A cloud model interpretation of jumping cirrus above storm top

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[1] A dynamically driven mechanism occurring above severe thunderstorms is described, which can explain the jumping cirrus phenomenon. A three-dimensional, non-hydrostatic cloud model is used to perform numerical simulation of a supercell that occurred in Montana in 1981. The jumping cirrus phenomenon is reproduced in the simulated storm. Analysis of the model results shows that the jumping cirrus phenomenon is produced by the breaking of the gravity waves excited by the strong convection inside the storm. The wave breaking process causes some moisture to detach from the storm cloud and jump into the stratosphere. The apparent upstream motion of the jumping cirrus is true only relative to the storm. The jumping cirrus phenomenon represents an irreversible transport mechanism of materials from the troposphere to the stratosphere. *INDEX TERMS:* 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Wang, P. K. (2004), A cloud model interpretation of jumping cirrus above storm top, *Geophys. Res. Lett.*, *31*, L18106, doi:10.1029/2004GL020787.

1. Introduction

[2] Among the many in situ observations made by T. Fujita, one of the most interesting and as yet unresolved is probably the *jumping cirrus* (also called *stratospheric cirrus*) above thunderstorms. In an earlier paper [*Fujita*, 1982], he described the phenomenon as follows:

> "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".

Fujita provided more detailed descriptions about the jumping cirrus phenomenon in a later paper [*Fujita*, 1989] in which he divided the observed stratospheric clouds into the following five categories:

[3] (1) Clean overshooting domes – this obviously has nothing to do with the subject in question here.

[4] (2) Curly-hair cirrus – cirrus originating at the head of an overshooting tower. Again, this is irrelevant to the present subject as no association of the jumping motion was mentioned.

[5] (3) Fountain cirrus – cirrus, which splashes up like a fountain, 1 to 2 min after an overshooting dome collapses into an anvil. This appears to be what mentioned in the quotation above.

[6] (4) Flare cirrus – cirrus that jumps 1 to 3 km above the anvil surface and moves upwind like a flare.

[7] (5) Geyser cirrus – cirrus that bursts up 3 to 4 km above the anvil surface like a geyser.

The last three categories are all associated with obvious vertical motion and appear to be the jumping cirrus he referred to earlier. Fujita further indicated that the jumping cirrus will drift away from an overshooting area if the above-anvil winds are faster than the translational speed of the overshooting area. If not, the jumping cirrus moves back towards the overshooting area, which will be covered with a thin or thick veil of stratospheric cirrus. This suggests that the cirrus would jump *upstream*.

[8] Thus far, there is no explanation of how these jumping cirrus can occur. Indeed, there are also doubts (although never written) about whether or not the observed phenomenon actually occurred as described above. The main point of contention seems to be on the propagation of the cloud: how can clouds, especially a thin cloud like cirrus, jump up from the downstream region of a thunderstorm upstream? It is the desire to answer this question that motivated this study. In this paper, an explanation is offered based on the numerical simulation results of a severe thunderstorm to show that Fujita's description is essentially correct and the mechanism responsible for it can be identified.

[9] In the following, the cloud model used for the simulation and the case of the thunderstorm studied will be briefly described. Then the analysis of the model results pertaining to the formation of the jumping cirrus and the explanation of it based on the model physics will be presented. A conclusion section will be given at the end.

2. The Cloud Model and the CCOPE Supercell

[10] The tool utilized for the present study is the Wisconsin Dynamical/Microphysical Model (WISCDYMM), which is a three-dimensional, quasi-compressible, time-dependent, non-hydrostatic primitive-equation cloud model developed at the University of Wisconsin-Madison by the author's research group. Thirty-eight cloud microphysical processes are included in the model. This model has been used successfully in several earlier studies and some details of it have been reported before [see, e.g., *Johnson et al.*, 1993, 1995; *Wang*, 2003].

[11] The storm chosen for the simulation for illustrating the plume-formation mechanism is a supercell that passed through the center of the Cooperative Convective Precipitation Experiment (CCOPE) observational network in southeastern Montana on 2 August 1981. The storm and its environment were intensively observed for more than 5 h by a combination of seven Doppler radars, seven research

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aircraft, six rawinsonde stations and 123 surface recording stations as it moved east-southeastward across the CCOPE network. *Miller et al.* [1988] and *Wade* [1982] provided many of the observations. This case was chosen because it is a typical deep convective storm in the US High Plains and it provides much detailed observational data for comparison with model results with regard to dynamics and cloud physics, and the author's group has obtained successful simulations of it previously [*Johnson et al.*, 1993, 1995; *Wang*, 2003].

