A Causational Argument for the Influence of Contrail Ice-particle Shape on Thermal Infrared Radiance Observations

Robert P. d'Entremont
Atmospheric and Environmental Research, Inc.
Lexington, MA 02421-3126 USA

David L. Mitchell
Desert Research Institute
Reno, NV 89512 USA

1 Introduction

Contrails and aviation-induced radiative forcing are receiving a renewed attention in the climate community by international government and private-industry concerns alike. Federal governments are interested from a climate-change perspective: if an "adverse" aviation impact on climate can be quantitatively established, policy changes may result that could help mitigate this influence – such a sequence of actions would be akin to the international ban on CFCs that has helped dramatically to turn the tide on stratospheric ozone depletion. In a desire to portray a "green" image to the public, aircraft manufacturers desire to be proactive about potential climate impacts so they can institute jet-engine design changes that modify in a "positive" sense jet-engine effluents and their subsequent impact on the natural cirrus environment.

Jet engines inject water vapor, soot, sulfates, and nitrates into the upper troposphere and lower stratosphere. We concern ourselves here with the atmospheric-chemistry issues of aviation only insomuch as they influence the formation of ice particles and contrails. Linear contrails – those thin-lined streaks that are visible directly behind a passing aircraft – behave like cirrus in that they both reflect and transmit incident solar energy and absorb upwelling Earth-emitted thermal energy. In the average, absorption of thermal energy wins out. Like cirrus, contrails are "greenhouse" clouds – but anthropogenic in nature – they trap more radiant energy than they shed, causing a net positive radiative forcing (net warming).

In comparison to the effects of carbon dioxide and rainforest burning, fresh linear contrails (on the order of a few tens of meters wide) themselves have a weak "instantaneous" impact on the overall radiative balance (climate) of the Earth-atmosphere system. However, contrails modify the atmospheric environment in a way that can greatly enhance the formation and persistence of cirrus clouds in an otherwise cloud-free environment, with associated effects on radiative forcing. How this anthropogenic forcing differs from the unperturbed natural forcing is of concern to atmospheric scientists. The influence of contrails and jet-engine emissions on the formation and maintenance of "anthropogenic" cirrus (hundreds and thousands of square kilometers in size) needs to be better understood in an atmosphere that would have otherwise been cloud-free. This indirect forcing (so called because both the extent and microphysical nature of contrail cirrus, which is currently poorly understood, depends on the precondition of the clear atmosphere) is important to understanding aviation impacts on climate.

The amount of water vapor that is injected into the upper atmosphere by jet engines is quite small in comparison to pre-existing natural sources. It is the soot-like particles in the jet-engine exhaust coupled with the rapid formation of ice particles immediately behind the jet engine that have a much more dramatic and longstanding impact on altering the natural environment. Contrails form in supersaturated air masses, regions of the upper troposphere and lower stratosphere wherein there is an overabundance of water vapor – a gas that we cannot see. Insofar as cloud formation – the deposition of ice particles that we can see – is concerned, these regions are conditionally unstable. Even with the abundance of water vapor, natural physical mechanisms that depose the vapor into ice crystals are not strong enough to upstage the delicate thermodynamic balance that exists in cloud-free, vapor-laden environments. The insertion of engine soot into the supersaturated air mass quickly upsets this delicate balance and can start precipitous formation of ice particles that spread at upwards of 8 km/hr to form longer-lasting contrail cirrus. It is helpful to think of this process as that of balancing an ice-cream cone on its tip: the precariously balanced cone is easily upset by a miniscule nudge anywhere along its top or sides. This causes the cone to fall quickly, altering its "state." Jet engine effluents can have a similar impact on the formation of cirrus clouds in supersaturated regions of the atmosphere. Subsequent contrail and cirrus production noticeably alters the radiative balance that was in place under the previously cloud-free, "natural" conditions in what is believed to be a net warming way. The degree of warming in a global sense is poorly understood in large part because our ability to detect and observe this phenomenon on global scales is weak, and our understanding of the physical processes at work is poor.

