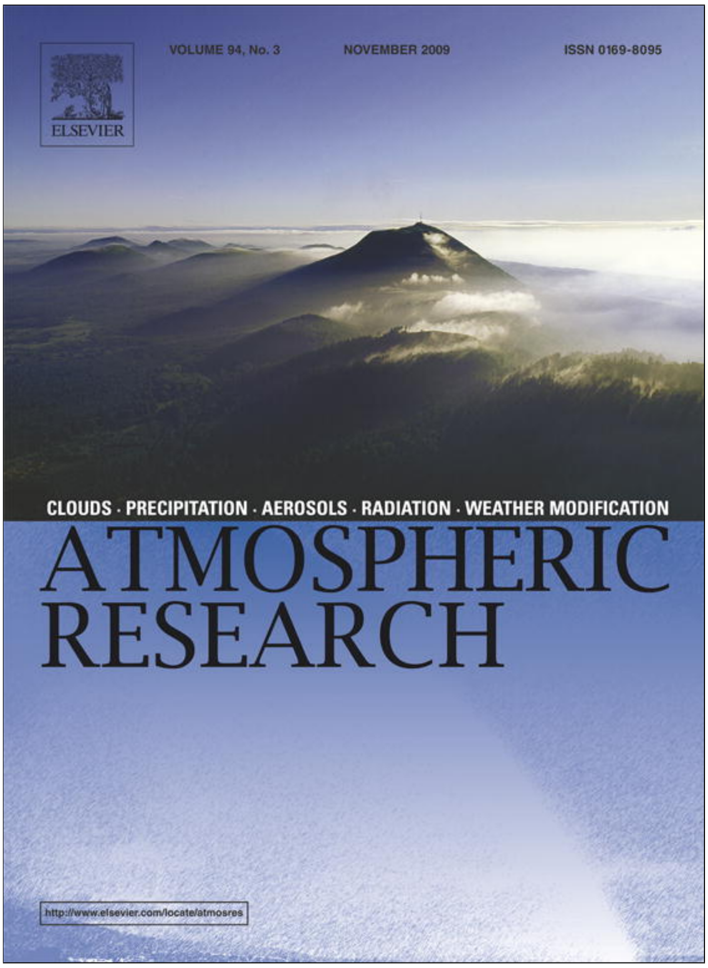
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Further evidences of deep convective vertical transport of water vapor through the tropopause

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ABSTRACT

A few years ago, we identified a deep convective transport mechanism, of water vapor through the tropopause, namely, storm top gravity wave breaking, such that tropospheric water substance can be injected into the lower stratosphere via this pathway. The main evidence presented previously was taken from the lower resolution AVHRR images of the storm anvil top cirrus plumes obtained by polar orbiting satellites. Recent observations have provided further supporting evidence for this important cross-tropopause transport mechanism. There are now many higher resolution satellite images, mainly from MODIS instrument, that show more definitely the existence of these plumes, many of which would probably be unseen by lower resolution images.

Furthermore, a thunderstorm movie taken in Denver (USA) area during STEPS2000 field campaign and another thunderstorm movie taken by a building top webcam in Zurich also demonstrate that the jumping cirrus phenomenon, first identified by T. Fujita in 1980s, may be quite common in active thunderstorm cells, quite contrary to previous belief that it is rare. We have used a cloud model to demonstrate that the jumping cirrus is exactly the gravity wave breaking phenomenon that transports water vapor through the tropopause.

These additional evidences provide increasing support that deep convection contributes substantially to the troposphere-to-stratosphere transport of water substance. This corroborates well with recent studies of the stratospheric HDO/H_2O ratio which is much highly than it would be if the transport is via slow ascent. The only explanation that can be used to interpret this observation at present is that water substance is transported through the tropopause via rapid vertical motion, i.e., deep convection.

1. Introduction

Water vapor is by far the most important greenhouse gas in the atmosphere that is responsible for the warming effect of the Earth surface. The current debates about the observed global warming phenomenon focus on the effect of CO_2 mainly because CO_2 is known to be increasing steadily in the atmosphere (Intergovernmental Panel on Climatic Change, 2007), whereas water vapor is usually assumed to be balanced by precipitation because of the short residence time of water vapor in the troposphere. The amount of water vapor is thought to be determined by the current climate condition (i.e., a response of climate) and it does not impose a permanent effect on the climate process. While this is true in the troposphere generally, it is not necessary so if the vapor concentration in the stratosphere is changing with time. Because the residence time of water vapor in the stratosphere is longer than a year, it is possible that the changing stratospheric water vapor should be considered as a climate forcing instead of simply a response.

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Some recent observations indicate that lower stratospheric water vapor (LSWV) concentration has been increasing by as much as 50% in the last 3–4 decades over Washington, DC and Boulder, Colorado (Oltmans et al., 2000). Presently it is unknown whether or not this is a global trend and if the trend will continue, but the fact that LSWV can change raises the possibility that it may play a role in global climate process and should be carefully examined.

