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Operational Implications of a Cloud Model Simulation of Space Shuttle Exhaust Clouds in Different Atmospheric Conditions

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SECTION 1. INTRODUCTION

This report is a condensation of the final report of a 24 month study of Shuttle exhaust clouds employing a three-dimensional cloud model [Chen and Zak, 1988]. It puts the results of that study in a context useful for personnel involved with the real-time forecasting or assessment of the toxic effects of Shuttle exhaust clouds. This study contributed to a fuller understanding and appreciation for the dominant controlling influence of the environment on exhaust cloud properties. While no attempt was made to reproduce the HCL deposition, basic cloud characteristics depicted by the model can be related to the HCL deposition problem. For example, it is assumed that a cloud with enhanced natural liquid cloud water from unstable, moist environments will enhance the deposition of HCL and extend its corridor of influence although such deposition may not be a continuous event owing to the upward and downward motions from the convective process. Also, inversions can trap the cloud and most of the HCL in the very low levels of the troposphere where the convection process is sandwiched between the ground and inversion. Pollutants would rise in the column then spread horizontally, predominantly in the direction of travel, but upwind as well, depending on the relative strengths of the outflow and wind at the top of the inversion.

Following a brief historical perspective, some basic descriptions of ground cloud formation, rise, dimensions and behavior in known atmospheres from photogrammetric calculation will be presented. Next will be simulation results with focus on answers to these questions: Can the Shuttle trigger natural severe convection (thunderstorms)? What is the contribution of atmospheric wind shear on cloud integrity? Can the ground cloud be trapped in very low levels of the atmosphere where it can transport HCL and aluminum oxide considerable distance? What are the effects of changing initial heat and moisture from rocket motors? This is followed by a statistical study of all ten cases with the aim of extracting some rules-of-thumb type correlations which could be tried and refined in an operational environment. This report concludes with a summary of findings and makes some recommendations.

Historical Perspective

The National Aeronautics and Space Administration (NASA) has been concerned with possible environmental impacts of the Space Shuttle since the early conceptual studies of the 1960's.

The main impacts on the lower troposphere were due to HCL produced by solid rocket booster exhausts during launch. A toxic cloud is generated at the launch tower from combinations of the combustion products from solid fueled and liquid fueled rocket motors together with water used for cooling and sound suppression. The latter is atomized, vaporized and vented to the atmosphere. Subsequent properties of the cloud are determined to a large extent by the characteristics of the atmosphere in which it is contained. Uncertainties existed in the early analyses, and these were the subjects of a variety of research and measurement programs. Of primary concern was and continues to be the toxic effects of this cloud called the ground cloud and the atmospheric properties influencing its behavior.

Early studies were concerned with the chemical composition of the ground cloud and, more importantly, the disposition of the nearly 23,000 kg of HCL produced in approximately the first 10 seconds after launch. It was anticipated that the ground cloud would rise, due to its buoyancy, stabilize, depending upon atmospheric properties, be transported by the wind, and, ultimately, decay from entrainment of dry air and natural diffusion.[1] The transport and diffusion processes received much attention and procedures for assessing and predicting HCL deposition were developed and implemented. The basic thermodynamics and microphysics of the exhaust cloud together with inherent influences of the ambient atmosphere were difficult problems for which analytical solutions were elusive, expensive (in terms of model development and computer resources needed) and still in a research mode. The launch of STS-1 heightened the importance of cloud processes and environmental interaction as there was an underestimated acidic fallout observed as far as 7.4 km from the launch pad at the Kennedy Space Center. This observation prompted further study to define the production mechanisms, investigate other possible forms of weather modifications which could result from Shuttle exhaust products, and to conduct a field measurement program to further define the properties of the exhaust and fallout. A two-dimensional cloud model with more realistic treatment of the cloud rise problem was employed to try to bracket the acid precipitation event. While very preliminary, the model provided further evidence of trapping effects of strong inversions in the low levels of the atmosphere and to the possibility of natural cloud growth enhancement from Shuttle cloud interaction. A report covered the first 4 Shuttle launches and documented the observed effects of the ambient atmosphere on rise rate, cloud dimension, dissipation, and other properties such as liquid water content, hydrometeor spectra, condensation nucleii, temperature,

[1] This is a simplification of complicated cloud growth and environment interaction process but serves to describe visual, qualitative observations.

vertical velocity, ice nucleii and humidity in the cloud and surroundings [Anderson and Keller, 1983]. Among the conclusions were that deluge water spray, atomized by the hot rocket exhaust, was the controlling mechanism in the formation of the fallout drops and that the exhaust cloud had sufficient buoyancy to lift drops (HCL) one millimeter in diameter for potential transport down wind. Range and azimuth for the fallout on a given day will depend almost exclusively on the low level atmospheric stability (temperature and moisture profile) and wind. It was recognized that further work was needed to confirm the preliminary 2-dimensional cloud model results and to better understand the atmospheric influences which governed cloud behavior. This is true not only because of the toxic cloud from routine launches, but as well as for future Galileo and Ulyses missions containing nuclear-fueled power cells. Current areas of interest also include the meteorology of the West Coast and the reduced tolerance levels for hydrazine. The latter demands increased precision in the toxic deposition prediction.

The research in this report is a direct result of previous concerns and needs to understand more fully atmospheric processes which govern the complex behavior of exhaust clouds. Operational techniques for assessing the HCL deposition are compromises among simplicity, accuracy, and timeliness. There are known deficiencies in operational models of the cloud rise and diffusion processes due to assumptions and simplifications. This study, while containing simplifications and assumptions, more realistically treats these processes since the same timeliness constraints are not applied, sufficient computer power was available and operational pressures were absent. This study extends and confirms results from previous studies. It characterizes the great variability from one ground cloud to another due to the dominant controlling influence of the environment.

Procedure

A three-dimensional model of the atmospheric convection process was employed to simulate cloud properties such as cloud growth, decay and movement from first principles of hydrodynamics and thermodynamics [Proctor, 1987]. The cloud model was modified to accept initial heat and moisture conditions from rocket exhaust and launch platform configurations. Model grid, domain, and initial conditions were optimized for efficiency (from a computer resource standpoint). They were also chosen so that there was the best match between model cloud properties and detailed observed cloud properties in known atmospheric conditions. The use of the three-dimensional model reflects the highly asymmetric nature of most observed rocket exhaust ground clouds.

Once the best observed-model match was obtained for four different Shuttle launch conditions, then case studies were run with the same rocket exhaust initialization but different atmospheric conditions. These conditions represented very unstable, moderately unstable, wind shear, and stable environments where the latter also contained a strong observed low-level inversion.

SECTION 2. OBSERVATIONS OF SHUTTLE CLOUDS

Three Shuttle exhaust clouds were photographed using 16 mm film from which cloud dimensions were calculated as the clouds rose and decayed under known atmospheric conditions. Aircraft measurements were made in another Shuttle exhaust cloud. The results of these measurements and cloud dimensions are summarized below in the context of the environment in which the clouds existed.

General Features

The visible clouds from all launches contained both particulates or smoke as well as liquid water.

The cloud is first formed from combinations of rocket exhaust products and liquid water used on the launch complex for cooling and sound suppression. Some water appears as a haze coming from the base of the cloud during the first few minutes. This is attributed to the atomized deluge spray and is primarily responsible for an observed liquid deposition (acidic fallout) near the launch complex [Anderson and Keller, 1983]. There are three parts to the cloud at first: the central column of rocket exhausts and atomized spray near the pad; the north piece from the venting of the solid rocket exhausts while the vehicle is on and slightly above the launch pad; and a south part from the LOX-hydrogen fueled main engines.

These merge more or less during the first minute to form a very irregular cloud mass which rises due to its own buoyancy. The southern part from the main engines appears to dissipate and contributes little to the total cloud mass. The cloud rises in a series of convective turrets. Although there are many turrets in the observed cloud systems, there appear to be two which are identifiable in each. Because the vehicle is rising slowly at first, there is an accumulation of heat, moisture, and smoke in the first 7.5 seconds or so near the ground. This accumulation appears to form one of the two persistent elements which we call the main bubble. The other persistent feature is a part of the cloud which appears to originate from the near vertical column of exhaust products in the region of about 500 m to 2000 m. This part of the cloud rises rapidly in the first 4 minutes to an altitude determined by the ambient atmospheric temperature structure but usually not above 3 to 4 km. It typically overshoots any temperature inversions then descends. The main bubble rises more slowly and reaches a maximum altitude in 7 to 9 minutes but this maximum is usually slightly less than the first bubble. On windy days the shape of the ground cloud is distorted and the entire cloud mass is tilted. It's convective nature is more difficult to detect but still exists.

The bases of the clouds rise gradually to the lifting condensation level in the absence of strong low level inversions. The effects of these inversions will be discussed under model results since one was not part of the observed shuttle clouds. Erosion of the cloud occurs through diffusion and entrainment of dry air but the rate depends upon the atmosphere in which it is embedded. More details of the observed clouds and atmospheric influences are discussed next.

Photogrammetry

The ground clouds from Shuttle Missions 41C (April 6, 1984), 41D (August 30, 1984) and 51A (November 8, 1984) were photographed from different camera sites around launch complex 39A, Kennedy Space Center, Florida. Calculations were made of cloud dimensions at one minute intervals. Details of these calculations are documented in Zak [1987]. Some of the results are summarized below.

Mission 41C. The atmosphere for this launch is shown in Figure 1. There is a significant inversion that begins about 1.2 km and the atmosphere is very dry. The photogrammetry results for the base and top of the ground cloud evolution are shown in Figure 2. The peak altitude of 2200 m was reached in 4 minutes from the column heat and moisture source. The cloud top collapsed to 1700 m until it began to dissipate after 9 minutes. The main bubble appeared to originate from the accumulation of heat and moisture near the ground. This included the bulk of the solid rocket exhausts from the north trench. It reached a maximum altitude of 1800 m in the 8 to 9 minute time frame, then began to decay quickly.

The relatively dry atmosphere appeared to contribute to more rapid decay of this cloud which probably contained very little natural liquid water to begin with although no measurements in the cloud are available. The near adiabatic lapse rate below the inversion contributed to the convective cloud growth process.

Mission 41D. The atmosphere for this launch is shown in Figure 3. There are very light westerly winds below an isothermal layer which began about 2.3 km and continued to 3.2 km where there was pronounced dry air. Below the isothermal region there was considerable moisture and instability. The calculated cloud bases and tops for this launch are shown in Figure 4. The cloud rose in the first 5 minutes to its peak altitude of 3500 m then began to collapse. The main bubble rose to about 3100 m in 7 to 8 minutes depending on the camera view. As we would expect, the cloud was larger than the 41C cloud in vertical dimension due to the weaker and higher inversion in the 41D atmosphere as well as to more available atmospheric moisture. The decay was

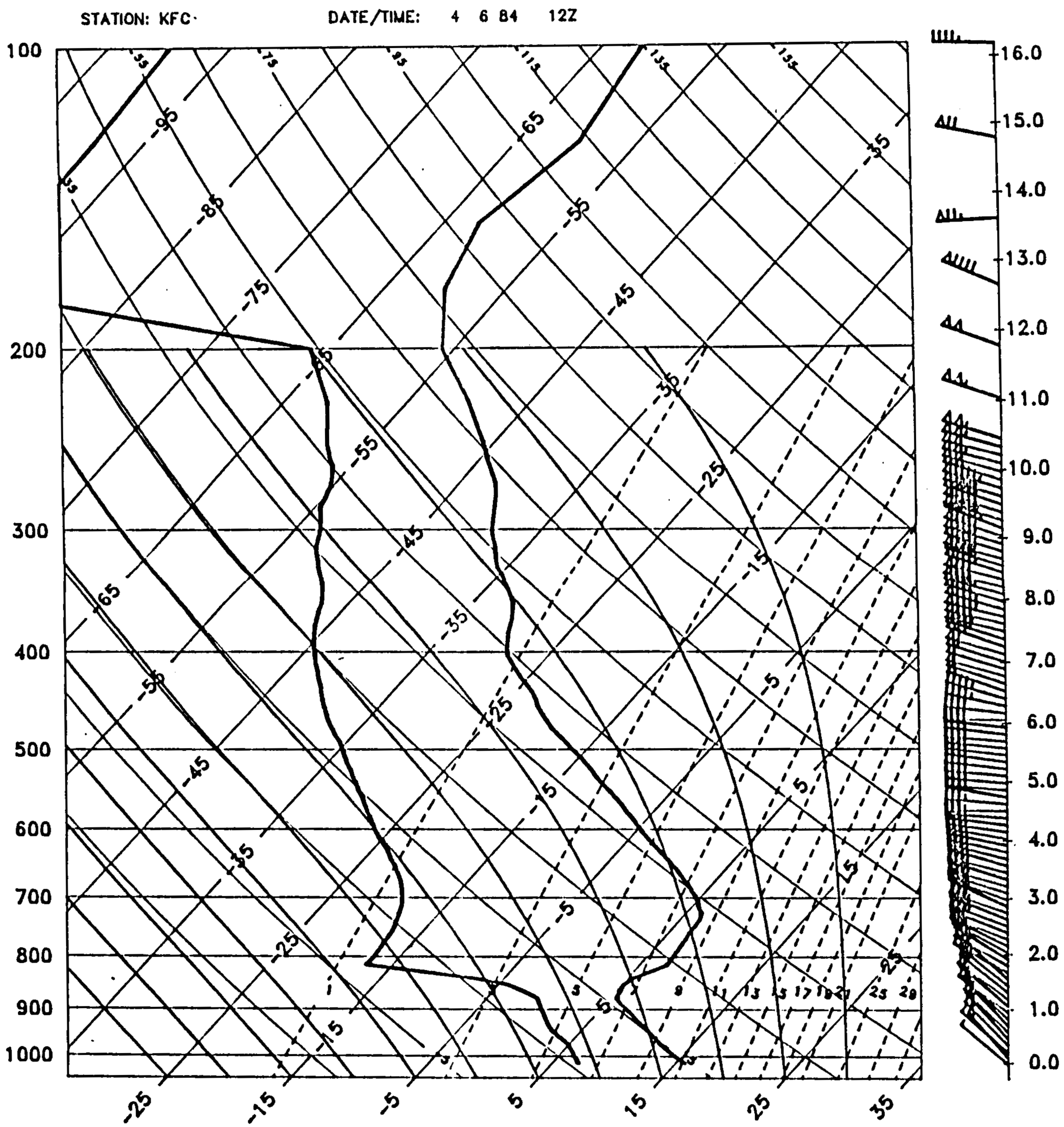

Figure 1. Observed upper-air sounding for Mission 41C, April 6, 1984, 1200 GMT.

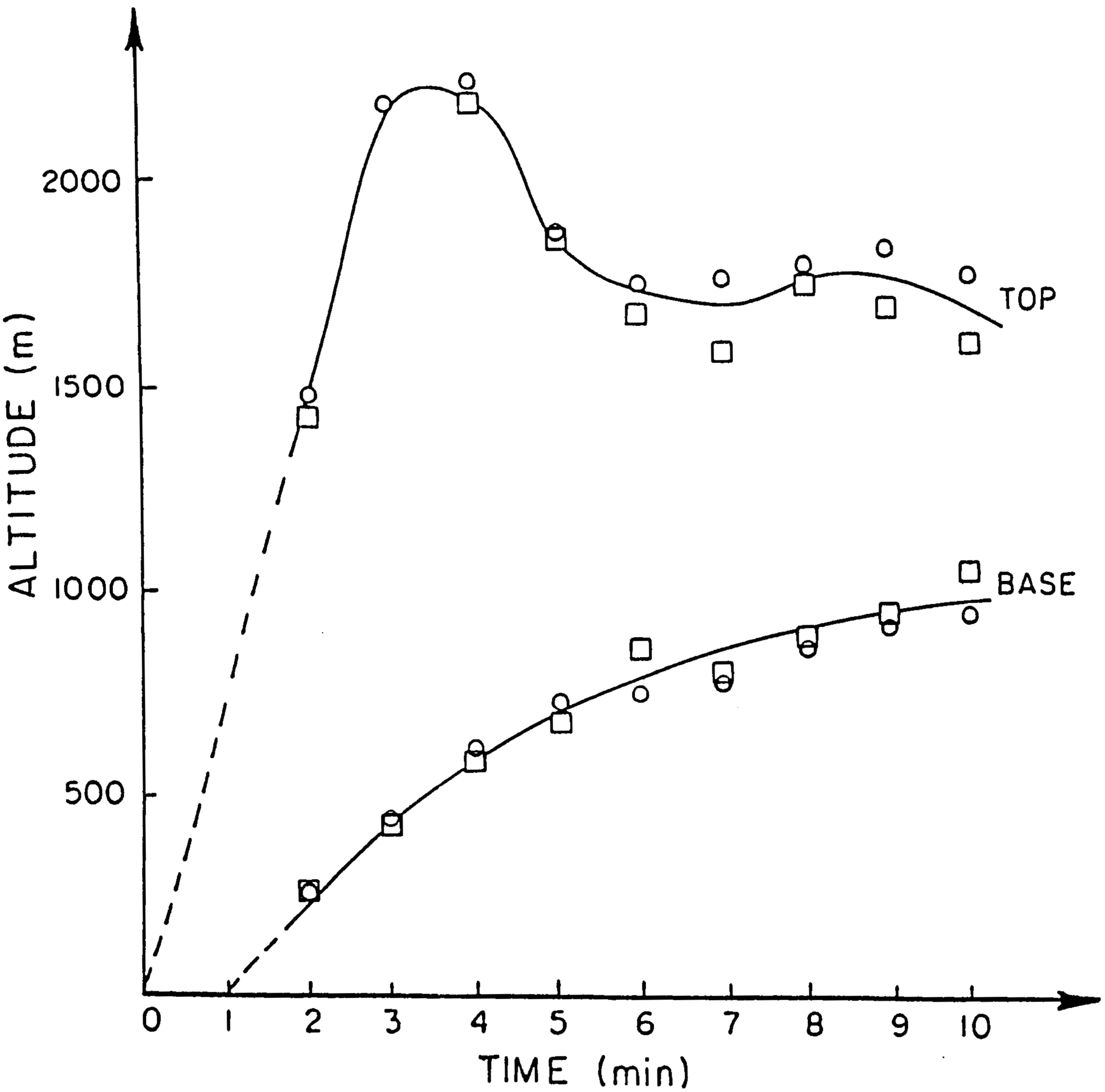

Figure 2. Altitude of the top and base of the Shuttle exhaust cloud versus time for Mission 41C.

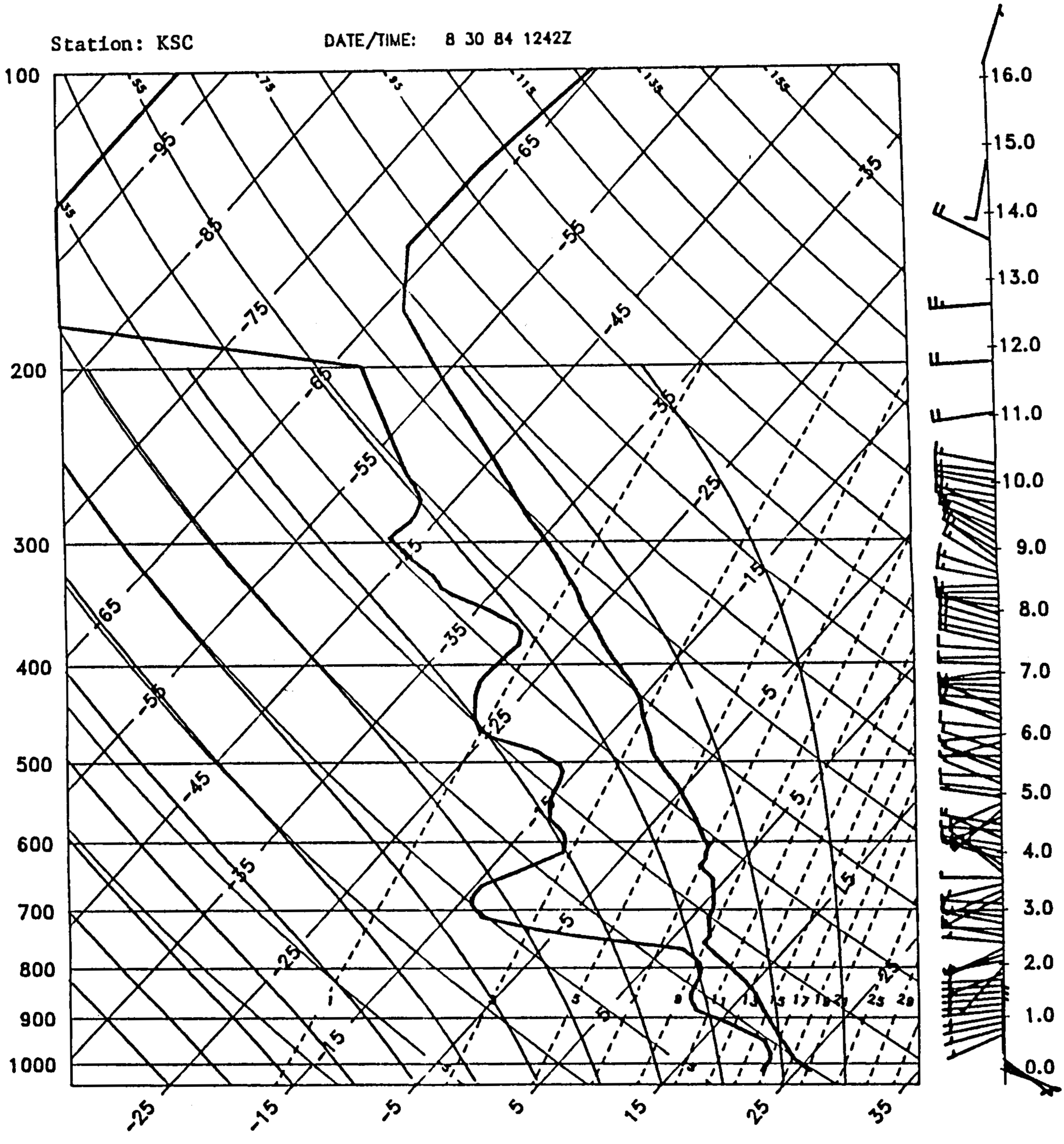

Figure 3. Upper-air sounding for Mission 41D, August 30, 1984 1242 GMT.

