et al., 2017; Iwasaki et al., 2010; Iwasaki et al., 2012; Khaykin et al., 2009; Khaykin et al., 2016; Phoenix et al., 2017; Pouilda et al., 1996; Randel et al., 2012; Ray et al., 2004; Sang et al., 2018; Sargent et al., 2014; Sayres et al., 2010; Smith et al., 2017; Wang et al., 2011; Weinstock et al., 2007). Both how the NAMA circulation affects the distribution of convective outflow and how important cross-tropopause convection beyond local source regions and increase the residence time of convectively influenced air masses (CIAMs) within the NAMA region, thus amplifying the impact of convection. Back trajectory analyses of in situ measurements, for example, have shown that the NAMA redistributes UTLS water vapor far beyond the convective source region (Pittman et al., 2007). Furthermore, meridional isentropic transport from low latitudes by the NAMA has also been proposed as a major source of water vapor within the NAMA region. Modeling and satellite observation comparison studies (Ploeger et al., 2013) suggest that the NAMA circulation serves as the source of moist parcels through northward transport by the western branch. However, additional studies have shown an anticorrelation between convection and the magnitude of the water vapor maximum over North America (Randel et al., 2015).

Both how the NAMA circulation affects the distribution of convective outflow and how important cross-tropopause convection is as a water vapor source to the local maximum, however, remain unclear. In order to understand the net impact of cross-tropopause convective outflow on the composition of the lower stratosphere in the NAMA region, it is necessary to understand the interaction between the seasonal evolution of deep convection over North America and the seasonal development of the NAMA circulation. To achieve this, we performed a trajectory analysis on all “overshooting tops” (OTs), deep convective updrafts that penetrate both the cirrus anvil and local tropopause, identified with GOES satellite images occurring from May through September of 2013. We were then able to quantify the fractional contribution of each convective source region to the lower stratosphere and to estimate the residence time for these CIAMs in the lower stratosphere over North America in the summer season.

Whether the primary source of the enhancement in stratospheric water vapor over the NAMA region is subtropical moisture transported isentropically by the NAMA or midlatitude convective moistening that is redistributed by the NAMA, a better understanding of the interaction of deep convection with the NAMA circulation is necessary to understand the water vapor budget of the lower stratosphere over North America during summer. We examine the interaction between regional sources of deep convection and the NAMA circulation with a multimonth climatology of tropopause penetrating convective events, or OTs, and a forward trajectory analysis to approximate the subsequent distribution of CIAMs. The OT climatology was constructed from GOES satellite imagery (Bedka & Khlopenkov, 2016), and a trajectory was initialized at each OT time and location and evaluated using Modern-Era Retrospective Reanalysis for Research and Applications, Version 2 (MERRA-2), winds to simulate the effect of the NAMA. From this work the seasonally, geographically, and altitude-dependent trends of (1) NAMA strength, (2) the distribution of cross-tropopause convection, (3) the relative contributions of each convective source region on the distribution...
of downstream CIAMs resulting from the interaction between convective frequency and the NAMA, and (4) the residence time of CIAMs within the NAMA are quantified.