One of the most urgent issues to be resolved about LSWV is where the water vapor originates. It is known that there are at least three pathways via which water vapor enters lower stratosphere: (1) slow ascent of water vapor from the troposphere by large-scale motion and turbulent diffusion through the tropopause; (2) rapid ascent from troposphere by strong convection or volcanic eruption (Danielsen, 1993; Dessler and Sherwood, 2004); and (3) oxidation of CH_4 in upper stratosphere and downward transport to the lower stratosphere (Brasseur et al., 1999). At present there appears to be no consensus on which pathway makes the most contribution.

This paper discusses our recent studies related to the pathway 2, namely, the transport of water vapor to the lower stratosphere by strong convection. Such strong updraft can be caused by either volcanic eruptions, which do not occur frequently, or deep convective storms that occur nearly at any instant around the world. In this paper we will focus on changes of the LSWV resulting from deep convective storms' activity. It has long been known that deep convection can transport substantial amounts of air vertically in both upward and downward directions (Lyons et al., 1986). Very much less is known about the complex dynamics occurring at the tops of tall cumulonimbus clouds, especially those reaching to altitudes equaling or penetrating the tropopause. High-resolution numerical modeling studies of airflows above and around convective storm turrets suggest that large-scale turbulent eddies with vertical motions of several meters per second or more are likely (Johnson et al., 1993, 1995; Droegemeier et al., 1997; Lin et al., 2005).

Observations of cirrus plumes above the anvils of some intense thunderstorms in satellite visible and infrared images show clear evidence of deep convective transport of water vapor through the tropopause. The phenomenon of such plumes was first clearly identified by Setvák and Doswell (1991) and Levizzani and Setvak (1996). By using a cloud model with explicit microphysics, Wang (2003) showed that these plumes form by pumping water substance (both water vapor and condensates) from the storm and transporting it into the stratosphere. The mechanism responsible for the transport through the tropopause is storm top gravity wave breaking.

The observational evidence of this mechanism presented by Setvak and Doswell (1991) and Levizzani and Setvak (1996) were the satellite images obtained by the AVHRR (Advanced Very High Resolution Radiometer) instruments on polar orbiting satellites of the storm anvil top cirrus plumes (Levizzani and Setvak, 1996). There are now even higher resolution satellite images obtained by MODIS (Moderate Resolution Imaging Spectroradiometer) instrument onboard the *Terra* and *Aqua* satellites and examples of these higher resolution plume images will be presented in the next section.

The earliest observational evidence of the convective transport of water vapor through the tropopause is the "jumping cirrus" phenomenon observed by Fujita (1982, 1989) who performed aircraft observation above severe storms. Wang (2004) showed that the jumping cirrus is precisely the product of gravity wave breaking reported by Wang (2003). For intense thunderstorms whose anvils are at the tropopause level, the sighting of jumping cirrus indicates possible transport of water substances trough the tropopause. There are now more ground-based observations of jumping cirrus and they will be presented in Section 3.

