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PROPAGATION AND LIFETIME CHARACTERISTICS OF THUNDERSTORM ANVIL CLOUDS OVER FLORIDA

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1. INTRODUCTION

Electrified thunderstorm anvil clouds extend the threat of natural and triggered lightning to space launch and landing operations well beyond the immediate vicinity of thunderstorm cells (Roeder et al. 1999). Formed in the upper troposphere from a supply of water vapor, super-cooled cloud droplets and ice crystals that are carried aloft by deep convective updrafts, anvil clouds are carried downstream by upper tropospheric winds (Detwiler and Heymsfield 1987). Composed of ice crystals, anvils can serve as conduits for lightning originating in their parent thunderstorms. Electrified anvil clouds have been observed over the space launch and landing facilities of Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) emanating from thunderstorm activity more than 100 nm distant. Mature anvils and even detached anvils can remain electrically charged for hours, posing the additional threat of triggered lightning if penetrated by a launch or landing vehicle (Garner et al. 1997).

Charging mechanisms in anvil clouds are complex; however, the general structure is a positively charged center surrounded by negatively charged exterior screening layers above and below. The screening layers can have an adverse effect on the ability of the Launch Pad Lightning Warning System (LPLWS) to detect electrification in an anvil cloud above the network. Real-time operational decisions are based on an imperative to avoid the optically non-transparent portions of anvil clouds. A comprehensive set of Launch Commit Criteria (LCC) for launches and Flight Rules (FR) for the Space Transportation System (STS: the "Space Shuttle") are used by the 45th Weather Squadron (45 WS) Launch Weather Officers (LWOs) and the Spaceflight Meteorology Group (SMG) to assure that flight vehicles remain well clear of such potentially hazardous clouds. The LWOs have identified anvil forecasting as one of their most challenging tasks when attempting to predict the probability of a triggered lightning LCC violation.

An objective technique for forecasting the horizontal extent of anvil clouds is needed to assist forecasters in predicting the probability of violating the triggered lightning LCC. The present effort is a continuation of a study that established the feasibility of developing observation-based anvil forecasting techniques and presented empirical evidence on the spatial and temporal scales of thunderstorm anvil clouds over Florida (Lambert 2000).

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2. METHOD OF ANALYSIS

Anvil cloud properties were measured in a subjective analysis of visible satellite imagery from channel 1 on the Geostationary Operational Environmental Satellite (GOES-8), 0.55-0.75 µm. GOES-8 digital data with a spatial resolution of 1 km were archived every 15 to 30 minutes and analyzed using the Man-Computer-Interactive-Data-Analysis-System (McIDAS). The McIDAS software provides the user with image enhancement capabilities that facilitate interpretation of cloud features.

Anvil clouds originating from small clusters of thunderstorm cells are readily evident in time loops of visible imagery. Classified as *cirrostratus cumulonimbogenitus*, anvils rapidly expand tens of kilometers or more following the wind flow in the upper troposphere. Anvil clouds are highly reflective to visible radiation during their growing and mature phases, obscuring views of the surface and lower clouds. Infrared imagery (channel 4, 10.2-11.2 µm) indicates effective black body temperatures less than 240K for anvils, consistent with upper tropospheric temperatures.

Within one to three hours after first appearing, the non-transparent portions of the anvil clouds observed in this study reached their greatest extent, defined as the mature stage. After reaching the mature stage the anvil clouds would begin to dissipate, revealing surface features and lower clouds beneath them. For each anvil observed a record was made of the maximum distance at the time of maturity from the leading non-transparent edge to the location where the parent thunderstorm complex originated, along with the coordinates of the originating location. Care was taken to avoid cases where downstream development of new thunderstorm cells took place under the initial anvil.

Atmospheric wind speeds and directions were determined for each anvil cloud by utilizing wind data from the nearest rawinsonde station that preceded the anvil observation by less than 12 hours. Wind speed and wind direction were averaged for an upper tropospheric layer most likely to contain the anvil, 300 to 150 mb, and a lower tropospheric layer that may influence the motion of thunderstorm cells, 900 to 500 mb. The dew point depression was also recorded for the upper tropospheric layer.

An anvil case day was defined as one in which the life histories of at least three anvil clouds were clearly evident, consistent with a pilot study designed by Mr. Sardonia, an LWO with the 45 WS. At times anvil-type clouds less than 30 km long were seen in two or three consecutive frames of the GOES-8 visible imagery before dissipating. Features of this type were not included in the analysis presented here.

