

# CONTRAILS AND CLIMATE CHANGE: AN INVESTIGATION OF THE ROLE OF AVIATION-INDUCED-CLOUDINESS ON THE IRISH CLIMATE USING AATSR IMAGERY.

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## ABSTRACT

Contrails, or ‘condensation trails’, produced in the wake of jet aircraft have been found to have a small but significant global net climate-warming effect [1]. When atmospheric conditions are favorable (i.e. when ambient atmospheric humidity is high and temperature is below a threshold value of typically less than  $-40^{\circ}\text{C}$ ), contrails can persist for several hours, grow to become several kilometers long and can also trigger additional cirrus-cloud formation as they spread - which can further impact climate! Due to Ireland’s proximity to the North Atlantic Flight Corridor, large volumes of high-altitude overflights cross Ireland daily. Contrails are essentially artificial-linear-ice-clouds at a lower temperature than the surrounding atmosphere and so are visible in 1 Km satellite imagery at the 11 and 12  $\mu\text{m}$  wavelengths; but are better detected in the temperature difference image between these two thermal channels. An automated Contrail Detection Algorithm (CDA) is applied to AATSR thermal imagery over Ireland, and the percentage contrail-coverage of each scene determined. Preliminary results, based on 2008 morning and evening AATSR overpasses show a similar annual average contrail-coverage when present of 0.25% and 0.19% respectively, even though air-traffic density is typically several times higher during the morning overpasses. Cases of excessive contrail-coverage, of up to 2.06% have been observed in combination with extensive cirrus-coverage over Ireland. Results from meteorological data indicate more highly favorable atmospheric conditions for contrail formation and persistence in 00h00 and 06h00 radiosonde ascents; which corresponds to a night-time peak in high-altitude flights over Ireland. Furthermore, exceptionally thick contrail-susceptible-atmospheric layers are found in conjunction with cases of excessive satellite-derived-contrail-coverage.

## 1. INTRODUCTION

Contrails are artificial linear ice-clouds that form in the wake of jet aircraft, when the hot and moist exhaust gases mix with much colder ambient air. Under suitable

meteorological conditions, contrails can persist for several hours and trigger additional cirrus cloud formation. Previous studies into the climate impact of linear contrails have found that contrails produce a small but significant net warming effect on the climate system [1], [2]. [1] assigned a global Radiative Forcing (RF) of  $+0.010\text{ Wm}^{-2}$ , while [2] quote a regional value over a high traffic location in the UK of  $+0.23\text{ Wm}^{-2}$  – one order of magnitude higher than the global estimated value. However, the climate impact of contrail-cirrus may be between 2 to 10 times larger than this. The high regional dependence of this effect suggests that for countries such as Ireland, who have a high density of air-traffic, these effects could be even greater than is outlined in [1]. [3] present an updated estimate of global linear contrail RF of  $+0.0118\text{ Wm}^{-2}$  for 2005 based on updated air-traffic operations data.

Persistent spreading contrails can induce additional cirrus cloud formation. [4] observed a statistically significant increase in cirrus cloud coverage in the North Atlantic flight corridor from 1984-1998. [4] observed the largest cirrus increase in summer, about +2.6% per decade in this flight corridor, which was found to be statistically significant at the 99.5% confidence level. In adjacent regions, with low air-traffic a slight but statistically insignificant negative trend in cirrus coverage was also observed. Another study by [5], which focused mainly on lower latitude regions, found indications of an increasing trend of about 1-2% cloud cover per decade due to aircraft. This was again in contrast to slightly negative trends in low air-traffic regions. No best-estimate for the RF of induced-cirrus-cloudiness is presently available, although [3] postulate that it could be  $0.033\text{ Wm}^{-2}$ , although with large uncertainties and based on a very low level of scientific understanding.

Ireland’s proximity to the North Atlantic Flight Corridor results in a large number of high-altitude (above 24,000 ft) overflights crossing Ireland daily, peaking during the early (eastbound traffic) and late (westbound traffic) morning. To what extent are Irish skies and climate

modified by these high altitude overflights? [6] observed a 15% increase in Irish cloud cover and a corresponding 20% drop in annual sunshine hours at four ground stations from 1881-1998. What proportion, if any, of this cloud cover increase can be attributed to increasing aviation activity over Ireland? In order to answer these questions, an objective evaluation of contrail coverage trends over Ireland is needed. Satellite imagery is the only source of data that allows the objective production of a cloud and contrail climatology over the course of a whole year. Presently, the Contrail Detection Algorithm (CDA) that operates on the dual thermal channels of AATSR (or AVHRR) imagery is deliberately tuned to have a low false alarm rate, but this results in a low contrail detection efficiency also [7]. However, the CDA provides a much more objective evaluation of contrail-coverage than was previously available from manual detections. Here it is applied to one year of AATSR imagery over Ireland and compared with contrail-susceptible atmospheric layers derived from radiosonde data. In this manner, this paper aims to provide a preliminary assessment of seasonal contrail distribution over Ireland for 2008.