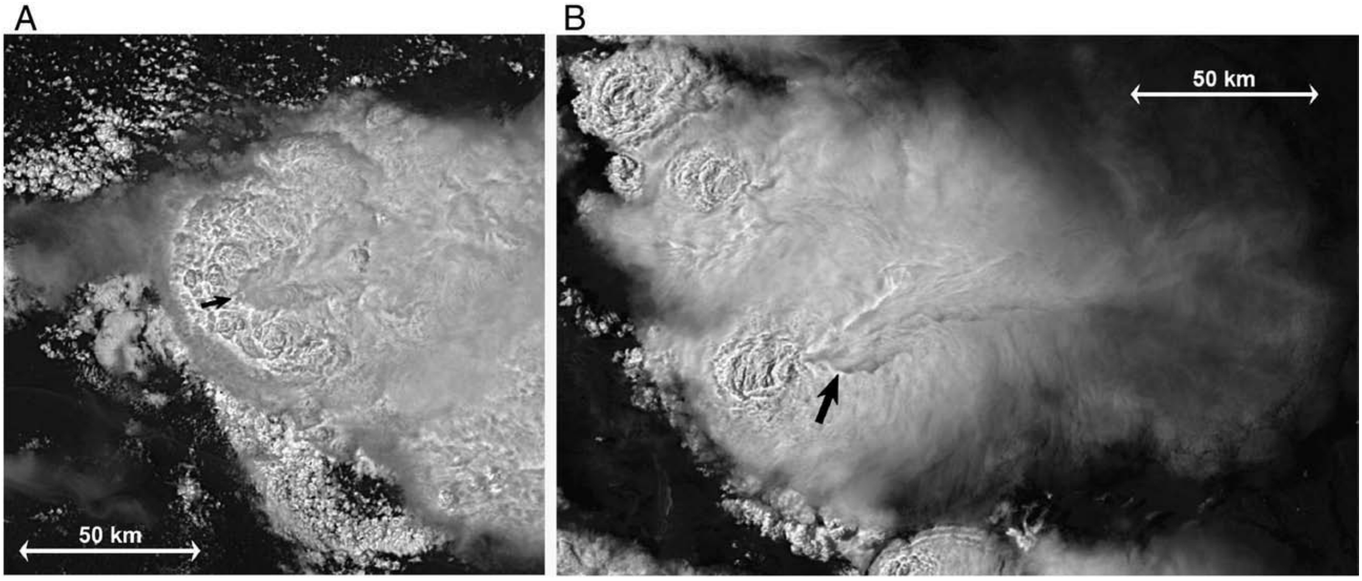

Fig. 1. (A). Examples of plume appearance (indicated by the black arrows) in the MODIS band 1, 250 m resolution imagery. Plume above a storm on 03 June 2003, 1925 UTC, Louisiana, U.S.A., MODIS/Aqua. In this case the plume is split into two "streams", each of these exhibiting cross-stream wave-like patterns–details which would never be seen at 1 km resolution. (B). Plume above a storm on 29 November 2007, 1820 UTC, Argentina, MODIS/Aqua. Even this plume exhibits many irregularities, various "fibers" within the main plume body, or even a "multiple-plume" structure. Also note the distinct vertical separation of this plume from the storm anvil top, revealed by a shadow cast by the plume's south edge at the underlying cloud tops. For further comments see the text.

2. MODIS satellite images

One of the significant steps towards an improvement of our understanding of the above-anvil plumes was the introduction of the MODIS instrument aboard the NASA's *Terra* (December 1999) and *Aqua* (May 2002) polar orbiting satellites. This instrument offers a total of 36 spectral bands, some of them up to 500 m and even 250 m resolution, making it suitable for plume microphysical studies (e.g. Fig. 3 in Setvák et al., 2007). The MODIS band 1 (0.62–0.67 μm), available at 250 m resolution, shows much finer details of plume structure than what has been available from any other satellites and their instruments until now, including the AVHRR 1 km imagery. Plumes, which appear at 1 km resolution as almost smooth featureless objects (Levizzani and Setvak, 1996), are resolved by MODIS band 1 as a much more complex phenomenon with various along-wind fibrous structure and across-wind wave-like perturbations (Fig. 1). Since MODIS also houses several thermal-window and water vapor absorption bands, all at 1 km resolution, it is possible to compare simultaneously the plume structures in the solar reflected bands (above) with above-storm gaseous water vapor features by examining the brightness temperature differences between the window and absorption bands (e.g. Setvák et al., 2008). More detailed studies of the cross-band relations are currently underway.

Note that given the timing of both of the MODIS satellites' orbits (late local morning for *Terra*, and local noon for *Aqua*) it is rather exceptional to find a well-developed convective storm in midlatitudes in their imagery (but not so rare in the tropics). Even rarer is to find a storm exhibiting a plume at such early time of the day. Based on GOES and MSG (*Meteosat Second Generation*, Schmetz et al., 2002) imagery, the plumes seem to be more common at later afternoon or early evening hours when storms are most likely to reach their peak intensity. Nevertheless, despite the MODIS orbit-timing problem, a broader world-wide study performed by one of us (MS) has documented the plumes to be occurring even at other regions than above Europe and North America—they can be found above other continents as well as above warm seas and oceans (Setvák et al., 2008). This indicates that plumes are a phenomenon of global importance, they can occur basically anywhere, from tropics to midlatitudes.

It should be noted here that the satellite data, including the MODIS imagery, do not provide us with any specific information concerning the persistence of plume material (ice particles, water vapor) in the lower stratosphere. They mainly show that the plumes are most often lifted well above the anvil top and their lengths frequently exceed the margins of regular storm anvils. The last fact indicates that plumes are either driven by stronger higher altitude winds, bringing the plume material further downwind than the anvil, or that they are located in a less evaporative environment, with a higher relative humidity. The real altitude of plumes and their quantitative vertical separation from the anvil top should be unambiguously documented by means of CloudSat (Stephens et al., 2002) and CALIPSO (Vaughan et al., 2004) observations, provided that the satellites manage to capture a storm with a plume, intersecting it by their vertically scanning radar and lidar. Since CloudSat and CALIPSO fly in a close satellite constellation together with Aqua (Stephens et al., 2002), the above mentioned timing problem of MODIS applies also to the CloudSat and CALIPSO data. Presently, we are searching (on a world-wide basis) for plume cases that would be scanned by these satellites.

In addition to improving our knowledge of convective storms and the stratosphere–troposphere exchange processes, the better understanding of the plume phenomenon will also lead to improvements in monitoring and nowcasting of potentially severe storms from space. Many storms with plume occurring above the anvil exhibit at the same time the cold-U feature (enhanced-V shape by older terminology, documented back at 1980s and early 1990s, e.g. Negri, 1982; McCann, 1983; Adler and Mack, 1986; Heymsfield et al., 1991). It will be highly beneficial to examine whether or not these two features are mutually linked and, if so, how much the plumes (if warmer than the underlying anvil top) contribute to the cold-U appearance.