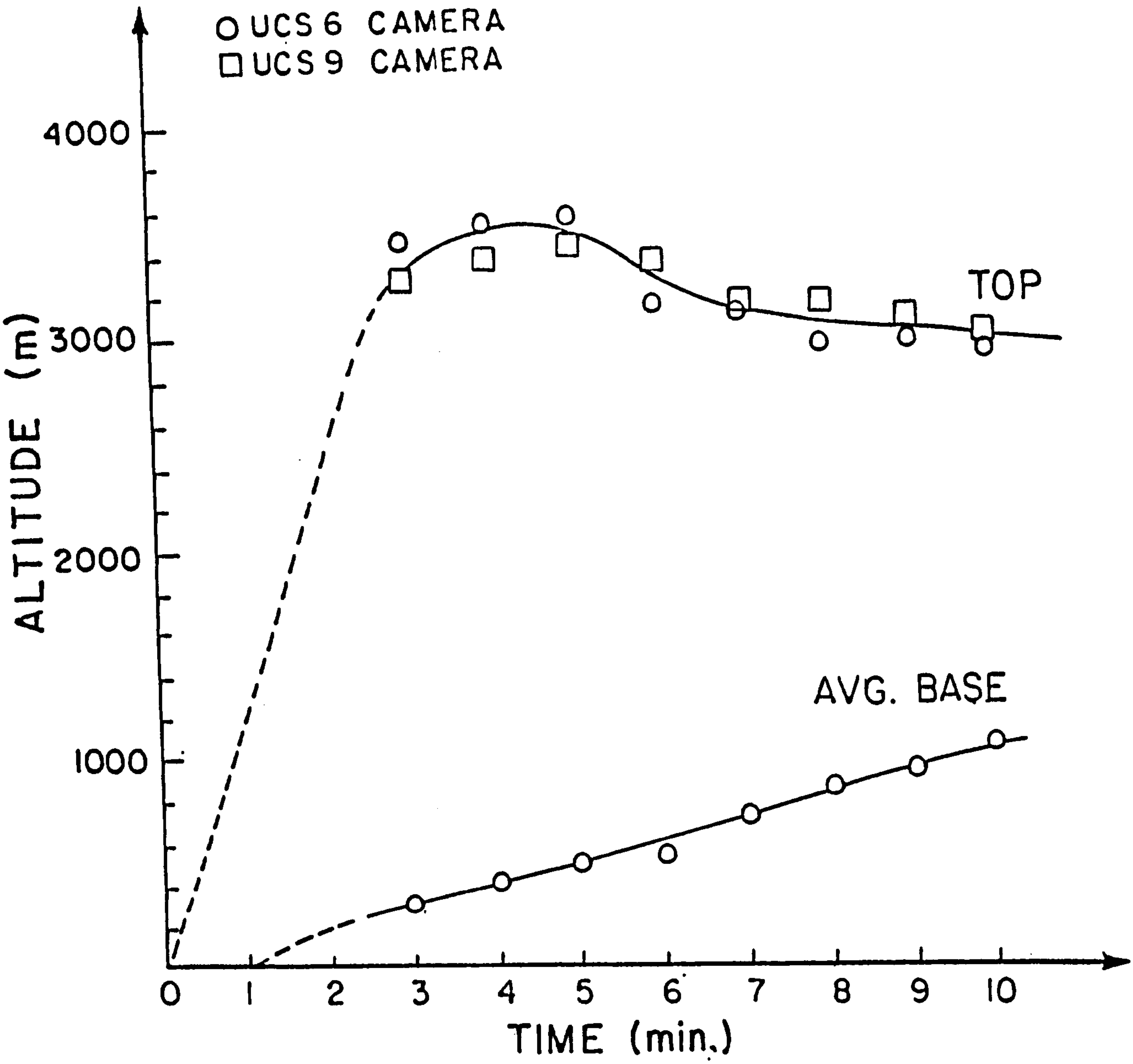

Figure 4. Altitude of the top and base of Shuttle exhaust cloud versus time for Mission 41D.

slower than for 41C but still had begun by 9 minutes. The bases also rose to about 1 km, the lifting condensation level. The volume was calculated to be about 3.4 x 10^9 m^3 at 5 minutes after launch. The irregular shape and convective bubbles can be seen in cloud pictures shown in Figure 5. A parcel of air with an upward velocity near the ground would reach saturation quickly from adiabatic cooling due to the high moisture content in the lower 2 km. Additional heat would be released to contribute to futher cloud growth as a result of the condensation process. This process would continue, according to parcel theory, until the air, now cooling at a slower rate, reaches a temperature colder than the environment; in this case about 3 km. This simple explanation does a reasonable job in explaining cloud growth in this case but will not be adequate in some cases.

Mission 51A. The atmosphere for this launch is shown in Figure 6. It has a strong but shallow inversion beginning at 2 km with pronounced dryness between 2 and 3 km. There is a cloud layer at 1300 to 1700 m reflected by total saturation in the sounding. The temperature lapse rate is near adiabatic below the inversion and there is pronounced wind shear throughout the lower 5 km. The cloud base and tops in this atmosphere are shown in Figure 7. The first bubble overshoots the inversion by about 400 m in 4 minutes then collapses to the inversion altitude. The shuttle cloud merged with the natural cloud layer so that the main bubble could not be seen from the ground (Fig. 8). Here again one can see the irregular shape of the cloud with the near neutrally buoyant piece from the north trench (solid rocket boosters) hanging near the surface in the first 5 minutes. The calculations of the cloud base was for an average base so that the lowest part visible in the digitized film frames looking east was not included. The appearance of the cloud reflects the rather strong shear especially at 5 minutes after

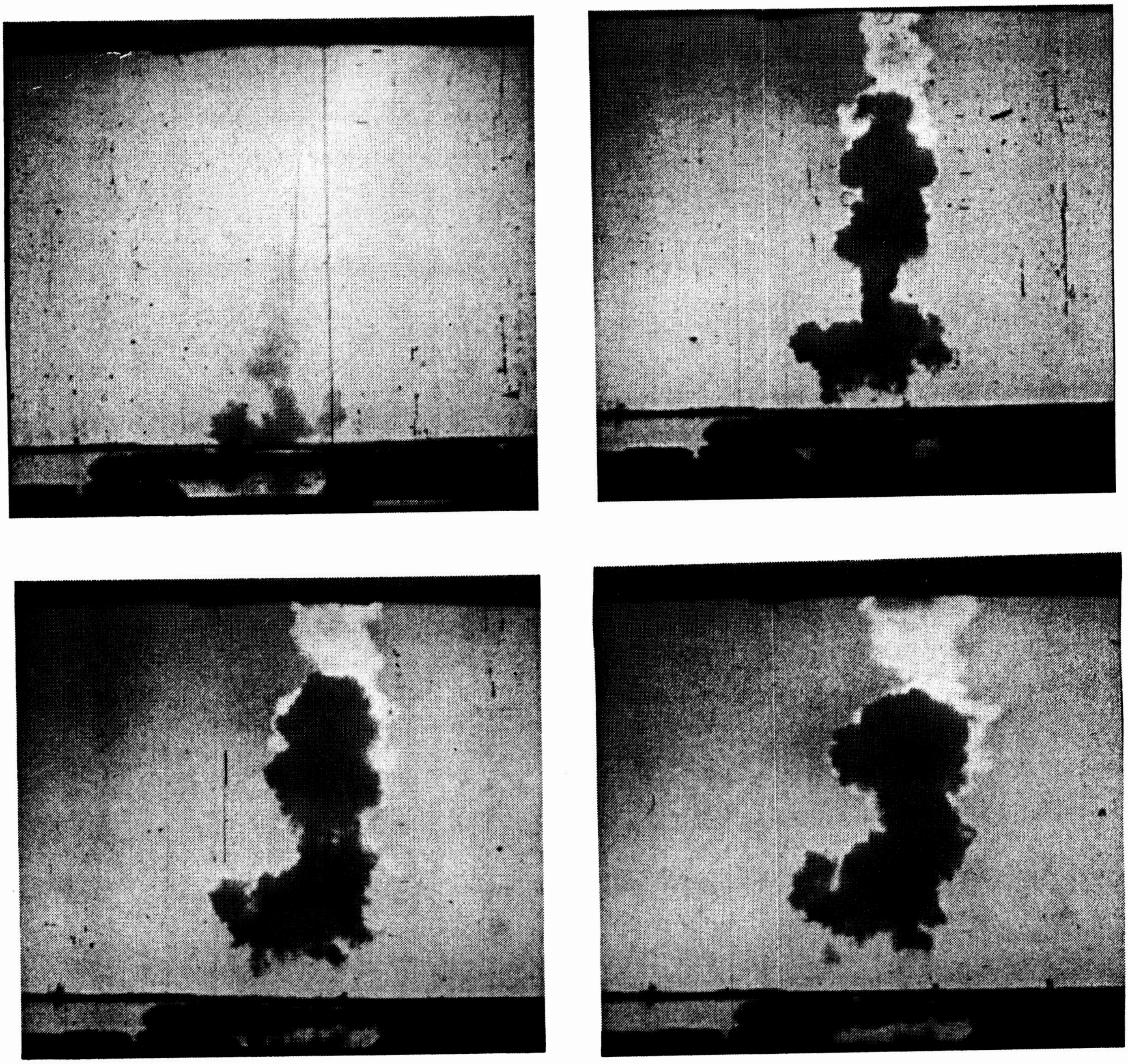

Figure 5. Photographs of digitization of 16mm film for the Shuttle Mission 41D ground cloud looking east at one minute (top left), 3 minutes (top right), 5 minutes (bottom left), and 7 minutes (bottom right) after launch.

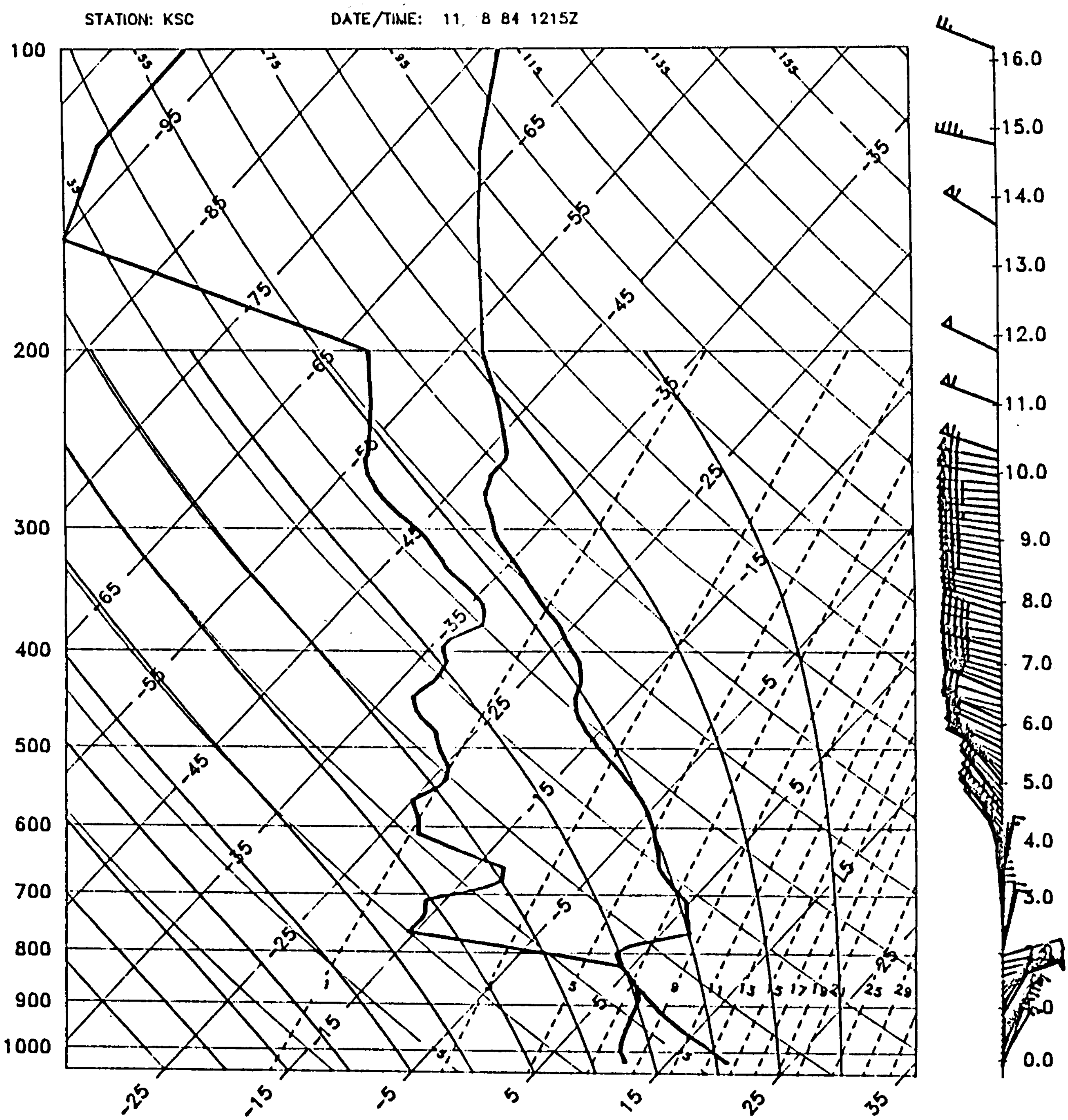

Figure 6. Observed upper-air sounding for Mission 51A, November 8, 1984, 1215 GMT.

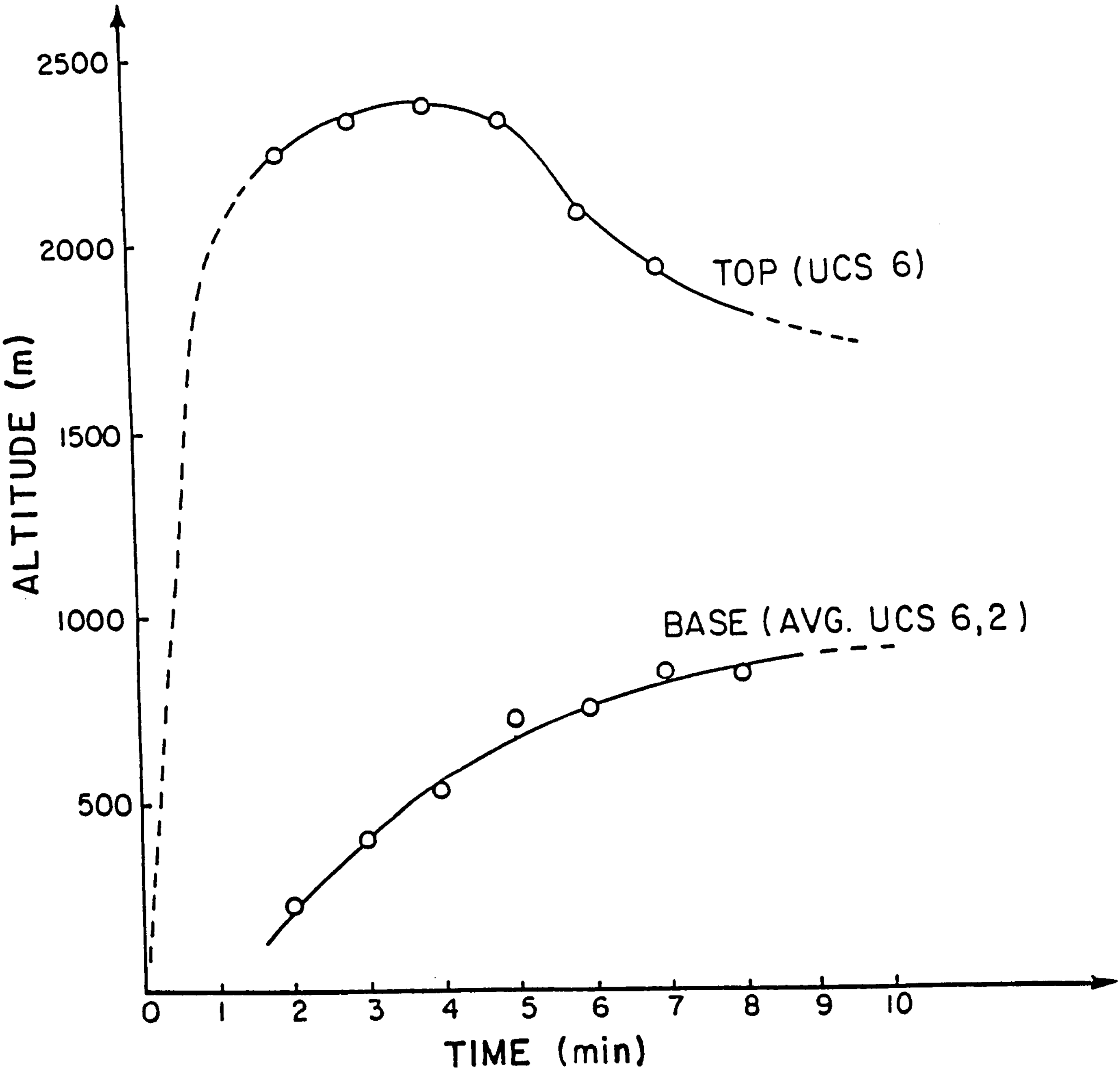

Figure 7. Altitude of top and base of Shuttle exhaust cloud versus time for Mission 51A.

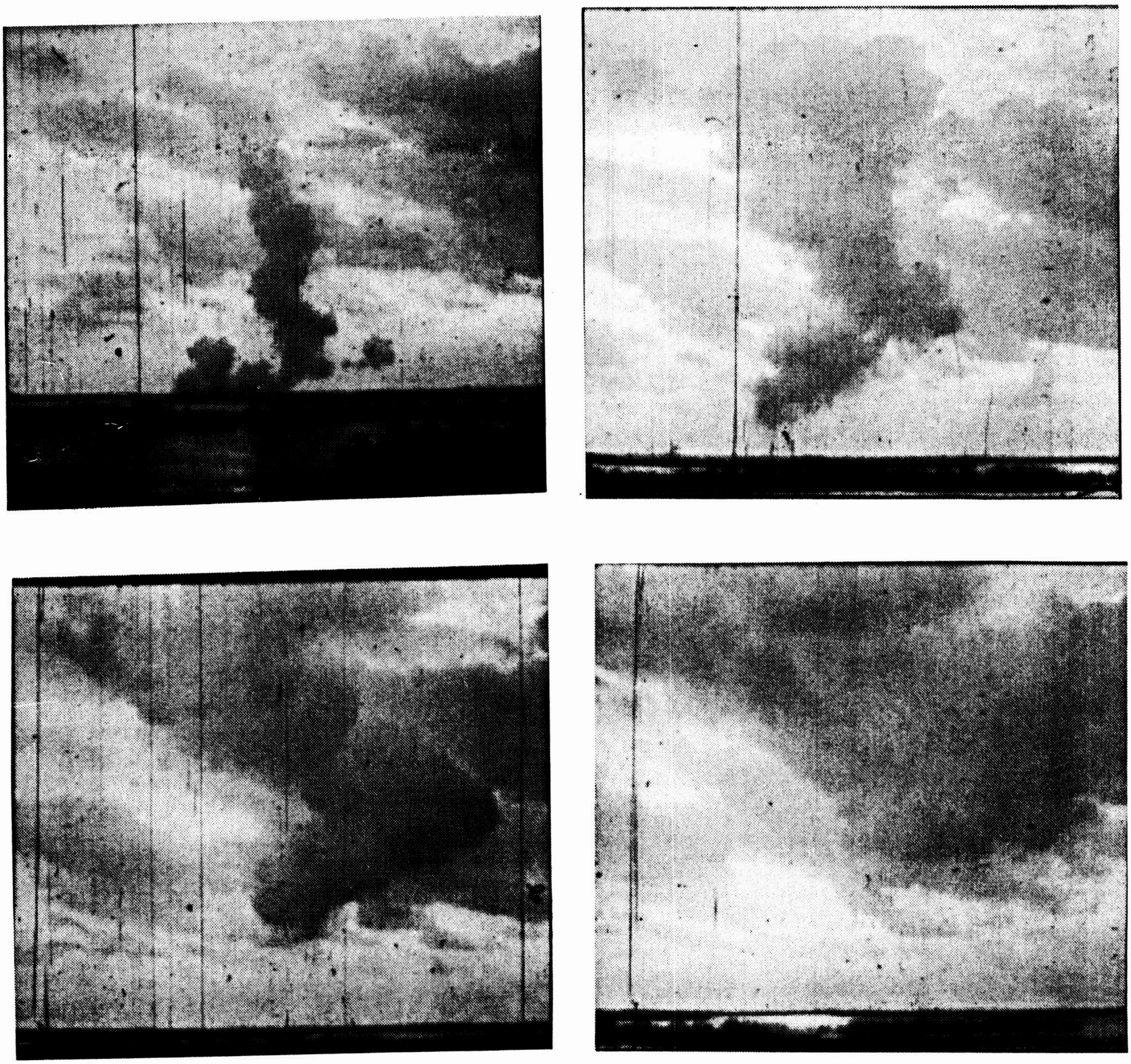

Figure 8. Photographs ot digitization of 16mm film frames for the Shuttle Mission 51A ground cloud looking east at one minute (top left), 3 minutes (top right), 5 minutes (bottom left), and 7 minutes (bottom right) after launch.

launch where the main cloud tilts significantly to the northwest. The wind below 700 m has a significant southern component which is blowing the lower part of the cloud to the south whereas the upper part is moving predominantly west; hence the northwest tilt. The convective nature of the cloud due to the steep lapse rate and natural buoyancy is apparent in the 3 minute picture of Figure 8 as well.

Aircraft Observations

Mission STS-3. Photogrammetry is not available for STS-3 except for some preliminary estimates from a series of ground still pictures provided by Marshall Space Flight Center [Anderson and Keller, Dec. 1983], but there were in-cloud measurements of vertical velocity and liquid water for this mission. The atmosphere is shown in Figure 9. The region below 2 km is slightly moist and unstable with the wind just above the surface from the west at about 15 ms^{-1}. There is a weak isothermal layer and dry region about 1 km and an inversion beginning at 2 km. In this case the ground cloud never reaches the main inversion but its growth is influenced by the isothermal layer around 1 km. Maximum tops were indicated by Anderson and Keller [1983] to be 1.2 km after about 4 minutes.

