JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D4, PAGES 3929-3936, FEBRUARY 27, 1998

Environmental conditions required for contrail formation and persistence

Eric J. Jensen,[1] Owen B. Toon,[2] Stefan Kinne,[3] Glen W. Sachse,[4] Bruce E. Anderson,[4] K. Roland Chan,[1] Cynthia H. Twohy,[5] Bruce Gandrud,[5] Andrew Heymsfield,[5] and Richard C. Miake-Lye[6]

Abstract. The ambient temperatures and humidities required for contrail formation and persistence are determined from in situ measurements during the Subsonic Aircraft: Contrail and Cloud Effects Special Study (SUCCESS) experiment. Ambient temperatures and water vapor concentrations were measured with the meteorological measurement system, a laser hygrometer, and a cryogenic hygrometer (all onboard the DC-8). The threshold temperatures are compared with theoretical estimates based on simple models of plume evolution. Observed contrail onset temperatures for contrail formation are shown to be 0–2 K below the liquid-saturation threshold temperature, implying that saturation with respect to liquid water must be reached at some point in the plume evolution. Visible contrails observed during SUCCESS persisted longer than a few minutes only when substantial ambient supersaturations with respect to ice existed over large regions. On some occasions, contrails formed at relatively high temperatures ($\geq -50°C$) due to very high ambient supersaturations with respect to ice (of the order of 150%). These warm contrails usually formed in the presence of diffuse cirrus. Water vapor from sublimated ice crystals that entered the engine was probably necessary for contrail formation in some of these cases. At temperatures above about –50°C, contrails can only form if the ambient air is supersaturated with respect to ice, so these contrails should persist and grow.

1. Introduction

During recent years, considerable attention has been focused on the climatic impact of clouds. Of particular interest is the possibility that as anthropogenic influences alter the atmosphere and climate, cloud properties may change, resulting in a cloud-climate feedback [Twomey, 1974; Ackerman et al., 1997]. Contrails formed by jet aircraft in the upper troposphere are ice clouds formed directly by anthropogenic injections into the atmosphere. Hence, contrails represent a direct anthropogenic influence on clouds and possibly on climate. Past studies have analyzed the effect of contrails on climate in particular regions by compiling climatologies of contrails based on ground-based observations [Liou et al., 1990]. Evaluation of the contrail influence on global climate will require use of satellite observations. Assessment of potential future contrail climate impacts based on projected air traffic requires a knowledge of the environmental conditions required for contrail formation. The contrail threshold conditions also provide information about how effective aircraft exhaust particles are as ice nuclei.

Numerous theoretical studies of the thermodynamics of contrail formation have been conducted during the past several decades (see Schumann [1996] for a detailed review). Appleman [1953] used simple arguments about the evolution of temperature and water vapor in aircraft exhaust plumes to predict threshold temperatures and pressures at which contrails could form. Attempts have been made to validate the predicted threshold temperatures using ground-based observations of contrails and nearly colocated radiosonde measurements of temperature and humidity [Peters, 1993; Busen and Schumann, 1995]. However, the inaccuracy of radiosonde humidity measurements and the separation between humidity measurements and the contrails have limited the usefulness of these studies. Recently, Schumann et al. [1996] reported in situ measurements of temperature and hu-

[1]NASA Ames Research Center, Moffett Field, California.
[2]University of Colorado, Department of Atmospheric Sciences, Boulder.
[3]Bay Area Environmental Research Institute, San Francisco, California.
[4]NASA Langley Research Center, Hampton, Virginia.
[5]National Center for Atmospheric Research, Boulder, Colorado.
[6]Aerodyne Research, Inc., Billerica, Massachusetts.

Paper number 97JD02808.
0148-0227/98/97JD-02808$09.00

midity at contrail onset times for a flight following a moderate-sized research aircraft. Their results were in aggreement with the theoretical predictions of threshold temperatures assuming liquid saturation in the plume is required for contrail formation.

In addition to determination of how frequently contrails form, it is also important to distinguish between transient and persistent contrails. The vast majority of visible contrails dissipate within a few minutes. Such contrails have little potential for affecting the radiation balance or climate. Occasionally, contrails are observed to persist and even grow. Sometimes, the contrails last for hours and spread into sheets. The persistence and spreading of contrails will determine their impact on the radiation balance. Hence, we need to determine the relationship between contrail lifetime and ambient conditions.

In this study, we have used measurements made during the Subsonic Aircraft: Contrail and Cloud Effects Special Study (SUCCESS) to correlate environmental conditions with contrail formation and persistence. Very precise in situ measurements of temperature and water vapor concentration were made with various instruments on the NASA DC-8 aircraft during SUCCESS. Contrails from the DC-8 were identified by chase aircraft, ground observers, DC-8 aft video, ER-2 nadir imaging, and satellite images. Below, we briefly review the standard theoretical treatment for predicting threshold conditions for contrail formation [Appleman, 1953]. Next, we describe the SUCCESS temperature, humidity, and contrail observations. Then we compare the theoretical predictions and observed threshold conditions. Finally, we discuss the implications of these results for current theories of contrail formation processes.