3. RESULTS

The life cycles of 167 anvil clouds were observed in GOES-8 visible imagery over the Florida peninsula and its coastal waters on 50 anvil case days during the months of May through July 2001. Daily averages of anvil distance, anvil orientation, wind speed and wind direction in the lower and upper troposphere, and dew point depression in the upper troposphere were determined. Figure 1 shows a scatter diagram of daily averages of layer averaged wind speed in the upper troposphere versus anvil distance. A linear regression of the two variables gives an intercept of 21 nm and a slope of 1.9 nm/kt. With a correlation coefficient of 0.85 the regression relation explains 73% of the variance of anvil distance by the wind speed. The non-zero intercept indicates that anvil clouds can be expected to reach a scale of about 21 nm when the upper level wind speed is near zero, just due to the inertia and divergence of the cloud mass itself.

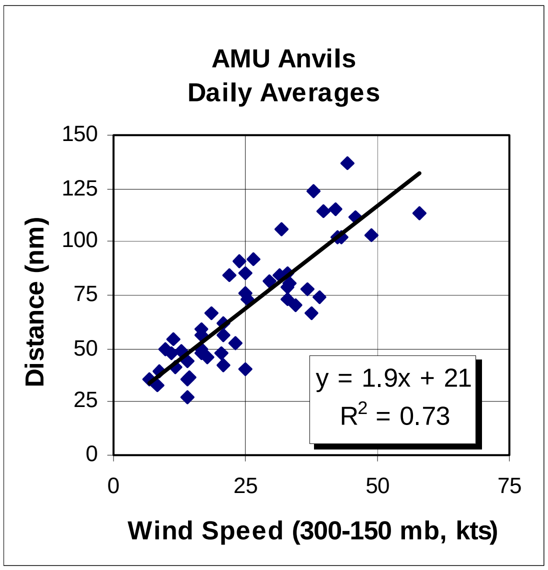

Figure 1. Upper tropospheric wind speed versus anvil distance for 50 anvil case days observed during the months of May through July 2001.

Figure 2 shows a scatter diagram of wind speed versus anvil length minus the offset, where the offset is 21 nm. The solid sloping lines indicate time scales that are consistent with the wind speed and anvil distances. For example, a length of 100 nm and a speed of 50 kts indicate a time scale of two hours. The time scale is referred to as an effective transport lifetime, indicating the approximate time it took the anvil to reach its maximum extent at maturity. The average effective transport lifetime is 1.9 hours with a standard deviation of 0.58 hours.

The results shown in Figure 2 are consistent with the feasibility study documented by Lambert (2000), based on 17 anvil case days during 1999 and 2000. That study included days during the Florida cool season, November through March, with upper tropospheric wind speeds as high as 72 kts. An effective average transport lifetime of 2.2 hours was derived.

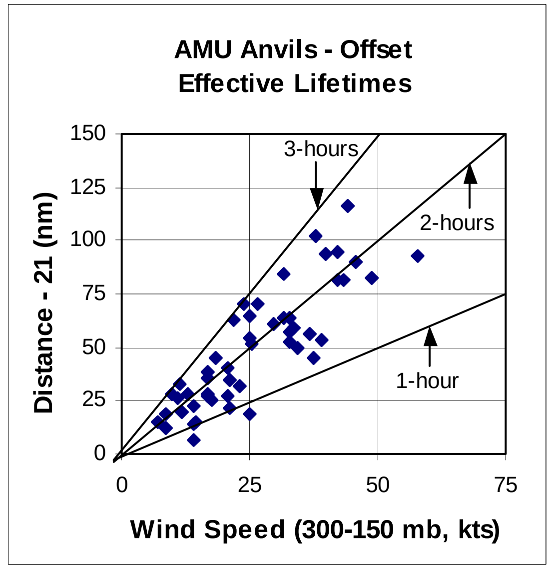

Figure 2. Daily averages of upper tropospheric wind speed versus anvil distance minus offset, where the offset, 21 nm, was determined by the linear regression shown in Figure 1. The sloping lines indicate effective transport lifetimes, calculated from the ratio of distance-offset to wind speed.

Figure 3 shows a scatter diagram of upper tropospheric wind direction versus anvil orientation for the 50 case days used to produce Figures 1 and 2. The correlation between wind direction and orientation is 0.97, indicating the marked influence of upper level winds on the downstream propagation of anvil clouds.