2. Methods

The OT climatology, derived from GOES data, represents a hemispheric record of convection covering the study domain from 29°S to 68°N and from 205 to 1.25°W, in which OTs are algorithmically identified using multispectral imagery from GOES-13 and GOES-15 with a horizontal resolution of approximately 4 km (Bedka & Khlopenkov, 2016). Note that updrafts that overshoot their anvil altitude but do not reach the tropopause are not included in this study. To represent the subsequent movement of convectively influenced air parcels, a three-dimensional trajectory analysis was performed for each OT for the time period from 1 May 2013 through 31 September 2013. The trajectories were initialized using the latitude, longitude, time, pressure, and potential temperature data of each observed OT provided by the OT climatology. Only OTs with detection probability ratings (as determined by the temperature differences between the OT and the anvil, tropopause as identified with the WMO lapse-rate definition and the MERRA-2 reanalysis data, and local level of neutral buoyancy) greater than or equal to 0.9 were used in this analysis. This threshold detected \( \sim 50\% \) of human-identified OTs randomly sampled throughout the world (Bedka & Khlopenkov, 2016). At this rating, the false detection rate was determined to be \( \sim 10\% \), and these errant detections were typically found in close proximity to actual OT regions, so inclusion of these samples in the trajectory analysis does not adversely affect the results. The Bedka and Khlopenkov (2016) OT identification method is a conservative methodology that underpredicts OTs allowing for high confidence in the OTs that are detected. The potential temperature of each OT was derived from the OT IR temperature and pressure derived from the OT height and MERRA-2 (Gelaro et al., 2017) reanalysis, using the method of Griffin et al. (2016).

Trajectory wind fields were taken from the MERRA-2 reanalysis. The trajectory calculations of the CIAMs are three-dimensional kinematic fourth-order Runge-Kutta method with a time step of 3 hr. Trajectories initialized at the location and time of individual OTs were calculated until the trajectory left the bounding box defined by the area of the study domain with a vertical extent from 350 to 550 K. About 350 K was selected as a lower bound for the purposes of the trajectory calculations, beyond which the CIAM is considered to have returned to the troposphere. CIAM trajectories below 370 K, while calculated, were not considered for analysis as the tropopause within the NAMA region is typically at 370 K. The following analysis will focus on the 370 and 400 K levels to differentiate between the more frequent “shallow” cross-tropopause convection, and the less frequent “deep” cross-tropopause convection, which have different geographic and seasonal source distributions. The use of MERRA-2 reanalysis winds for trajectory calculation is limited by the native resolution of the reanalysis (0.5° × 0.625°), and in particular by the influence that the convective overshoots may have had on stratospheric winds at the point of trajectory initiation that is not represented by the reanalysis.

The OT and CIAM trajectory climatology do not represent a complete budget of cross-tropopause convection occurring in the study region and over the time period considered. This is because the GOES OT data were acquired every half hour, while the average lifetime of an OT is several minutes (Bedka & Khlopenkov, 2016). Consequently, the OT dataset used in this study represents a small percentage of the total number of OTs that occurred and should not be used to estimate total convective outflow. The OT dataset, however, is still valid for analyzing large scale trends and distributions because the consistent and frequent sampling, the long time period under study, and the large region of interest retain the major features of OT frequency, depth, and geographic distribution.

In order to facilitate the discussion of the interaction of convective outflow with the NAMA, the study domain was divided into seven regions as shown in Figure 1: (1) the intertropical convergence zone west (Intertropical Convergence Zone [ITCZ] West), (2) the intertropical convergence zone east (ITCZ East), (3) the Sierra Madre, (4) the Gulf of Mexico, (5) the West Coast, (6) the Central United States, and (7) the East Coast. These regions exhibit characteristic differences in convective frequency and depth of penetration over the summer season. In the ITCZ, the convergence of the trade winds and the ascending branch of the Hadley circulation combined with warm sea surface temperatures generates consistent convection throughout the summer (Amador et al., 2006). The ITCZ was split into two regions to better track the circulation of air masses within the NAMA. Convection over the Sierra Madre during the summertime is largely a result of the North American Monsoon driven by Pacific and Gulf of California moisture (Adams & Comrie, 1997;
In the Gulf region, warm-season daytime convection contributes significantly to total convection in the southeastern United States during the summer (Carbone & Tuttle, 2008; Rickenbach et al., 2015). Convection over the Central United States during the summer is characterized by severe single-cell, multi-cell, and supercell storms that often organize in squall lines or mesoscale convective systems (Fritsch et al., 1986; Kelly et al., 1985; Smith et al., 2012). The East and West Coast regions comprise the remainder of the area in the study domain. The above described seven regions represent the primary geographic sources of convective outflow that interact with the NAMA within the larger study area. Convection originating from areas outside of these named regions, but within the larger study domain, is referred to as out of bounds (OOBs) in the discussion.