2. Theoretical Prediction of Contrail Threshold Temperatures

The first detailed analysis of the environmental conditions required for contrail formation was conducted by Appleman [1953], and the topic was recently reviewed in detail by Schumann [1996]. These analyses were based primarily on the assumption that the temperature and water vapor mixing ratio in the plume are both controlled by entrainment of ambient air into the plume. Using this assumption we can calculate the water vapor concentration and temperature in the plume given the ambient temperature and water vapor concentration as well as the emission indices for heat and water vapor (heat and water vapor mass per gram of fuel burned).

Appleman [1953] argued that whenever the available moisture was greater than that required to reach saturation in the plume, a contrail could form. He thus calculated threshold temperatures for contrail formation graphically. The threshold temperature turns out to be a function of both the ambient relative humidity and the ambient pressure. Using the U.S. Standard Atmosphere (40°N) temperature and pressure profiles, Appleman showed that contrails should typically form under ambient ice-saturated conditions at pressures below about 300 mbar. This analysis also indicated that formation of contrails in dry ambient air should typically only be possible near 220 mbar.

In situ investigations of cirrus clouds over the past several years have indicated that ice nucleation can occur in air that is subsaturated with respect to liquid water but saturated with respect to ice. This distinction is particularly important in the very cold upper troposphere. For example, at −65°C, liquid saturation is not achieved until the saturation with respect to ice (RHI) reaches 185%. Measurements in wave clouds over the Rocky Mountains during SUCCESS showed clear evidence of ice crystal formation in air at relative humidity with respect to liquid water (RH) < 90% [Jensen et al., 1997]. These results suggest that the most basic requirement for ice crystal formation in aircraft plumes might be that ice saturation be achieved at some time during the plume cooling. Hence, we should attempt to distinguish whether liquid saturation is actually required for contrail formation.

To calculate the threshold temperature numerically, we must derive an expression for the evolution of the the saturation with respect to ice (S_i) in the plume. We begin by writing the plume water vapor mixing ratio in terms of the change in temperature (see Schumann [1996] for a more detailed derivation):

$$w_{plm} = w_{amb} + \frac{c_p \Delta T EI_{H_2O}}{EI_{heat}} \qquad (1)$$

where w_{amb} is the ambient water vapor mixing ratio, c_p is the specific heat capacity of air, ΔT is the difference between the plume temperature and the ambient temperature, EI_{H_2O} is the emission index for water vapor, and EI_{heat} is the emission index for heat. Next, we convert from mixing ratio to water vapor number density:

$$n_{w,plm} = n_{w,amb} + \frac{n_{air} c_p EI_{H_2O} \Delta T R_w}{EI_{heat} R_d} \qquad (2)$$

where n_{air} is the ambient air number density, $n_{w,amb}$ and $n_{w,plm}$ are the ambient and plume water vapor number densities, and R_d and R_w are the gas constants for dry air and water vapor. Then the ice saturation in the plume is given by

$$S_{i,plm} = \frac{n_{w,amb}}{n_{sat,i}(T_{plm})} + \frac{n_{air} c_p EI_{H_2O} \Delta T R_w}{n_{sat,i}(T_{plm}) EI_{heat} R_d} \qquad (3)$$

where $n_{sat,i}$ is the saturation water vapor number density. The saturation with respect to liquid water can be calculated in an analogous manner. The plume saturation depends upon the ambient air density and humidity. As pointed out by Busen and Schumann [1995], not all of the energy liberated by the engine combus-