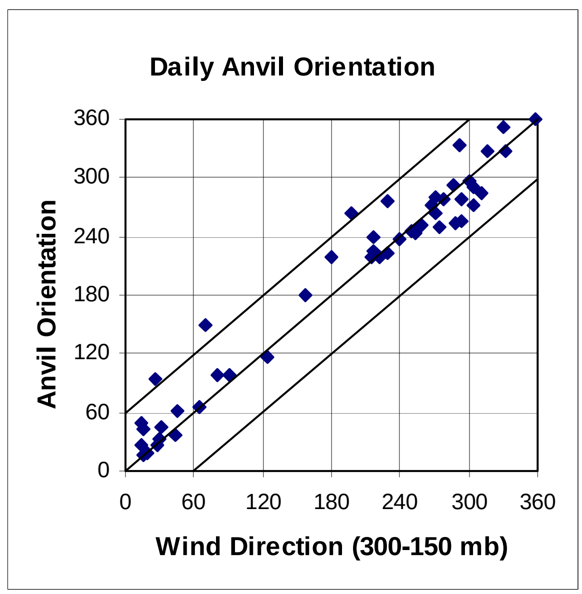

Figure 3. Upper tropospheric wind direction versus anvil orientation for the 50 anvil case days in the present study. The correlation between wind direction and anvil orientation is 0.97.

The wind direction and anvil orientation points in Figure 3 lie closely along the 1:1 diagonal with a spread of about 60 degrees. The layer-averaged upper level winds were from the southwest through northwest for most of the case days, with a secondary maximum of occurrence in the northeast sector. The average upper level wind direction for the 50 case days is 345°, only one degree greater than the average anvil orientation. This indicates that the upper level wind direction gives a nearly unbiased indication of anvil orientation.

Figure 4 shows the difference between the wind direction and anvil orientation as a function of upper tropospheric wind speed. The overall standard deviation of directional differences is 26°. However it can be seen that the largest spread of differences is found when the wind speed is less than about 20 kts. For wind speeds greater than or equal to 20 kts the standard deviation of directional differences is 18°

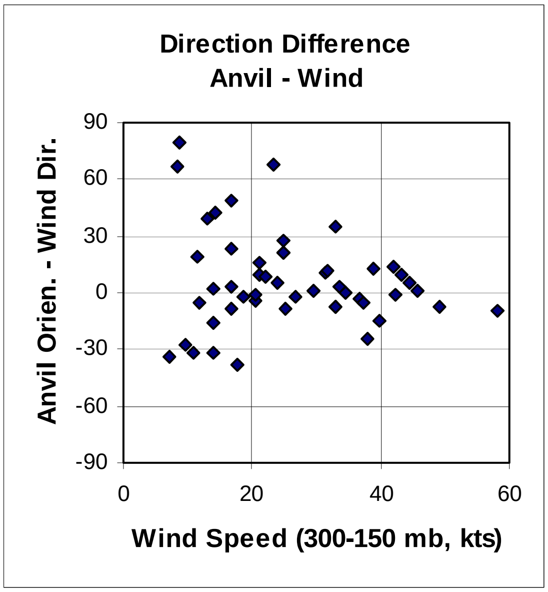

Figure 4. Upper tropospheric wind speed versus the difference between anvil orientation and upper tropospheric wind direction, derived from the data shown in Figure 3. Note that the differences are largest at the lowest wind speeds.

The decrease in directional errors with increasing wind speed seen in Figure 4 is consistent with a simple geometric interpretation. The distance between the end of the non-transparent portion of the anvil at maturity and the point where the parent thunderstorms originated increases with increasing upper level wind speed. Uncertainties in measuring the bearing between the two points become smaller as the distance between them increases, provided the location errors of the points are independent of their separation distance. Additional sources of error include spatial and temporal changes in wind fields at the rawinsonde sites and anvil locations, and vertical variations in wind direction within the anvil layer.

4. Summary and Conclusions

Natural and triggered lightning from thunderstorm anvil clouds represent significant hazards to space launch and landing operations. Electrified anvil clouds can propagate downstream from their parent thunderstorms, persisting for several hours. The results of this and other studies are leading to a better understanding of anvil cloud characteristics that can contribute to the design of improved forecast tools, needed to assist forecasters in assessing the threat of anvil lightning.

An analysis of visible and infrared imagery from GOES-8 over the Florida peninsula and coastal waters has been executed to determine the propagation and lifetime characteristics of thunderstorm anvil clouds originating from clusters of thunderstorm cells. A joint analysis of tropospheric wind speed and direction data from nearby rawinsonde stations has revealed significant correlations that can be interpreted in terms of propagation and lifetime characteristics. Anvil extent is highly correlated with wind speed in an upper tropospheric layer from 300 to 150 mb, while anvil orientation is highly correlated with wind direction in the same layer. The average anvil transport lifetime is about 2 hours with a standard deviation of about 30 minutes.

5. REFERENCES

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