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# Cirrus Clouds and Contrails: A Comparative Analysis

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Cirrus Clouds and Contrails:  
A Comparative Analysis

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(From Penn State)

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**Ronald Nuñez**

## **Cirrus Clouds and Contrails: A Comparative Analysis**

**Major:** Applied Meteorology

**Mentor:** Dr. Mary Snow

### **ABSTRACT**

Cirrus clouds have been classified by height since studies on these clouds began. Unfortunately, this method of classification does not take into account condensation trails, or contrails. As a result, there is no consensus concerning whether contrails can be categorized as a type of cirrus cloud or are a different phenomenon altogether. Cirrus cloud formation differs from contrail formation, but other properties, such as their thickness and occurrence, are very similar. Although contrails usually disappear without significantly impacting the atmosphere, occasionally contrails may act as a generating mechanism for cirrus clouds. The nuclei used for cirrus clouds and contrails originate from different sources, but both phenomena go through similar freezing processes as they develop.

Updating the current cloud classification model might allow contrails to be classified as cirrus clouds. Further studies are also needed in order to better understand the net radioactive properties of both contrails and cirrus clouds.

### **Introduction**

Clouds have been studied by scientists around the world for many years along with the effects that they have on the environment. Until recently, however, cloud study has been mostly limited to lower and mid-level clouds. High-level clouds, or cirrus clouds, have been generally ignored in science. They were difficult to identify and were not thought to have much effect on the atmosphere. However, with new advances in technology, it was discovered that cirrus clouds indeed impact our atmosphere in more ways than originally thought. As a result, information available on cirrus clouds is limited.

The increase in aircraft use has also initiated a new study of the condensation trails that jet aircraft leave behind. These “contrails” have many properties similar to the naturally-occurring cirrus clouds in the atmosphere. However, there is much disagreement over whether contrails are true cirrus clouds. Some research classifies them as the same thing (Peter, Krieger, Zobrist & Marcolli, 2007), but other researchers refer to them as different phenomena with similar qualities (Penner, Lister, Griggs, Dokken, & McFarland, n.d.). The purpose of this research is to determine if contrails produced by aircraft are correctly classified as a form of cirrus cloud, or whether they are a different atmospheric event altogether.

### **Literature Review**

There is a lot of information currently available on cirrus clouds and contrails compared to a couple years ago. Advances in technology have made it easier to study both of them in ways that were previously impossible. Virtually every aspect of the cirrus cloud is now studied and analyzed. The Optical Society of America (OSA), the American Meteorological Society (AMS), and the American Geophysical Union (AGU) sponsored an intense conference in 1998 where several scientists convened to present their research on cirrus clouds. The result of the conference was a work entitled *Cirrus*, which combined all the information known about cirrus clouds into one convenient hardcover book.

The book contained a wide spectrum of information, from the basic definition of a cirrus cloud, to its microphysical properties. Well into the book, contrails were mentioned. The authors implied that contrails could be considered to be cirrus clouds, yet no such definitive categorization was offered (Lynch, Sassen, Starr, & Stephens, 2002).

Other published works, such as *Aviation and the Atmosphere* (Penner et al., n.d.), have provided information on contrails, even comparing them to cirrus clouds, but no conclusive definition was given. Several websites address contrails and cirrus clouds, but none of them give a definite answer of whether or not a contrail is a cirrus cloud, a precursor to a cirrus cloud, or something different altogether. This research brings together and analyzes various studies conducted on contrails and cirrus clouds, and it draws a conclusion of their relationship with the information currently available.

## **Methodology**

Starting with the book *Cirrus*, (Lynch et al., 2002), which initiated the researcher's interest in contrails in relation to cirrus clouds, the research process began with an investigation of the peer-reviewed literature that detailed several features of both contrails and cirrus clouds. After all the relevant data were collected, a comparative analysis was conducted using several attributes of both contrails and cirrus clouds. A conclusion was reached on the relationship between the two.