3. Results and Discussions

3.1. The Jumping Cirrus Phenomenon in the Simulated Storm

[12] Before the model results are discussed, it is worthwhile to make clear that the appearance of the jumping cirrus phenomenon in the simulation does not imply that it actually occurred in the CCOPE storm. It merely indicates that the jumping cirrus phenomenon could occur in a severe storm such as this one, and if it does it is most likely due to the mechanism suggested here. This is because that the model solves mathematical equations based on well-known physics and these physics can explain various phenomena seen in the simulation results. Thus the purpose of this study is to point out that the jumping cirrus phenomenon as described by Fujita could happen under favorable environmental conditions and can be explained by simple dynamics.

[13] Figure 1 shows a series of 12 snapshots of the RHi (relative humidity with respect to ice) profiles in the central east-west vertical cross-section (y = 27 km) of the simulated storm every 120 s from t = 1320 to 2640 s. High RHi regions represent locations of high probability of ice crystal formation and hence is a reasonable approximation of the cloud boundary, especially the cloud top region [*Wang*, 2003]. To focus on the cloud top region, these snapshots are windowed to 10–20 km vertically and 20–55 km horizontally, with the vertical scale stretched in these views. The range of the vertical axis is from 10 to 20 km and that the general shear direction is from left to right (west to east).

[14] At t = 1320 s, the storm top exhibits a two-wave pattern: one crest located at the main updraft region (x ~ 30 km) and the other at x ~ 40 km. At this stage the overshooting is not yet well developed and the highest point of the cloud is only slightly higher than the tropopause at 12.5 km [*Johnson et al.*, 1993]. However, the wavy nature of the storm top is already obvious. At t = 1440 s, a cloudy patch starts to emanate from the bulge in the cloud top below. This patch is the precursor that eventually develops into full-fledged jumping cirrus. The white arrow pointing at x ~ 34 km indicates the approximate position of the left (west) edge of the patch. At the same time, the overshooting top subsides, changing from a height of ~13 km to ~12.5 km, a drop of ~500 m. This seems to correspond to what *Fujita* [1982] described as the "collapse of the overshooting dome". While the overshooting top is subsiding, the wave crest located at x ~ 40 km starts to bulge up and tilt upstream. At 1560 s, a "jumping cirrus" in the form of a cirrus tongue has developed with its front edge located at x ~ 32 km and reaching an altitude of ~15 km. The cirrus tongue is already located higher than the overshooting top and is moving upstream. Note also that a third wave crest appears at x ~ 48 km at this time. Thus the average

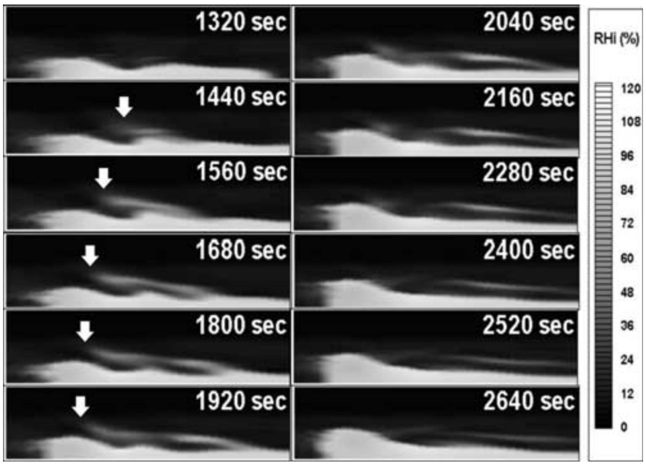

Figure 1. Snapshots of the RHi profiles in the central east-west cross-section of the simulated storm from t = 1320 s to 2640 s.

"wavelength" of the waves on cloud top is approximately 9 km, although the distance between the first two upstream wave crests is only 6–7 km. The "tail" end of the jumping cirrus seems to originate from the detachment from the third wave crest.

[15] As time goes on, the cirrus reaches further west and higher altitude as can be seen by the locations of the white arrows at the front edge. Since the altitudes of the jumping cirrus are both ~15 km at 1560 and 1680 s, the maximum altitude probably occurred somewhere in between these two times. This upstream and upward motion corresponds to what Fujita described as the "cirrus cloud which jumps upward from behind the overshooting dome". This ascending sequence of the jumping cirrus lasts about 6 min within which the cirrus rises from z ~ 12 km to ~15 km. The average vertical speed of the jump is therefore about 8 m s^{-1}. Considering that this altitude is well within the lower stratosphere where normal vertical motion is very weak, this is a substantial vertical speed and certainly justified to be described as "jumping". The development of the simulated cloud top up to this stage seems to verify Fujita's description of jumping cirrus.

[16] Fujita did not give descriptions of what happened to the cirrus after jumping upward and upstream. The model results provide additional information for possible development in the later stage. After reaching its maximum height at t ~ 1680 s, the tongue subsides gradually but still extends to further upstream, reaching x ~ 30 km and 29.5 km at t = 1800 s and 1920 s, respectively. Since the cirrus has moved a horizontal distance upstream of about 5 km from t = 1440 s to 1920 s, the average horizontal speed is therefore about 10 m s^{-1}, comparable to the vertical speed. This by no means says that the speed is uniform; rather the speed is greater initially and then decreases.