The ability of general circulation models (GCMs) to prescribe and predict the presence of cold supersatured air parcels in the upper troposphere and lower stratosphere (UTLS) determines substantially their ability to characterize accurately the magnitude of contrail (and contrail-cirrus) radiative forcing. Most NWP models in a routine sense do not represent accurately (or at all) the interactions between temperature, water-vapor and jet exhaust that (may or may not) cause contrails to form and evolve. Understanding cirrus and contrail microphysics and their influence on radiative forcing is key to assessing with skill any contrail impact on climate. It is intricately related to three sub-areas of physical processes: 1) the UTLS water budget, 2) microphysical formation and dissipation processes, and 3) radiation. Each of these three physical processes has influence over one another in highly nonlinear ways. All of these processes must be faithfully represented in climate models before they can routinely provide a realistic assessment of the contrail-climate impact.

Of key importance in radiative studies of contrails and their influence on global climate are (1) their microphysical properties – size, shape, number – which in turn prescribe how the radiant energy flux interacts with cirrus at the ice-particle level; (2) how these interactions influence space-based radiance observations and whether their signature is unique to aviation-induced (as opposed to "natural") cirrus; (3) their coverage, both spatial and temporal, on global scales over the full diurnal cycle; and (4) how these factors modify an otherwise natural (i.e., non-anthropogenically induced) net radiation balance. Of immediate interest in this review are items (1) and (2).

Satellite-based contrail detection/retrieval techniques may not (yet) be robust enough for the purpose of assessing climate change. Nonetheless, results of such projects must provide (a) a defensible assessment of the global state of contrails and contrail cirrus – frequency of occurrence, diurnal cycles, microphysics; and (b) a radiative modeling capability that can be used with confidence in GCMs (including predicting their occurrence and evolution). Technically speaking this may be considered a numerical modeling effort – however, it is reasonably clear at this juncture that improvements in contrail modeling (for GCMs) will not advance without the help of satellite-based remote sensing.

2 Radiative transfer in contrails and cirrus

If indeed contrails and contrail cirrus can be discriminated from natural cirrus with repeatability, it is because their ice-particle microphysical attributes (size, shape, number, refractive index) differ, and that these differences moderate upwelling top-of-atmosphere (TOA) radiances in a significant and unique way. Particle-radiation interactions that occur at the individual particle level drive any wavelength-dependent satellite radiance signatures that might separate natural from anthropogenically altered cirrus. In this sense, an understanding and assessment of the varying algorithms' microphysical assumptions are needed insomuch as they influence satellite-based multispectral radiance signatures, either observed or theoretically expected.

This section contains descriptions of the important radiative properties of contrails and contrail-cirrus. Understanding the information content of upwelling radiances requires knowledge of contrail microphysics: in particular, size distributions and irregular ice-particle shapes. These govern the particle-radiation interactions that occur on the individual particle level. Attenuation of the incident radiant energy flux depends on a distribution of particle shapes and sizes in the contrail, and their orientation with respect to the incident and scattered light.

Mie theory is an exact solution of Maxwell's equations for perfect spheres, and it predicts the interaction of spheres with an incident radiance field at the particle level. As computers became increasingly popular their capabilities were brought to bear on many computationally burdensome scientific problems. Scientists argued that the interaction of "randomly oriented, irregularly shaped" particles with an incident electromagnetic energy flux would be well modeled in the average by Mie theory. Shortly thereafter this was rebutted both by computational studies and observation.

There is no single theory that predicts attenuation by irregulars throughout the full range of size parameters $x = \pi D / \lambda$. (Here "D" is the long-axis dimension of an irregularly shaped ice particle.) Complicating factors that make this difficult are the way that ice-particle shape, internal structure, and orientation vary in naturally occurring contrail and cirrus size distributions. Even "exact" solutions of absorption and scattering efficiency of complex, idealized shapes (hex columns, plates, bullet rosettes) take a lot of computer time for just limited ranges of "x." More importantly, unlike Mie theory for spheres, there is of yet no single theory for irregulars that works for all "x." Common theories for ice particles and radiation interactions that occur at the individual particle level include the Finite Difference Time Domain (FTDT), T-matrix, geometric optics, and the Discrete Dipole Approximation (DDA).