## **Data Analysis**

### *Definitions and Appearance*

*Cirrus Clouds.* Cirrus clouds are defined as thin and wispy clouds found very high in the atmosphere (*Cirrus Clouds*, n.d.). These clouds are found at the top of the troposphere, and they are identified as high-level clouds when compared to lower clouds such as stratus. Cirrus clouds are composed entirely of ice crystals instead of liquid moisture. They form at temperatures below  $-40^{\circ}\text{C}$  (Lynch et al., 2002), and they are typically found at heights greater than 20,000 feet.

Cirrus clouds, when looked at from below, appear as long, thin strands of hair. The term *cirrus* in Latin means “hair,” which is where the name for the cloud originated (Stillman, 2006). These clouds are also referred to as “mare’s tails” due to this distinct feature (Figure 1). The reason for this visual feature is actually the result of virga. Virga is precipitation that is produced by the cloud that does not reach the ground. As the precipitation is released from the cloud, it evaporates, either quickly or after falling some distance, depending upon the moisture content of the air through which it falls. As the ice crystals are gets carried away by the wind, they leave a trail, that when viewed from the surface, looks like strands of hair.

*Contrails.* Condensation trails, most commonly known as contrails, are clusters of criss-crossing or parallel lines left behind by high altitude aircraft (Minnis, 2003). Contrails vary in size, but have the distinct shape of white streaks that can last between a few minutes and a few hours (Figure 2).

### *Classification*

*Cirrus Clouds.* The four major cloud families are divided based on their height. The highest of these cirrus clouds are subdivided into three different kinds of clouds based on their physical appearance. These clouds are Cirrus, Cirrostratus, and Cirrocumulus (*Cloud Atlas*, n.d.). Cirrus clouds appear fibrous and threadlike, and they are most commonly seen with the “tails” dragging behind them. Cirrostratus clouds appear when there are several cirrus clouds grouped together to form a veil that covers portions of the sky. They are known to cause halo appearances



*Figure 1.* Typical "mare's tails" on a cirrus cloud.

(From <http://www.raggedcastle.com> )



*Figure 2.* Jet contrails across the sky.

(From NOAA)

around the moon and sun as light from them is refracted by the ice crystals. Cirrocumulus clouds often occur in unstable air, usually associated with convection or orographic lifting due to mountains. They appear as cloud banks of small, white flakes. Recently, another way for classifying cirrus clouds has been developed. This new classification method uses the cloud's layer thickness to determine the cloud type. This will be discussed later (See Optical Depth).

*Contrails.* Contrails have not been studied in much detail until recently. As a result, in-depth classification of contrails does not yet exist. Basic classification, however, divides contrails into three types: short-lived, persistent, and persistent spreading (Heil, 2004).

Heil (2004) explains that short-lived contrails are formed when a jet aircraft traverses dry air. Contrails need moisture to sustain themselves, so short-lived contrails usually last only 30 minutes or less. They appear as short, white lines behind a plane. If there is more moisture in the air, persistent contrails form. Persistent contrails are similar to short-lived except they are bigger and last long after the plane has disappeared (Heil, 2004).

However, neither short-lived nor persistent contrails last long enough to have a significant impact on the atmosphere. The third kind of contrail, persistent spreading, lasts the longest of the three, and they cover more areas of the sky as time passes. Persistent spreading contrails eventually evolve into natural cirrus clouds. This is the first link found between contrails and cirrus clouds; both result in natural cirrus clouds under the right conditions.

*Generating Mechanisms*

*Cirrus Clouds.* Regardless of their subcategories, all cirrus clouds are formed through similar generating mechanisms that are needed in order to “trigger” their formation (Lynch et al., 2002). The five different generating mechanisms are as follows: Synoptic, injection cirrus, mountain-wave updraft, cold trap, and contrail-cirrus.

The most common variety of cirrus clouds form from synoptic-scale forces. These forces include jet streams and other events or phenomena that occur in the troposphere. This method of generation is unique from the others in that the formation of cirrus begins at the top of the cloud where particle generation occurs, then moves downwards.

The next two mechanisms, injection cirrus and mountain-wave updraft, are similar processes with the exception of their driving force. Injection cirrus clouds are formed during the updraft stage of a thunderstorm. As the air becomes unstable and rises up rapidly, it pushes up microscopic foreign particles that serve as nuclei. When these nuclei combine with water vapor floating high in the atmosphere, heterogeneous freezing occurs forming anvil-shaped cirrus clouds. Mountain-wave updrafts occur the same way, except that the updraft is induced by orographic lifting rather than thunderstorms.