[17] Afterwards, the cirrus becomes thinner to resemble a plume and the left half of it is almost detached from storm anvil below. The cirrus plume eventually becomes unstable and breaks into two parts. The western part seems to collapse on, and merge with, the overshooting dome. This could correspond to what *Fujita* [1989] described about the stratospheric cirrus veiling over the overshooting dome.

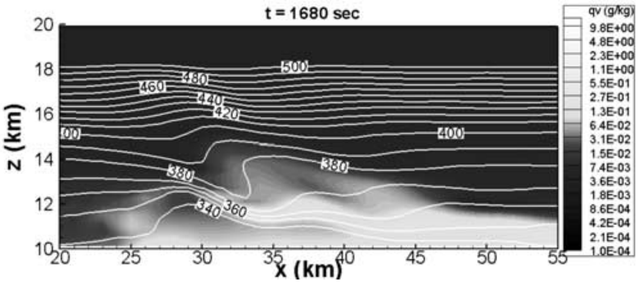

Figure 2. Snapshot of the q_v profiles with overlaid potential temperature (θ) contours in the central east-west cross-section of the simulated storm at t = 1680 s.

[18] The eastern part of the cirrus, which is attached with the anvil up to 2160 s, becomes gradually lifted and detached at 2280 s, orientating itself nearly parallel to the anvil. The detached cirrus plume thins and drifts downstream. It becomes nearly invisible after 3600 s. As the cirrus plume dissipates, the overshooting dome becomes more prominent, as can be seen from the development in the period 2040–2640 s. The jumping cirrus phenomenon only occurred once in the entire 150-minute simulation.

3.2. The Mechanism for Jumping Cirrus Formation

[19] What is the mechanism responsible for the formation of jumping cirrus as described in the preceding subsection? First of all, the apparent jumping motion towards upstream is only true in the relative sense. The frames in Figure 1 are plotted *relative* to the storm. This is because in the simulation the storm is moving to the east at a speed of about 30 m s^{-1}. We need to subtract this mean motion from the computed winds in order to keep the storm core remaining more or less in the center of the computational domain. So the apparent "upstream" motion of the cirrus is only true relative to the storm. *Fujita* [1982] reported the cirrus' motion relative to the overshooting dome, which is also a storm-relative description. In view of the 30 m s^{-1} mean wind subtracted from the computed winds, the horizontal motion of the jumping cirrus simulated in the present study is moving to the east at ~20 m s^{-1} relative to the earth surface.

[20] On the other hand, the vertical speed of the jumping cirrus is unaffected by the above adjustment. Thus the 8 m s^{-1} upward speed of the cirrus mentioned in the preceding subsection is the true speed.

[21] Careful analysis of the model results shows that the jumping cirrus forms as a result of cloud top gravity wave breaking. It is well known that severe storms excite gravity waves [e.g., *Alexander et al.*, 1995; *Lane et al.*, 2001, 2003]. Under sufficient unstable conditions, wave breaking can occur that may result in part of the storm, especially the cloud top, becoming detached and ejected upward into the lower stratosphere. The same wave breaking mechanism is also responsible for the formation of the jumping cirrus here. This can be seen from Figure 2 where the central cross-section of water vapor mixing ratio (q_v) at 1680 s overlaid with potential temperature (θ) contours are plotted. The 380 K θ-contour shows clear sign of wave breaking. Similar plots with additional overlay of wind vectors in the wave-breaking regions are shown by *Wang* [2003].

[22] *Fujita*'s [1982, 1989] observation of the sequence that the jumping cirrus occurred after the overshooting dome collapsed is also reproduced by the simulation. This seems to indicate that the wave energy associated with the dome collapsing propagates downwind and contributes to the breaking. At present we don't know whether this is the case, and if so, the magnitude of the wave energy necessary to cause the breaking. If this is indeed the case, it would suggest that if the wave energy is dissipated more efficiently in the overshooting area, presumably due to a combination of the conditions inside the storm and the stability above the dome, wave breaking and hence the jumping cirrus downwind would not occur. This agrees with the later development of the simulated storm which shows that the overshooting dome rose higher and wave breaking even occurred on top of the dome, but no more jumping cirrus as defined here occurred.

[23] *Lane et al.* [2003] used a very high-resolution, two-dimensional model to perform a simulation of a thunderstorm using the sounding in Bismarck, North Dakota in 1997. They found that the upstream-propagating gravity waves break. Their analysis indicates that the wave breaking is due to the build up of a local critical layer in the cloud. This is also the probable cause of wave breaking in the simulated CCOPE storm reported here. The wave analysis of the present case is being conducted and the results will be reported in the near future.