A NOAA aircraft made measurements of parameters within the STS-3 ground cloud. These are summarized in Table 1. The vertical velocity of 4.0 ms^{-1} is sufficient to lift mm size droplets. Liquid water contents of 0.3 g kg^{-1} is low but consistent with the available atmospheric moisture in the low troposphere. There are significant fluctuations of vertical velocity within the cloud so that the average values at the different times might be more comparable with model results to be presented in the next section.

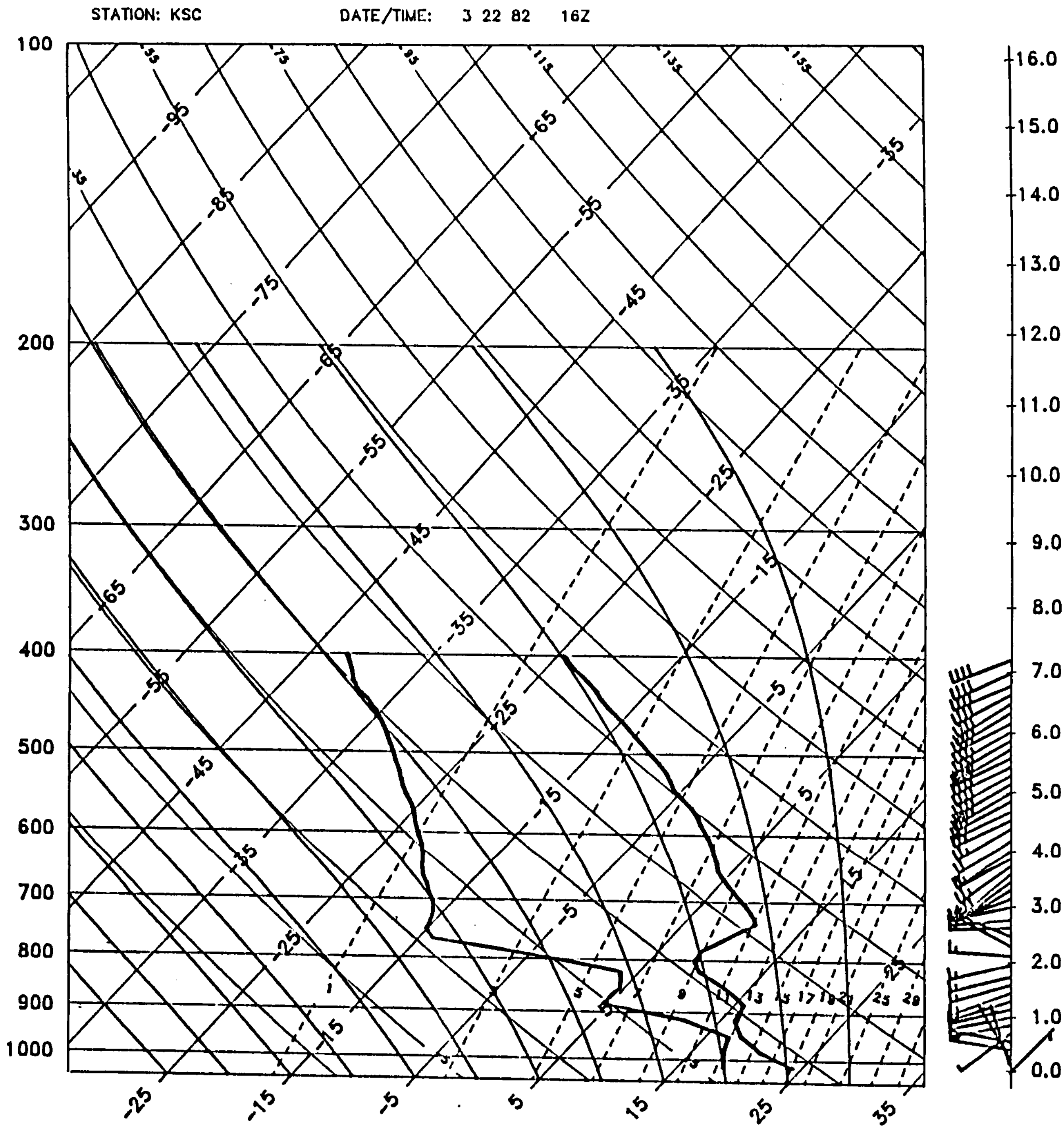

Figure 9. Upper-air sounding for STS-3 Shuttle launch March 22, 1982, 1600 GMT.

Table 1. Summary of STS-3 Insitu

Aircraft Measurements

Time after launch (min)	Aircraft Altitude (m)	Maximum liquid water content (g kg^{-1})	Maximum vertical velocity (m sec^{-1})
4	700	0.3	4.0
7	990	0.3	4.0
9	800	0.2	4.2

SECTION 3. MODEL RESULTS

Up to this point we have discussed cloud dimensions, internal cloud properties, and atmospheric influences for four cases where observations were available. This section will discuss first how well the model cloud compared with observed clouds, then how model clouds behaved in different types of atmospheres.

Model-Observation Comparisons

Comparisons are summarized in Table 2. In general the model performed well. Maximum cloud tops and liquid water contents were all within 10% of observed values but the time to maximum cloud top was about 1 minute slower in model results. The two bubbles were reproduced in the model clouds as were the asymmetries. Model clouds did not always have the same shapes as observed clouds but some of this difference was due to averaging in photogrammetric calculations and in differences between smoke and water clouds. The vertical tilt was also consistent with observations in atmospheres with relatively strong winds. Model clouds are discussed more fully for individual cases below.

Unstable Atmospheres

There are questions concerning cloud rise in unstable atmospheres. Can the shuttle produce a cloud system in a very unstable, moist environment which could develop into a thunderstorm or into a cloud with a sustaining precipitation mechanism? How high into the atmosphere could a shuttle cloud rise and how large could it become? What is the role of an elevated weak inversion in an otherwise unstable atmosphere?

Table 2. Comparisons of Observed Clouds with Model Clouds

Parameter Observed/Model

Shuttle Mission	Time After Launch	Maximum Top (km)	Average Base (km)	Average Width (km)	Average Max.* Liq. Water (g/Kg)	Average Vertical Velocity (m/s)
41C	3 min	2.2/-	0.3/-	0.7/-	-/-	-/-
	6 min/7 min	1.7/1.6	0.7/1.2	1.1/0.7	-/0.3	-/0.5
	9 min	1.8/1.4	0.8/1.2	1.3/0.5	-/0.2	-/0.4
41D	3 min	3.3/2.8	0.4/0.1	0.7/1.6	-/0.6	-/8.5
	6 min	3.3/3.2	0.5/0.1	1.1/1.7	-/0.7	-/3.5
	9 min	3.0/3.2	0.8/0.7	1.2/1.7	-/1.0	-/2.4
51A	3 min	2.2/2.4	0.4/1.3	0.8/1.6	-/0.4	-/5.3
	6 min	2.0/2.4	0.7/1.3	1.0/2.0	-/0.7	-/3.1
	9 min	1.7/-	0.7/-	0.9/-	-/-	-/-
STS-3	4 min	1.0/1.4	0.2/0.1	1.2/1.4	0.3/0.4	0.7/3.2
	7 min	1.2/1.4	0.4/0.7	1.9/1.4	0.3/0.4	0.6/0.6
	9 min	1.2/1.2	0.4/0.7	2.0/1.1	0.2/0.2	0.6/0.1

*The Max. liquid water and vertical velocity for model results is the highest value of the horizontal cloud domain average computed from 200 m thick horizontal "pancakes".

Mission 41D is an unstable, moist atmosphere (Fig. 3) with a relatively weak inversion so it should help us to answer the last question. Model results for this sounding are shown in Figure 10. In this perspective plot of liquid water contours one can see the convective bubbling in the model and the collapse of the highest turret between 5 and 7 min. The tic marks are 1 km intervals so that the maximum altitude of about 3.2 km is consistent with observations. The vertical velocity reaches a maximum in the 3 to 4 minute time period with values of about 8 ms^{-1} in Figure 11. This is indicative of the relatively strong convection in the low levels due to the combination of unstable atmosphere and natural cloud buoyancy. However, there is still no comparison to natural convection. Very little precipitation developed in the model simulation. In order to see if the model cloud would continue to grow, we added moisture near the inversion and essentially eliminated the inversion from the 41D sounding. The modified sounding for this hypothetical case called MOS41D is shown in Figure 12. Now, according to parcel theory, the cloud should continue to rise to at least 4 km. Results are shown in Figure 13. The maximum altitude was nearly the same as for 41D and the vertical motion (not shown) was actually less in both peak value and average. There was more cloud water and a small amount of precipitation but not enough to reach the ground. One possible explanation for the vertical motion suppression is in the precipitation loading. Another is in the vigorous entrainment process which appeared to be taking place near cloud top. Apparently, the inversion in the original atmosphere prevented some of the entrainment as has been observed in studies of marine stratocumulus clouds [Chen and Cotton, 1987]. The MOS41D cloud begins to dissipate by 8 minutes.

Two more unstable soundings were used to verify the lack of vertical growth. The first of the two is an observed sounding at KSC prior to the

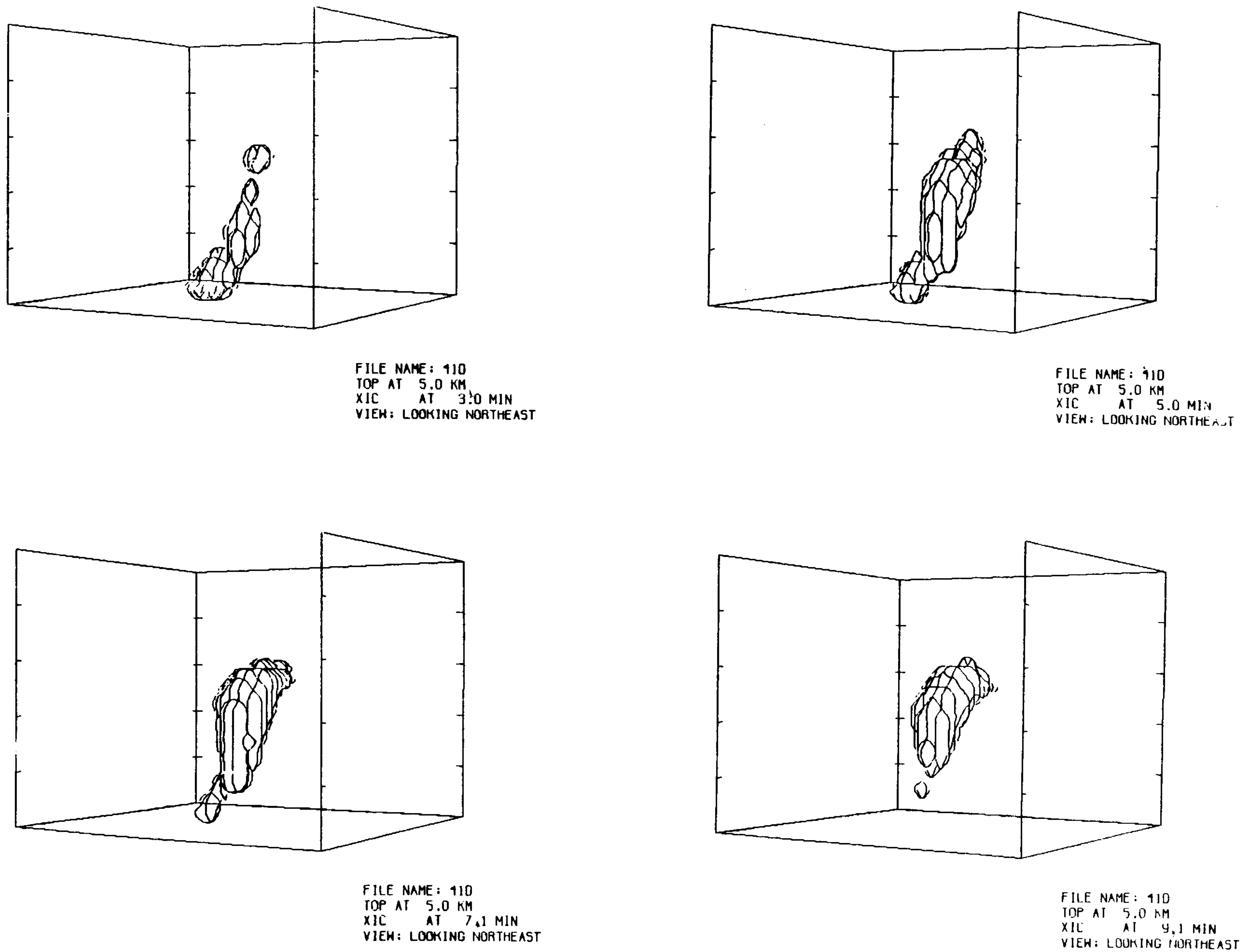

Figure 10. Perspective view of model cloud water at 3, 5, 7 and 9 minutes after initialization for Mission 41D looking northeast.

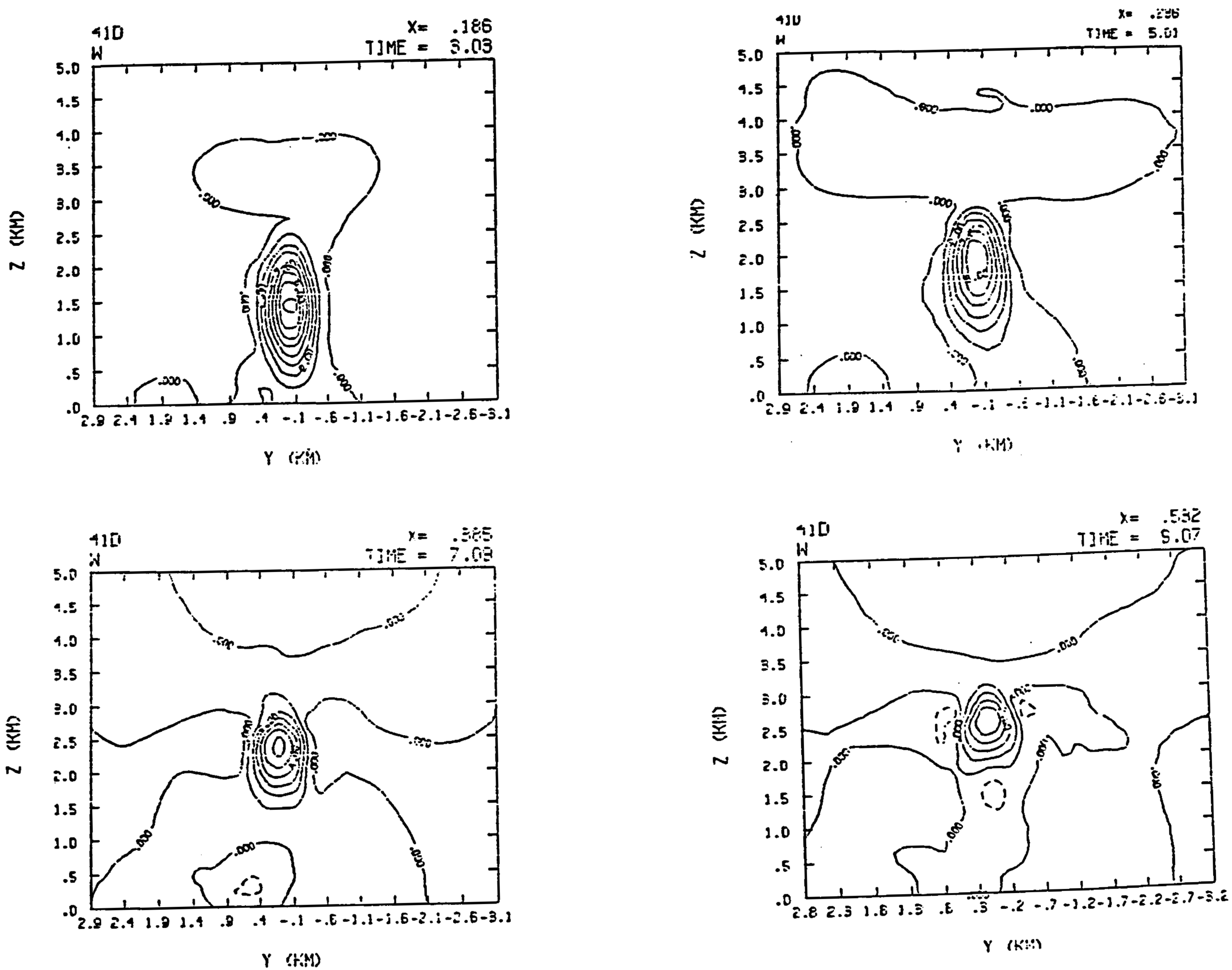

Figure 11. YZ cross section of vertical velocity for 3, 5, 7 and 9 minutes after model initialization for Mission 41D.

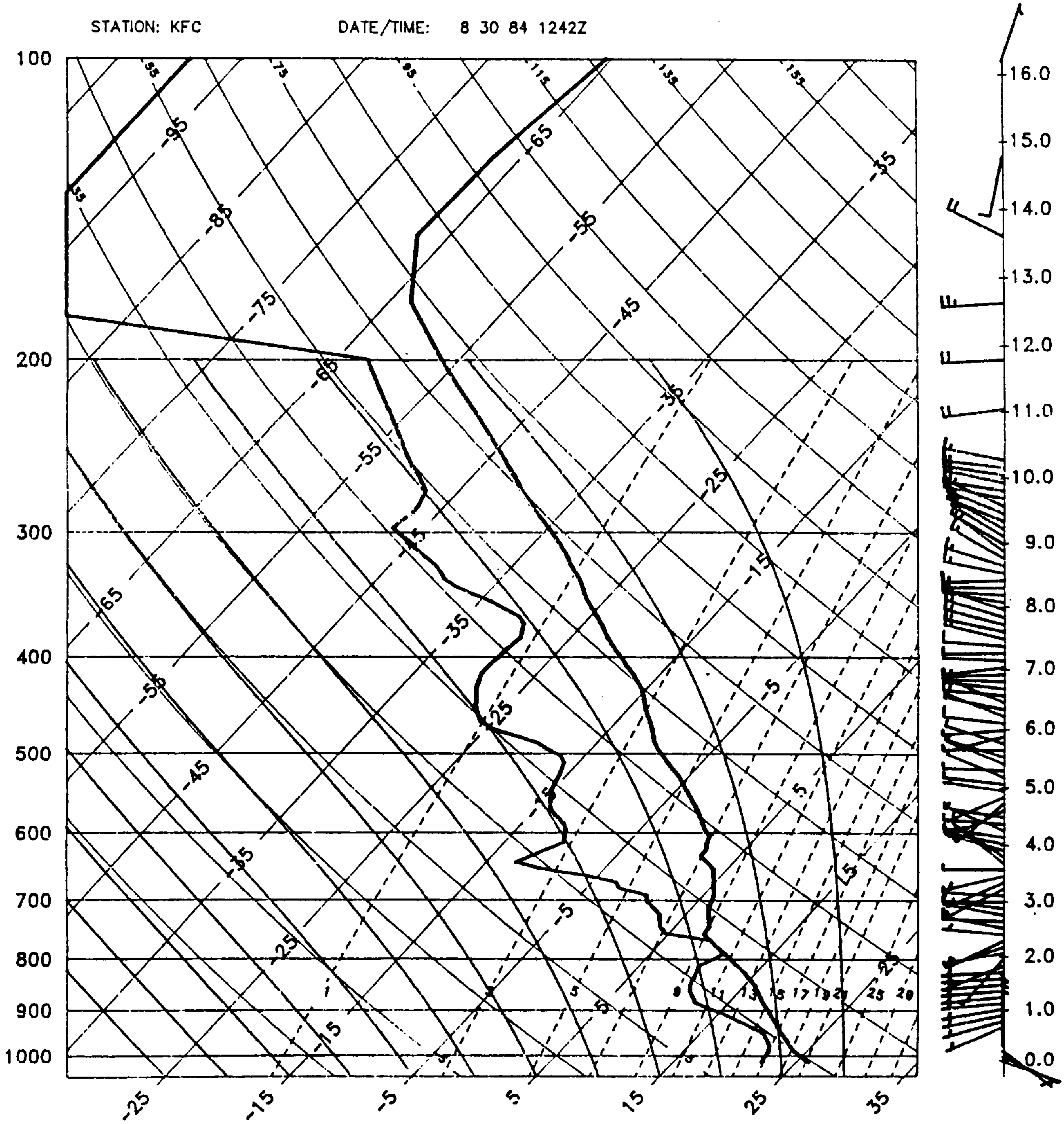

Figure 12. Upper air sounding for Mission 41D with modification of both vertical temperature and moisture distributions (case MOS41D).