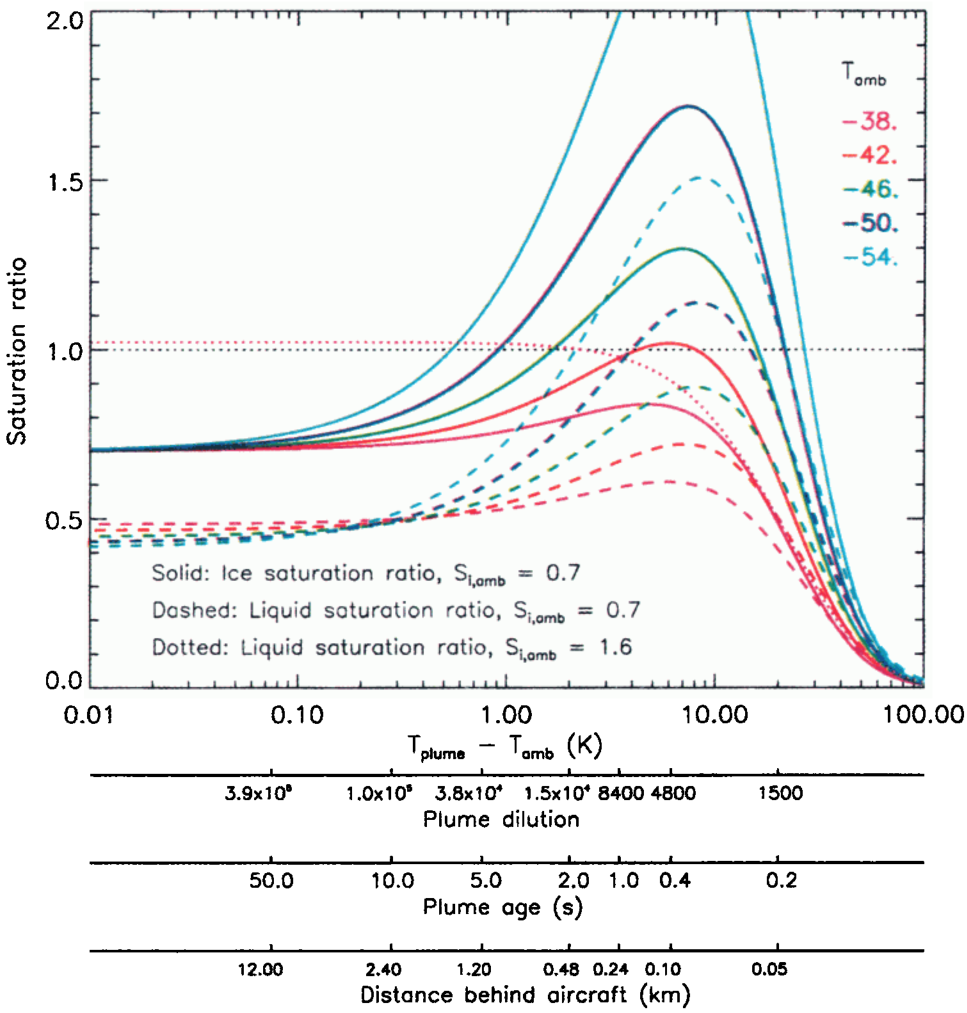

Plate 1. Plume saturation ratios (ice and liquid water) are plotted versus plume temperature enhancement for various ambient temperatures and an ambient RHI of 0.7. Axes below the plot indicate the plume dilution, age, and distance behind the aircraft (assuming air speed of 240 m/s) corresponding to the temperature enhancement. The plume age was estimated on the basis of results from a detailed fluid dynamics model of plume evolution [Miake-Lye et al., 1993]. For the ambient pressure and RHI assumed in this calculation, the plume never reaches water saturation for ambient temperatures above about –48°C. The dotted curve corresponds to ambient conditions that are just barely supersaturated with respect to liquid water.

tion is converted to heat in the exhaust plume. Hence, the heat emission index, EI_{heat}, must by replaced by $EI_{heat}(1-\eta)$ where η is the efficiency of the engine. For modern commercial jet engines, the efficiency should be about 0.3. This is an important correction: the threshold temperature calculated by assuming $\eta = 0.3$ is about 2 K higher than that for $\eta = 0$.

The plume saturation is plotted versus ΔT for various ambient temperatures in Plate 1. Parameter values used (typical for modern jet engines) were EI_{heat} = 4.2 x 10^{11} erg/g fuel, $\eta = 0.3$, EI_{H_2O} = 1.25 g H_2O/g fuel. The temperature difference ΔT is inversely proportional to the plume dilution N. Using a dynamical model of the plume evolution [Miake-Lye, 1993], we have also related the plume dilution to distance behind the aircraft. Just behind the engine, the plume gas is very hot and hence the saturation ratio is near 0. As the gas cools due to entrainment of ambient air, the saturation vapor density decreases rapidly, so the saturation ratio increases rapidly. Eventually, the detrainment of water vapor takes over, and the saturation ratio decreases again. The peak saturation ratio increases with decreasing ambient temperature.

It is important to note that the plume saturation versus ΔT, calculated with this method, should be very realistic in spite of the simplicity of the model. The result does not depend upon the detailed three-dimensional structure of the plume. The only assumption made is that the water vapor and temperature in the plume are controlled by entrainment of ambient air. At a given position behind the aircraft, the plume dilution may be very different at different distances and directions from