In our retrievals we use a particle-radiation interaction theory for ice-particle irregulars called the Modified Anomalous Diffraction Approximation. MADA formulates the cirrus absorption efficiency Q_{ABS} for irregularly shaped ice particles as a scaled multiple of the anomalous diffraction approximation $Q_{ABS,ADA}$ according to the relation

$$Q_{ABS} = Q_{ABS,ADA} (1 + c_1 + c_2) , \tag{1}$$

where

$$Q_{ABS,ADA} = 1 - \exp (-8 \pi n_{ICE} D_{EFF} / 3\lambda) , \tag{2}$$

n_{ICE} is the imaginary refractive index at wavelength λ (see Figure 1), and D_{EFF} is the ratio of the third and second moments of the ice-particle size distribution. This definition applies to both liquid water and ice clouds (Mitchell 2002). The first term "1" on the right side of Eq. (1) represents absorption due to the particle's geometric cross section. The term "c_1" describes absorption of incident radiant energy that is internally reflected or refracted by the particle. The third term "c_2" represents a process called "photon tunneling" (Mitchell 2000) by which photons traveling tangentially beyond the particle's physical cross section undergo tunneling to the particle surface. Once the energy flux is tunneled to the particle, the waves may be refracted at the critical angle, or may propagate as a surface wave along the surface. The former type of tunneling may enhance absorption while the latter only enhances scattering (Mitchell 2000). Both types of waves from tunneling continually dampen as they propagate, releasing energy via large-angle diffraction. Figure 2 contains an illustration depicting this process.

Mie theory (for spherical particles) predicts that tunneling (also known as optical resonance) is *strongest* when (1) the wavelength and effective particle size are comparable and (2) when the real part of the refractive index is high (relative to values for water and ice). But the overall tunneling *efficiency* depends on particle shape (Mitchell et al. 2006), and is at a maximum for spheres. As particle shape becomes more irregular, or as particle aspect ratio departs more from unity, tunneling becomes less influential. In MADA, tunneling strength is represented by the tunneling efficiency T_E, which ranges between 0 (no tunneling) and 1 (spheres). Most of the particles in young contrails and in the small mode of cirrus are quasi-spherical in nature (Korolev and Isaac, 2003; Minnis et al., 1998; Lawson et al., 1998), with high T_E (Mitchell et al. 2006). Particles in the cirrus large mode, such as bullet rosettes and aggregates, are more irregular and have low T_E. MADA theory predicts that tunneling-based absorption efficiencies differ by a factor of two between 11 and 12 μm (see Figure 3), resulting in satellite-observed brightness temperature differences that are shape dependent, as shown in Figure 4.