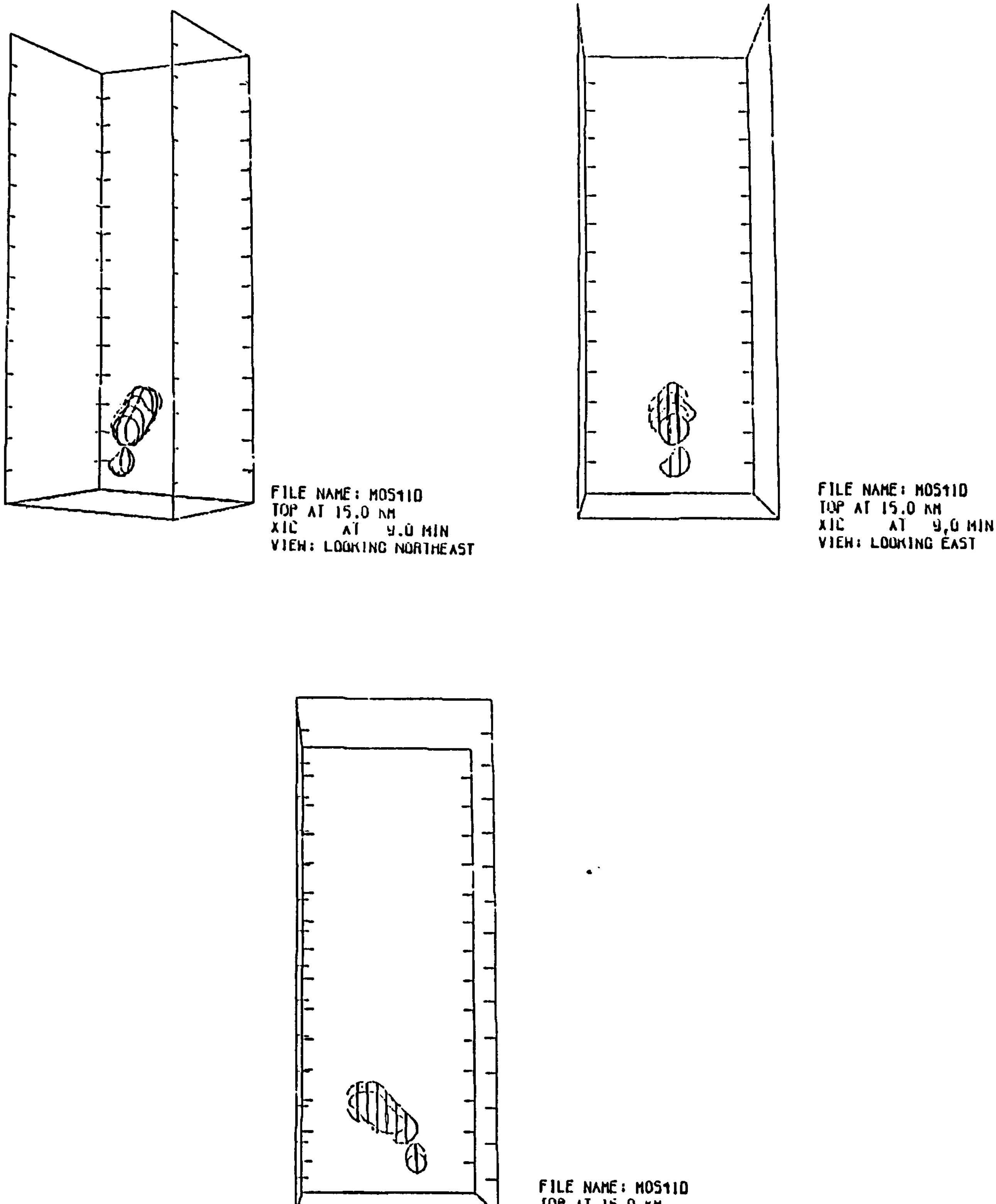

Figure 13. Model cloud water at 9 minutes looking northeast (top left) east (top right) and south (bottom) for case MOS41D.

subsequent development of thunderstorms. This sounding called UNS is shown in Figure 14. The only ingredient lacking for severe instability is more low level moisture. Model results for this case are unimpressive as shown in Figure 15 at 5 minutes. The liquid water cloud is small and about the same height as 41D and MOS41D. Again the entrainment process coupled with the reduced low level ambient moisture are responsible for the small size.

The final unstable case was a sounding produced from a mesoscale model [Kaplan et al., 1982] in Figure 16. Model results for the MASS case in Figure 17 indicate liquid cloud developing from the rocket exhaust column up to 6 km but the part above 2.5 km dissipates rapidly. The main cloud settles to about 2.0 km after 7 min. The added moisture in the MASS atmosphere produced more liquid cloud but there was weaker vertical motion consistent with a less steep lapse rate below 2 km.

In no case did a cloud with organized thunderstorm-type convection develop in model results. The inflow and outflow in the horizontal wind failed to develop in these model clouds compared to the severe convection that can develop with this same model triggered by a more substantial thermal perturbation. Although a very unstable low level atmosphere might produce a cloud which can exist for short periods up to 6 km, the entrainment process, small size of the rocket perturbations acting over a short time period, and lack of organized larger scale motion in the atmosphere preclude the development of significant convection. The worst case from a longevity standpoint and vertical motion strength appears to result from an unstable atmosphere below 2.5 km capped by an inversion to reduce the entrainment process.

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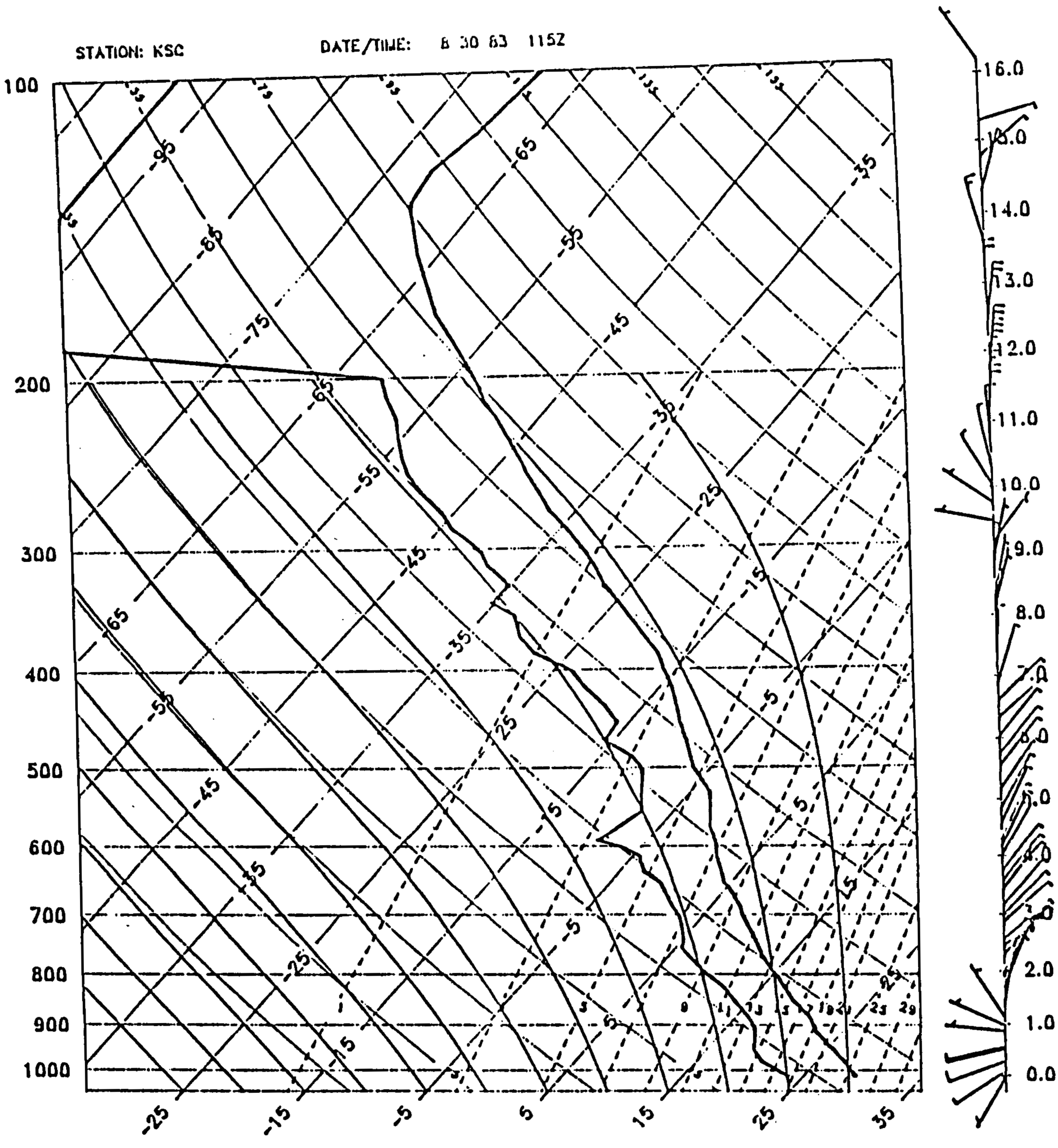

Figure 14. Observed upper-air sounding for Kennedy Space Center, FL August 30, 1982 01156Mt (case UNS).

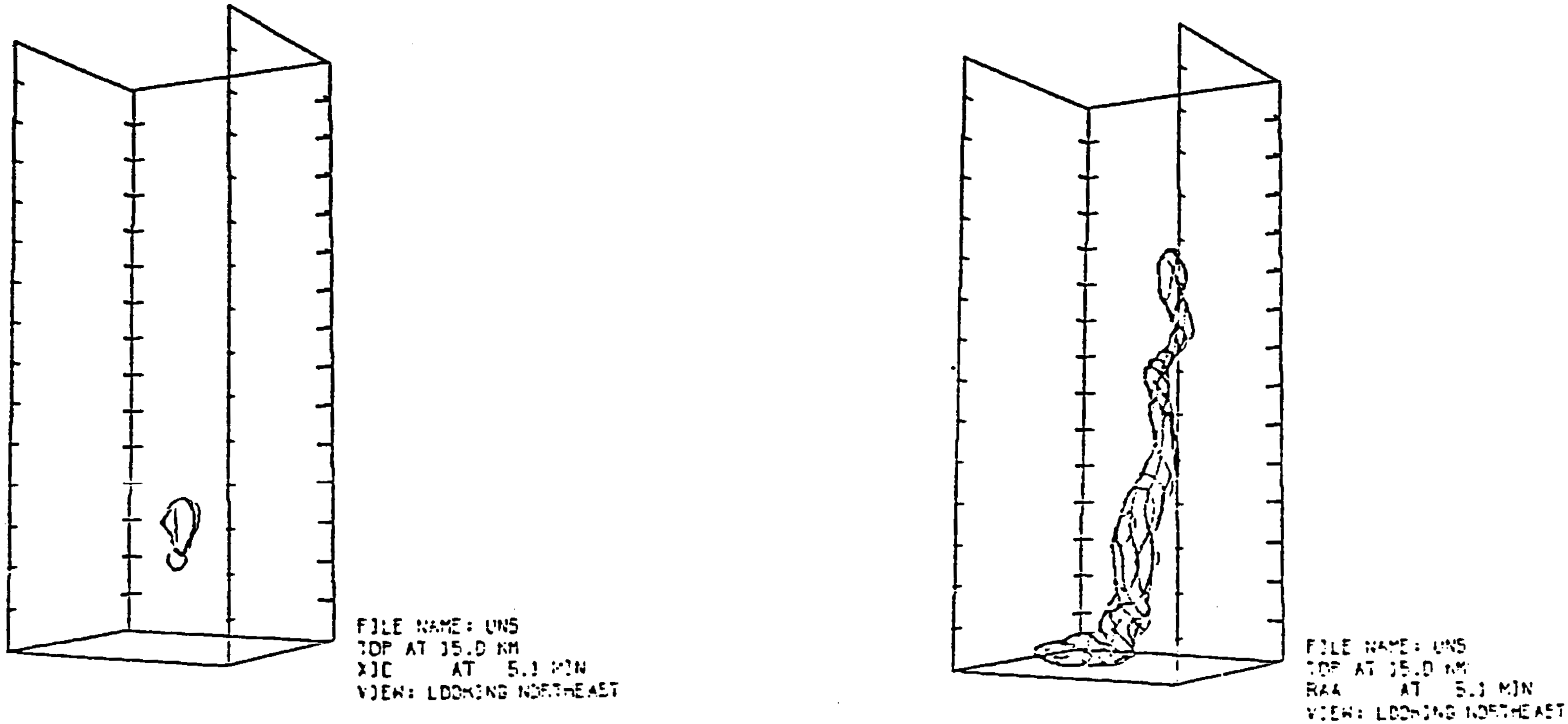

Figure 15. Model cloud water (left) and smoke (right) for the UNS sounding at 5 minutes after initialization looking northeast.

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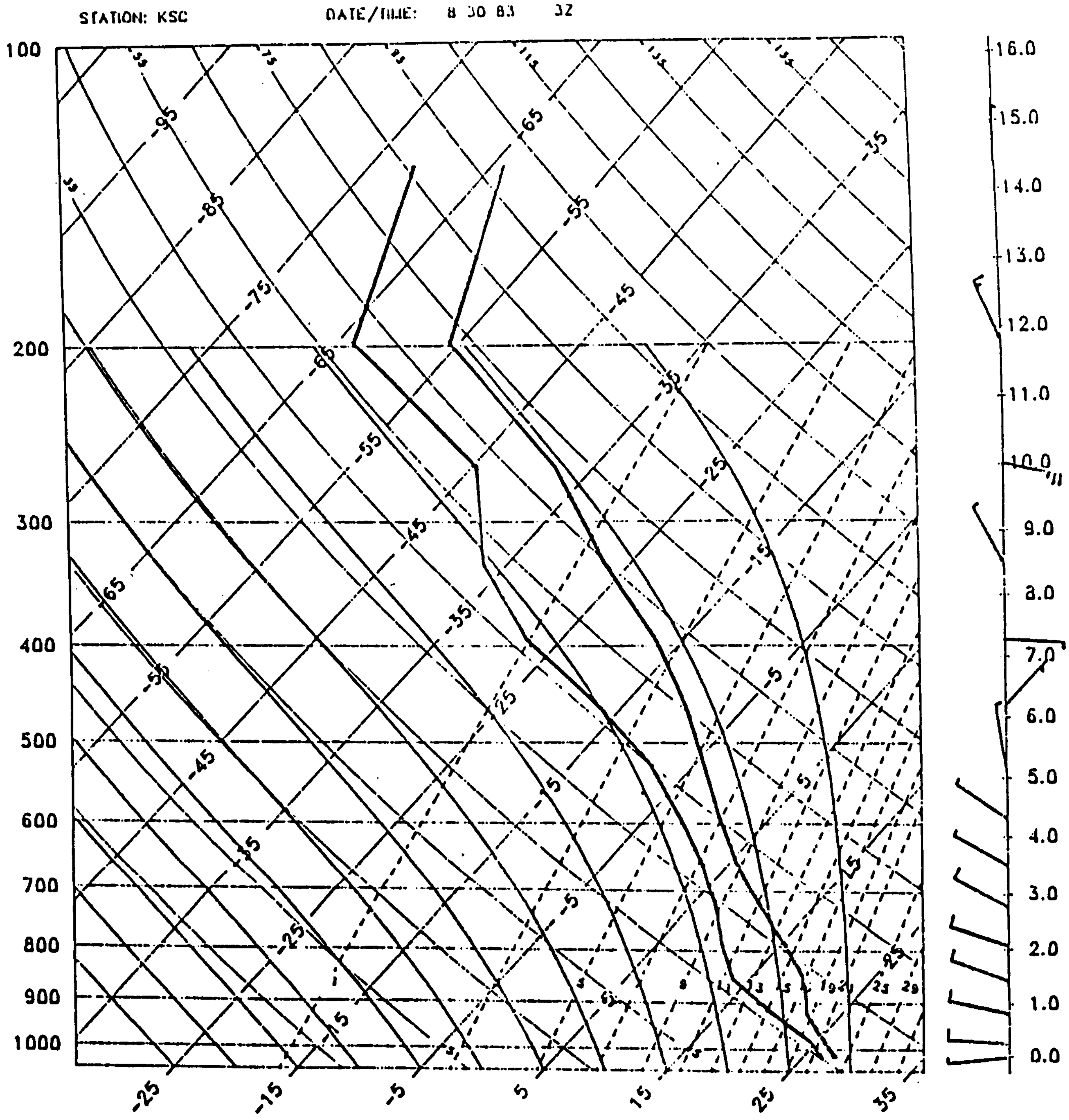

Figure 16. Upper-air sounding generated by a mesoscale model (case MASS).

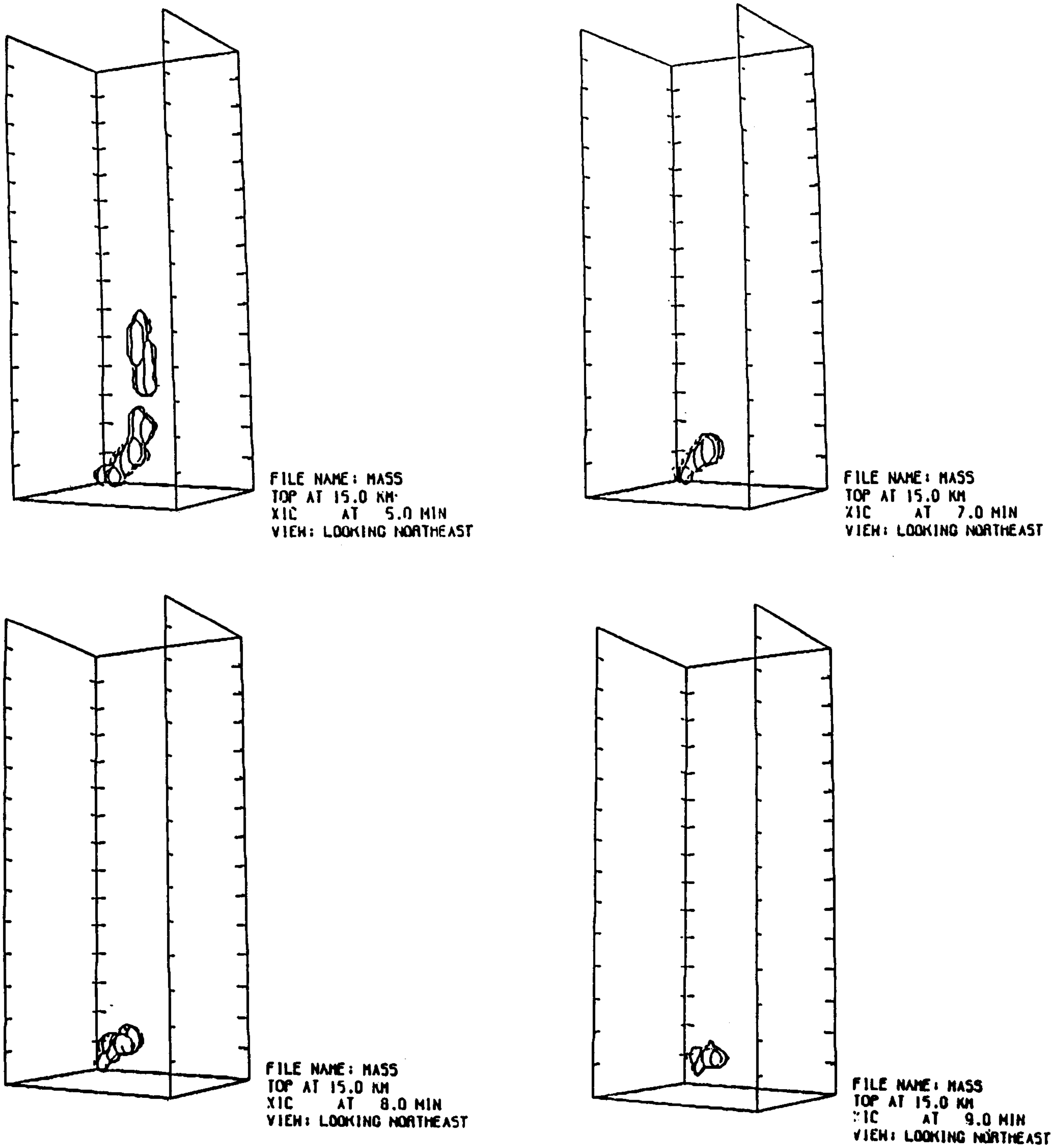

Figure 17. Model cloud water for the MASS sounding at 5, 7, 8 and 9 minutes after initialization looking northeast.

Double Initial Conditions

In one experiment, we doubled the amount of heat and moisture available from the rocket-launch system in the same atmosphere as case UNS. As shown in Figure 18, the volume of cloud water increased significantly and the ground cloud grows to 4-5 km at 6 minutes compared to about 3.3 km for standard initialization. Vertical velocity at 6 minutes had a peak of 5 m/s compared to a peak of 2.5 m/s for case UNS. Also, there is a small region of water cloud originating from the rocket exhaust column between 9 and 12 km similar to case MASS. This is most likely due to condensation from upward motion and cooling in the relatively moist upper troposphere. Despite the increased size and vertical motion, this cloud appears to be in its dissipating stages already in the simulation and further growth would not be expected.

Shuttle Cloud versus Naturally Triggered Convection

There are significant differences between the ground cloud from a Space Shuttle launch and a convective cloud naturally triggered in an unstable environment. First of all, the time scale for natural convection is on the order of 30 minutes and spatial scale about 30 to 300 km^3. The trigger to start the convective process for a Florida summer environment is frequently differential heating or organized atmospheric discontinuities such as sea breeze fronts or outflow boundaries. These trigger mechanisms can be active beyond 30 minutes and occupy considerable volumes of air. The atmospheric dynamic response to the thermal discontinuity is horizontal surface convergence over areas on the order of 600 to 1600 km^2 [Watson, et al.,1987] which leads directly to upward motion. The natural cumulus cloud of about 1 km in diameter begins to grow both vertically and horizontally into towering cumulus of about 2 km in diameter. These may rise from 1000 m (the lifting

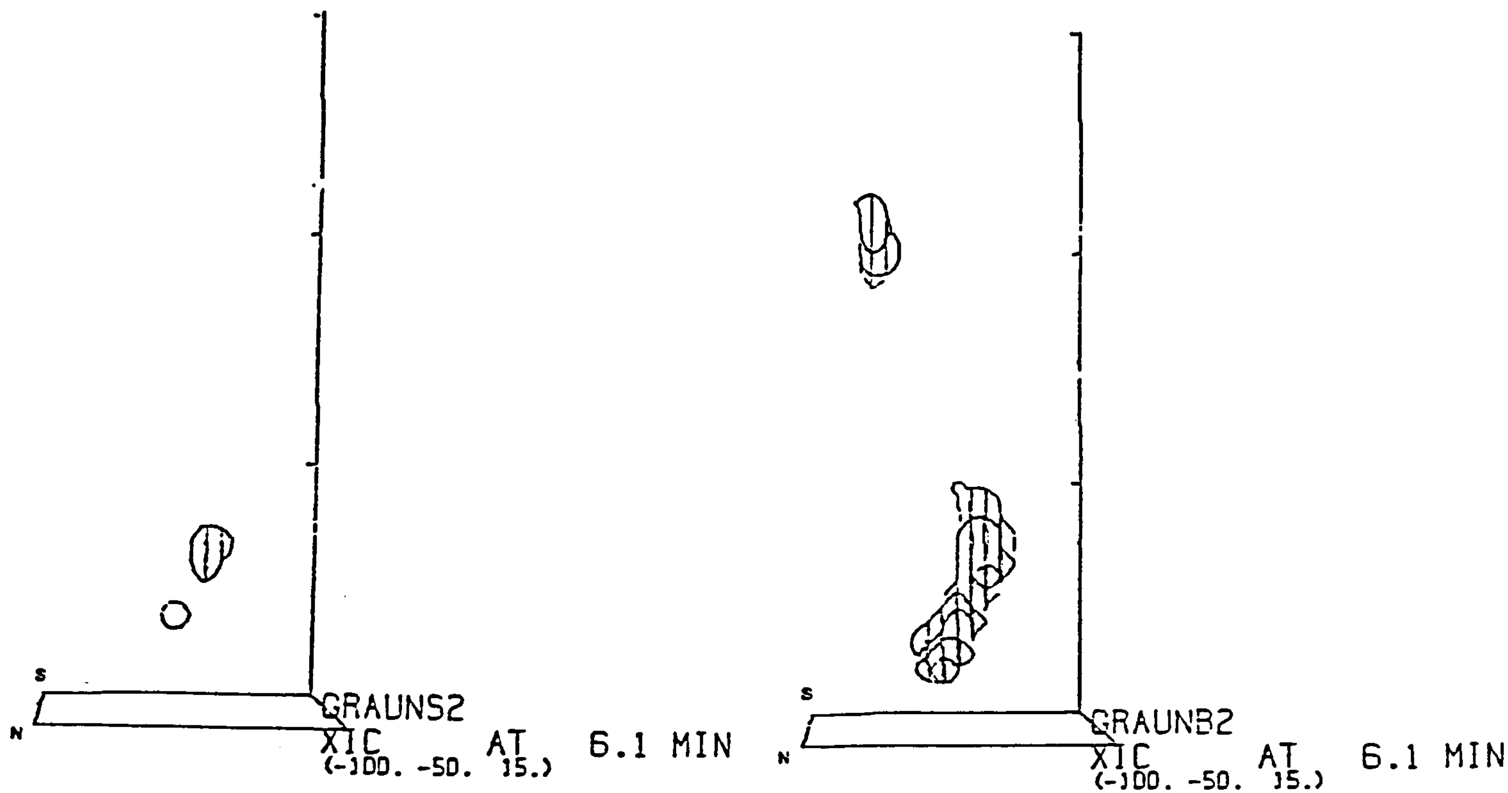

Figure 18. Cloud water contours for case UNS (left) and UNSDB (right) at 6 minutes after initialization looking south.

condensation level) to 5-6 km or higher when the precipitation process begins. They may continue to grow to 15 km or higher before they begin to decay in 30 minutes to an hour.