## 2. AUTOMATED CONTRAIL DETECTION FROM SATELLITES

The low brightness temperature of contrails in the thermal infrared and their characteristic linear shape allow them to be detected by passive remote sensing methods. Linear contrails are visible in the 11 and 12  $\mu\text{m}$  channels of AVHRR and AATSR, but due to their higher transmissivity at the shorter thermal wavelength, they show up more clearly in 11-12  $\mu\text{m}$  temperature difference images. As discussed in [7], accurate numerical evaluation of the percentage contrail-coverage of a given scene is extremely difficult. Manual evaluation of contrail-coverage is a highly subjective and time-consuming process. Contrail-coverage over central Europe from AVHRR imagery, derived from manual counts ranged from 0.5 to 1.5% for the same time frame, highlighting the subjectiveness of the

manual process. [7] proposed a fully automated algorithm for evaluating contrail coverage in AVHRR 11 and 12  $\mu\text{m}$  thermal imagery, and the same method is applicable to AATSR imagery. This automated Contrail Detection Algorithm (CDA) provides a more objective and efficient method of evaluating the contrail-coverage of a given scene.

The CDA has two main inputs; the 11-12  $\mu\text{m}$  temperature difference (TD) image and the 12  $\mu\text{m}$  image. Normalization and filtering techniques are applied to these images, and linear features which are potentially contrails extracted. In order to identify which of these objects are contrails, the algorithm subjects each to a series of threshold ‘checks’ to reject those which are definitely not contrails [7].

The CDA has been applied to AATSR imagery of Ireland and the surrounding coastal waters, as shown in Figure 1a for 17/03/2009 at 11:18UTC. Figure 1b shows the 11-12  $\mu\text{m}$  temperature difference for this region, and Figure 1c the linear features extracted by the CDA prior to checking. Figure 1d shows the features identified by the CDA as contrails, with a contrail-coverage in this area of 2.06%. The CDA was run with conservative threshold criteria, therefore this value of  $\sim 2\%$  contrail-coverage, although exceptionally high for the area, is nonetheless considered to be a conservative estimate of the contrail-coverage in this scene. Validation of the results was conducted by visual analysis which indicates that there were very few false alarms, whereby an object is erroneously defined as a contrail, however the detection efficiency is estimated to be approximately 30%.

## 3. SENSITIVITY OF THE CDA

The contrail classification scheme within the CDA can be ‘tuned’ by modifying several free parameters, namely the intensity, linearity and size of extracted linear features. Other parameters relating to the normalization and filtering of the input images may also be modified, however to achieve comparable results

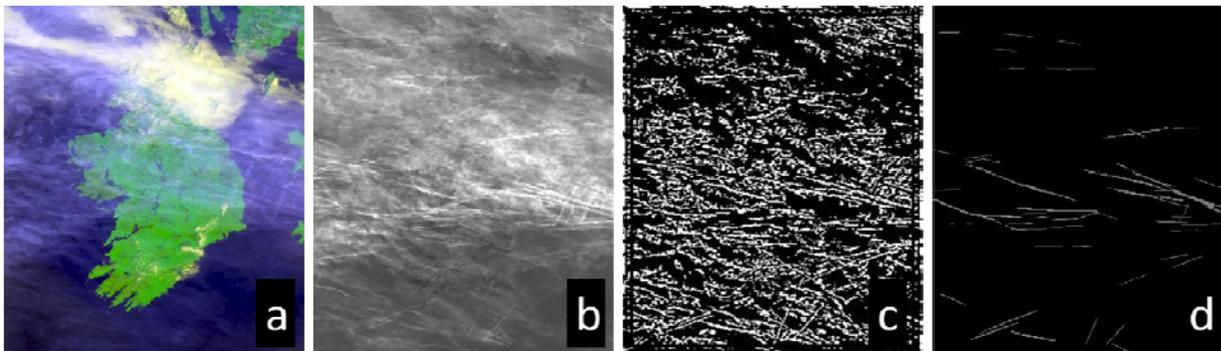


Figure 1: AATSR image for 17/03/2009 at 11:18UTC. a) True colour image, b) 11-12  $\mu\text{m}$  temperature difference image, c) extracted linear features and d) identified contrails ( $\sim 2\%$  coverage).

with other studies, these parameters are fixed to the original values outlined in [7], and attention is focused exclusively on the sensitivity of the contrail definition thresholds within the classification scheme.