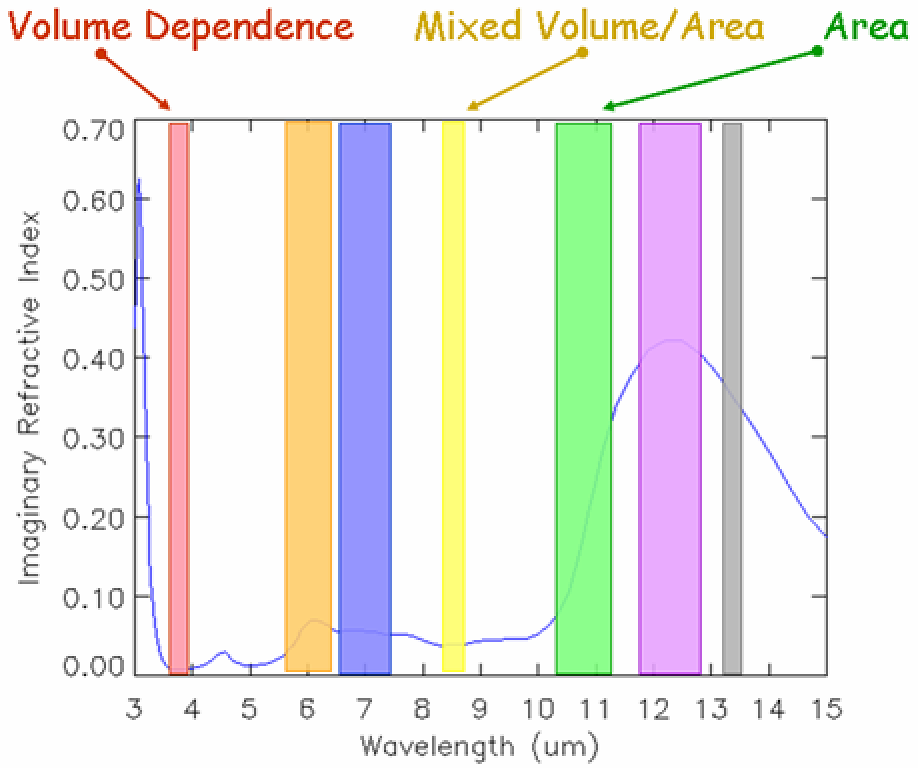

Figure 1. Illustration of the transition from volume to cross-sectional-area absorption dependence as wavelengths increase from the MWIR through to the TIR. Note that the imaginary refractive index for ice is plotted in blue

Another thermal-infrared window channel that contains helpful information on ice-particle size is the LWIR, centered near 8.55 μm. Figure 5 contains the MADA-predicted theoretically expected satellite observations of the 8.6-11-μm brightness temperature difference as a function of both ice-particle effective size and cirrus ice-water path for a typical mid-latitude atmosphere. Note that the differences are largest for the smallest particles. To a first approximation this is because the imaginary refractive index of ice at 8.55 µm (n_{ICE} = 0.039) is a factor of six smaller than that at 11 µm (where n_{ICE}= 0.25); thus it is more likely that an 11-µm photon will be absorbed by an ice particle. The difference in brightness temperature observations at these two wavelengths is an indicator of how long the photon mean path is, and therefore how large D_{EFF} is. Based on this result it is reasonable to expect that the largest 8.55/11-µm differences indicate the presence of small particles.