[24] Since the jumping cirrus occurs in regions of high instability, the turbulence level in the cloud is also high and there will undoubtedly be mixing with the stratospheric air. The sighting of jumping cirrus thus indicates the tropospheric air and moisture being injected into and mix with the stratospheric air, a troposphere-to-stratosphere transport process. It is clearly diabatic, as the potential temperature is not conserved during the transport process. A more thorough discussion of this subject is given by *Wang* [2003].

[25] The three different jumping cirrus categories by *Fujita* [1989] appear to be the same phenomenon occurring either at different intensity scale or in a slightly different cloud top environment (such as stratification in the stratosphere, the wind shear, etc.) Other than that, the same wave breaking mechanism seems to explain the main characteristics of all three. Among the three categories, the 'geyser' cirrus appears to be the most vigorous variety, as it can go up 3–4 km above the anvil. Although Fujita did not associate the geyser cirrus with upwind motion, it is clear that the geyser column tilts upstream from the photograph he provided [*Fujita*, 1989, Figure 28].

[26] *Setvák et al.* [2002] reported the sighting of a smaller scale jumping cirrus on 24 May 1996 late afternoon from an airplane above Alabama and Georgia. Figure 3 shows a side-by-side comparison between the photograph of the jumping cirrus taken by *Setvák et al.* [2002] and the rendered RHi 30% contour surface of the simulated storm top at 1440 s. The bulge to the west of the overshooting top in the simulated cloud top strikingly resembles the photographed jumping cirrus in the relative location, the upstream-leaning orientation and the surge-shape. This resemblance lends more weights to the theory of jumping cirrus as described above.

4. Conclusions

[27] The above analysis shows that the behavior of jumping cirrus as observed by Fujita can be explained satisfactorily by the gravity wave breaking mechanism atop

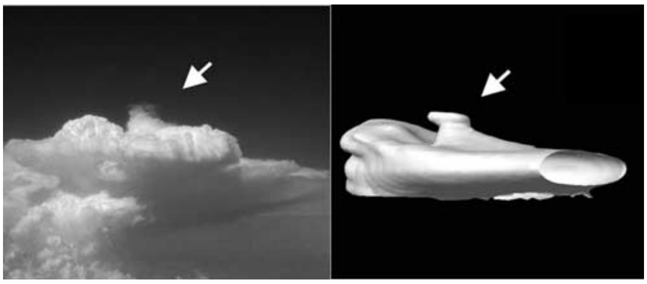

Figure 3. (Left) Jumping cirrus photographed by Martin Setvák on 24 May 1996 late afternoon from an airplane above Alabama and Georgia (Courtesy of Martin Setvák). (Right) RHi 30% contour surface of the simulated storm at t = 1440 s. The vertical dimension is enhanced to match the perspective view of the photograph.

thunderstorms. The gravity waves are excited by the strong updrafts in the storm and the breaking is caused by high instability near the cloud top. Thus, the occurrence of jumping cirrus indicates the presence of such instability, which should imply that the thunderstorm is severe. Such knowledge is potentially useful to meteorological studies.

[28] If it is verified that the wave breaking is caused by the built-up of local critical layer in the cloud, the sighting of jumping cirri then indicates that the storm-relative wind speed is the same as the gravity wave speed. Thus if the latter can be deduced from high-resolution satellite images of thunderstorms, then the occurrence of jumping cirrus should indicate similar wind speed locally and hence provides a method of cloud top wind retrieval. Such information is potentially useful for the data assimilation purpose for numerical weather prediction models.

[29] In addition, since the jumping cirrus phenomenon represents an irreversible, diabatic troposphere-to-stratosphere (TTS) transport process, the sighting frequency of jumping cirrus may represent the TTS transport magnitude by gravity wave breaking to some extent. At present there is no such statistics in existence. However, since the jumping cirrus seems to be closely associated with the anvil top plume phenomenon [*Wang*, 2003] and the latter seems to be easier to detect from satellite images than the jumping cirrus because of its larger scale, the two frequencies must be similar. It may be worthwhile to develop an algorithm to automatically detect plumes from satellite images.

[30] At present we don't have adequate knowledge on the details of gravity waves atop severe thunderstorms and the environmental conditions most conducive to wave breaking. We need more observational studies to help gathering facts and more careful model studies to help resolving this important issue.

[31] **Acknowledgments.** I thank Martin Setvák who graciously provided the photograph of the jumping cirrus. Helpful comments of Vincenzzo Levizani and an anonymous reviewer that result in improvements of this paper are gratefully acknowledged. This research is supported by NSF grants ATM-0234744, ATM-0244505, NOAA NESDIS-GIMPAP project and NASA Grant NAG5-7605.

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