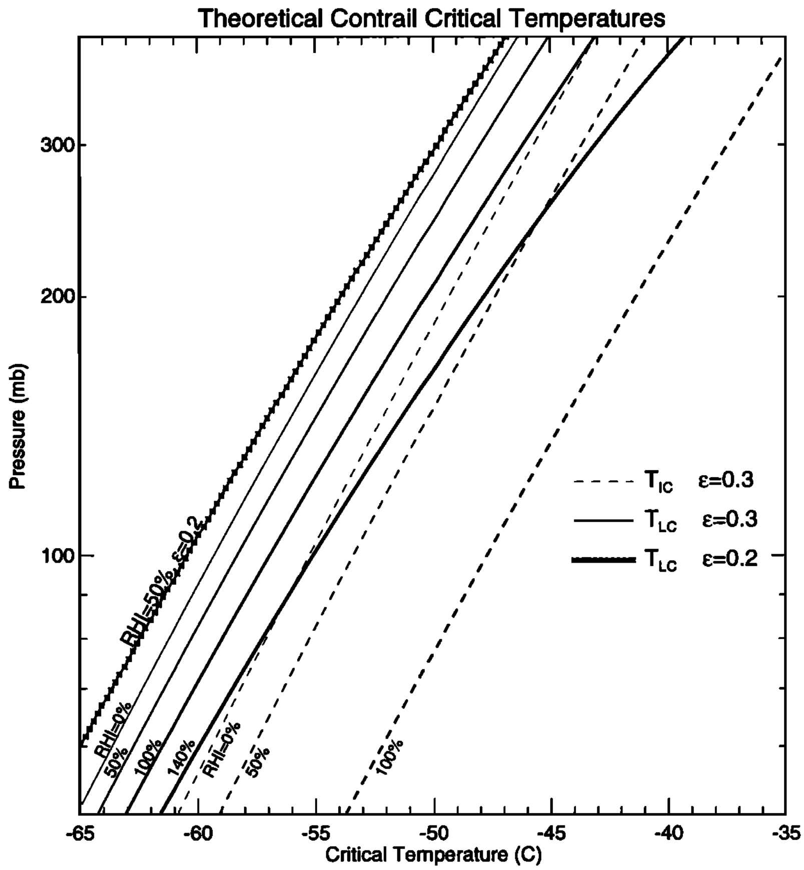

Figure 1. Threshold temperatures based on Appleman [1953] theory are plotted versus ambient pressure for ambient RHIs of 0, 50, 100, and 140%. Contrail formation is predicted to occur whenever the ambient temperature is to the left of the solid curves (corresponding to the ambient RHI and pressure). Solid curves are based on the assumption that liquid saturation in the plume is required for contrail formation. Dashed curves correspond to the assumption that only ice saturation is required. Threshold temperatures are also shown for an engine efficiency of 0.2.

the plume axis. However, at any given point, the dilution should control the temperature, the water vapor mixing ratio, and the RHI.

Appleman [1953] defined the threshold temperature for contrail formation as the ambient temperature such that the maximum plume RH would just exceed 1. We shall refer to this temperature as the liquid-saturation threshold temperature (T_{lc}). As discussed above, another logical threshold temperature is that such that saturation with respect to ice is just barely achieved within the plume (T_{ic}). These threshold temperatures are functions of the ambient pressure and humidity. Given the ambient environmental conditions, the threshold temperatures can be calculated by finding the highest ambient temperature for which the peak plume saturation ratio is just above 1.0. We have written a simple FORTRAN code for this calculation. The code can be obtained from the authors on request.

Figure 1 shows the threshold temperatures plotted versus pressure for various assumed relative humidities with respect to ice. A curve is included for a lower engine efficiency (0.2) to indicate the relatively large sensitivity to this parameter. Schumann [1996] used a slightly different method to calculate the threshold temperatures. He used the fact that under threshold conditions the curve of partial pressure of water vapor in the plume versus plume temperature will be tangent to the saturation vapor pressure versus temperature. The threshold temperatures calculated here agree well with those reported by Schumann. Coleman [1996] developed an analytic expression for the threshold temperature as a function of pressure and water vapor mixing ratio. The threshold temperatures calculated here differed from the analytic expression by no more than 0.5 K.

3. SUCCESS Measurements of Environmental Conditions and Contrails

The environmental conditions that determine whether contrail formation is possible are temperature, relative humidity, and total atmospheric pressure. As part of the meteorological measurement system (MMS) onboard the NASA DC-8, temperature was measured with three different Rosemount probes. Special maneuvers were conducted on most flights to calibrate the temperature measurements and to allow correction for aircraft speed and attitude. The uncertainty of the MMS temperature measurement has been estimated to be no more than 0.3 K.

Water vapor concentration was measured with a laser hygrometer [Collins et al., 1995] on the DC-8. The accuracy of the laser hygrometer dew point measurement is estimated to be about 0.2 K. Along with the temperature uncertainty discussed above, this gives an absolute uncertainty in RHI of about 5–10%, depending on the temperature. On April 24 the laser hygrometer data was affected by a voltage offset, so we have used results from the cryogenic hygrometer on the DC-8 [Heymsfield and Miloshevich, 1993]. During time periods when both water vapor instruments were operating at temperatures above about –50°C, the results were in good agreement (Anderson, B. E., private communication, 1997). The combination of uncertainties in measured pressure (about 5–10%) and RHI lead to uncertainties in the calculated threshold temperatures of 1–2 K. Uncertainty in engine efficiency (about 25%) also contributes substantially to the uncertainty in T_{lc}.

