GROUND-CLOUD-RELATED WEATHER MODIFICATION EFFECTS

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1. INTRODUCTION

The proposed heavy lift launch vehicle (HLLV) would emit a large amount of thermal energy to the atmospheric boundary layer. The buoyancy resulting from this thermal energy release will raise the exhaust ground cloud to an altitude from several hundreds to several thousands meters, depending upon the ambient meteorological conditions. Meanwhile, the upward convective motion of the ground cloud and the surrounding air may result in the formation of a water-saturated cloud and associated precipitation. In addition, cloud microphysical processes may be affected by the production in the rocket exhaust of both cloud condensation nuclei (CCN) and ice-forming nuclei (IN).

The principal concerns about inadvertent weather modification by SPS rocket effluents are (1) the possibility that the ground cloud might temporarily modify local weather and (2) the cumulative effects of nearly 500 launches per year. We shall discuss these issues of concern through the consideration of (1) the possible alteration of the microphysical processes of clouds in the general area due to rocket effluents and debris and cooling water entrained during the launch and (2) the direct dynamical and thermodynamical responses to the inputs of thermal energy and moisture from the rocket exhaust for given ambient meteorological conditions.

2. MICROPHYSICAL ASPECTS

The central issue of these aspects is the possible production of cloud condensation nuclei and ice nuclei in the rocket exhaust ground cloud. Cloud condensation nuclei serve as particles upon which water vapor condenses to form water droplets that in turn form clouds and fogs. They play an important role in determining the colloidal stability of clouds and the formation of precipitation. In general, the addition of CCN may tend to slow down the warm rain-formation processes if the total CCN exceeds 10^3 cm^{-3}. However, if very large hygroscopic particles (giant nuclei with radii $>25 \mu m$ like those expected to come from launch pad debris) are present, the rain-formation process may be accelerated. In the Florida area, some rainfalls are associated with condensation-freezing processes in a deep convection cloud system. In an IN-deficient, supercooled cloud, the addition of IN is expected to stimulate ice nucleation processes and lead to precipitation, although the effectiveness of this process by means of artificial cloud seeding remains controversial.

The recent measurements of Atlas/Centaur ground cloud[1] indicated that concentrations of CCN were meteorologically significant. The initial emission was approximately 1.2×10^{17} CCN (active at 0.5% supersaturation); later, CCN were produced in the ground cloud at a rate of approximately 1 CCN $cm^{-3}s^{-1}$. Field and laboratory measurements[1,2] of a Tital III ground cloud indicated that both the IN and CCN concentrations were of meteorological significance. The initial emission of CCN from the Tital III was approximately 10^{18} (active at 0.5% supersaturation) and further CCN were produced at a rate of 0.5 - 1 CCN $cm^{-3}s^{-1}$ for a period of four hours after launch. The high concentration of cloud condensation nuclei observed in both solid- and liquid-fueled clouds could alter the frequency and persistence of fogs and haziness on the surface and the precipitation processes in warm clouds.

3. DYNAMICAL AND THERMODYNAMICAL ASPECTS

The proposed HLLV would emit approximately 1.08×10^{11} cal/s of thermal energy together with 2.02×10^7g/s of water to the atmosphere. Approximately 15 s of exhaust would be contained in the ground cloud. The thermal energy provides sufficient buoyancy to lift the ground cloud and surrounding air to higher altitudes. During the course of rising, air cools through adiabatic expansion and, under certain conditions, reaches saturation to form water-saturated cloud. Cloud convection is, then, further enhanced through release of latent heat, and, in some situations, it could lead to precipitation.

The phenomenon of a wet, saturated cloud formed by rocket exhaust has been observed on several occasions. Perhaps the most comprehensive and unique data are those obtained during a Tital III launch on December 13, 1978 at Kennedy Space Center. Temperature and dew point soundings prior to the time of launch indicate that air in the surface boundary layer is humid but potentially stable as shown in Fig. 1. Rocket effluents produced a saturated white cloud having the characteristics of a moderately-sized, vigorous cumulus cloud. Aircraft measurements taken 25 minutes after launch indicated that the ground cloud was still saturated with a liquid water content of about 0.1 g/m^3. Thereafter, only portions of the ground cloud were found to be saturated; however, liquid water content was still detectable until 51 minutes after launch.