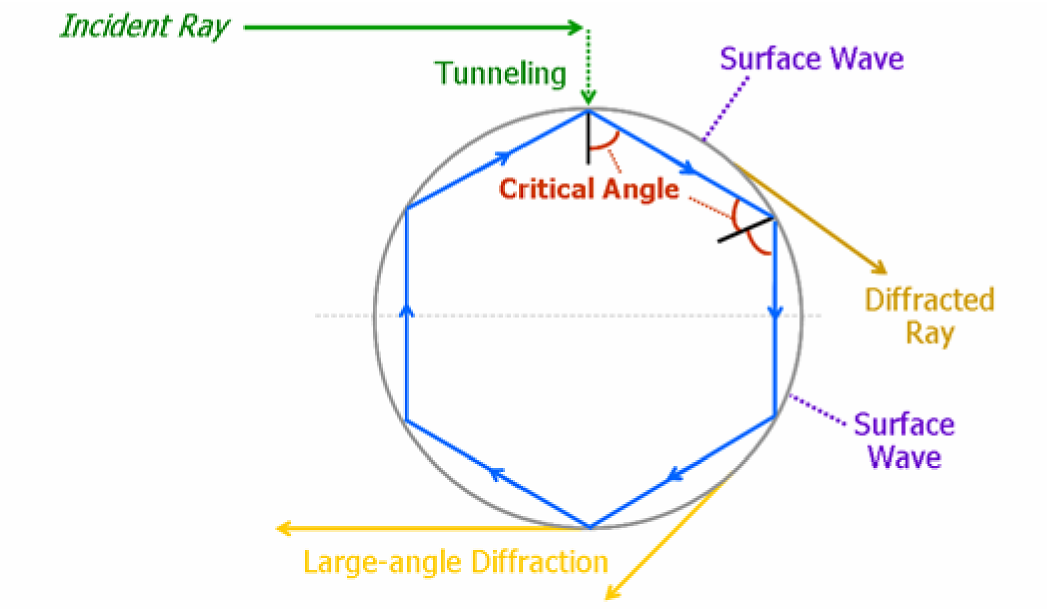

Figure 2. In the process of photon tunneling, energy traveling near but not directly or tangentially within the particle's cross section is focused" (re-directed) toward edge domain of the particle where they can interact as directly incident photons do. Tunneling is most efficient for spheres, but is strongest when the real refractive index is high

It is seen in Eq. (1) that the functional simplicity of the MADA formulation allows valuable insight into the various microphysical factors (shape, size) that govern particle-radiation interactions (at the individual particle level), thereby helping to address a key question of what causes differences in radiative forcing among contrails, contrail cirrus, and cirrus. MADA isolates a new causational argument for the influence of ice-particle shape on longwave brightness-temperature difference signatures that until now has not been well understood. MADA helps prescribe the degree to which shape and size influence contrail and cirrus brightness temperatures at 8.55, 11, and 12 µm (see Figure 4). In using these channels we complement Ackerman et al. (1998), who have noted the usefulness of these spectral bands in contrail and cirrus analysis; however, they make no quantitatively causational argument for the influence of shape on the tri-spectral radiance signatures. Minnis et al. (1998) found that new contrails have small particles, and Lawson et al. (1998)

found them to be "spheroidal" in nature. Figure 6 contains an example of how the influence of the two microphysical properties, shape and size, on brightness temperature might be exploited for the purpose of discriminating contrails from contrail and natural cirrus in satellite imager data.

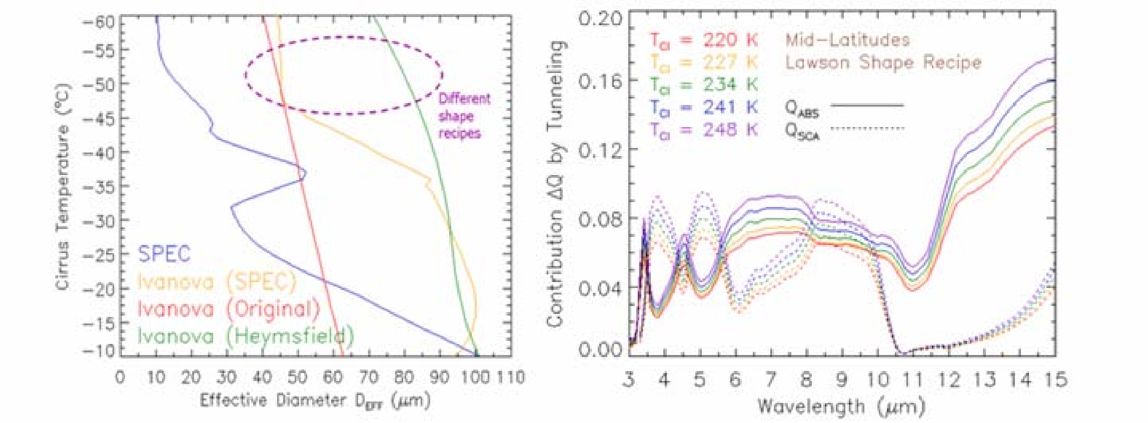

Figure 3. Samples of MADA-predicted tunneling contributions to overall absorption and extinction efficiencies for different PSDs and effective diameters (right), as parameterized by cirrus temperature (used here as a surrogate for effective particle size (left) – higher temperatures have larger ice particles)

Retrieving the ice-particle sizes and shapes helps prescribe their radiative properties at multiple wavelengths using MADA theory; these in turn can be used by a radiative flux model such as the Rapid Radiative Transfer Model (RRTM; Clough et al., 2006) to compute the impact of contrails and contrail cirrus on local and global radiative forcing.