3. Results

In order to assess the effect of the NAMA on cross-tropopause convective outflow, we begin by independently evaluating the seasonally dependent properties of the location and strength of the NAMA circulation as well as the location, frequency, and depth of cross-tropopause convection.

Figure 1. The seasonal and altitude-dependent variability in strength and location of the North American monsoon anticyclone (NAMA). (a) The time series of the maximum Montgomery potential between 140 and 50° W at 370 K. (b) The position of that maximum Montgomery potential with time indicated by color. (c and d) The same as panels (a) and (b) at 400 K.
To quantify the location and strength of the NAMA, the maximum Montgomery potential over North America (defined between 50° and 140°W) at various potential temperatures in the UTLS is used. Montgomery potential, defined as

$$M = \Phi + CpT$$

where $\Phi$ is the geopotential height, $C_p$ is the specific heat of air at constant pressure, and $T$ is the temperature, is the streamfunction for geostrophic wind on isentropic surfaces. Montgomery potential is used to evaluate the circulation in lieu of geopotential height to allow for analysis using potential temperature as the vertical coordinate and has been used to identify anticyclones on isentropic surfaces previously (Ploeger et al., 2013; Popovic & Plumb, 2001; Santee et al., 2017). Figure 1 shows the maximum Montgomery potential as a function of time between May and September of 2013 (left panels) as well as the corresponding geographic position of the maximum over North America for both 370 and 400 K (right panels). The NAMA typically is not present in May (Diem et al., 2013), begins to form in June, reaches its greatest strength in mid-July, and remains strong through the end of August (values around $3.56 \times 10^5$ m$^2$/s$^2$ at 370 K and around $3.72 \times 10^5$ m$^2$/s$^2$ at 400 K). The strengthening of the NAMA circulation also increases with altitude, as can been seen in the greater increase in Montgomery potential from May to July at 400 K compared to 370 K. Further, from the location of the Montgomery potential maximum, the northward slant in the vertical structure of the NAMA is visible. The maximum values at 400 K cluster about 5° further north than those at 370 K.

As a result of these features, cross-tropopause convection that reaches to 400 K and above, and cross-tropopause convection occurring during July and August will be impacted more by the NAMA circulation. Cross-tropopause convection as observed by the GOES OTs also exhibits strong seasonal, geographical, and altitude dependencies. Figure 2 shows the fractional population of daily OTs (normalized by total daily OTs for all regions) identified by GOES within each geographic region (described in section 2) as a function of time from May through September of 2013 at 370 and 400 K. By isolating the analysis to only the initial geographic location, altitude, and time of the OT, the distribution of cross-tropopause convection prior to NAMA effects is considered. The total number of OTs in each region is influenced not only by the underlying frequency of convection but also by the size of the region in question.

At 370 K, the tropical regions of ITCZ East and ITCZ West contribute the majority of OTs at all time periods (35% each) with a maximum in August for ITCZ West. The Sierra Madre region also contributes a significant fraction (up to 34%) beginning in July and extending through September with a maximum monthly average of 18% of total OTs in July. The Gulf region is active, to a lesser degree, throughout the warm season (on average 13% of total OTs across all months) with episodic contributions from June through September. The Central United States, East Coast, and the West Coast regions are minor contributors (combined contributing only 3% of total OTs over all time periods).