Model calculations indicated that, under the same meteorological condition, the HLLV thermal effluent could generate a much more vigorous convective cloud than a Titan effluent did as shown in Fig. 2. The maximum cloud liquid water content in the HLLV cloud was predicted to be about 3 times that of the Titan cloud as compared in Fig. 3 (where an initial thermal energy of 9.4×10^{10} cal was assumed in the Titan cloud). Furthermore, a light precipitation with a maximum rainwater of 0.07 g/kg was predicted for the HLLV cloud, but the duration of a saturated cloud was shorter. Virtually all the liquid water and precipitation are from the atmosphere, not from the content of the HLLV and Titan rocket exhaust.

The above relationships should not be used to scale predictions of HLLV effects. For example, under a potentially unstable condition with a deep surface boundary layer where the temperature lapse rate is adiabatic, quasi-steady-state convective clouds with similar intensities could be generated by all types of rockets in which the exhaust thermal energies are different by two orders of magnitude. The predicted precipitations are slightly different in intensity for different types of rockets.

In view of the nonlinearity and the relative insensitivity of the results to the rocket energy output in some situations, a climatology of the HLLV impacts should be conducted for a given launch site and for an updated HLLV reference information. Cloud modifications from SPS effluents are sensitively dependent upon the ambient meteorological conditions. Generally, the conditions that favor onshore flow without strong westerlies above the planetary boundary layer are conducive to greater inadvertent weather modification by SPS rocket launches in the Florida area. Characteristic synoptic weather regimes that would fall into this category were identified in a theoretical study of space-shuttle exhaust cloud.[3]

CONCLUSIONS

The huge amount of thermal energy contained in the exhaust of the proposed HLLV would in some situations induce a saturated, wet convective cloud or enhance an existing convective activity. The degree and duration of these effects depend upon the ambient meteorological conditions. Generally, the effects would be more pronounced in potentially unstable air, which is conducive to natural cloud formation. Nevertheless, the effects would be limited to the general area of the launch site. The observed long-lasting high concentrations of cloud condensation nuclei produced during and after a rocket launch may appreciably affect the frequency of occurrence and persistence of fogs and haze. In view of the high mission frequency proposed for the SPS vehicle launches, a potential exists for a cumulative effect. More studies are needed in this regard.

REFERENCES

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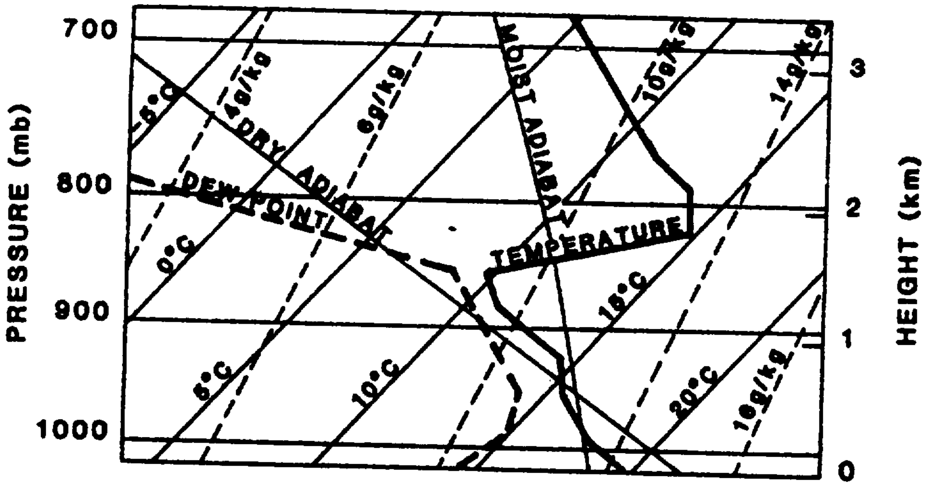