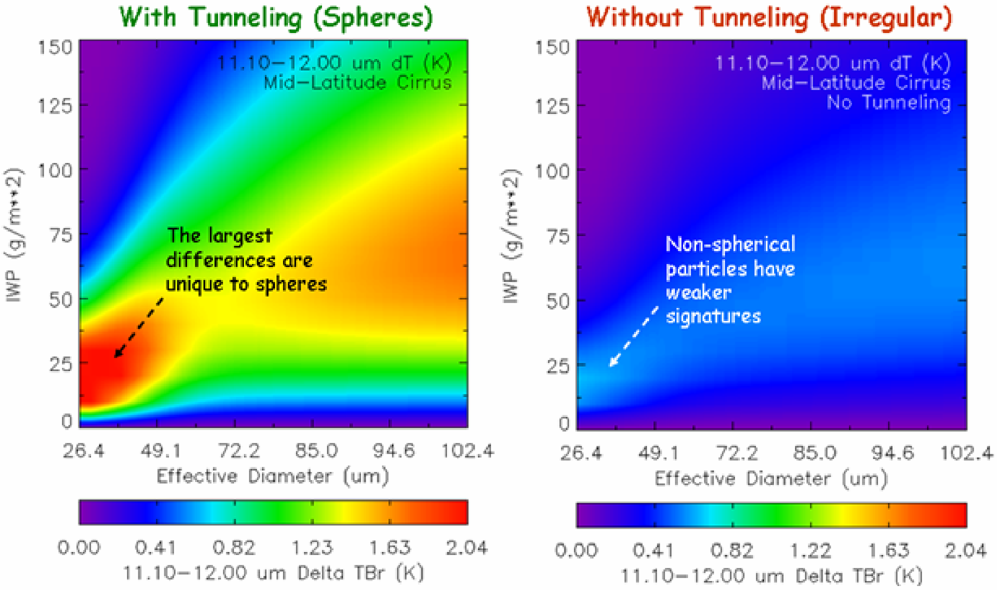

Figure 4. Plots of the theoretically expected brightness temperature differences between 11 and 12 μm with (left) and without tunneling (right), as a function of ice-particle size and cirrus ice-water path. Note that the color scales are the same for both plots; and that the tunneling maximum ΔT is 2 K, while the non-tunneling ΔT maximum is 0.5 K, indicating that the largest differences correspond to the "most spherical" ice particles