The pattern of convection reaching 400 K is distinctly different from that reaching 370 K. First, the total number of OTs at 400 K is significantly smaller than at 370 K (on average 142 OTs/day at 400 K over all time compared to 2,280 OTs/day at 370 K). Second, the combined ITCZ regions contribute a smaller fraction of the total from May through September (52%, down from 70%), while the Sierra Madre and the Central United States contribute a greater portion of total OTs (together contributing 26%, up from 13%). This is likely due to the fact that tropical ITCZ convection generally does not reach altitudes as high as convection over the Sierra Madre or the Central United States (Amador et al., 2006; Nesbitt et al., 2008; Smith et al., 2012). Combined with the thermodynamic structure of the atmosphere, convection in these regions reaches 400 K more frequently per storm than ITCZ convection, particularly later in the season. In July and August the Sierra Madre region contributes a monthly average of 23% of total OTs (compared to the 23% contributed by the ITCZ West and 26% by ITCZ East), and during August the Central United States has sporadic but large bursts of cross-tropopause convection that at times exceed the contribution from any other region at the time (up to 57% of total OTs).

The intersection of the seasonal, geographic, and altitude-dependent variability determines how the NAMA circulation affects the distribution of air masses that have been impacted by cross-tropopause convection, and the lifetime of these air masses within the NAMA region. Figure 3 shows an analysis of the fractional composition of total CIAMs that have influenced the air over a given region for a given time period. The contribution of each source region to the composition is indicated by color. The regions are delineated by the...
Figure 2. Seasonal and geographic dependent variability in cross-tropopause convection as shown by a daily timeseries of GOES overshooting tops for the regions defined in section 2 as a fraction of the daily total over the entire domain evaluated at 370 K in panel (a) and at 400 K in panel (b).
blue lines in the figure, and CIAMs marked as OOB are sourced from outside the frame of the figure. The number of CIAMs indicated represents the average number in a 3-hr period during the month indicated and includes both CIAMs whose initial location was within the underlying region as well as CIAMs sourced by convection in other regions that have been transported into each region via the broader circulation. Any individual CIAM may be counted multiple times before it falls below 350 K or exits the bounds of the study domain and is eliminated. Most CIAMs exit the study domain between 1 and 2 days after initialization, with the shorter periods being a few hours and the longer up to 2 weeks. This is highly dependent on season, altitude, and region.

Between May and August at 370 K the transition from a more zonal flow to an anticyclonic circulation centered over northern Mexico at 370 K or the Central United States at 400 K is evident in the greater proportion of ITCZ and Sierra Madre CIAMs that are advected to the northern regions. For example, in May CIAMs originating in the ITCZ and Sierra Madre regions comprise 6.0% of CIAMS for the Central U.S. region, but in August they comprise 68.9%. This seasonal transition from a predominantly zonal flow to an anticyclonic
Figure 4. The time evolution from May through September of the effect of the North American monsoon anticyclone (NAMA) circulation on the distribution of air masses affected by cross-tropopause convection sourced from initial regions over the different regions as determined by trajectory analysis at 3-hr intervals. Contributions to convectively influenced air masses (CIAMs) over a given geographic region (panel) from different source regions (color) are shown as a fraction of total overshooting top trajectories within all seven regions. Panel (a) shows 370 K, and panel (b) shows 400 K.
circulation corresponds with both the increase in the value of the Montgomery potential maximum from May to August and a shift in the geographic location of the maximum localizing to a cohesive cluster over northern Mexico and the Central United States (Figure 1) consistent with the strengthening of the NAMA. This shows that the NAMA is likely driving the anticyclonic circulation and its influence on the distribution of CIAMs. Similarly, at 400 K, the increase in the likely NAMA-driven anticyclonic circulation is shown by the much greater population of CIAMs originating in the Central United States and particularly in the Sierra Madre regions evident in all regions: in August at 370 K the Central U.S. and Sierra Madre regions combined contribute on average 17.5% of CIAMs in each region, but at 400 K they contribute 39.4%. At both levels, the seasonal dependence of cross-tropopause convection is visible in the significant increase in total number of CIAMs from May through August.