In several cases, contrails were generated in the presence of ambient cirrus clouds. As discussed below, it is possible that water vapor from ice crystals ingested into the engines may have been partly responsible for contrail formation in some cases. To estimate the ambient ice water content, we used the Counterflow Virtual Impactor (CVI) measurements. This instrument samples all particles with radii larger than about 3 μm and measures their water content with a downstream Lyman-α hygrometer [Twohy et al., 1997].

Times when the DC-8 was (or was not) generating contrails were identified several ways: on some of the flights, the NASA T-39 trailed the DC-8 with a forward video camera; an aft directed video camera was mounted on the DC-8; on flights over the Department of Energy (DOE) Atmospheric Radiation Testbed Site (CART) in northern Oklahoma, ground observers photographed and recorded DC-8 contrails; nadir imaging from the ER-2 (flying above the DC-8) occasionally showed the presence of a DC-8 contrail. In some cases the lifetime of the DC-8 contrail could be estimated by observations from the DC-8 (when the aircraft was circling), from the T-39 when it was trailing the DC-8, or by ground observers.

4. Results

A list of contrail cases identified is given in Table 1, along with the temperatures, pressures, and relative humidities with respect to ice measured by the DC-8 instrumentation. The liquid saturation contrail threshold temperatures (T_{lc}) corresponding to the ambient pressure and RHI are also given. For some of the cases, estimates of the contrail lifetime are given. Most of the contrails identified lasted no longer than a few minutes. A few cases of persistent contrails are included. Also, several "threshold" cases are included when the DC-8 had just begun to generate a contrail. Finally, we identified a few cases when the environment was near the threshold temperature, but contrails were not visible.

The difference between the observed temperatures and the threshold temperatures corresponding to the observed pressure and RHI are plotted versus temperature for the DC-8 contrail cases in Figure 2. Within the uncertainties in the measurements, visible contrails from the DC-8 were observed only when the ambient temperature was below T_{lc}, suggesting that liquid saturation in the plume is indeed required for contrail formation. For the threshold cases (shown as squares in Figure 2) the ambient temperature ranged from 0 to 2 K below T_{lc}. The only cases with ambient temperatures slightly above T_{lc} were the relatively warm contrail cases. In these cases the ambient air was very near liquid water saturation (see discussion below). If only ice saturation were required for contrail formation, then contrails should have been observed at temperatures 4–5 K higher than indicated by the threshold cases in Table 1. Even if the engine efficiency were as high as 0.4, the observed threshold temperatures would still be more consistent with the liquid saturation threshold than the ice saturation threshold.

We have also identified times when $T_{lc} < T < T_{ic}$ using the DC-8 in situ data and examined the T-39 video during these times. No visible contrails were apparent. It is possible that some ice crystals do nucleate under these conditions but not enough to generate a visible contrail. When the ambient temperature is between T_{lc} and T_{ic}, the plume is ice supersaturated for less than a second (see Plate 1). Hence, under these conditions, ice crystals would have very little time to grow, and a relatively small number density of ice crystals would not generate a visible contrail.

If the ambient air is not supersaturated with respect to ice, then contrail formation should not be possible at temperatures above about –45°C to –50°C, for a typical range of pressures at commercial aircraft cruise altitudes (see the 100% RHI T_{lc} curve in Figure 1). However, several DC-8 contrails were observed at higher temperatures; as an extreme example, on April 20, 1996, the DC-8 generated a contrail at an ambient temperature of –36.2°C. In all of these warm contrail cases the ambient air was strongly supersaturated with respect to ice (RHI $\geq$ 140%). In the warmest cases (events number 5, 8, 9, and 10 in Table 1) the ambient air was very nearly supersaturated with respect to liquid water. Even though the RHIs in these cases were very large, the temperatures were slightly above the calculated T_{lc} (see Figure 2). Patchy, diffuse cirrus were also present when these warm contrails were generated.

The occurrence of these warm contrails can be explained two ways. First, within the limits of mea-