3. Ground-based observations of jumping cirrus

3.1. STEPS 2000 Colorado thunderstorm

Another evidence of water vapor transport through the tropopause into the lower stratosphere is the jumping cirrus phenomenon. This is a phenomenon first reported by Fujita

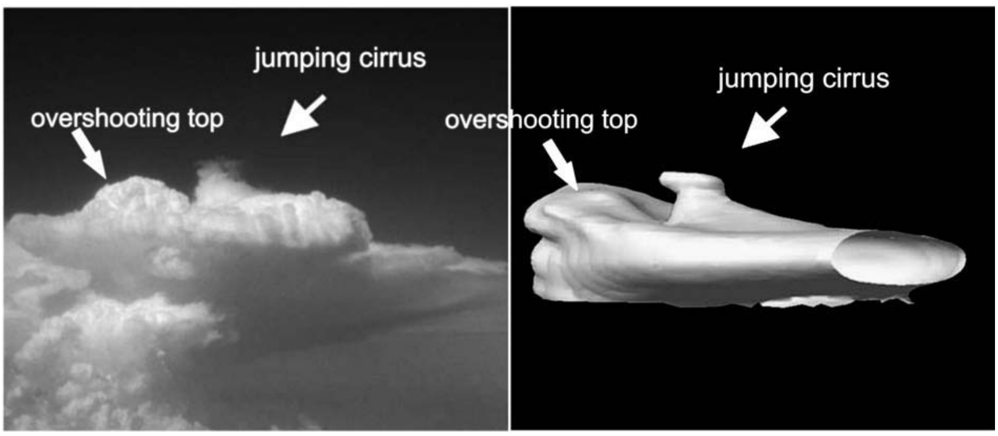

Fig. 2. (Left) Jumping cirrus photographed by Martin Setvak on 24 May 1996 late afternoon from an airplane above Alabama and Georgia. (Right) RHi 30% contour surface of the simulated storm at $t = 1440$ s using a 3-dimensional cloud-resolving model. The vertical dimension is enhanced to match the perspective view of the photograph (from Wang, 2004, with changes).

who performed aircraft observation of severe storms carried out at the cloud-tops levels. Fujita (1982) reported that "one of the most striking features seen repeatedly above the anvil top is the formation of cirrus cloud which jumps upward from behind the overshooting dome as it collapses violently into the anvil cloud". In a later paper (Fujita, 1989) he gave more detailed descriptions and even divided the phenomenon into different categories. Wang (2004) used a cloud model to demonstrate that the "jumping cirrus" described by Fujita can be explained satisfactorily by the gravity wave breaking at the cloud top. Fig. 2 shows a comparison between the observed and modeled jumping cirrus, showing that the model-produced jumping cirrus is very similar to the observed one in nearly all major aspects: both plumes are pointing toward upstream; both are located at approximately the same position behind the overshooting top, and both are approximately the same relative size. Wang (2004) also showed that time sequence of the jumping cirrus occurrence in the model follows closely to that described by Fujita (1982) as quoted above.

Using a three-dimensional cloud-resolving model to simulate thunderstorms, Wang (2004) demonstrated that the jumping cirrus phenomenon represents transport of water substance into the stratosphere if the storm anvil is already at the tropopause level. This implies that the sighting of jumping cirrus indicates possible water substance injection into the stratosphere and, if so, its frequency should be directly related to the quantitative aspect of this injection. It is thus important to examine whether the jumping cirrus phenomenon occurs relatively frequently or rarely. Normally this phenomenon is best observed from the perspective provided by a high altitude aircraft. However, when viewing conditions are favorable, jumping cirrus and related gravity wave phenomena can be observed from ground-based cameras.

On 20 July 2000, a time-lapse camera system located near Fort Collins, CO (40.6°N; 104.9°W) was operational as a component of the Severe Thunderstorm Electrification and Precipitation Study (STEPS 2000). The primary focus of STEPS 2000 was investigating the co-evolving dynamical, microphysical and electrical parameters of High Plains storms producing primarily positive cloud-to-ground (CG) lightning (Lang et al., 2004). The camera (a Pulnix CCD camera fitted with an auto iris, 50° nominal field of view lens recording onto S-VHS tape) was oriented to look eastward from the foothills over the STEPS operational domain centered in extreme northwestern Kansas.