By sharp contrast, the time scale of the rocket trigger mechanism is in seconds and occupies an area near the surface of 500 x 500 m at most. The atmospheric response to this impulse is rather fast with a cloud developing in the first minute with properties very dependent on the atmosphere. It typically reaches its maximum altitude in about 4-5 minutes from the column portion of the exhaust and 6 to 9 min from the region nearer the ground. The maximum altitude is about 3.5 km in a moist unstable Florida environment and diameter is about 1 km.

Observations near ground clouds and model results consistently indicate that the shuttle exhaust system trigger is too small and short-lived to allow the atmosphere to organize its dynamic structure to support sustained significant convection.

Stable Atmospheres

Stable atmospheres for this discussion include soundings with strong inversions below 3.0 km even though the atmosphere below the inversion might be unstable in the usual meteorological sense.

Case 51A. The atmosphere for this case was shown in Figure 6. There is a significant inversion beginning about two kilometers. Below the inversion there is a layer of saturation near 1.5 km representing natural stratocumulus clouds in the environment. The air is relatively dry below the clouds and the lapse rate is near adiabatic. From the surface to 1.3 km height the winds are from the northeast then they shift to northerly above 2 km. This case has stronger wind shear in speed and direction than the other soundings. Photographs of the observed ground cloud were shown in Figure 8. Notice that the cloud base rises faster than in case 41D due to the steeper lapse rate and strong winds near the surface. After 7 minutes this cloud cannot be seen due to the natural cloud layer with which it blends. Model results show the basic characteristics of this cloud as discussed earlier. Of particular interest is the rather strong vertical velocity of 6 ms^{-1} at 3 minutes in the yz cross section, Figure 19, despite the tilted channel from the wind shear. Also, the liquid cloud is effectively capped by the inversion as shown in Figure 20 and its liquid water content of 1.0 g kg^{-1} is concentrated in about 1 km of vertical thickness. This liquid would be available to supplement the atomized deluge water in acid fallout, however, the relatively dry atmosphere below the cloud on this day would most likely cause significant evaporation before reaching the ground. The smoke field for this launch is shown in Figure 21 to show the effect of the wind shear at different levels on the appearance of the column. The net result is a combination of convective bubbling, diffusion, and differential horizontal transport.

CASE INV. This last case is significant because it contains a very strong low level inversion. The sounding shown in Figure 22 is for Vandenberg AFB, CA and typical of the West Coast environment. The depth of the boundary layer is about 500 meters. Model results in Figure 23 show that this inversion is strong enough to trap the ground cloud below it. The perspective plot in Figure 24 shows the trapping and lateral dispersion of both smoke and liquid water at 5 minutes. Because there is less convection, however, there will be less natural liquid water to contribute to acid deposition, but diffusion and horizontal transport could spread the accumulated rocket exhaust and deluge liquid over a larger area. Also, its concentration in a small

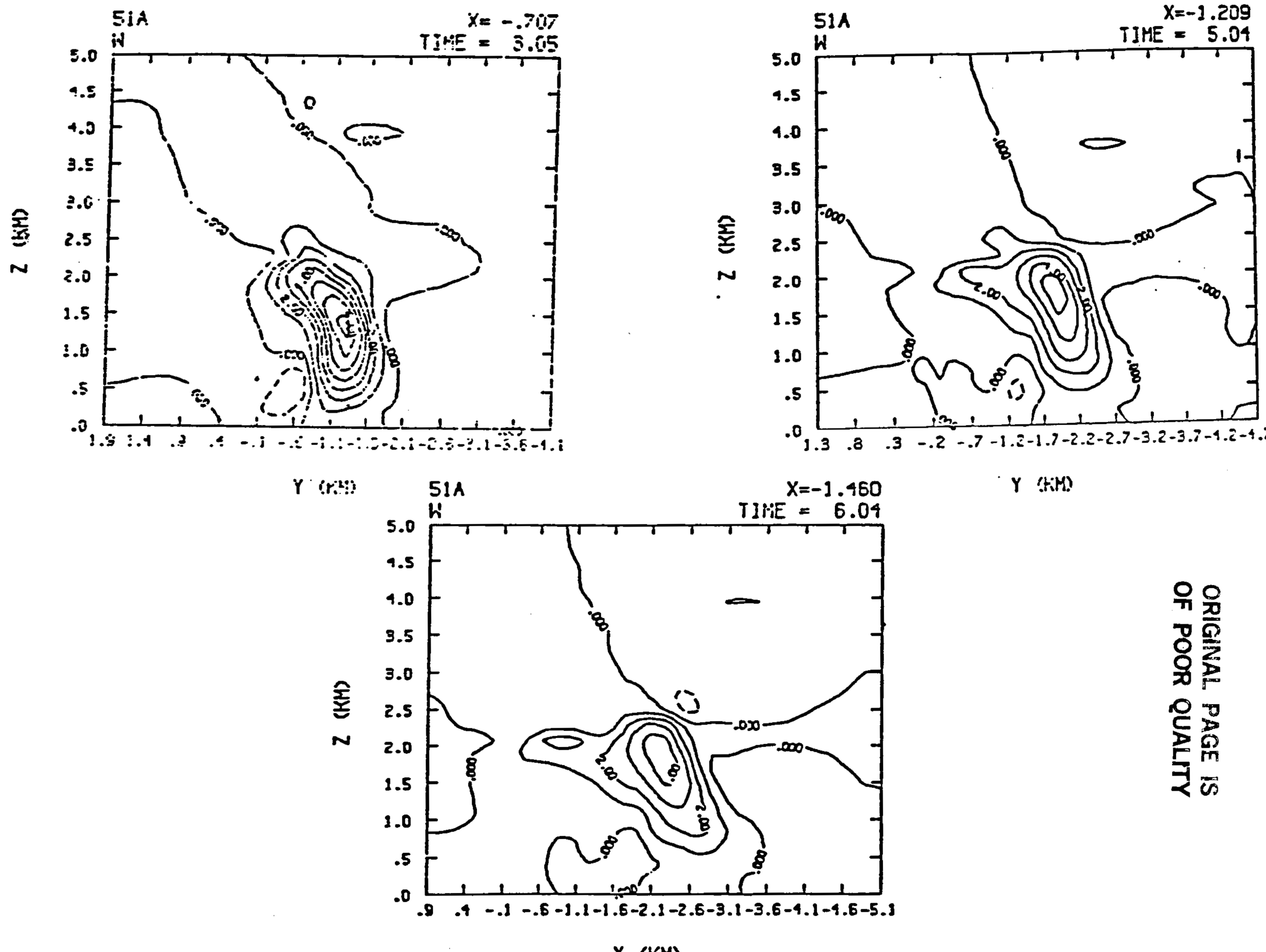

Figure 19. YZ cross section for vertical velocity at 3, 5 and 6 minutes after initialization for Mission 51A

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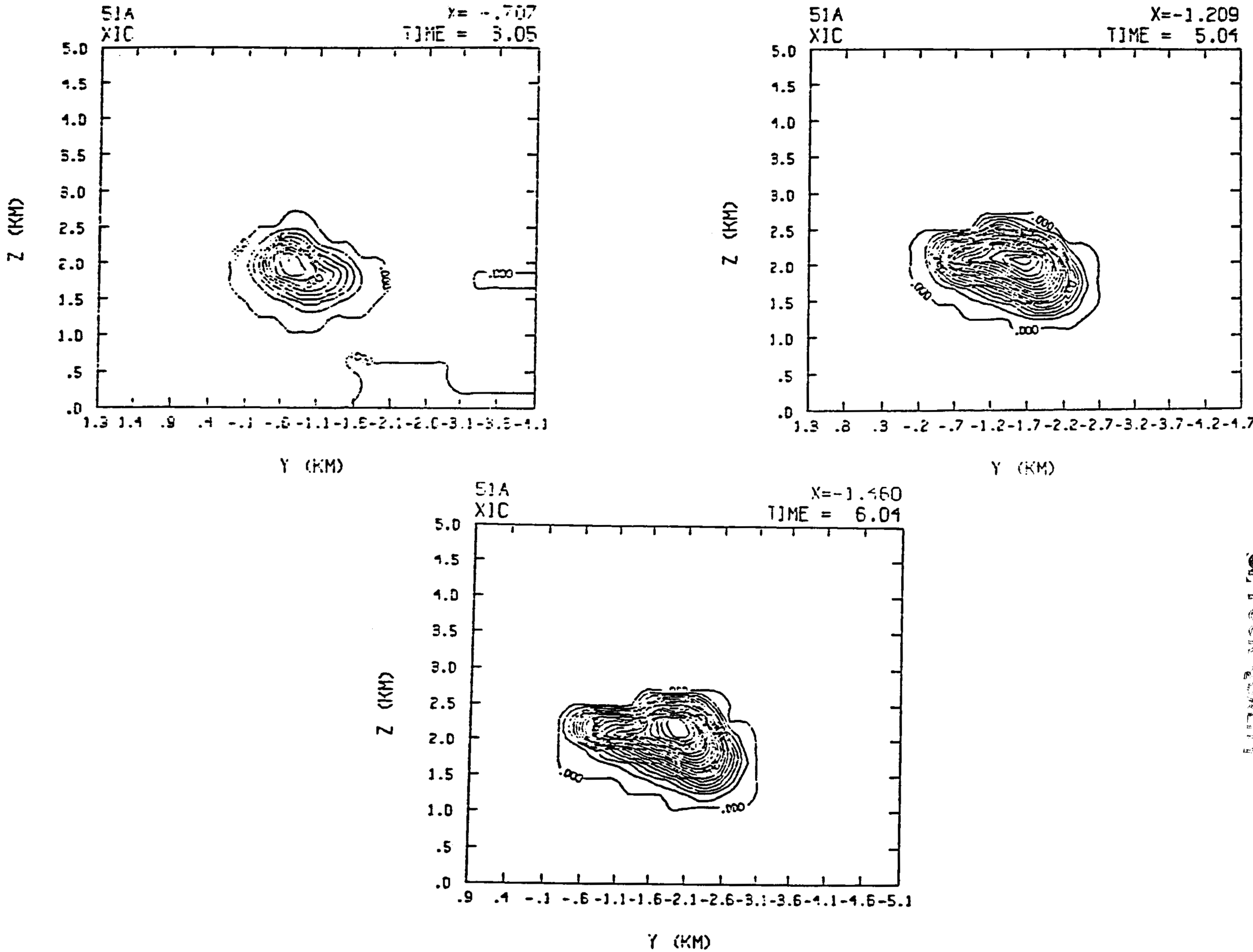
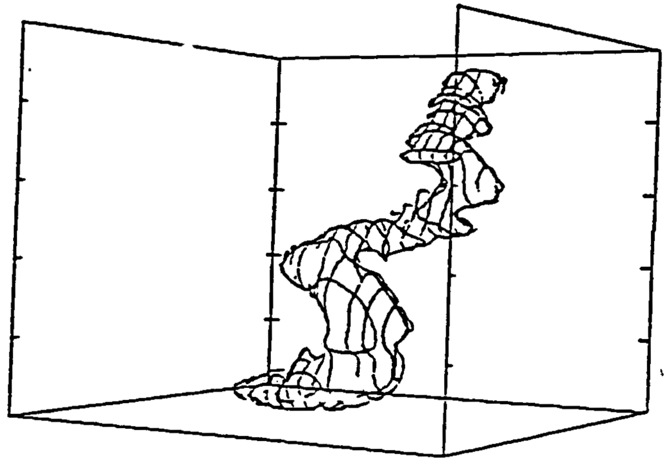
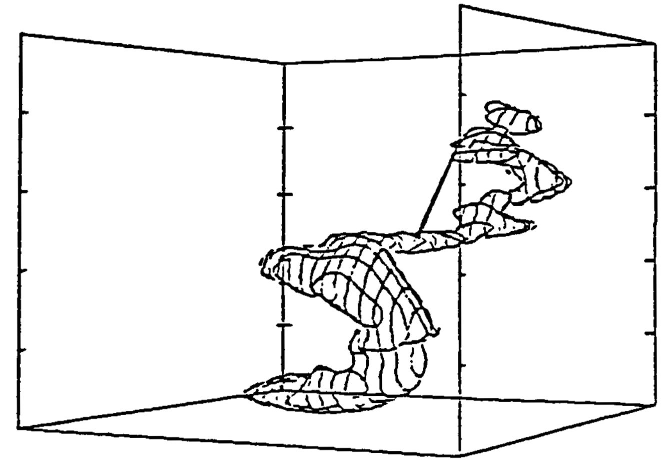


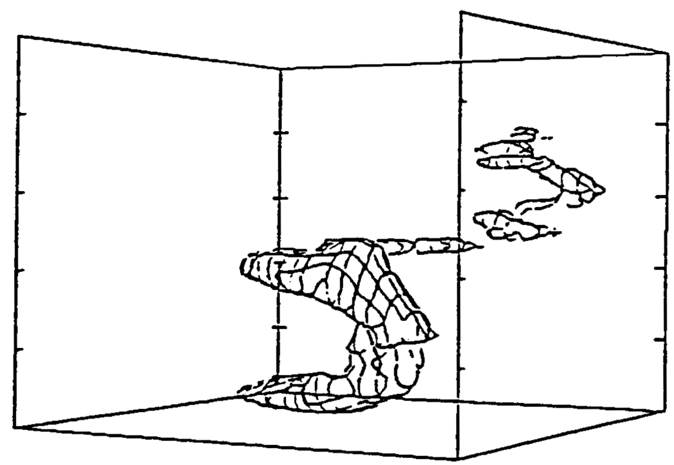
Figure 20. YZ cross section for liquid cloud water at 3, 5 and 6 minutes after initialization for Mission 51A.



File Name: 51A
Top at 5.0 KM
RAA at 3.1 MIN
View: Looking Northeast



File Name 51A
Top at 5.0 KM
RAA at 5.0 MIN
View: Looking Northeast



File Name: 51A RAA at 6.0 MIN
Top at 5.0 KM View: Looking Northeast

Figure 21. Model smoke contours at 3, 5 and 6 minutes after initialization for the Mission 51A sounding looking northeast.

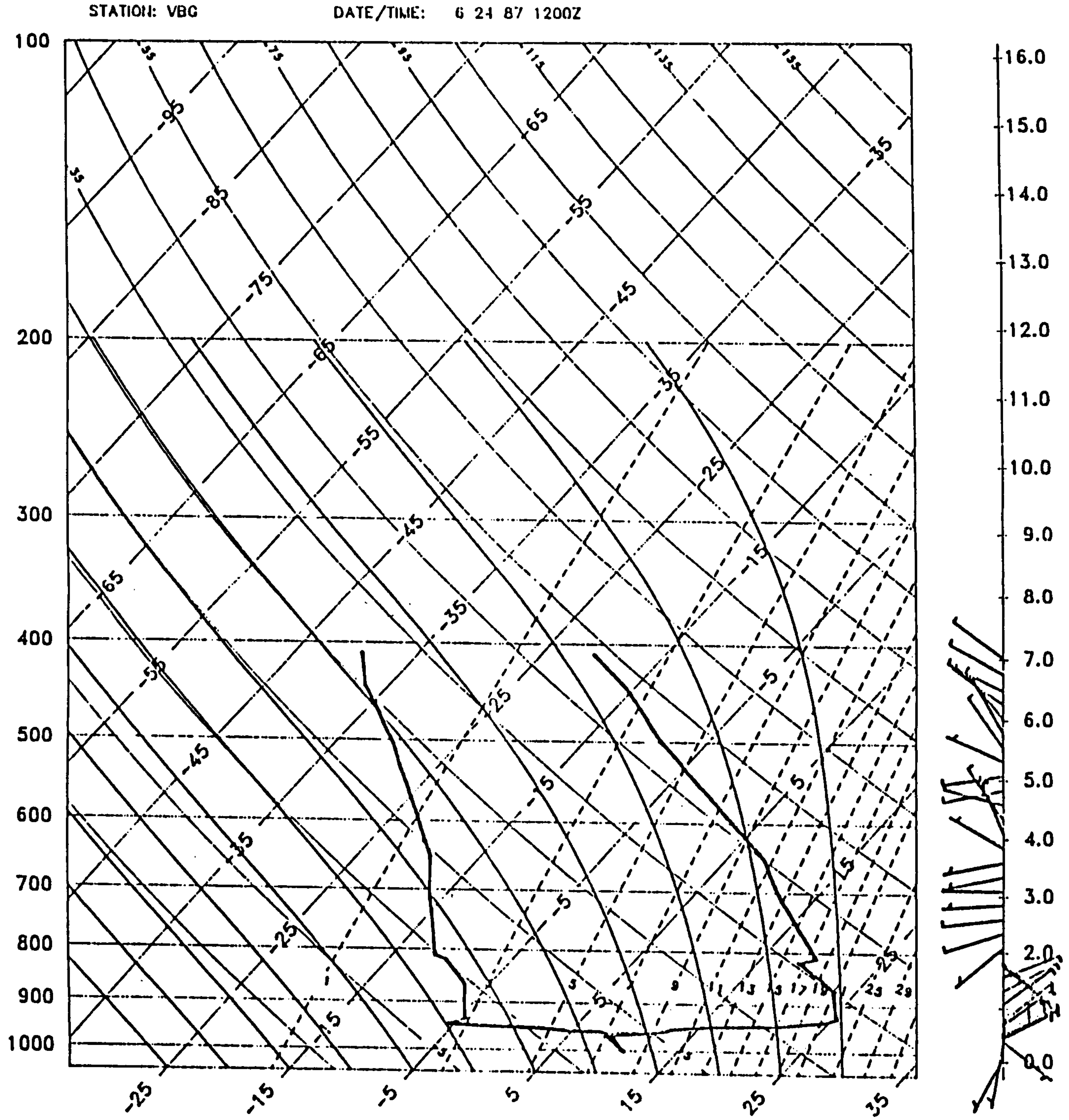


Figure 22. Observed upper-air sounding for Vandenberg AFB June 24, 1987, 1200 GMT (case INV).

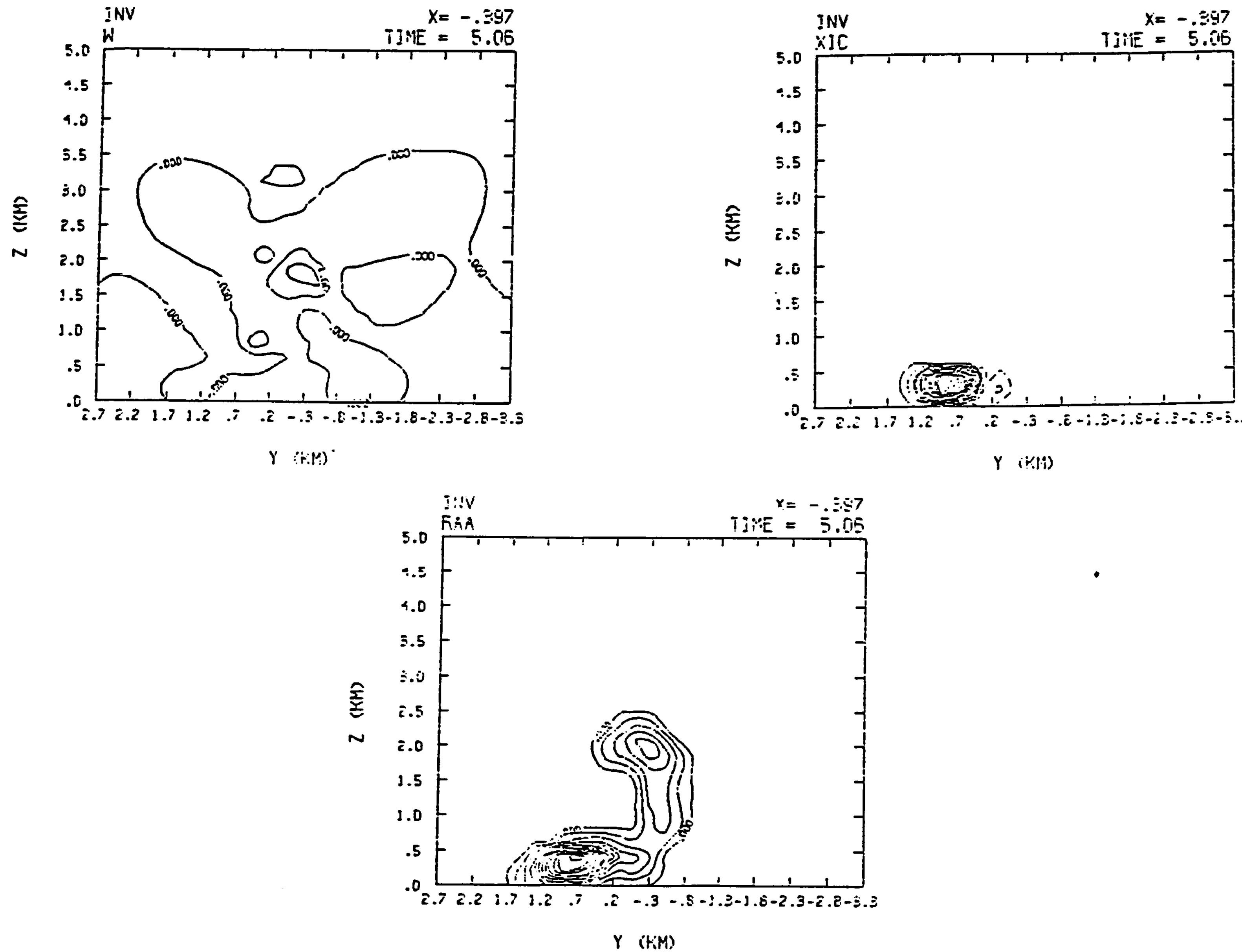


Figure 23. YZ cross section for vertical velocity, cloud water and smoke 5 minutes after initialization for the Vandenberg inversion (INV).