Table 1. Contrail Events From SUCCESS

#	Date[b]	Time, UT	Temp, °C[c]	p, mb[c]	RHI, %[c]	RH, %[c]	Lifetime	T_{lc}[d]	T_{ic}[e]
1	4/15[a]	18.4222	–50.9	277	26	16	≤ 2 min	–49.0	–45.3
2	4/16	17.9417	–49.0	278	135	84	≤ 2 min	–44.6	NA[f]
3	4/16	18.4833	–57.2	240	105	60	2–3 min	–48.3	NA
4	4/16	21.4483	–56.0	242	114	66	≤2 min	–47.7	NA
5	4/20	17.0193	–36.2	367	143	99	≥15 min	–38.3	NA
6	4/20	19.7890	–55.3	265	125	73	5–10 min	–46.3	NA
7	4/20	20.3489	–54.9	267	128	75	5–10 min	–46.1	NA
8	4/24	17.2496	–39.9	303	146	99	threshold	–40.3	NA
9	4/24	17.9894	–39.5	307	146	99	≤5 min	–40.2	NA
10	4/24	18.0017	–40.2	303	144	97	≤5 min	–41.3	NA
11	4/24	18.0494	–43.1	287	146	96	≤5 min	–42.2	NA
12	4/24	18.1706	–51.0	250	125	76	≤5 min	–46.6	NA
13	4/29	19.4025	–53.7	180	5	3	threshold	–53.6	–49.8
14	4/30	18.1714	–50.1	272	58	36	threshold	–48.4	–44.0
15	5/3	18.2417	–50.3	257	55	34	threshold	–49.0	–44.6
16	5/8	17.5722	–49.5	261	138	85	2–3 min	–45.2	NA
17	5/12	22.9500	–52.4	239	160	96	3 hours	–44.1	NA
18	4/15	18.3131	–49.0	277	18	11	No contrail	–49.1	–45.5
19	4/29	18.4475	–44.0	375.4	83	54	No contrail	–44.2	–39.1
20	4/29	19.4164	–53.3	179.9	5	3	No contrail	–53.6	–49.8

[a]Read 4/15 as April 15.
[b]All dates are 1996.
[c]Ambient.
[d]Liquid-saturation threshold temperature: Ambient temperature required such that saturation with respect to water will be reached in the plume.
[e]Ice-saturation threshold temperature.
[f]Not Applicable: Ambient RHI is > 100%, so $T < T_{ic}$ always, by definition.

surement uncertainty, the ambient air may have been slightly supersaturated with respect to liquid water. The plume saturation would then have evolved as indicated by the magenta dotted curve in Plate 1. As the plume diluted sufficiently, water saturation would be reached. In this case, the contrail formation would have essentially been driven by the presence of numerous ice nuclei from the exhaust as the plume. That is, the only reason the contrail would be visible is that within the plume far more ice nuclei and ice crystals were present than in the ambient air.

The problem with the above explanation is that no optically thick cirrus clouds were present. If the ambient air were supersaturated with respect to liquid water, then most of the ambient aerosols should have been activated (and subsequently frozen), resulting in thick cirrus. The ambient air was probably just below liquid saturation, since optically thick cirrus clouds were not present. An alternative explanation is that the ambient diffuse cirrus present was necessary for the contrail formation. Water vapor available for ice nucleation in the plume will include ambient water vapor, water vapor from the fuel combustion, and sublimated ice crystals that entered the engine or were entrained early in the plume evolution. Air entering the engine and air entrained into the plume before the dilution reaches 1000 would be heated to temperatures at least 30 K above ambient (see Plate 1), and the ice crystals would sublimate rapidly. In our simple plume model, this vapor source is equivalent to increasing the water vapor emission index. Including this vapor source for cases where ambient ice water content measurements were available (cases 5, 9, and 10), we found that the plumes would have reached water saturation. In other words, in these cases the ambient air was very near liquid water saturation, so only a slight addition of vapor to the plume from the engine exhaust and entrained ambient ice would have resulted in liquid saturation as the plume approached the ambient temperature.

An obvious conclusion from this analysis is that whenever contrails form at temperatures above about –44°C to –50°C, they will be forming in ice-supersaturated air and should be able to grow and persist. It would be interesting to examine the statistics of contrail heights using lidar observations. Contrail frequency at temperatures above ≃ –50°C should correspond to the frequency of saturation with respect to ice at these temperatures.

5. Contrail Persistence

The vast majority of contrails observed during the SUCCESS experiment lasted no longer than a few minutes. The contrails typically dissipated rapidly when the aircraft vortices became unstable and broke up. In