Fig. 1. Basic Sounding for 1936 EST 13 December 1978, CAPE CANAVERAL, Florida

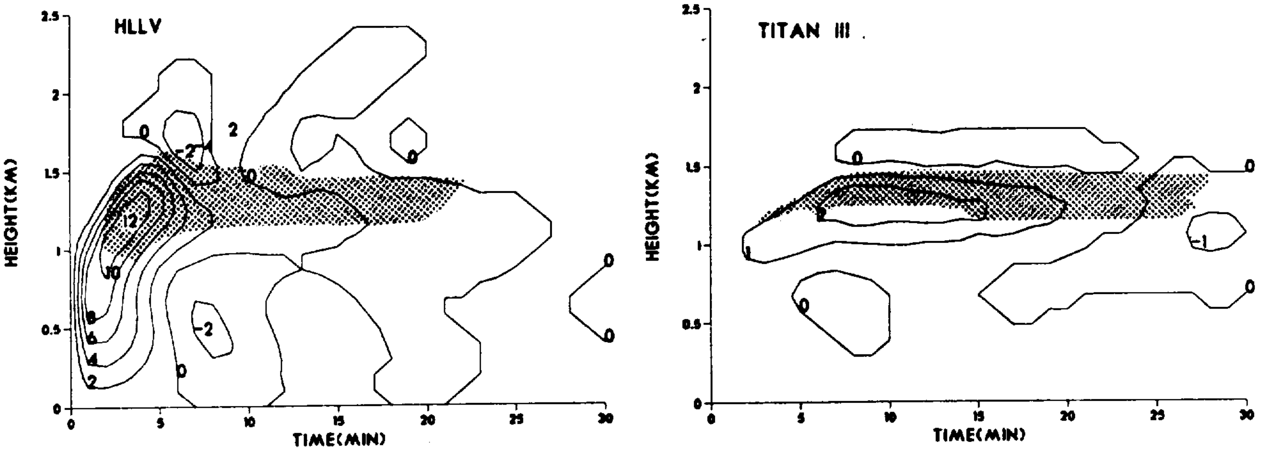

Fig. 2. Comparison of predicted maximum vertical velocity (m/s) between HLLV and Titan III ground clouds. Shaded areas indicate saturation regions.

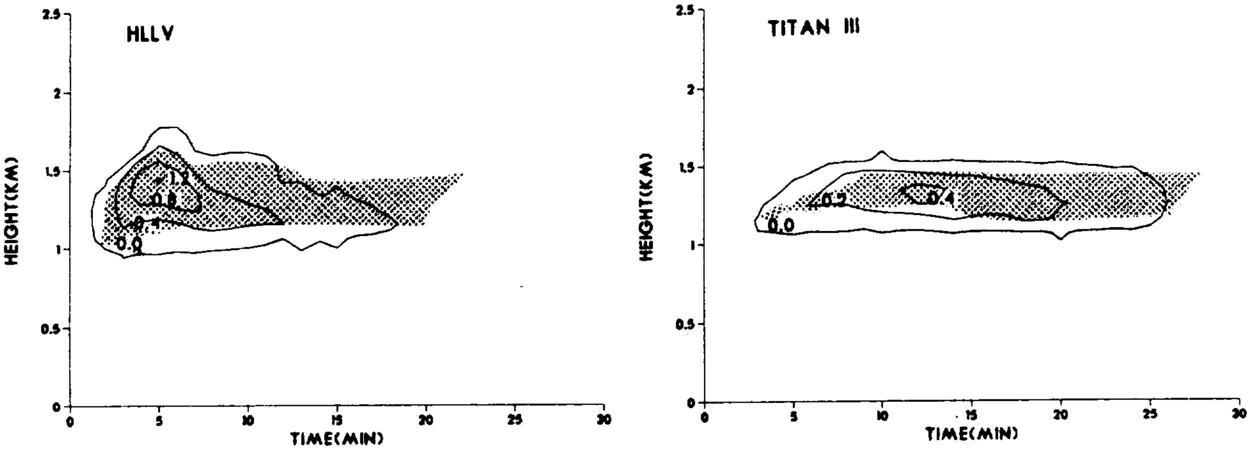

Fig. 3. Comparison of predicted mean cloud liquid water content (g/kg) between HLLV and Titan III clouds. Shaded areas indicate saturation regions.