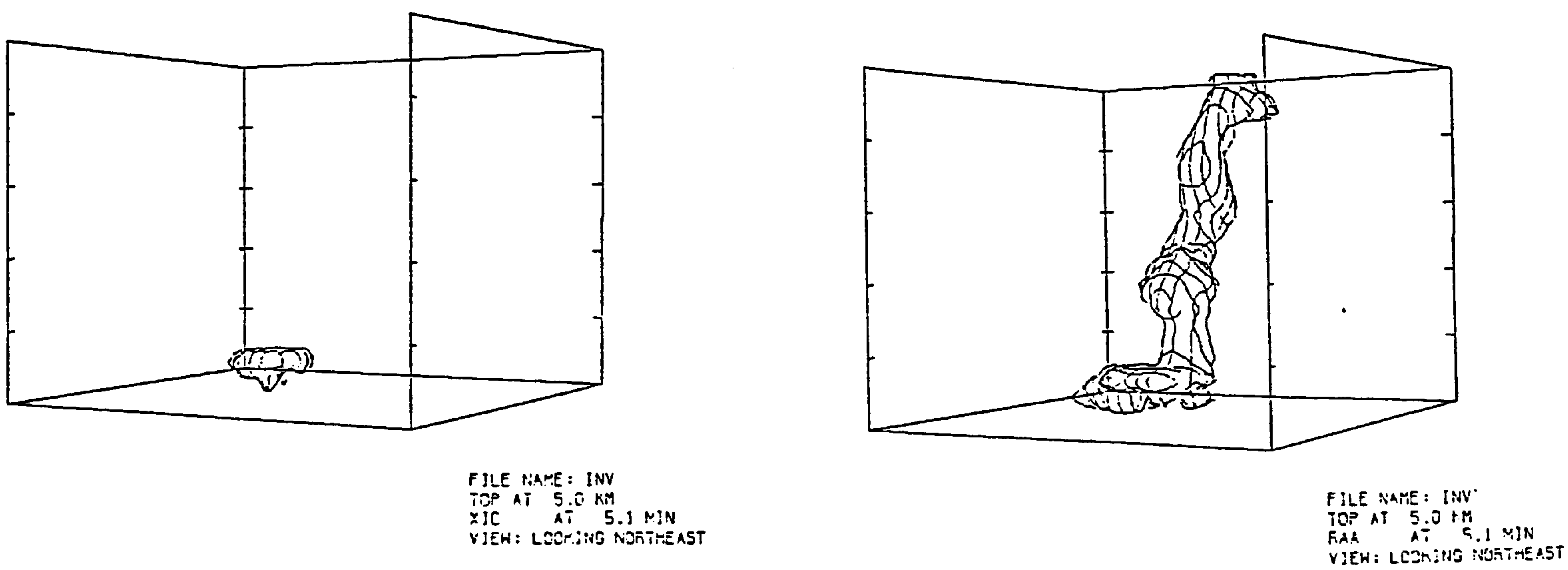


Figure 24. Cloud water (left) and smoke contours (right) looking northeast at 5 minutes after initialization for the Vandenberg (INV) sounding.

depth and relative longevity, since it is somewhat protected from entrainment at the top, could present hazards to aviation, hills, towers, etc. Deposition should occur in pulses as convective bubbles penetrate the inversion and collapse; however, by 5 minutes much of the vertical motion seems to be over below 500 m. This might be a result of model resolution as there are only 2 grid points in the vertical below 500 m. Note that at a nominal 5 ms^{-1} updraft, it would only take about 100 seconds for mm drops to reach the top of their trajectory and begin descending.

SECTION 4. EMPIRICAL FORECAST TECHNIQUES

Introduction

The simulations discussed earlier were performed with the TASS model in an effort to better understand the dynamics of the Shuttle exhaust cloud in a variety of environments. Data from ten of these simulations were utilized to determine if some of the characteristics of the exhaust clouds as indicated by the model can be predicted from routine observations. If such a predictable relationship can be demonstrated, statistically, then forecasters could estimate the behavior of the exhaust cloud based largely on observed environmental variables.

Methodology

In this study the vertical atmospheric structure employed to initialize the TASS model was derived from seven observed soundings at the Kennedy Space Center and Vandenberg Air Force Base as well as one sounding derived from the MASS model [Kaplan et al., 1982] simulation of the environment at the Kennedy Space Center near the time of a Shuttle launch. Modified versions of the 8/30/84 mission 41D unstable sounding are employed in the remaining two simulations which comprise the 10 simulations utilized in this statistical analysis. All of the dates of these case studies, which included both highly stable and convectively unstable regimes, are listed in Table 3, while the soundings employed in the 10 simulation experiments were presented in the previous sections or in the companion report.

Two simulated cloud parameters were selected as potential predictands: TASS simulated maximum cloud top height and maximum layer liquid water content. These were categorized for all 10 case studies. These two variables

Table 3. Case Studies for Rocket Exhaust Ground Cloud Simulations

CASE	ABBREV.	DATE	TIME (GMT)	ATMOSPHERE
KSC Mission 41C	41C	04/06/84	1200	Dry, unstable, inversion
KSC Mission 41D	41D	08/30/84	1242	Moist, unstable, inversion
Modified Mission 41D	UNS41D	08/30/84	1242	Moist, very unstable
Modified Mission 41D	MOS41D	08/30/84	1242	Moist, very unstable
KSC Mission 51A	51A	11/08/84	1215	Unstable, Windy, inversion
VBG Inversion	INV	06/24/87	1200	Strong inversion
TITAN Explosion	TITAN	04/18/86	1815	Stable
KSC Unstable Sounding	UNS	08/30/83	0115	Very unstable
Model Atmosphere	MASS	08/30/83	0300	Very unstable
KSC Mission STS-3	STS-3	03/22/82	1600	Unstable, inversion

were selected because they represent the height to which potential pollutants could rise and the amount of cloud water available to supplement the atomized deluge water for post-launch acid deposition. In an effort to determine the most reliable objective predictors of these 2 variables, data from the observed soundings, MASS model-generated soundings, and modified observed soundings were employed to calculate the correlation coefficient and the "line of best fit" between the TASS-simulated parameters and environmental variables. All TASS-simulated information was restricted to the evolution of simulated variables over 9 minutes of "real" time. The description of the assumptions concerning heat and moisture input from the Shuttle itself, are described in the companion report. Table 4 depicts the environmental parameters calculated for each sounding employed in the statistical analyses of the 10 simulation experiments. There were seven parameters derived for each sounding: 1) 500 mb lifted index, LI (C^o); 2) surface temperature, TS (C^o); 3) surface dewpoint temperature, TDS (C^o); 4) average dewpoint depression over a 50 mb deep layer summed from 1000 mb to 700 mb, $\overline{T-TD}$ (C^o); 5) average dewpoint temperature over a 50 mb deep layer summed from 1000 mb to 700 mb, $\overline{TD}$ (C^o); 6) the maximum vertical increase in temperature (inversion) over any 50 mb deep layer between 1000 mb and 700 mb, INVMAX (C^o); and (7) an index which combines all of these six variables, $I = -LI + TS + TDS - (\overline{T-TD}) - INVMAX + \overline{TD}$. The basic dynamical assumption behind the selection of the specified variable was to find a simple indicator of: 1) positive buoyant energy (LI), 2) surface static energy (TS + TDS) which approximates $C_pT + Lq_s + \phi$ where ϕ is the geopotential (zero at the surface), 3) average lower tropospheric column relative humidity ($\overline{T-TD}$), 4) the average lower tropospheric moisture (TD), and 5) the intensity of a restraining "lid", (INVMAX) all of which represent simple buoyancy-related thermodynamical

TABLE 4. Comparison of Environmental Parameters and Model Results for Ten Cases

PARAMETER									
	MODEL		DETERMINED FROM SOUNDING						
CASE	MAX CLOUD HEIGHT	MAX LAYER LIQUID WATER (Altitude)	LI (°C	TS (°C)	TDS (°C)	INV MAX (°C)	$\overline{T-TD}$ (°C)	$\overline{TD}$ (°C)	I (°C)
41D 8/30/84 1242 GMT	3200m	1.00 g/kg (200m)	-6	26	23	0	5	10	60
51A 11/08/84 1215 GMT	2400	1.20 (200m)	6	20	13	4	7	0	16
MASS 08/30/83 0300 GMT	2400	0.39 (1200m)	-5	28	26	0	4	15	70
UNS41D 08/30/84 1242 GMT	3300	0.80 (300m)	-6	26	23	0	5	10	60
INV 06/24/87 1200 GMT	400	0.86 (200m)	16	11	11	16	18	-6	-34
TITAN 04/18/86 1815 GMT	800	0.0	10	17	8	1	11	-6	-3
41C 04/06/84 1200 GMT	1600	0.20 (200m)	6	16	7	3	11	-4	-1
UNS 08/30/83 0400 GMT	3300	0.29 (200m)	-4	23	22	3	4	14	56
STS-3 03/22/82 1600 GMT	1400	0.17 (200m)	0	24	17	2	10	2	3
MOS41D 08/30/84 1242 GMT	3300	1.00 (200m)	-6	26	23	0	3	13	65
AVERAGE	2170	0.59	1	22	17	3	8	5	32
S	1074	0.16	8	4	7	5	4	8	34
S^2	1,153,476	0.026	64	16	49	25	16	64	1156

indices that forecasters have used in the past to estimate convective cloud height, intensity, and rate of development. The 700 mb level was selected as the highest level for dewpoint, inversion strength, and dewpoint depression calculations because both observed ground truth and TASS simulations indicated that the top of the Shuttle exhaust cloud rarely penetrated significantly beyond about 3,000 meters. A 50 mb increment was employed as a representative sounding layer because it is somewhat similar to the depth over which significant layer data from rawinsondes would be available.

In an effort to determine how "predictable" are TASS simulated maximum cloud top height and maximum liquid water content in a TASS vertical layer from observed environmental parameters, we plotted scatter diagrams and then performed linear regression analysis. The hypothesis was that a linear functional relationship exists between the predictor and predictand thus enabling one variable to be "predictable" from another. Correlation is like covariance to the extent that it is a measure of the degree to which variables vary together or a measure of the intensity of association [Panofsky and Brier, 1965]. This can be determined subjectively by plotting a scatter diagram and determining the goodness (or badness) of fit of a line through the data or, more objectively, calculating R, the correlation coefficient and line of regression from:

$$R_{12} = \frac{(\overline{X_1 X_2} - \overline{X}_1 \overline{X}_2)}{(\overline{X}_1^{\,2} - (\overline{X}_1)^2)^{1/2}\ (\overline{X}_2^{\,2} - (\overline{X}_2)^2)^{1/2}}$$

and $X_2 = A + BX_1$, where: X_1 and X_2 are the two variables which, presumably, are related via a linear function (in this case TASS-simulated maximum cloud tops or maximum layer liquid water content for X_2 and a thermodynamic parameter from the observed upper air sounding for X_1); A is a constant and B is the slope of the line of regression [Panofsky and Brier, 1965]. This line is drawn so as to minimize the sums of squares of the deviations of individual values of X_2 from those predicted by the line. B can be determined from:

$$B = \frac{\overline{X_1 X_2} - \overline{X}_1 \overline{X}_2}{\overline{X_1^{\,2}} - (\overline{X}_1)^2}$$

Discussion

The results of the statistical analyses are shown in Figures 25-36 as well as Table 5. There is a marked difference in the predictability of TASS-simulated maximum cloud top heights as opposed to the predictability of maximum layer liquid water content from observed environmental variables alone. The former being well predicted while the latter being very poorly predicted. An examination of Figures 25-36 and Table 5 indicates that, with the exception of the inversion intensity, cloud top height is rather well correlated in a linear sense, with all of the thermodynamic variables. This is apparent from the close "fit" associated with the linear function as well as the relatively high values of R depicted collectively in Table 5. All but the strength of the inversion maximum correlate above 80%. The average dewpoint depression is the best predictor, while the combined index, lifted index, average dewpoint and surface static energy follow sequentially. F test values for these correlation coefficients rate significant at the 99% level, hence, indicating the unlikelihood that they are due to chance alone. It is quite apparent that a very strong relationship exists between the TASS-

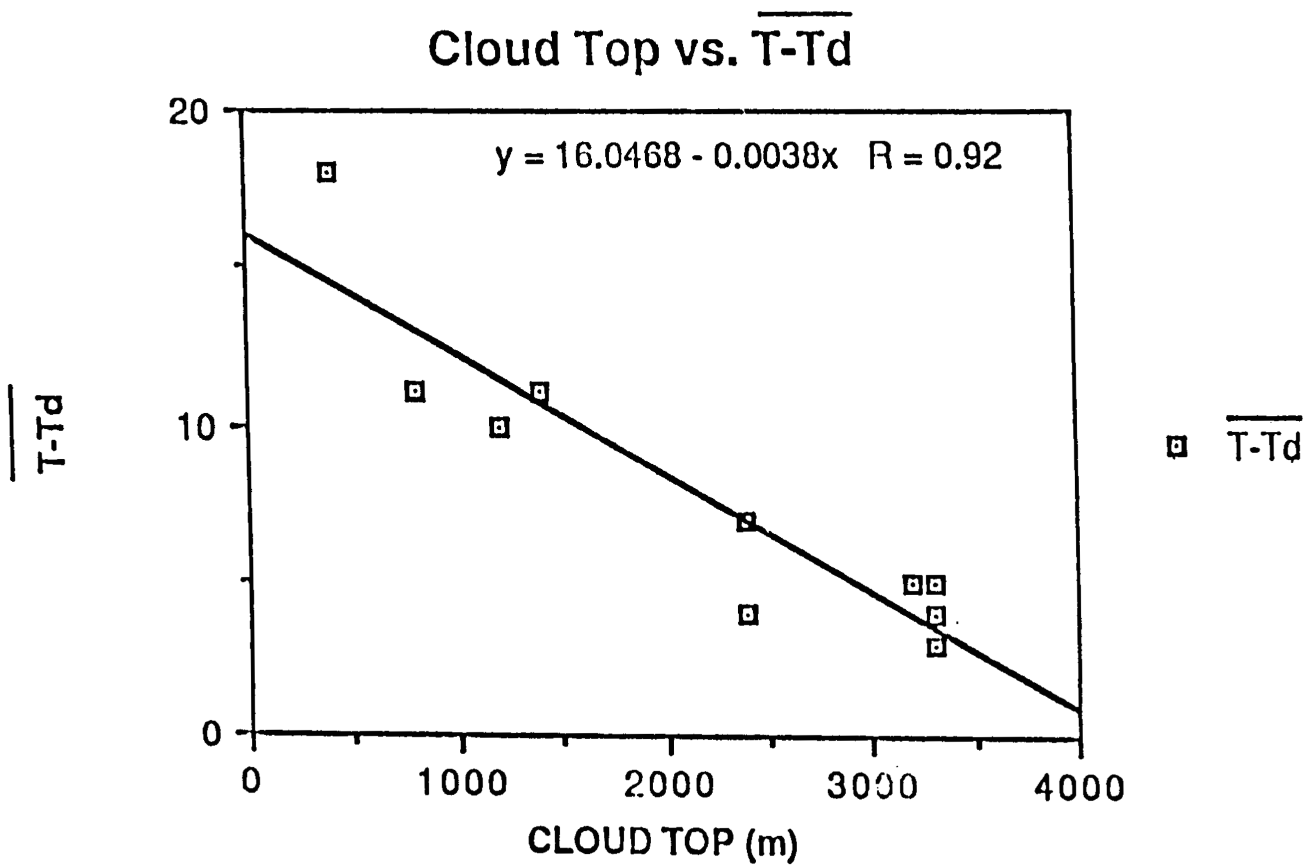

Cloud Top vs. T-Td
y = 16.0468 - 0.0038x R = 0.92
20
10
0
0
1000
2000
3000
4000
CLOUD TOP (m)
T-Td
T-Td

Figure 25.

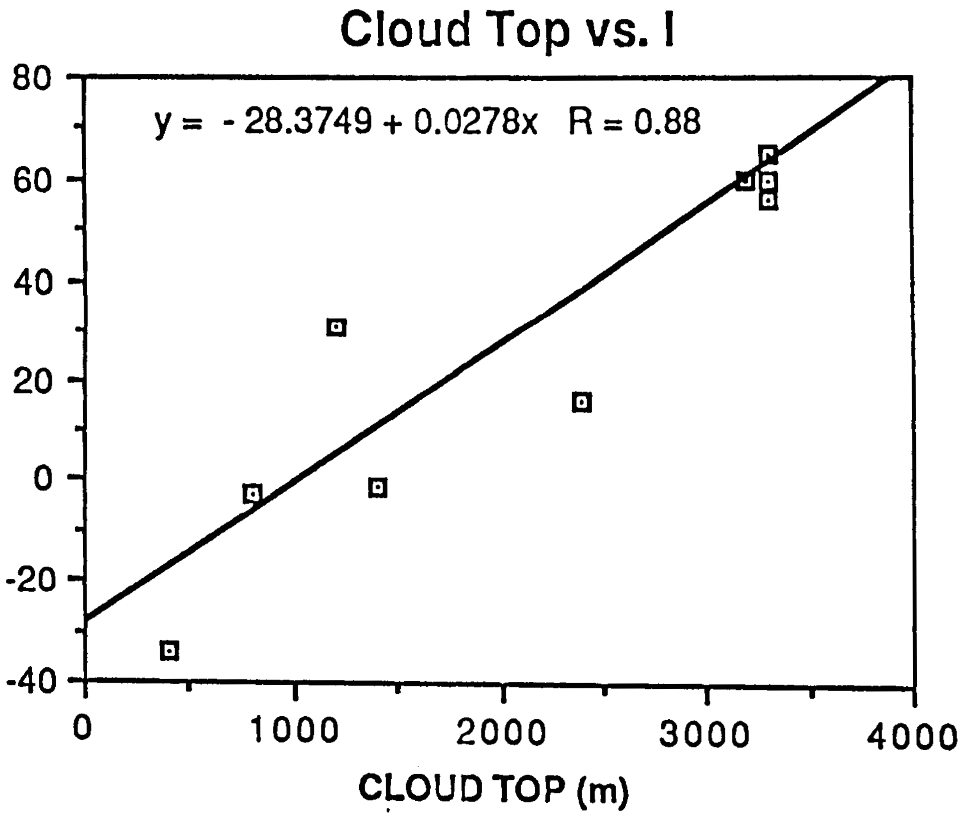

Cloud Top vs. I
y = - 28.3749 + 0.0278x R = 0.88
80
60
40
20
0
-20
-40
0
1000
2000
3000
4000
CLOUD TOP (m)

Figure 26.