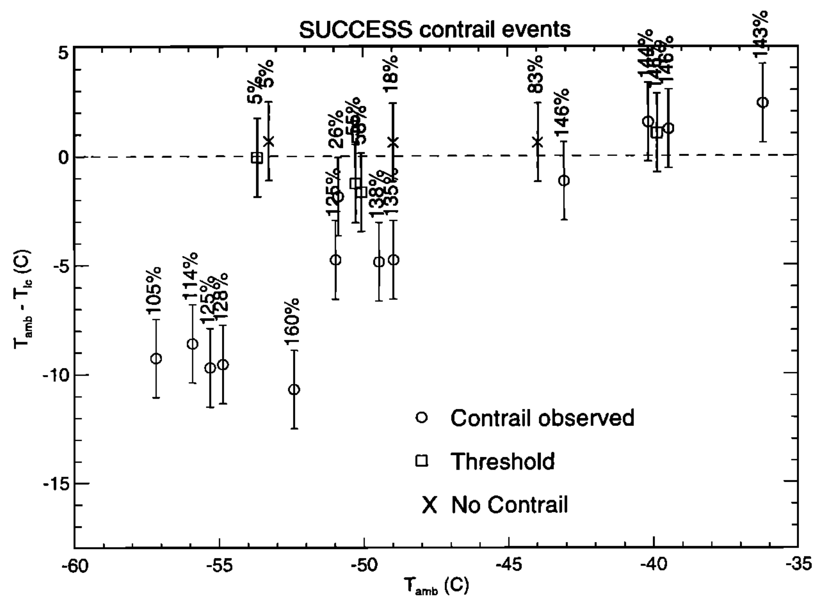

Figure 2. Differences between the ambient temperature and the liquid saturation threshold temperature (T_{lc}) are shown for the SUCCESS contrail cases (see Table 1). The ambient relative humidities with respect to ice are shown above each point. Within the range of uncertainty, contrails were only observed when the ambient temperature was at or below T_{lc}, such that the plume would have reached saturation with respect to liquid water. Several threshold cases are shown (squares) when the contrails had just begun forming. The crosses indicate cases when contrails were definitely not visible.

all of the cases listed in Table 1 for which the contrails persisted longer than a few minutes, the ambient air was substantially supersaturated with respect to ice. This result is reasonable since under subsaturated ambient conditions, the plume will not remain saturated longer than about 10 seconds, even without vapor depletion due to crystal growth (see Plate 1), and ice crystals in the contrails with sizes of a few microns or less will sublimate in less than a minute after the plume is subsaturated.

On May 12, 1996, the DC-8 generated a contrail off the coast of California which persisted for over 3 hours [Minnis et al., 1997]. The contrail generated by the DC-8 racetrack flight pattern was clearly visible in GOES-8 satellite images as the contrail advected over California. The relative humidities with respect to ice indicated by the laser hygrometer ranged from 110% to 170% throughout the racetrack flight path. Hence, the DC-8 was flying in an extensive region with highly supersaturated air and patchy, diffuse cirrus. The persistent contrails observed during SUCCESS often formed in regions with patchy cirrus present.

For some of the cases listed in Table 1 (e.g., cases 2, 5, and 16), the ambient air was substantially supersaturated with respect to ice, but the contrails still persisted no longer than a few minutes. Closer analysis of the in situ water vapor and temperature measurements for these cases indicates that these contrails often formed in narrow vertical layers or small patches of high humidity. The vertical structure of the ambient relative humidity may be very important for contrail persistence. If the air just below the contrail formation level is very dry, then the ice crystals will sublimate as soon as they grow large enough to begin sedimenting. Relatively small ice crystals could remain in the humid layer, resulting in a persistent subvisible contrail. Aged, subvisible contrails were often observed during the SUCCESS experiment with ground-based lidar (Sassen, K., personal communication, 1997).

6. Discussion

We have used precise in situ measurements from the SUCCESS experiment to evaluate the threshold temperatures for visible contrail formation. The results of this analysis are consistent with the theoretical calculations assuming that liquid saturation must be reached in the plume for contrail formation. In several of the contrail events listed in Table 1, large ambient supersaturations with respect to ice existed with either diffuse cirrus present, or no cirrus present. These regions were prime for contrail formation. The lack of optically thick cirrus in these regions suggests that relatively few effective heterogeneous ice nuclei were present, and upper tropospheric clouds may be very sensitive to introduction of effective heterogeneous nuclei.

Contrails are frequently visible at distances as close as 25–35 m behind the aircraft engines [Busen and Schumann, 1995]. Using an analytical model of ice crystal growth in the exhaust plume, [Kärcher et al., 1996] showed that the number density of ice crystals nucleated must be at least about 10^4 cm^{-3} in order for the contrail to be visible this quickly. Simulations of aerosol and ice crystal nucleation and growth in the exhaust plume suggest that the most likely mechanism for nucleation of the contrail crystals is heterogeneous freezing of sulfate coated soot particles [Kärcher et al., 1995, 1996; Brown et al., 1996, 1997]. The simulations suggested that freshly nucleated sulfuric acid/water aerosols could not grow large enough to spontaneously freeze in the time required.

The simulations reported by Kärcher et al. [1995, 1996] and Brown et al. [1997] were run under ambient conditions where saturation with respect to liquid water was not quite reached within the plume. However, the SUCCESS measurements reported here along with the in situ observations reported by Schumann et al. [1996] suggest that liquid saturation in the plume is indeed required for visible contrail formation. Future modeling studies of contrail formation should attempt to explain the sudden onset of visible contrails at T_{lc}. As suggested by Kärcher et al. [1996], the higher plume supersaturation may allow growth and freezing of freshly nucleated H_2SO_4/H_2O droplets (without internally mixed soot particles) to play a substantial role in the contrail formation process. Also, if contrails do not form until the ambient temperatures drop below T_{lc}, then the soot particles are not necessarily very effective heterogeneous freezing nuclei. Kärcher et al. [1996] estimated that an ice germ/soot contact angle less than about 60° was required to explain contrail formation at temperatures just above T_{lc}. The results from this study suggest that T must be below T_{lc} for contrail formation, so the contact angle may be larger (corresponding to less effective freezing nuclei). The fact that the ambient temperature needs to be below T_{lc} may also indicate that liquid water droplets must be activated (and subsequently freeze in order to generate a sufficient number of ice crystals for a visible contrail.