Cold trap is a recently-discovered type of mechanism that applies mainly to subvisual clouds. Cold trap cirrus clouds occur at very cold and high altitudes, usually from  $-70^{\circ}$  to  $-90^{\circ}\text{C}$  at 15-20km. They occur most commonly in the tropics, as it is the only place to find the correct conditions. The ice crystals that make up these clouds are much smaller than those of the other cirrus clouds. Little information is known about this type of mechanism.

*Contrails.* The final generating mechanism for cirrus clouds consists of aircraft-induced contrails. All contrails are generated from aircraft-supplied moisture and nuclei, which provide the necessary constituents for cirrus cloud formation (Penner et al., n.d.). Contrail formation will be discussed in more detail in the next section.

*Aero Trails.* One feature usually ignored when discussing contrails and cirrus clouds are aircraft-induced aerosol particles. These microscopic particles usually consist of soot, sulfur, and some metals that are released from aircraft engines in an invisible trail (Schumann et al., 1996). These aerosol particles are different from the naturally-occurring ambient aerosol particles that are found in the atmosphere. They still have an impact on the atmosphere as they help with contrail formation, and it is theorized that they might even affect natural cirrus formation. To distinguish between aircraft-induced aerosols and natural aerosols, this paper will identify the former as “aero trails” which is short for aerosol trails.

### *Composition*

*Cirrus Clouds.* The composition of cirrus clouds is not yet fully understood. Current research shows that cirrus clouds are formed from the freezing, whether heterogeneously or homogeneously, of haze particles that condensed onto Cloud Condensation Nuclei (CCN) (Lynch et al., 2002). These nuclei can come from one of the several generating mechanisms described earlier. Some of those involved in heterogeneous nucleation are sulfates in the atmosphere, but recent studies suggest minerals and organic compounds may also be present in significant quantities (Penner et

al., n.d.). The sources for the sulfate nuclei include stratospheric and volcanic sulfuric acid droplets (Lynch et al., 2002).

When water vapor contacts the nuclei, ice crystals form of varying sizes that in aggregate form the resulting cirrus clouds. Thus, the relative humidity must be high enough for water vapor to be readily available for freezing and for the formation of cirrus clouds to occur. The air must be both cold and humid. It is important to note, however, that while all cirrus clouds are comprised of ice crystals, not all clouds containing ice crystals are cirrus clouds. Other clouds, such as altostratus, also contain ice crystals.

*Contrails and Aerostrails.* Aircraft engines emit exhaust that contains not only soot, sulfur, and several kinds of metals but also carbon dioxide and water vapor (Lynch et al., 2002.). These aerostrails exist regardless of weather conditions. They might result in short-lived contrails, or even persistent contrails if the air is humid. However, if the atmosphere is conducive to cirrus formation, persistent spreading contrails may form. The aerostrails provide the CCN needed for contrail formation where natural aerosols were missing.

Some of the emissions in engine exhaust are carbon and hydrogen, which are present in jet fuel. Once the hydrogen mixes with the ambient air, water vapor forms. If the conditions for saturation are reached or exceeded, water droplets will form. The CCN provided by aerostrails then provide the ice nuclei needed for heterogeneous freezing resulting in contrails. Aircraft exhaust might lead to cirrus clouds where no clouds would have formed otherwise due to this process (Lynch et al., 2002).

### *Optical Depth*

*Cirrus Clouds.* Since the beginning of cloud research, cloud types have been identified primarily by their altitude. Cirrus clouds were identified mainly by their height in the atmosphere. Recent studies, however, are incorporating cloud thickness into cloud classification schemes. The optical depth, or vertical thickness, of a cirrus cloud helps not only to identify one type of cirrus cloud from another, but also a cirrus cloud from a different cloud category altogether.