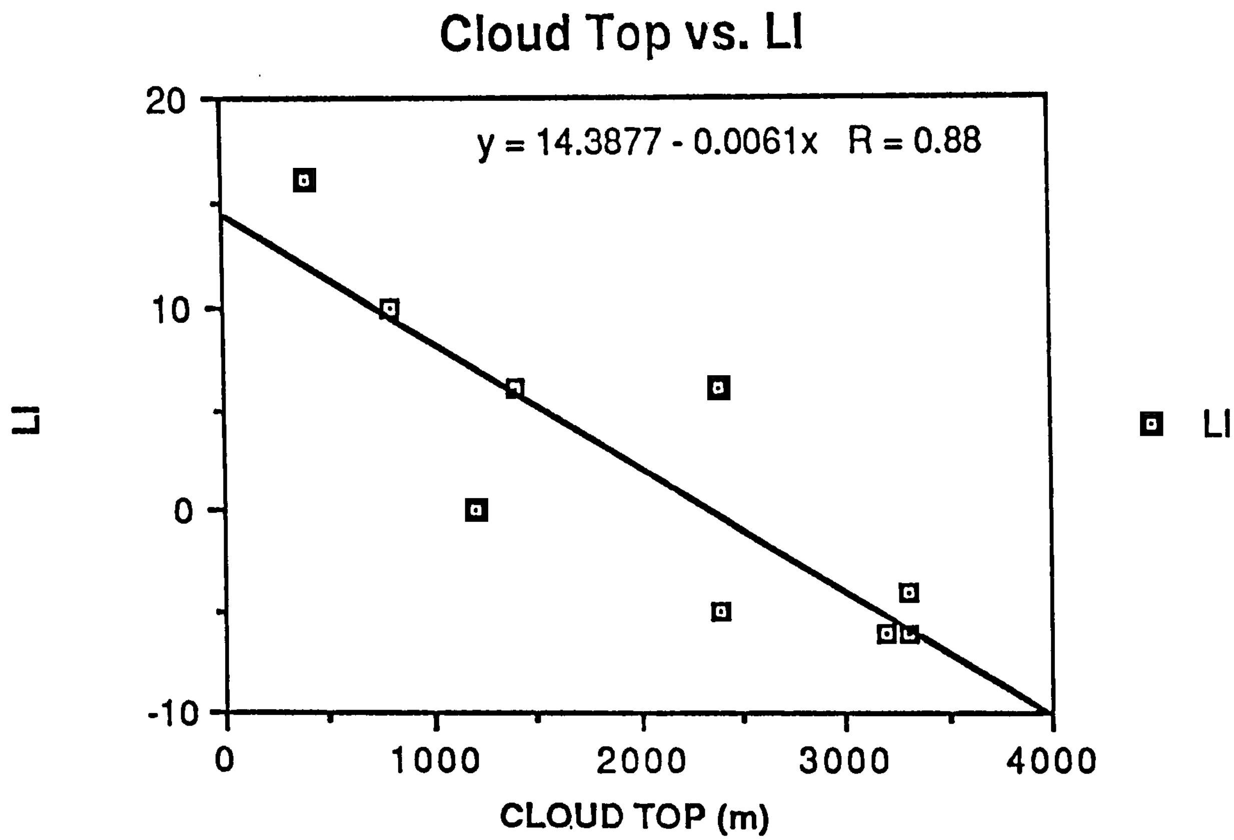
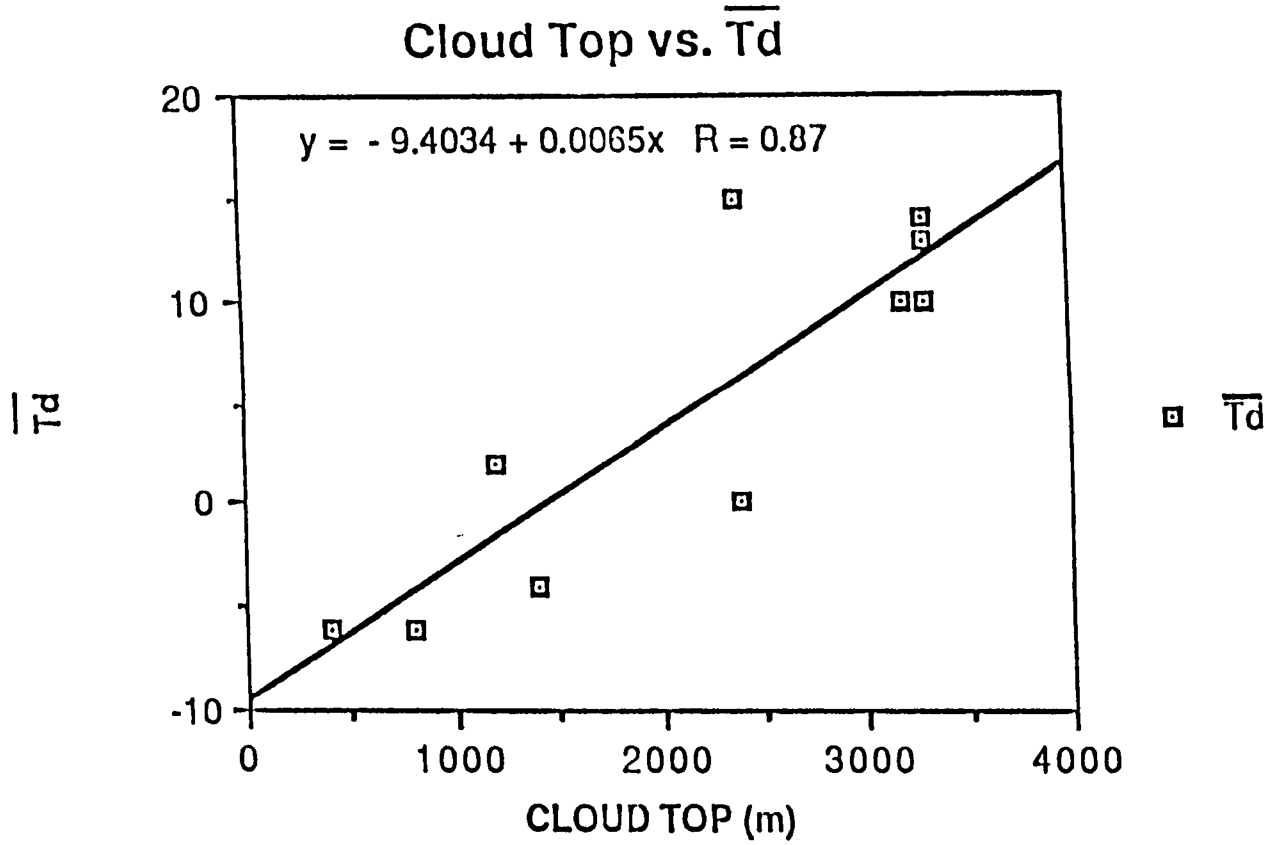

Cloud Top vs. LI
y = 14.3877 - 0.0061x R = 0.88
20
10
0
-10
LI
0
1000
2000
3000
4000
CLOUD TOP (m)
LI

Figure 27.



Cloud Top vs. Td
y = - 9.4034 + 0.0065x R = 0.87
20
10
0
-10
Td
0
1000
2000
3000
4000
CLOUD TOP (m)
Td

Figure 28.

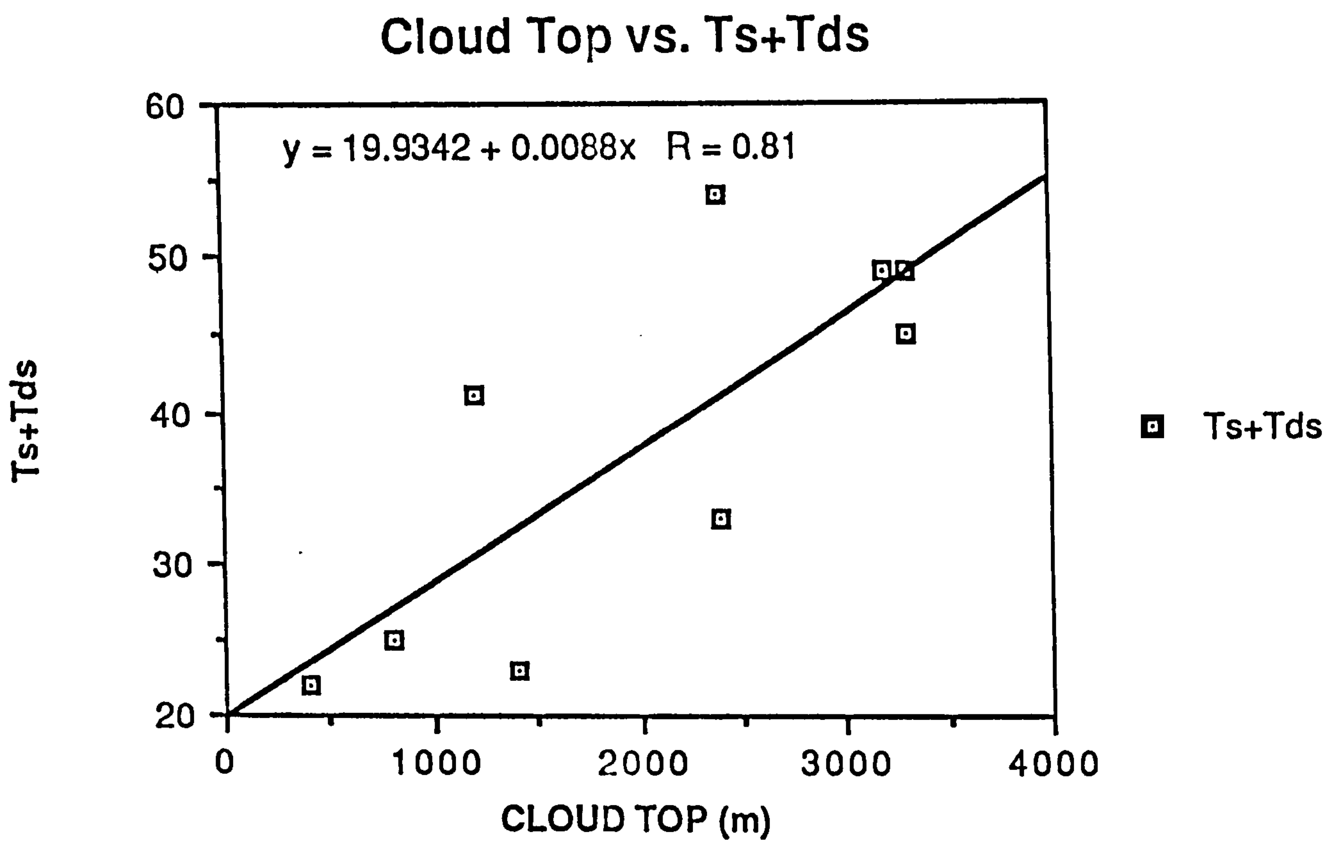
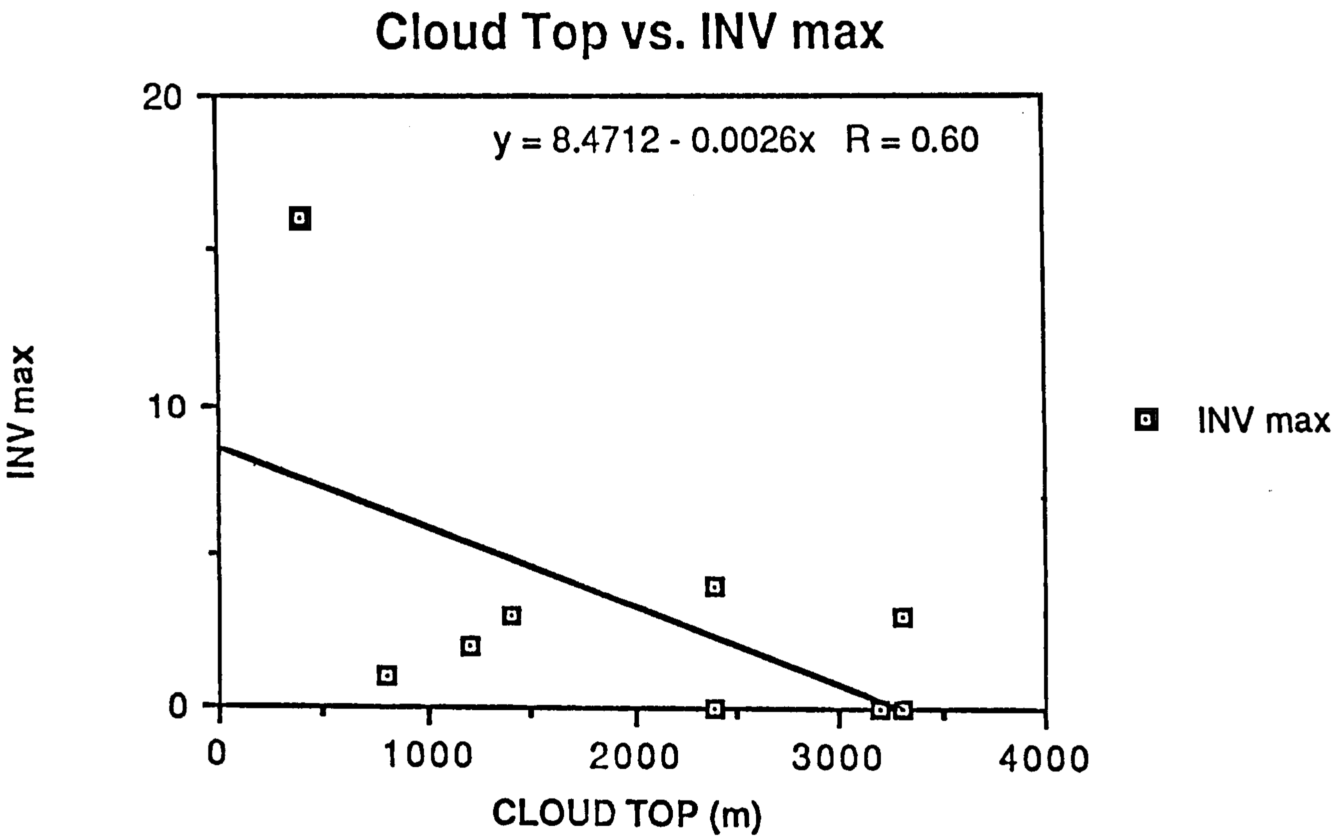

Cloud Top vs. Ts+Tds
y = 19.9342 + 0.0088x R = 0.81
60
50
40
30
20
0
1000
2000
3000
4000
CLOUD TOP (m)
Ts+Tds
Ts+Tds

Figure 29.



Cloud Top vs. INV max
y = 8.4712 - 0.0026x R = 0.60
20
10
0
INV max
0
1000
2000
3000
4000
CLOUD TOP (m)
INV max

Figure 30.

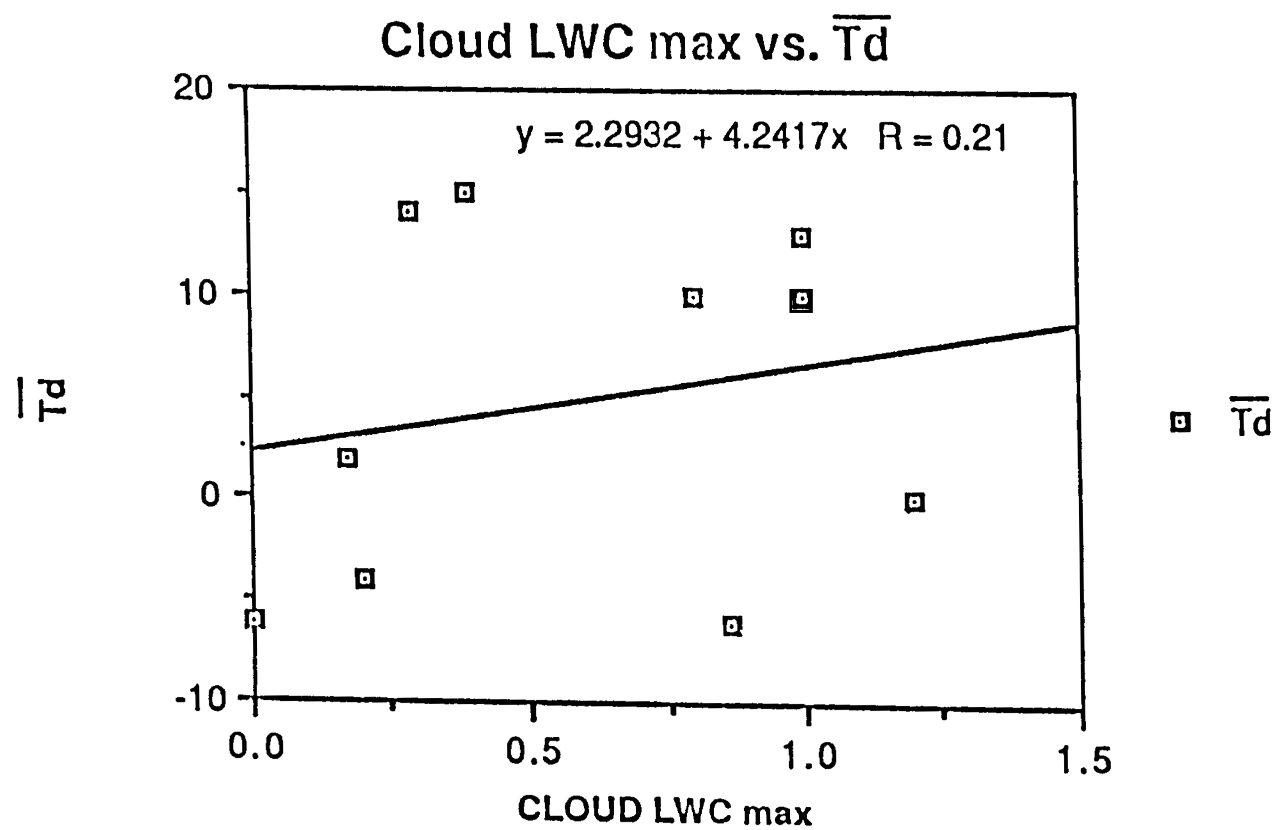

Cloud LWC max vs. $\overline{Td}$
y = 2.2932 + 4.2417x R = 0.21
20
10
0
-10
0.0
0.5
1.0
1.5
CLOUD LWC max
$\overline{Td}$
$\overline{Td}$

Figure 31.

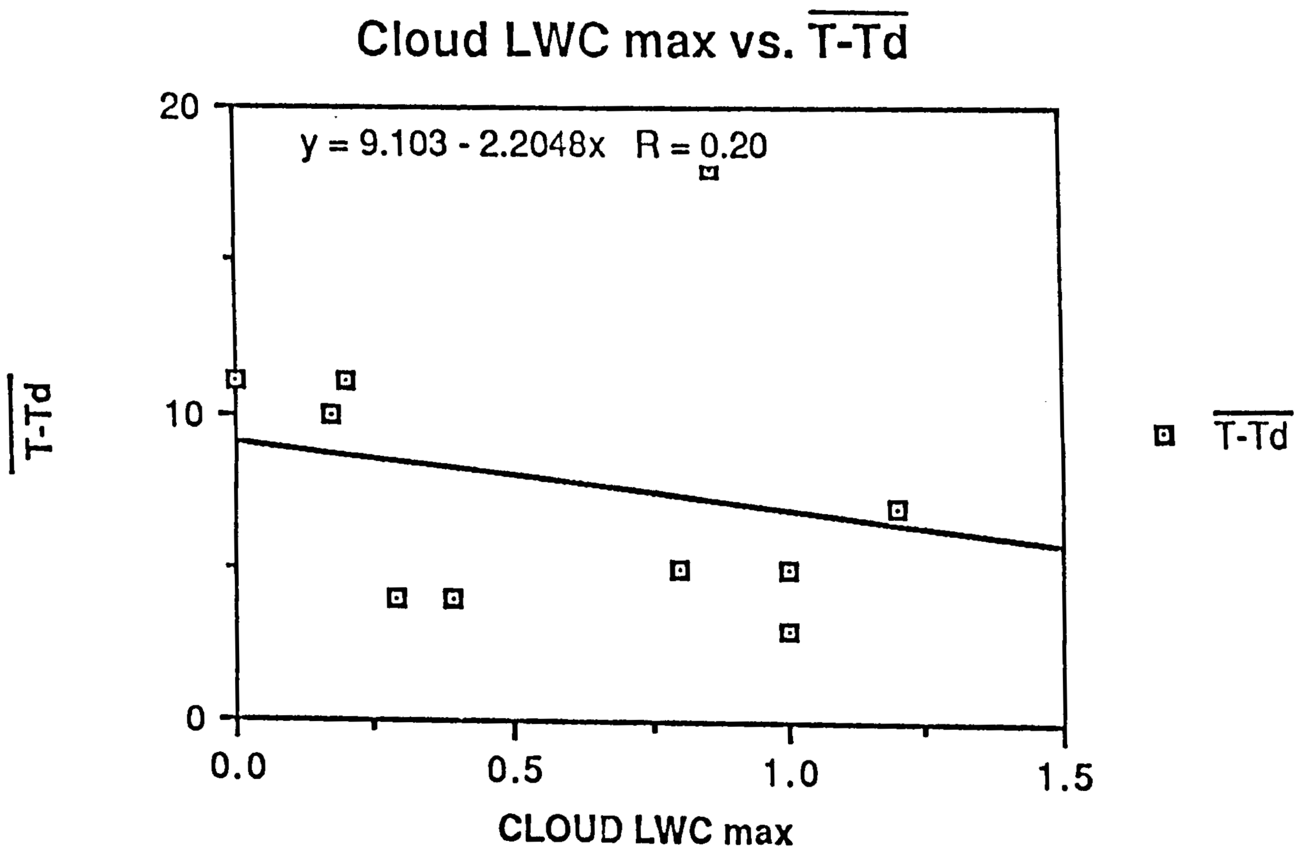

Cloud LWC max vs. T-Td
y = 9.103 - 2.2048x R = 0.20
20
10
0
T-Td
0.0
0.5
1.0
1.5
CLOUD LWC max
T-Td

Figure 32.

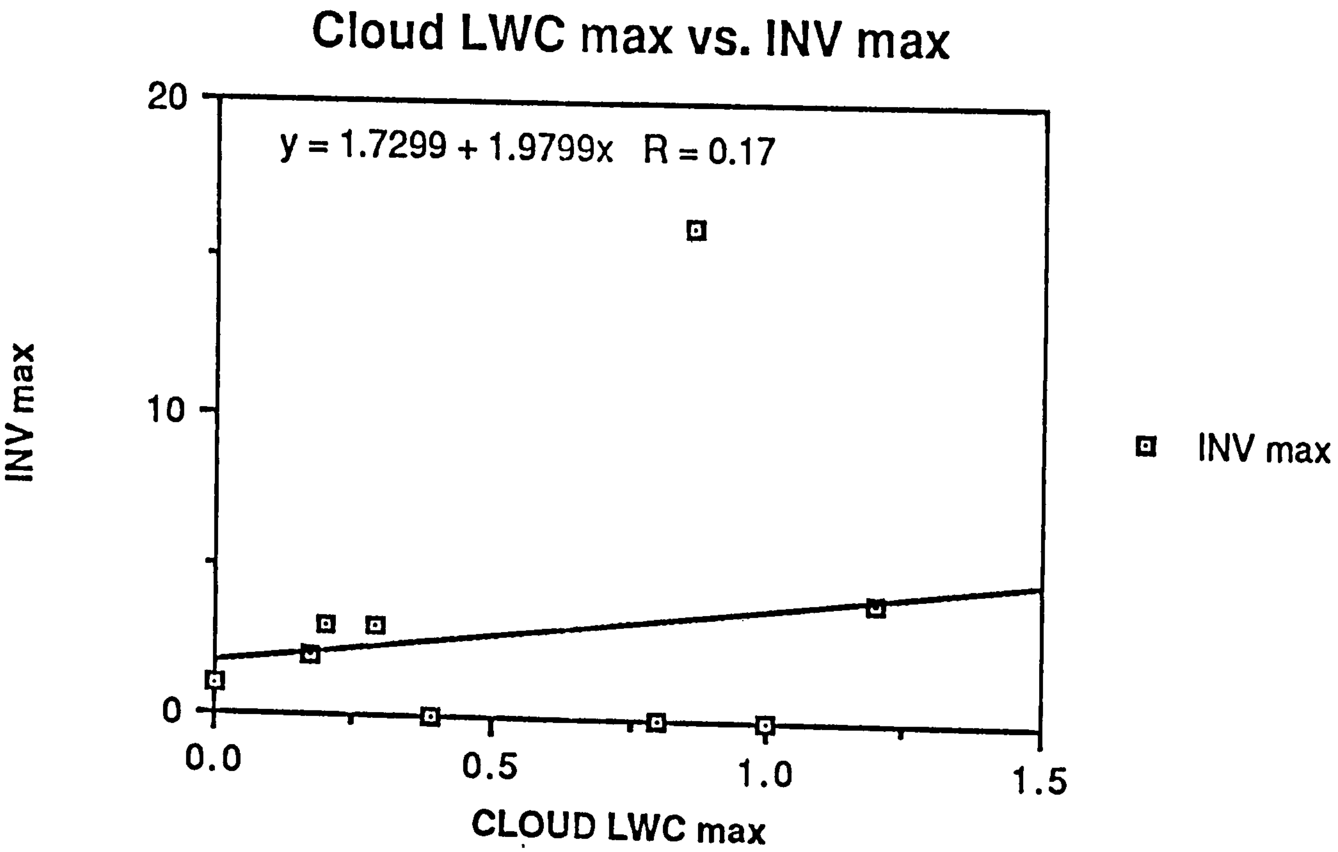

Cloud LWC max vs. INV max
y = 1.7299 + 1.9799x R = 0.17
20
10
0
0.0
0.5
1.0
1.5
INV max
CLOUD LWC max
INV max

Figure 33.