If some fraction of the aircraft exhaust particles are effective ice nuclei, then some ice crystals should nucleate in the exhaust plume even when only ice supersaturation is reached. Attempts were made to sample exhaust plumes without contrails during SUCCESS; however, the plumes were very difficult to find without a visible contrail present, so relatively few clear plumes were sampled. Apparently, no plumes were sampled under ice-supersaturated and water-subsaturated conditions. Hence, all we know for certain now is that visible contrails do not form when $T_{lc} < T < T_{ic}$. It is possible that some ice crystals form under these conditions but too few for a visible contrail. In future field studies of exhaust plumes and contrails, it would be interesting to investigate this regime to see whether ice crystals are indeed formed under these conditions.

Acknowledgment. This research was supported by NASAs Subsonic Assessment Program, directed by Howard Wesoky.

References

Ackerman, A. S., O. B. Toon, J. P. Taylor, D. W. Johnson, P. V. Hobbs, and R. J. Ferek, Effects of aerosols on cloud albedo: Evaluation of Twomey's parameterization of cloud susceptibility using measurements of ship tracks, *J. Atmos. Sci.*, in press, 1997.

Appleman, H., The formation of exhaust contrails by jet aircraft, *Bull. Am. Meteorol. Soc.*, *34*, 14–20, 1953.

Brown, R. C., R. C. Miake-Lye, M. R. Anderson, and C. E. Kolb, Aerosol dynamics in near-field aircraft plumes, *J. Geophys. Res.*, *101*, 22,939–22,953, 1996.

Brown, R. C., R. C. Miake-Lye, M. R. Anderson, and C. E. Kolb, Aircraft sulfur emissions and the formation of visible contrails, *Geophys. Res. Lett.*, *24*, 385, 1997.

Busen, R., and U. Schumann, Visible contrail formation from fuels with different sulfur contents, *Geophys. Res. Lett.*, *22*, 1357, 1995.

Coleman, R. F., A new formulation for the critical temperature for contrail formation, *J. Appl. Meteorol.*, *35*, 2270–2282, 1996.

Collins, J. E., Jr., G. W. Sachse, L. G. Burney, and L. O. Wade, A novel external path water vapor sensor, paper presented at the 5th Annual Meeting of the Atmospheric Effects of Aviation Program, NASA, Virginia Beach, VA, April 23–28, 1995.

Heymsfield, A. J., and L. M. Miloshevich, Homogeneous ice nucleation and super cooled liquid water in orographic wave clouds, *J. Atmos. Sci.*, *50*, 2335–2353, 1993.

Jensen, E. J., et al., Ice nucleation processes in upper tropospheric wave-clouds observed during SUCCESS, *Geophys. Res. Lett.*, in press, 1997.

Kärcher, B., T. Peter, and R. Ottmann, Contrail formation: Homogeneous nucleation of H_2SO_4/H_2O droplets, *Geophys. Res. Lett.*, *22*, 1501, 1995.

Kärcher, B., T. Peter, U. M. Biemann, and U. Schumann, The initial composition of jet condensation trails, *J. Atmos. Sci.*, *53*, 3066, 1996.

Liou, K.-N., S. C. Ou, and C. Koenig, An investigation on the climatic effect of contrail cirrus, Lecture Notes in Engineering, Vol. 60, pp. 138–153, Springer-Verlag, New York, 1990.

Miake-Lye, R., et al., Plume and wake dynamics, mixing and chemistry behind a high speed civil transport aircraft, *J. Aircr.*, *30*, 467–479, 1993.

Minnis, P., et al., Transformation of contrails into cirrus clouds during SUCCESS, *Geophys. Res. Lett.*, in press, 1997.

Peters, J. L., New techniques for contrail forecasting, AWS/TR-93/001, AD-A269 686, pp. 31, Air Weather Service, Scott Air Force Base, Ill., 1993.

Schumann, U., J., On conditions for contrail formation from aircraft exhausts, *Meteorol. Z.*, *5*, 4–23, 1996.

Schumann, U., J., et al., In situ observations of particles in jet aircraft exhaust and contrails for different sulfur-containing fuels, *J. Geophys. Res.*, *101*, 6853, 1996.

Twohy, C. H., A. J. Schanot, and W. A. Cooper, Measurement of condensed water content in liquid and ice clouds using an airborne counterflow virtual impactor, *J. Atmos. Ocean. Tech.*, *14*, 198–202, 1997.

Twomey, S., Pollution and the planetary albedo, *Atmos. Environ.*, *8*, 1251–1256, 1974.

Eric Jensen, NASA Ames Research Center, MS 245-4, Moffett Field, CA 94035, (e-mail: ejensen@sky.arc.nasa.gov)

(Received April 7, 1997; revised August 25, 1997; accepted September 25, 1997.)