Figure 5. The geographic distribution of the duration of convectively influenced air masses (CIAMs) within the North American monsoon anticyclone (NAMA) region (red box) binned by 0.5° × 0.5°. The color contours indicate the average duration of time spent within the NAMA box by CIAMs initialized in that geographic bin. The blue lines indicate the analysis regions and the numbers indicate the average duration for a CIAM initialized within that region. Panels (a) and (b) show May at 370 and 400 K, respectively. Panels (c) and (d) show August at 370 and 400 K, respectively.
In both May and August and at 370 and 400 K, the OOB CIAMs are sourced primarily from the western ITCZ west of 140°W. In May these CIAMs are transported across the study domain by the strong westerly flow, while in August they are caught in the NAMA circulation and transported through the other regions. The fractional contribution of OOB CIAMs at 400 K is lower (e.g., the average fractional contribution of OOB CIAMs in all regions is 12.8% at 370 K and 6.4% at 400 K in August) as less deep cross-tropopause convection occurred in the ITCZ west of 140°W compared to other regions.

Figure 4 shows the time evolution of the total population of CIAMs at 370 and 400 K in each region. The initial source region of the CIAMs is indicated by color. Consistent with the results seen in Figure 3, the influence of the likely NAMA-driven anticyclonic circulation manifests most clearly at 370 K in the West Coast, Central U.S., and East Coast regions at the beginning of July. Here we see in detail the large influx of ITCZ W and Sierra Madre sourced CIAMs where they had largely not been present earlier in the season. This signal continues through August before subsiding through September. At 400 K, the influence of the likely NAMA-driven anticyclonic circulation on CIAM population begins earlier with a clear but transient signal of circulation in late June (shown most clearly in the West Coast, Central U.S., and East Coast regions by an upick in ITCZ W, ITCZ E, Gulf of Mexico, and Sierra Madre CIAMs) that subsides before returning in strength in early July coincident with the signal at the 370 K level and continuing through August and September. The large increase in cross-tropopause convection at the upper level over the Central U.S. region in August is also shown by the transport of Central U.S. sourced CIAMs around the anticyclonic circulation at 400 K and is visible as far the Sierra Madre region.

Another means of quantifying the effect of the NAMA on cross-tropopause convection is to calculate the duration of each CIAM trajectory within the NAMA region (defined here as the area between 16 and 60° N and between 55 and 135°W, and represented by the red box in Figure 5). Figure 5 shows the geographic distribution of initial OT locations grouped in 0.5°×0.5° bins for the months of May and August at 370 and 400 K. The color contours correspond to the average number of hours CIAM trajectories from each bin spent within the NAMA box. The numbers indicate the average residence time in hours for CIAMs sourced from each convective region. The average duration of a CIAM within the NAMA box is much longer in August than in May. The longer duration within the NAMA box is due to more consistently closed Montgomery streamfunctions that trap trajectories before they disperse. Maximum residence times in August reach 300 hr as compared to 220 hr in May. In both months, the average residence times within the NAMA box were higher at 400 K than at 370 K, but the geographic extent of entrapment within the NAMA box was greater at 370 K. The greater residence times in August and in the upper levels of the UTLS likely correspond to the variation in strength of the NAMA seasonally and with altitude (Figure 1). The greater geographic extent of residence times greater than 2 days in August and at lower levels is likely a result of both the seasonal and altitude dependence of NAMA structure as well as the seasonal and altitude dependence of cross-tropopause convection (Figure 2). The geographic maximum of residence times centered on the Sierra Madre region in August is likely due to the frequent centering of the Montgomery potential maxima over that region which increases the probability of entrapment per CIAM (Figure 1).