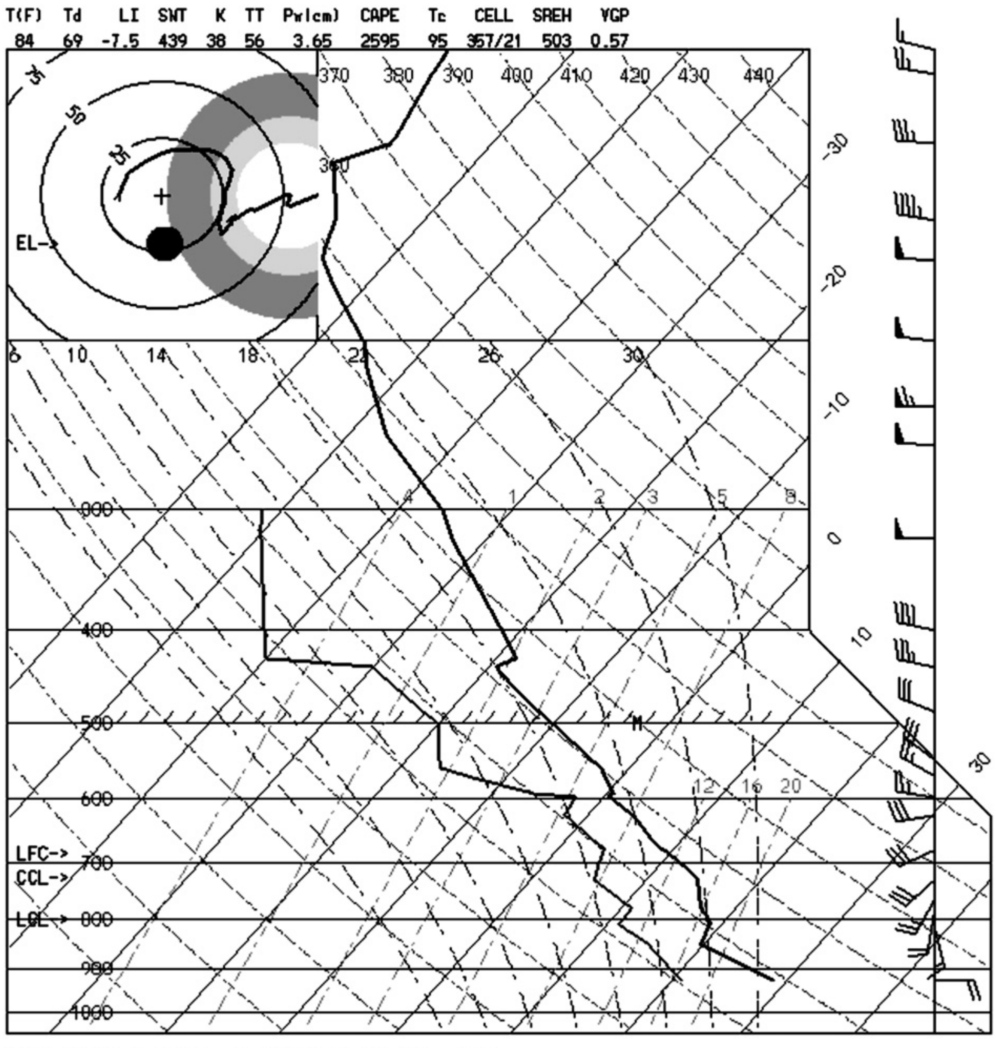

Fig. 3. Skew-T/Log-P diagram of the Dodge City, KS sounding at 0000 UTC 21 July 2000, the closest to the storm system, about 2 h after the plume event had ended (Courtesy of NCAR/RAP).

Primary target were the supercellular storms which frequently occur in the region in summer.

By early afternoon on 20 July 2000, orogenic convection formed over the Front Range of the Rockies with numerous cells moving eastward into the plains while intensifying during the late afternoon. As shown by the Dodge City, KS sounding at 0000 UTC 21 July 2000 (Fig. 3), the air mass into which the convective systems were advancing had large values of CAPE (~2500 J/kg), as well as high values of storm relative helicity (~500 m^2/s^2), conditions favorable for the development of storms with supercellular characteristics. The camera system recorded the tops of a cluster of super- and multi-cellular storms moving almost due eastward into northeastern Colorado beginning about 2000 UTC. Very intense upward vertical motion was evident in many of the convective towers in the system, indicative of the potential for severe weather. These storms produced at least one small (F0) tornado and about a dozen reports of large hail from 20 to 64 mm in diameter.

At 2200 UTC, the rear portion of the storm fills much of the camera field of view, with the classic thunderstorm anvil being apparent (Fig. 4A). However, less obvious from a still picture but graphically evident in the time-lapse imagery, is a region of diaphanous, wave-like cirriform clouds clearly above and perhaps detached from the main anvil top. As the storm progressed further eastward during the next 2 h, this cirriform layer, which was undergoing considerable undulatory and turbulent motion, became more evident as it appeared to