Figure 3 shows the different depths that are commonly found in cirrus clouds and what they look like. Their depth, for purposes of this project, is synonymous with optical thickness. Cirrus clouds seen by the human eye are thin clouds, with an OD range of 0.03-0.3 microns, and opaque clouds have an OD range of 0.3-3.0 microns. Once the cloud grows to a thickness that exceeds 3.0 microns, it is no longer classified as a cirrus cloud. At this point, it becomes an altostratus cloud.

Table 1

*Cirrus Cloud Categories and Approximate Optical Depths (OD) Based on Cloud Transparency and Color* (From Lynch et al., 2002)

Category	OD range in microns	Description
Subvisual	<0.03	Invisible against the blue sky
Thin	0.03-0.3	Translucent, retains a bluish
Opaque	0.3-3.0	color
Altostratus	>3.0	Usually appears white Disk of sun becomes indistinct.

A lesser-known cloud-type is the subvisual cloud. Until recently, its existence was unknown since it is not visible to the eye. The development of lidar helped detect these clouds in the OD range below 0.03 microns (Lynch et al., 2002.). Little is known about their characteristics and properties. More study is needed on subvisual clouds.

*Contrails.* Contrail thickness has been difficult to determine due to the difficulty in detecting them with satellites. Lidar observations have detected contrails in the range of 0.05 and 0.5 microns in optical depth. Other studies have shown that thickness ranges from 0.15 to 0.25 microns (Schumann, 2005). Aerocontrails are very variable in thickness, as they depend too heavily on the atmosphere around them to make an accurate estimate. As the studies show, contrails and cirrus clouds have a similar optical thickness further suggesting their close relationship.

#### *Occurrence*

*Cirrus Clouds.* Although cirrus clouds occur throughout the entire year, their most common appearance occurs during boreal winter, or the months of December, January, and February (Lynch et al., 2002). However, other studies show that they occur just as frequently in boreal summer in places like Indonesia and part of the African Congo. The reason for the difference in cirrus occurrence is not yet fully understood, but it has a lot to do with the relative humidity of the atmosphere. Again, the air needs to be cold and humid for cirrus clouds to form. This explains the high concentration of cirrus clouds near the tropics. The warm air in the tropics travels up to humidify the cold upper-troposphere resulting in plentiful amounts of cirrus.

*Contrails.* The frequency or area of coverage of Earth by contrails has been measured in only a few regions (Lynch et al., 2002). Like cirrus clouds, contrail frequency peaks in boreal winter and early spring, specifically around February and March. Contrail frequency, though, has an added factor that cirrus clouds do not, and that factor is air travel. Contrails are affected by time of year and geographical location like natural cirrus, but they are also affected by the amount of aircraft flying at a certain place and time. According to Lynch et al. (2002), contrail frequency is well correlated with the fuel consumption in the same region. This means that contrail coverage is limited by the number of aircraft flights as well as by atmospheric conditions. In order for persistent spreading contrails to form into natural cirrus, the atmospheric conditions undoubtedly play an important role.

After every aircraft in the U.S. fleet was grounded following the terrorist attacks of September 11, a study was conducted to determine how significantly aircraft-induced contrails affect the environment. The grounding of all the aircraft was followed by the immediate disappearance of contrails and overall a smaller amount of cirrus clouds covering the sky (Travis, Carleton & Lauritsen, 2002). This observation reiterates the importance of airplanes and the aerotrails they produce in the formation of contrails and, to a lesser extent, cirrus clouds.

### *Net Radiative Properties*

*Cirrus Clouds.* One of the most prevalent controversies among atmospheric scientists today is the net radiative forcing that cirrus clouds have (or exert) on the

environment. Different studies show different results, so no general consensus has been reached on this topic.

All clouds have some kind of impact on our atmosphere, and cirrus clouds are no exception. Due to the limitations of technology until relatively recently, the effects of cirrus clouds on the environment have not been precisely quantified. Scientists did not believe they had any significant impact on the environment. With the introduction of radar and lidar, however, the importance of cirrus clouds was made apparent.