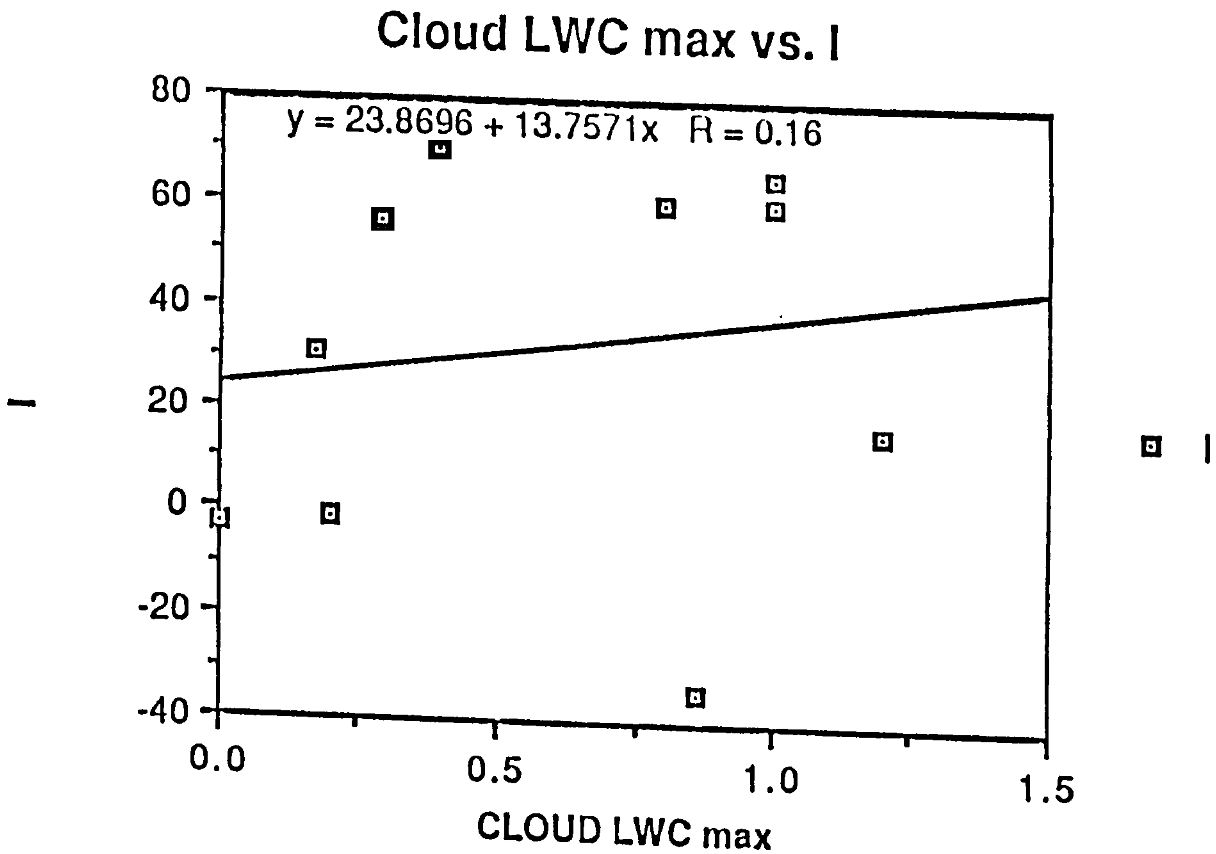

Cloud LWC max vs. I
y = 23.8696 + 13.7571x R = 0.16
80
60
40
20
0
-20
-40
0.0
0.5
1.0
1.5
CLOUD LWC max
I

Figure 34.

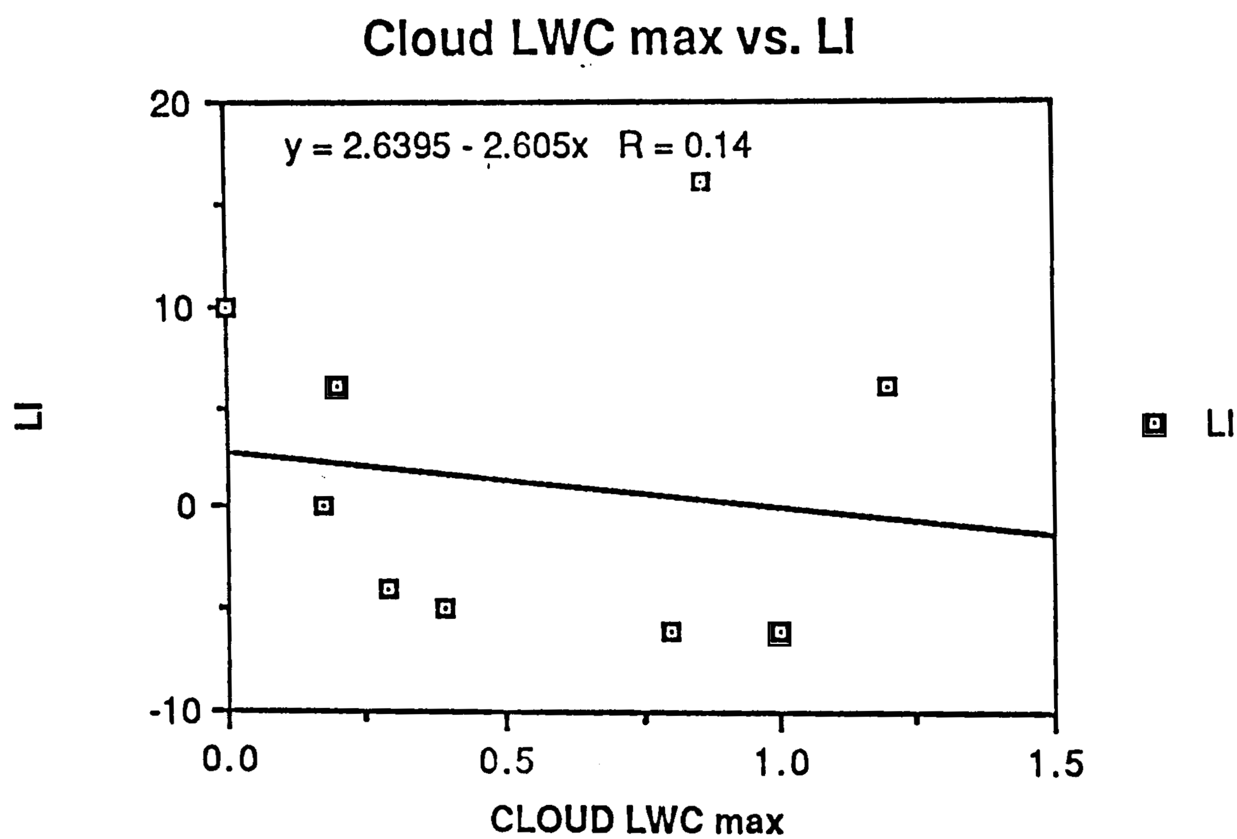
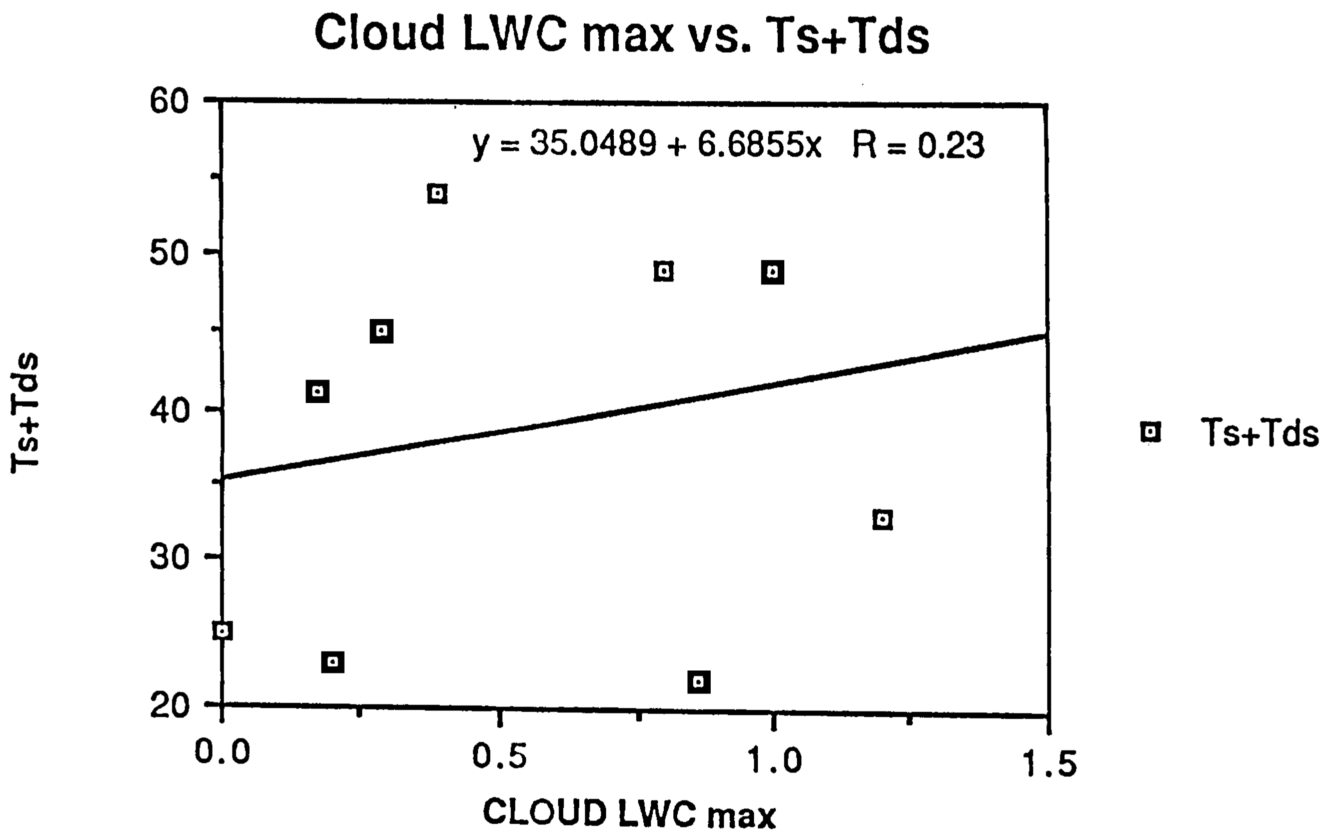

Cloud LWC max vs. LI
y = 2.6395 - 2.605x R = 0.14
20
10
0
-10
0.0
0.5
1.0
1.5
CLOUD LWC max
LI
LI

Figure 35.



Cloud LWC max vs. Ts+Tds
y = 35.0489 + 6.6855x R = 0.23
60
50
40
30
20
0.0
0.5
1.0
1.5
Ts+Tds
CLOUD LWC max
Ts+Tds

Figure 36.

TABLE 5: CORRELATION COEFFICIENTS (R) FOR COMPARISON BETWEEN MODEL GENERATED MAXIMUM CLOUD TOP HEIGHT AND MAXIMUM LIQUID WATER CONTENTS WITH ENVIRONMENTAL PARAMETERS

ENVIRONMENTAL PARAMETER (see text)	LINEAR CORRELATION COEFFICIENT (R)	
	MAXIMUM CLOUD TOP HEIGHT	MAXIMUM LAYER LIQUID WATER CONTENT
$\overline{T-TD}$	-0.92	-0.20
I	0.88	0.17
LI	-0.88	-0.14
$\overline{TD}$	0.87	0.21
TS+TDS	0.82	0.09
INVMAX	-0.60	0.18

simulated cloud top height and the average column dewpoint depression. This was further verified by comparing photogrammetry for missions 41D and 51A to the TASS-simulated cloud top height. Excellent verifications were achieved further supporting the concept that TASS accurately simulates the top of the Shuttle exhaust cloud. One can intuitively assume that cloud top height is strongly dependent upon the available buoyant energy in the column which is strongly dependent upon the environmental relative humidity, i.e., the greater the amount of moisture for buoyancy, the less cloud erosion by evaporation and the deeper the cloud. All of the environmental variables which are a direct function of moisture correlated significantly high with cloud top height.

It is also interesting to note which case studies were the most difficult to "fit" or correlate. As the predictability of a given variable became weaker, case studies STS-3, UNS, MASS, and 51A tended to contribute the largest percentage of the variance. In the case of UNS and STS-3 simulated cloud tops appear to be lower than would be expected from the line of best fit yet for the 51A case study just the opposite was true. The former tend to have in common the fact that each sounding was rather inhomogeneous, i.e., there was either a very moist layer sandwiched between 2 very dry layers or vice versa; hence, the distribution of relative humidity and positive buoyant energy was not uniform over a substantial depth of the tropospheric column, reducing the hardiness of the statistical relationship between the observed variables and the TASS-simulated maximum cloud top height. In spite of these "outliers", and assuming that TASS replicates the exhaust cloud dynamics accurately, observed T-TD, LI, TD, TS + TDS, and the Index (I) are all useful predictors of Shuttle exhaust cloud top height with the T-TD variable being an excellent predictor. The best predicted (most highly correlated) cases include the very moist unstable soundings and the very dry stable soundings where there is a fairly uniform vertical distribution of either very moist or dry air. A slight exception to the above statement being the 6/24/87 Vandenberg inversion sounding where a very shallow moist layer exists, but throughout most of the column it is extremely dry and stable. Here, the effect of the low-level inhomogeneity in the sounding was overwhelmed by the deep, very dry homogeneous layer.

While TASS-simulated maximum cloud top height is well correlated with most observed thermodynamical variables, TASS-simulated maximum layer liquid water content (LWCmax) was not. Very low values of the correlation coefficient, R, all less than .22, exist for LWCmax and the same 6 variables as can be seen in Figures 30-36. The best of the poor group is $\overline{TD}$, with $\overline{T-TD}$, INVMAX I, LI, and TS + TDS following in order of decreasing correlation coefficient. The fit is so bad for LI and TS + TDS that 2 lines can be drawn indicating multiple clusters. In fact, the sign of R is positive for INVMAX indicating just the opposite correlation trend than one would intuitively expect, i.e., relatively high LWCmax values with stronger inversions. This may reflect inherent weakness in TASS but is more likely an indication of the transient nature of LWXmax values and the more complex nonlinear dynamics associated with shallow inhomogeneous vertical layers of moisture on positive buoyant energy. Total liquid water content integrated over the entire cloud is probably a much more predictable variable when employing these statistical techniques than is LWCmax for a given layer since, for example, a shallow moist layer located close to the Shuttle heat source could produce large values of LWCmax even though most of the column contained a homogeneous very dry stable sounding. An excellent example of this can be seen in the 6/24/87 Vandenberg inversion (case INV). Here all of the LWC is near the ground so that a low layer could have a great deal of LWC while most of the column is cloudless. LWCmax is relatively transient and probably better suited for nonlinear statistical analyses than simple linear analyses. Case studies 41D, MOS41D, UNS41D all derived from the mission 41D sounding represent the only consistently predictable case studies, i.e., studies which correlate well with the LWCmax values predicted by TASS. This is a warm, moist, unstable sounding in which all of the simulations produced maximum values of liquid water between 0.8 and 1.0 gram/kilogram. Since the values of LWCmax were usually at very low levels, i.e., 200-300 meters, they would not guarantee, necessarily, that there were deep layers of high relative humidity or significant instability in a given column; hence, limiting the effectiveness of variables averaged over deep layers.

Summary

In summary, a simple statistical analysis employing linear regression indicated that TASS-simulated cloud top height can be predicted from a variety of thermodynamic variables observed at model initialization time. This was not true for the maximum liquid water content simulated by the TASS model for a given layer. The excellent correlation for the former and the poor for the latter probably reflects the fact that maximum cloud top height is forced by deeper, less transient physical processes while maximum layer liquid water content is forced by relatively shallow more transient physical/dynamical processes. This relatively small sample indicates that very useful forecasts of height of the Shuttle exhaust ground cloud can be obtained by determining the mean relative humidity or dewpoint depression in the lower troposphere and employing the functional relationship such as depicted in Figure 25. On the contrary, it is extremely difficult to accurately estimate the level or the amount of maximum layer liquid water content <u>without</u> running the TASS model or a similar model.

SECTION 5. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The cloud model can produce clouds which resemble the Space Shuttle ground cloud in size, volume, maximum tops, vertical motion, liquid water content, movement, growth and decay for the cases where measurements existed. The bubble motion of different convective elements was also reproduced in the model but the rise time was about a minute slower in the model than for observed clouds.

The combined effects of ambient atmospheric temperature, moisture content and wind are dominant factors in the shape, maximum cloud top, liquid water contents, vertical velocity and longevity of simulated ground clouds. Model clouds show relatively high degrees of asymmetry in all runs. Maximum asymmetry occurs with maximum low level wind shear. The initial partioning of heat and moisture from the launch system as well as the separation or location of the input (eg., surface grid points affected) is important in the initial shape of the lower ground cloud, but not important to max cloud top in model results. Wind shear in the column smoke field dramatically altered the appearance of the column. There were sections of the vertical column which were tilted nearly 90° in response to wind direction and speed changes.

Different amounts of low level moisture and heat in the environment controlled the production of liquid cloud water in the model. Amount of cloud water produced in the model ground cloud was very sensitive to the amount of available moisture and degree of saturation in the lower 3 km of the atmosphere. Some atmospheres (TITAN), which were very dry in the low levels (less than 3 km), failed to generate any natural cloud liquid water in the model.

Maximum cloud tops can exceed 3 km in unstable, moist atmospheres, both the maximum observed top in any simulation with realistic initial conditions was about 4.0 km. The most unstable atmosphere presented to the model did not produce a sustaining precipitation-generating cloud. When the size of the initial heat and moisture was doubled for the unstable atmosphere, a significantly larger (liquid water content) cloud developed. It continued to rise to about 12 minutes, but the cloud top reached stabilization at only 4.5 km.

The presence of a temperature inversion helped to prevent erosion of the cloud top through entrainment. When the inversion was eliminated the cloud decayed more quickly. A strong low level inversion trapped the ground cloud below it. Max tops were only about 500 m in one case. Maximum cloud top from the model can be estimated from observable atmospheric low level parameters. Maximum liquid water content can not be so estimated.

Recommendations

Further research is needed on the effects of wind, wind shear, and model resolution on cloud water generation and cloud integrity. Additional study effort is also needed on how to retain the fundamentals of full cloud models in an operational environment with implied reduced computer speed and storage. These models should be easy to execute and provide output displays which are easy to interpret. A further suggestion is to implement precipitation scavenging and treatment of HCL in the cloud model and to modify output routines to depict HCL surface deposition. Finally, we would recommend the use of a cloud model in the operational environment for any of the following conditions:

- A low level temperature inversion (any temperature increase with height below 1 km). For these situations, the operational model now employed could produce misleading results.
- Winds greater than about 7 m/s in the atmosphere below 4 km; the wind could prevent the merging of all cloud elements or split the vertical cloud into discontinuous segments; the wind shear could also alter cloud moisture during its vertical development phase.
- Low levels of the atmosphere near saturation and unstable; this could produce significant additional liquid cloud water as well as more vigorous vertical motions for toxins to rise further and fall slower.
- Days with naturally existing towering cumulus or rain showers with which the ground cloud could interact in one of two ways: increase the liquid water content of the natural cloud slightly or be affected by precipitation from a natural cloud to enhance deposition of toxic cloud material.
- Days when anticipated low level winds would move the cloud over populated areas.

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16. ABSTRACT

A three-dimensional cloud model was used to characterize the dominant influence of the environment on the Space Shuttle exhaust cloud. The model was modified to accept the actual heat and moisture from rocket exhausts and deluge water as initial conditions. An upper-air sounding determined the ambient atmosphere in which the cloud could grow. The model was validated by comparing simulated clouds with observed clouds from four actual Shuttle launches. Results are discussed with operational weather forecasters in mind. The model successfully produced clouds with dimensions, rise, decay, liquid water contents and vertical motion fields very similar to observed clouds whose dimensions were calculated from 16 mm film frames. Once validated, the model was used in a number of different atmospheric conditions ranging from very unstable to very stable. In moist, unstable atmospheres simulated clouds rose to about 3.5 km in the first 4 to 8 minutes then decayed. Liquid water contents ranged from 0.3 to 1.0 g kg^{-1} mixing ratios and vertical motions were from 2 to 10 ms^{-1}. An inversion served both to reduce entrainment (and erosion) at the top and to prevent continued cloud rise. Even in the most unstable atmospheres, the ground cloud did not rise beyond 4 km and in stable atmospheres with strong low level inversions the cloud could be trapped below 500 m. Wind shear strongly affected the appearance of both the ground cloud and vertical column cloud. The ambient low-level atmospheric moisture governed the amount of cloud water in model clouds. Some dry atmospheres produced little or no cloud water. An empirical forecast technique for Shuttle cloud rise is presented and differences between natural atmospheric convection and exhaust clouds are discussed.

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