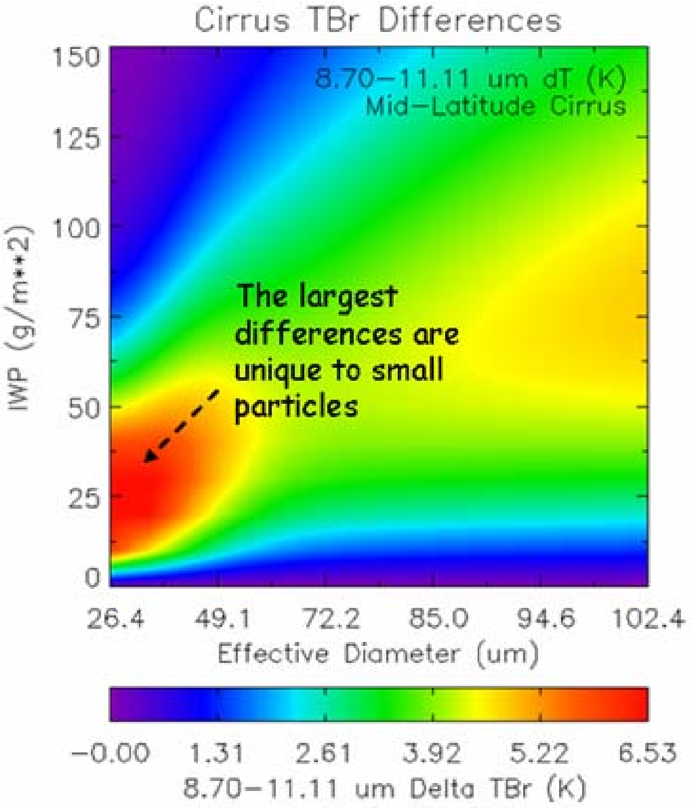

Figure 5. Theoretically expected brightness-temperature differences between 8.7 and 11 µm, as a function of ice-water path and effective diameter. Since ice absorption at 8.70 µm has a stronger volume dependence (weaker cross-section dependence) and 11 µm is a dominantly area cross-section dependent region, the 8.7-µm brightness temperatures tend to be higher for smaller particles.

3 Summary Remarks

Satellite-based contrail detection techniques must begin at understanding the nature of particle-radiation interactions that occur on sub-millimeter and micrometer-sized scales. These interactions govern the way that contrails and contrail cirrus appear in satellite images in such a way that may afford the ability to discriminate them from nearby natural cirrus. Isolating them from one another allows us to isolate their differential forcing impacts – i.e., to distinguish between anthropogenic and natural forcing – and give climate modelers insight into the dominant radiative processes at work in the cirrus/contrail environment. Armed with a more complete knowledge of these physical processes, along with observations of contrails and contrail cirrus over long time periods and over large spatial scales, the way is paved for increasingly more accurate GCM climate forecasts whose predictions have the potential to influence policy on regional, national and international scales.