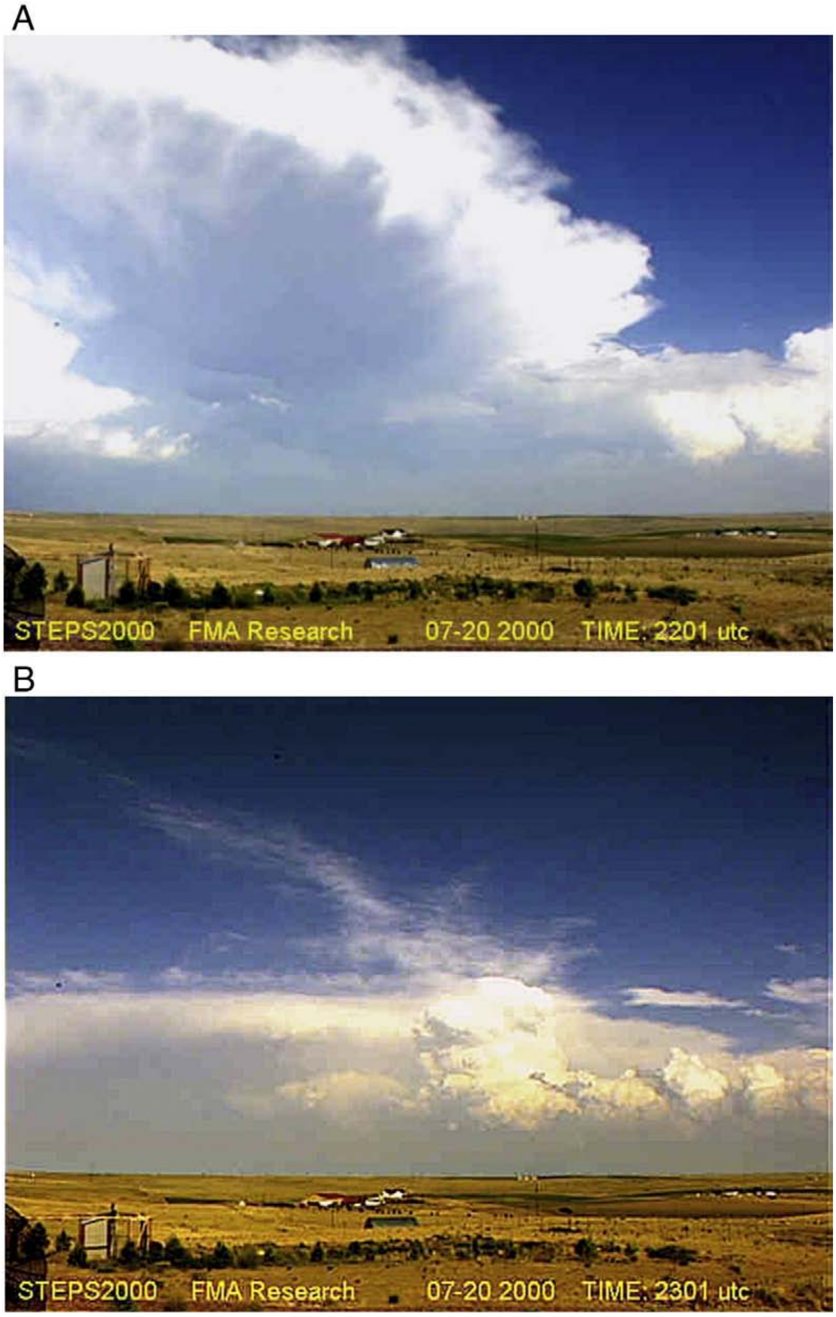

Fig. 4. (A) A frame from the time-lapse video looking eastward over the STEPS 2000 domain at 2201 UTC on 20 July 2000, showing the development of the trailing plume of undulatory cirriform clouds above the main thunderstorm cluster anvil top. (B). Same as panel (A) except for 2301 UTC.

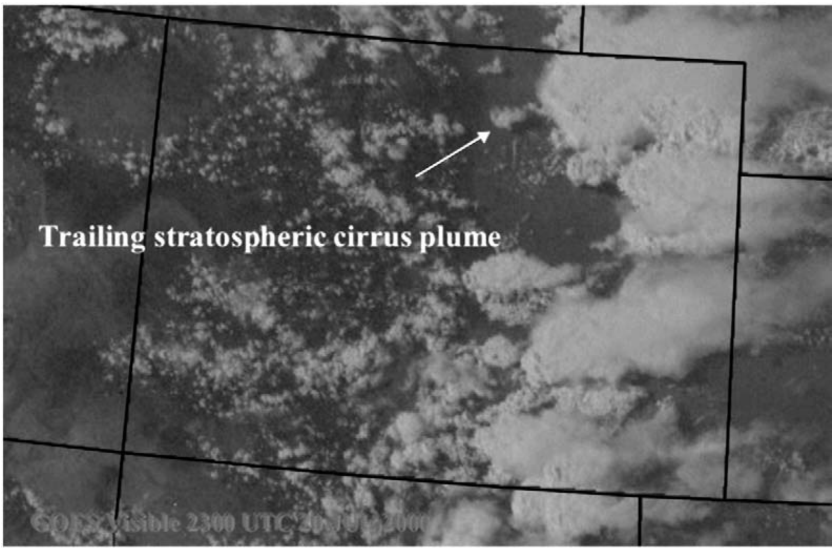

Fig. 5. GOES visible image at 2300 UTC 20 July 2000 showing the large cluster of intense thunderstorms moving eastward into northeastern Colorado, with the trailing high altitude cirriform plume above the level of the main storm cloud tops.

partially separate from and lag behind the overall cloud system. Regional soundings reveal that strong westerly winds of 20–33 m/s were in the upper layers of the troposphere, but began decreasing in velocity even before the tropopause (15.5–16.5 km) was reached. Above the tropopause, there was a rapid fall off of westerly winds, with a reversal to stratospheric east and northeasterly flow <10 m/s above 18 km. The trailing plume of presumably stratospheric material is clearly seen in Fig. 4B. Upon viewing the time-lapse video, the explanation of the trailing plume becomes clear. The forward motion of the storm simply outpaced that of the cirriform layer injected to higher altitudes. A GOES visible satellite image at 2300 UTC shows the trailing cirriform layer (Fig. 5).This video is available at the following URL: http://windy.aos.wisc.edu/pao/jumping_cirrus_movies.htm.

Routine time-lapse video monitoring of storms in this region have shown jumping cirrus is not an uncommon storm top feature. This particular event was made more photogenic due to the unusual wind structure which permitted the upper level cirriform plume to slowly separate from and trail behind the parent storm and thus remain more visible.