Cirrus clouds have the potential to both cool and warm the atmosphere on a given day. A cirrus cloud has an albedo effect when the sunlight directed towards Earth strikes the cloud and is reflected back into space. This process cools the Earth. Cirrus clouds also have a greenhouse effect. When a cloud reduces the radiative heat loss emitted by Earth and directed back into space, this process warms the environment (Figure 3). The process that dominates determines whether the clouds bring a net cooling effect or a warming effect. Kinne (1998) showed that low-level clouds have a weak greenhouse effect and strong albedo effect. As a result, their net radiative force is negative and they cool the atmosphere. Cirrus clouds, on the other hand, were shown to have a stronger greenhouse effect warming the atmosphere as a result.

Other studies support the theory of cirrus clouds warming the environment, claiming that a greater number of thin cirrus clouds will allow more heat into the atmosphere, as well as keep more heat from escaping (Penner et al., n.d.). Although no consensus has been reached, the overall effect that studies are showing is a net warming of the atmosphere by cirrus clouds.

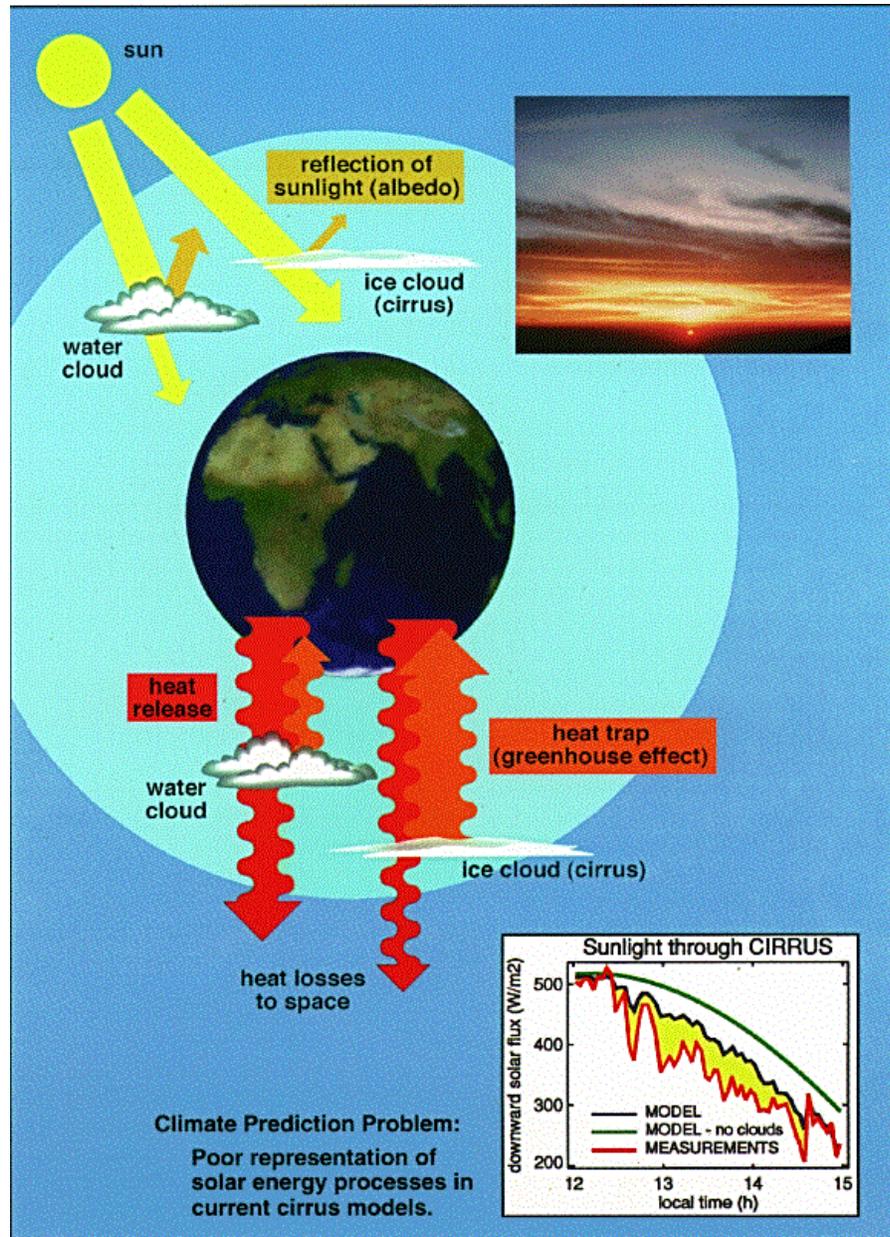


Figure 3. Radiative forcing and cloud types (From Kinne, S. 1998).