4. Conclusions

Using a trajectory analysis applied to OTs identified with GOES satellite imagery, we quantify the effect of the NAMA circulation on cross-tropopause convection from May through September of 2013. The interaction of the NAMA with cross-tropopause convection is controlled by seasonal, vertical, and geographic variability both in NAMA strength and location and in the frequency and distribution of cross-tropopause convection. Both the NAMA and cross-tropopause convection over the domain considered are least active in May and reach a maximum in late August. However, while the NAMA is generally stronger at higher levels, cross-tropopause convection reaching these levels is less frequent. At all levels the ITCZ regions contribute the most to cross-tropopause convection over North America, but at higher levels the Sierra Madre and Central U.S. regions become major contributors. As a result, the effect of the NAMA on cross-tropopause convection begins to manifest in late June at upper levels and early July at lower levels as duration within the NAMA circulation rises from approximately 20 to 70 hr. Simultaneously, the distribution of CIAMs over each geographic region begins to show influence from other regions in the NAMA. This interaction reaches a maximum in late August with durations of between 200 and 300 hr in the NAMA and CIAMs originating...
from each region present over most other regions within the NAMA in significant proportions. We demonstrate how entrainment within the NAMA circulation of up to 2 weeks can result in cross-tropopause convection influencing UTLS composition “downstream.” Regions with significant influence include the ITCZ at all levels and the Sierra Madre and Central U.S. region at upper levels.

Given the instability of the NAMA, we chose a study region larger than the instantaneous geographic extent of the NAMA, which is defined by a closed contour of the Montgomery streamfunction at the potential temperature level of interest. The use of a larger region or “NAMA box” ensured consideration of all cross-tropopause convection likely to be influenced by the upper level anticyclonic circulation. The circulation of all the CIAMs within the study region cannot be solely attributed to the effects of the NAMA; however, the seasonal differences in advection of CIAMs allow for sufficient distinction between the UTLS under a largely zonal flow and the UTLS influenced by the NAMA.

Prior studies examining in situ observations of convectively influenced air in the UTLS over the southeastern U.S. have shown the influence of the NAMA (Pittman et al., 2007; Ray et al., 2004; Smith et al., 2017; Weinstock et al., 2007). In these studies trajectory analysis revealed that CIAMs at higher latitudes were advected via the NAMA to lower latitudes. Our study uses a temporally and geographically larger dataset of cross-tropopause convection to quantify the interaction of the NAMA with cross-tropopause convection. Our trajectory analysis confirms the results observed previously and provides a more detailed look at the interaction between both the geographical and seasonal trends in cross-tropopause convection and the dynamical evolution of the NAMA, with implications for the water vapor budget of the lower stratosphere and the North American stratospheric water vapor maximum. We show that once the NAMA is established, the majority of CIAMs initialized from OTs within the stratospheric circulation are subtropical in origin indicating the significance of isentropic transport at lower levels. But at 400 K and above during August, CIAMs initialized from OTs over the Central U.S. account for an average 14.5% of CIAMs within all of the non-ITCZ regions, that is, those most influenced by the NAMA, suggesting the importance of mid-latitude convection on water vapor in the upper levels of the UTLS. Further, in the context of future observational studies of water vapor enhancements and their impact on UTLS chemistry our results indicate regions, time periods, and altitudes of greatest probability of encountering CIAMs.

As our analysis is limited to 2013, however, it does not assess the potential for interannual variability in NAMA strength and location or variability in cross-tropopause convective frequency and distribution. Analysis of more years of OT data would allow for improvement in the definitions of the regions of convective activity as well as the region used to represent the extent of the NAMA. In addition to extending our analysis to include more years, an investigation identifying regions and time periods where parcels most frequently leave the NAMA and enter the broader stratospheric circulation would be valuable.

Overall, our analysis demonstrates that the effect of summertime cross-tropopause convection on the UTLS is strongly influenced by the NAMA circulation from July through September. Air masses influenced by regional cross-tropopause convection may circulate within the NAMA for periods up to two weeks. As a result, cross-tropopause convection from each geographic source region can influence UTLS composition within all regions impacted by the NAMA circulation. Source regions with the greatest cross-tropopause convective activity have the greatest influence on the overall NAMA area (the ITCZ at lower levels has the greatest influence in all NAMA regions and the Sierra Madre at upper levels has the greatest influence in all non-ITCZ NAMA regions).

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