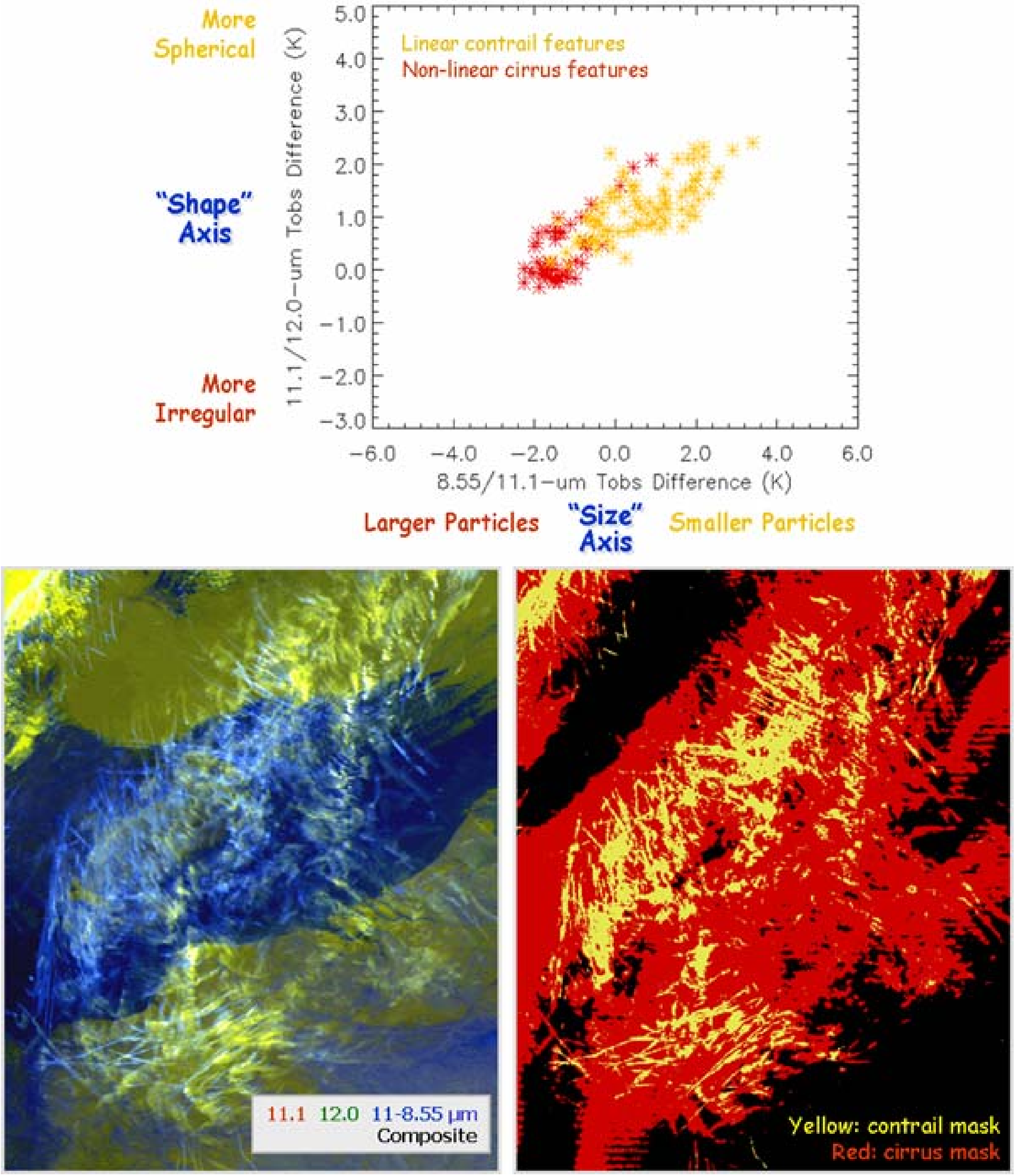

Figure 6. Scatterplot of observed brightness-temperature difference signatures (top) for a daytime MODIS contrail image (bottom left); and the corresponding cirrus/contrail mask (bottom right). In the scatterplot and in the cloud mask image, yellow pixels denote linear contrail features; red represents nearby contrail cirrus and cirrus pixels, identified using the multispectral cloud-mask algorithm described in d'Entremont and Gustafson (2003). Aqua MODIS image is over the English Channel, valid 1225 UTC 9 Dec 03

4 References

Ackerman, S. A., C. C. Moeller, K. L. Strabala, H. E. Gerber, L. E. Gumley, W. P. Menzel, and S.-C. Tsay, 1998: Retrieval of effective microphysical properties of clouds: A wave cloud case study. *GEOPHYSICAL RESEARCH LETTERS*, **25**, NO. 8, 1121-1124.

Clough, S. A., M. W. Shephard, E. J. Mlawer, J. S. Delamere, M. J. Iacono, K. Cady-Pereira, S. Boukabara, P. D. Brown, 2005: Atmospheric radiative transfer modeling: a summary of the AER codes. *J. Quant. Spectrosc. Radiat. Transfer*, **91**, 233-244.

d'Entremont, R. P., and Gary B. Gustafson, 2003: Analysis of geostationary satellite imagery using a temporal differencing technique. *Earth Interactions,* **7**, No. 1, 1-25.

Korolev, A., and G. Isaac, 2003: Roundness and aspect ratio of particles in ice clouds. *J. Atmos. Sci*., **60**, 1795-1808.

Lawson, R. P., A. J. Heymsfield, S. M. Aulenbach, and T. L. Jensen, 1998: Shapes, sizes and light scattering properties of ice crystals and a persistent contrail during SUCCESS. *GEOPHYS. RES. LETT*., **25**, 1331-1334.

Minnis, P., D. F. Young, D. P. Garber, L. Nguyen, W. L. Smith, Jr., and R. Palikonda, 1998: Transformation of contrails into cirrus during SUCCESS. *GEOPHYS. RES. LETT*., **25**, 1157–1160.

Mitchell, D. L., A. J. Baran, W. P. Arnott, and C. Schmitt, 2006: Testing and comparing the modified anomalous diffraction approximation. *J. ATMOS. SCI*., **63**, 2948-2962.

Mitchell, D.L., 2002: Effective diameter in radiation transfer: Definition, applications and limitations. *J. ATMOS. SCI*., **59**, 2330-2346.

Mitchell, D.L., 2000: Parameterization of the Mie extinction and absorption coefficients for water clouds. *J. ATMOS. SCI.,* **57**, 1311-1326.