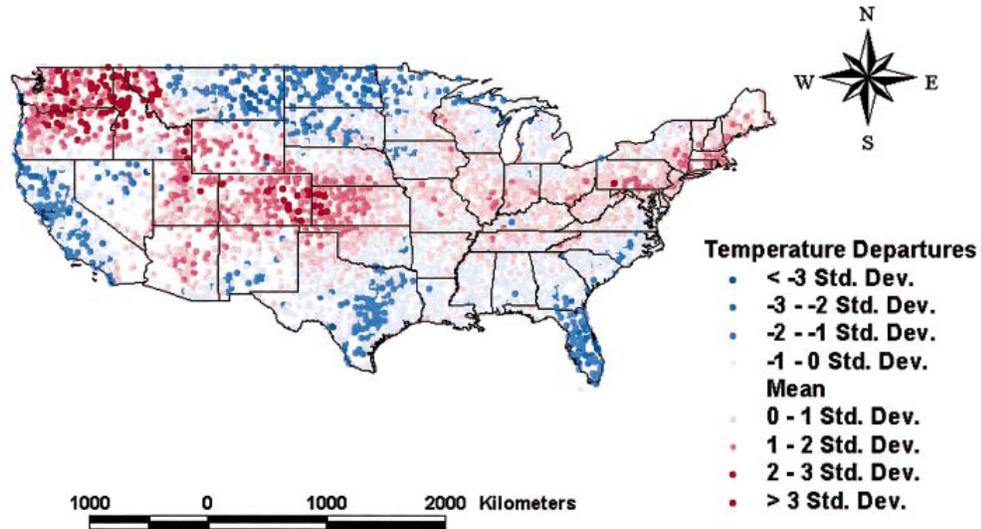
*Contrails.* Similar to cirrus clouds, the net radiative properties of contrails are still poorly understood, although several advances have been made with recent technological breakthroughs. It is currently known that, like cirrus clouds, contrails reduce the amount of shortwave radiation reaching the earth through the albedo effect, as well as reduce the longwave radiation leaving the earth through the greenhouse effect (Figure 3). When discussing radiative forcing, only persistent spreading contrails are acknowledged. Current research suggests that short-lived and persistent contrails do not last long enough or form in great enough numbers to have any significant impact on climate (Heil, 2004).

The studies done post-September 11 showed some interesting features of persistent spreading contrails that were not able to be studied until then. Temperatures were recorded for various areas of the country from September 11 to September 14. The temperatures of each day and night, as well as the temperature ranges between day and night, were recorded and compared to those for the years 1971-2000 (Travis et al., 2002). The analysis provided surprising results (Figure 4).

Temperatures during the three days following September 11 rose higher than any of the average temperatures for those days recorded since 1971. The most drastic temperature changes occurred where the heaviest air traffic occurred. Figure 4 shows that the biggest changes happened in the Northeast, Northwest, and Great Plains, all areas of heavy air travel. The temperature range from day to night was made smaller by contrails since contrails not only cooled the earth during the day and kept it warmer during the night. However, Travis et al. (2002) found that contrails had an overall cooling effect on climate.