3.2. Bavarian thunderstorm as seen from Zurich, Switzerland

Another fine example of jumping cirrus comes from a movie taken by a webcam installed at the top of the Institute for Atmospheric and Climate Science Building in the Federal Institute of Technology (ETH) at Zurich, Switzerland which shows clearly the jumping cirrus phenomenon atop storms. This thunderstorm system developed around 1500 local time on 8 May 2003 in Bavaria area of Germany. Fig. 6 shows two snapshots taken from the movie. The webcam was pointing towards the north.

At the time of the recording, the storm system was moving generally from west (left in the figure) to east (right) although the precise direction of the motion cannot be determined from the movie alone. The tilting of the cumulonimbus towers was generally towards the east, indicating that the upper level wind direction was also westerly. The movie shows that this was a multi-cellular storm system with active cells forming and dissipating one after another. From the movie it is also clear that for all storm cells that had reached the level such that an anvil appears at the top, jumping cirrus phenomenon quite similar to the breaking waves at the sea surface invariably occurred. This seems to imply that the jumping cirrus is not confined to a specific cell with rare dynamic configurations, but rather a phenomenon associated with the general thunderstorm environmental condition.

The time-lapse movie also shows that the phenomenon fits the descriptions of Fujita (1982, 1989) and the model results of Wang (2004) very closely. First of all, the top of the jumping cirrus always pointed towards the west, i.e., the upwind direction. Its location was always somewhat downwind from the overshooting top. The general duration of the jumping cirrus associated with each cell was a few minutes, in general agreement with that estimated by Wang (2004). The general extent of the cirrus in both horizontal and vertical directions also appeared to be similar to that shown in Fig. 2. All these characteristics strongly suggest that the jumping cirrus phenomenon is indeed due to the breaking of gravity waves at the cloud top level in sheared flow as proposed by Wang (2003, 2004). Similar studies about the wave breaking associated with deep convective storms have been performed by Lane et al. (2001, 2003) and the characteristics of the breaking waves at the cloud top described by them are essentially the same as ours even though they did not explicitly related the breaking waves with jumping cirrus. This video is available at the following URL: http://windy.aos.wisc.edu/pao/jumping_cirrus_movies.htm.

4. Implications of the deep convective cross-tropopause transport of water substance

In previous sections, direct evidences of cross-tropopause transport of water substance are presented. These are just a few examples serving to illustrate the process; actual cases can be observed practically daily, especially from satellite images. They give strong support that deep convective