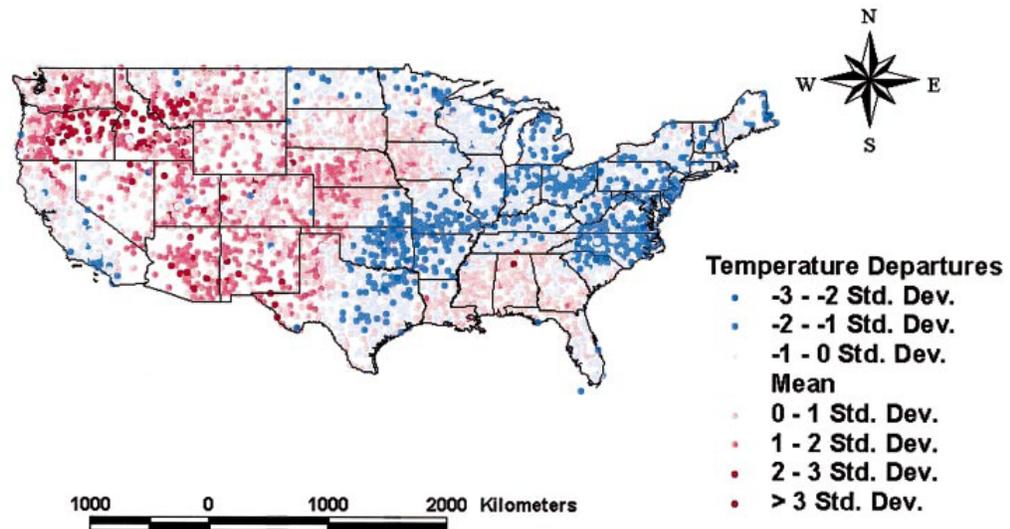
(a)

### 11-13 September 2001 Maximum Temperature Departures from Normal



(b)

### 12-14 September 2001 Minimum Temperature Departures from Normal



*Figure 4.* Temperature changes caused by lack of contrails, discovered following the grounding of all aircraft the days after September 11

(From Travis et al., 2004).

*Aerosols and Aero Trails.* Aero trails and aerosols are similar in nature except for their origin. While sulfate aerosols come from stratospheric and volcanic sulfuric acid droplets, aero trails come from jet engine exhaust emissions which include soot, water vapor, and hydrocarbons. Aero trails, however, have less of an impact on the environment than aerosols. Like contrails, they also seem to exhibit a cooling effect on the atmosphere. Aero trails have a solar reflectance that exceeds their greenhouse effect properties, thus causing the cooling (Penner et al., n.d.). These effects are minimal, but they must not be confused with contrail radiative properties.

### **Conclusion**

Cirrus clouds and contrails are popular topics among atmospheric scientists due to the realization of their significance in the radiative heat balance. Understanding them both is crucial to being able to predict how they will affect the future. This paper identified several features of cirrus clouds and contrails to determine if they are the same atmospheric phenomena.

Through their definition and appearance, it was clear that cirrus clouds and contrails were different from each other. Similarly, cirrus clouds and contrails differ through their generating mechanisms and composition. Once they were subdivided into different categories, some similarities were found. While short-lived and persistent contrails shared no characteristics of cirrus clouds, persistent spreading contrails were found to be a generating mechanism for cirrus clouds. Under the right conditions, a persistent spreading contrail will form what appears to be a naturally-formed cirrus cloud, practically indistinguishable from other naturally-formed cirrus.

Through their composition, additional differentiations were made by introducing aerotrails. Aerotrails are often mistaken for contrails when discussing contrail formation. While aerotrails form regardless of temperature, persistent spreading contrails will only form when temperatures are low enough and moisture content is high enough. Thus, the main difference between a persistent spreading contrail and a cirrus cloud is the source of their nuclei. Clouds get the nuclei needed for formation from ambient aerosols, while persistent spreading contrails get the required nuclei from aerotrails.

Optical depth and occurrence for both contrails and cirrus clouds are relatively similar. The thickness of contrails is similar to that of thin cirrus clouds, and both occur primarily in the winter months. Finally, although their net radiative properties differ slightly, not enough is known about either of to reach definitive conclusions. Contrails are shown to have a net cooling effect on the atmosphere, although they are capable of both cooling via reflectivity, and warming via the greenhouse effect.

The results of this paper suggest that contrails in general cannot strictly be called cirrus clouds due to the different properties of them. Persistent spreading contrails, however, eventually resemble natural cirrus clouds, with the major difference being that they were created by artificial means. Cirrus clouds are characterized primarily by their height. Clouds have been classified that way for years.

It is recommended that new methods for classifying cirrus clouds be implemented, such as cirrus cloud types being defined by their generating mechanisms in addition to their height and ice crystal composition. This would allow the “contrail cirrus” to be acknowledged as a type of cirrus cloud and eliminate the confusion involved with the study of these atmospheric phenomena.

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