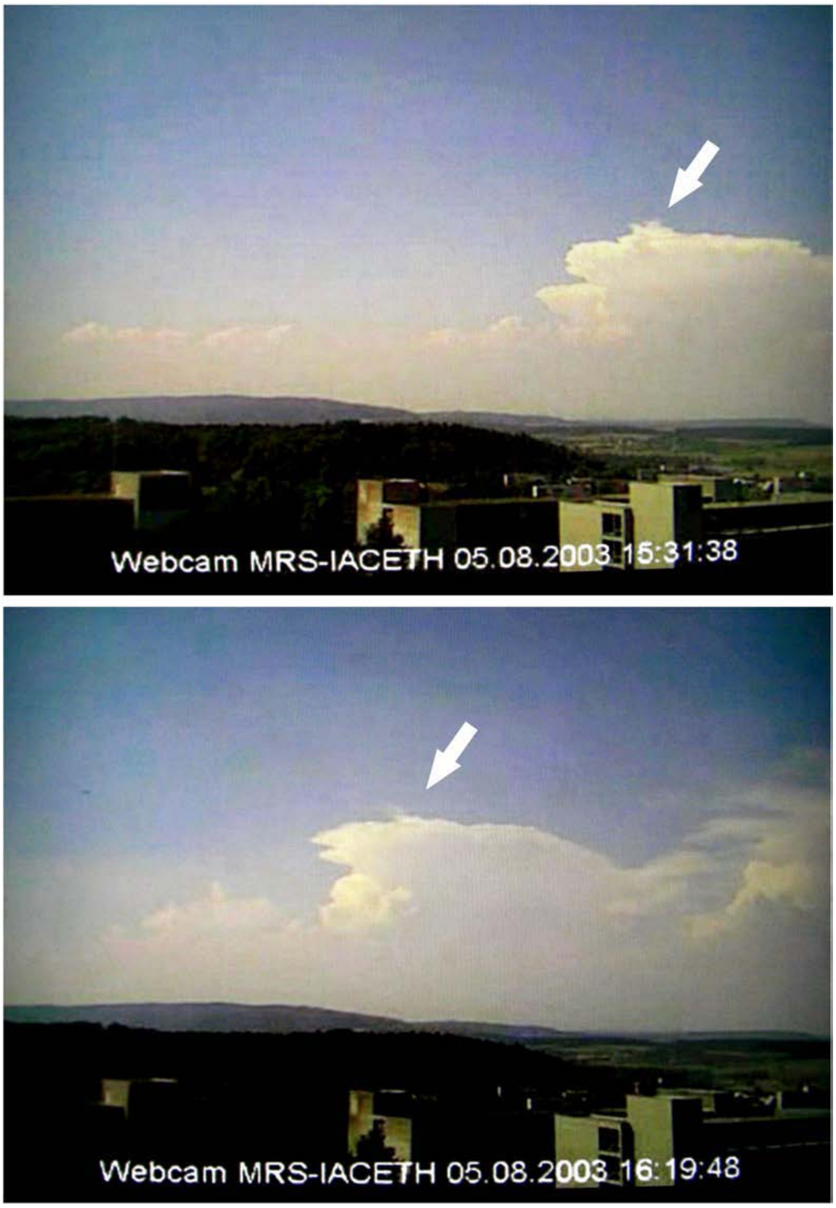

Fig. 6. Two frames (top—15:31:38 LST and bottom—16:19:48 LST) of a movie of a thunderstorm occurred on 5 Aug 2003 in Bavaria region of Germany, as seen by a webcam mounted on top of the Institute of Atmospheric and Climate Science Building, Federal Institute of Technology (ETH), at Zurich, Switzerland. Arrows point to the cloud top region where the jumping cirrus can be seen.

transport of water substance into the lower stratosphere is not a rare phenomenon. This implies that the deep convective transport plays a very important role in determining the water vapor concentration in the lower stratosphere.

Recent measurements of the heavy water to normal water ratio (HDO/H_2O) in the stratosphere lend further support to the significance of the deep convective transport. Analysis of FIRS balloon observations of CH_4 and H_2O isotopes indicates a very small contribution of D from CH_3D in the lower stratosphere (McCarthy et al., 2004), hence we only need to consider the transport of H_2O by the ascending tropospheric air. Being heavier, HDO vapor is more prone to condensation and hence more readily to precipitate out from the atmosphere as compared to the lighter H_2O. If the condensation occurs in a slow ascent process, the ratio will be low because more HDO molecules will have condensed and hence precipitated out before they reach the stratosphere. Conversely, if the condensation occurs in a very rapid process, such as in the updraft core of an intense storm, the HDO (either in vapor or condensed form) will have much less time to condense and precipitate, and hence the ratio will be higher (Moyer et al., 1996).

Furthermore, Hanisco et al. (2007) analyzed NASA WB-57 aircraft observational data of the HDO/H_2O ratio sampled in the upper troposphere and lower stratosphere with level legs between 10 and 19 km in the region near Ellington Field in Houston, TX, during June/July 2005. The observations show that water vapor in the lower stratosphere above 380 K potential temperature (called "overworld" in Holton et al., 1995) is isotopically heavier than expected. Measurements in an airmass with anomalously high concentrations of water vapor show isotopic water signatures that are characteristic of evaporated ice lofted from the troposphere during convective storms. Observed H_2O and HDO concentrations in the plume of enhanced water and in the background stratosphere suggest that extratropical convection can account for a significant fraction of the observed water vapor in the summertime overworld stratosphere above the mid-North American continent.

Direct evidence of the presence of ice particles in the stratosphere is also observed. Danielsen (1993) observed the presence of stratospheric anvil during the Stratosphere–Troposphere Exchange Project (STEP) in Darwin, Australia in Jan–Feb, 1987. More recently, Corti et al. (2008) analyzed in situ the remote sensing aircraft data from the Tropical Convection, Cirrus, and Nitrogen Oxides Experiment (TROCCINOX) in the State of Sao Paulo, Brazil in February 2005 and the Stratosphere-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-O3) experiment in Darwin, Australia, in November/December 2005. They found ice particles in the stratospheric overworld and concluded that the only possible explanation is that most ice particles are transported by deep convection. Similarly, Khaykin et al. (2009) performed balloon-borne soundings of water vapor, particles and ozone in the lower stratosphere next to mesoscale convective systems during the monsoon season over West Africa in Niamey, Niger, in August 2006, and showed also the presence of ice particles in the lower stratosphere.

Both the high HDO/H_2O ratio and the presence of ice crystals in the stratosphere can be explained by convective transport which, in turn, can be explained by the dynamical process shown here and in Wang (2003, 2004, 2007) to account for the penetrative behavior.

5. Conclusions

In the above sections we presented both direct and indirect evidences that tend to support the notion that the deep convective injection of water vapor through the tropopause in form of overshooting top plumes and jumping cirrus may be a phenomenon of common occurrence rather than a rarity. Wang (2003) estimated that the deep convective transport rate of water vapor from the troposphere into the stratosphere may be as high as 5×10^8 kg per day if all storm cells behave similar to the one modeled there. Even a fraction of this quantity can produce significant impact on the thermodynamic structure of the lower stratosphere which may further influence the global climate (Polvani and Kushner, 2002).

At present there is no rigorous statistics to show how frequent such event occurs. To achieve a more quantitative estimate, it is necessary to develop a method of global survey based on remote sensing data. Satellite data is probably the best choice in this regard because of its global coverage. Recent work of Setvák et al. (2008) who have documented LSWV generation by mid-latitude severe storms using the MSG data represents an important step towards realizing this goal.

If water vapor or ice crystals can be transported by this mechanism into the stratosphere, then it is also possible for other trace species (gases or aerosol particles) to be so transported. Many of these species may be strong greenhouse gases and/or active participants in atmospheric chemistry.

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.atmosres.2009.06.018.

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