The first of the ‘checks’ within the classification scheme compares each extracted object against a binary mask which eliminates objects below certain normalization and temperature thresholds. This check excludes cloud edges and shorelines which can sometimes show a high temperature difference signal and are not always excluded by the normalization filter, due to its high-pass properties. Reducing this intensity threshold increases the number of contrails identified by the algorithm, but an increased proportion of these features may not be genuine contrails and may be cloud edges or cirrus streaks (Figure 2). A value of 2.5 is found to give a good compromise between a low number of erroneous features whilst also identifying genuine contrails.

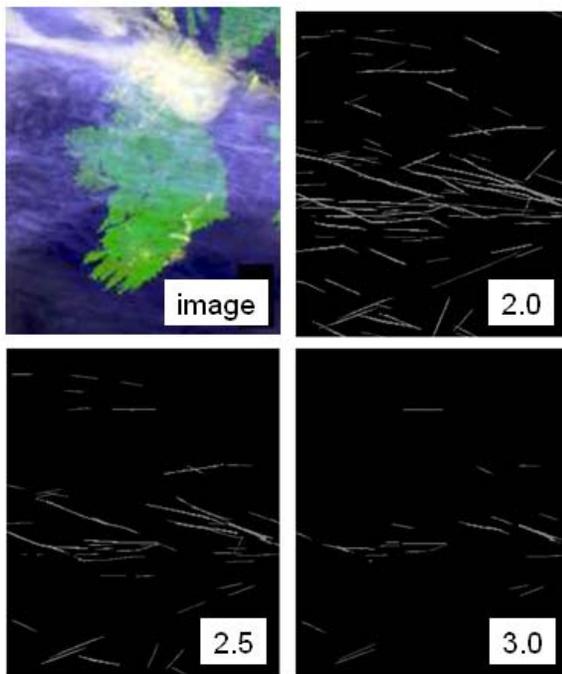


Figure 2: Contrail detection using different intensity threshold factors

Reducing the intensity threshold by 20% from its default value of 2.5 to 2.0 resulted in an increase in contrail coverage by 155%, with a 45% increase in the number of contrails identified. Increasing the intensity threshold by 20% from 2.5 to 3.0 saw a decrease in the amount of contrail coverage of 62% and a halving in the number of contrails distinguished.

Additionally, objects are only considered as contrails if they occupy a minimum number of pixels and have a minimum length. In this manner, the ‘size’ threshold

ensures that short line elements and other processing artifacts are rejected. Reducing this value results in a larger number of contrails being detected, however the false alarm rate rises commensurately with a larger number of small features primarily associated with cirrus streaks being falsely identified as contrails. It has been estimated that approximately 90% of contrail false alarms are actually cirrus streaks that have been misidentified as contrails [8]. It also raises the more general question of the physical characteristics that distinguish contrails from cirrus streaks, and how to define the point at which a ‘contrail’ stops being regarded as a contrail and can be considered as cirrus? For areas of high air-traffic a lower threshold value may be considered for this parameter in order to identify more contrails, as the signal to noise ratio between actual contrails and false detections is higher.

Finally, the linearity condition requires that the correlation of pixel coordinates conforms to a straight line along the filter direction. Modification of the linearity threshold has little effect, as filtering by a 19x19 linear filter kernel has already been performed, however, this additional linearity check ensures that the object under consideration is straight enough to be regarded as a contrail. A threshold value of 0.975 is used which disregards very diffuse and bent structures such as cirrus streaks which may not previously have been eliminated.

Using the same parameters for a near coincident AVHRR and AATSR image shows that contrail coverage from the AVHRR exceeded that of the AATSR image with almost twice as many contrails identified. Upon visual inspections, some of these additional contrails appear to be genuine however the number of false identifications also rose, demonstrating the difficulty of applying universal parameters to all images and all sensors. A similar detection efficiency for both AVHRR and AATSR can be achieved by setting the minimum length requirement to be longer in the AATSR-tuned parameters, resulting in a much lower false alarm rate for that sensor. However, despite these limitations, the CDA remains the most objective and efficient tool by which to identify contrails on large volumes of satellite imagery.

#### 4. CONTRAILS FROM AATSR

AATSR images from 2008 for the region extending from 52-56°N and 11-4°W were evaluated using the CDA. The CDA was used with restrictive threshold criteria to reduce false contrail detections, but this consequently impedes its actual contrail detection capabilities, ultimately resulting in a conservative estimation of contrail-coverage [9],[7]. From the 126 AATSR images available in 2008 for this region, an annual average

Table 1: Seasonal average contrail-coverage over Ireland for 2008 from AATSR morning and evening overpass, with seasonal average overflights through Irish airspace for 2008

	Morning (~11:15UTC)			Evening (~21:45UTC)			Average Number of Overflights
	Average cc	Average cc when present	Frequency of occurrence	Average cc	Average cc when present	Frequency of occurrence	
Winter (DJF)	0.15%	0.22%	66.67%	0.09%	0.21%	42.86%	21,975
Spring (MAM)	0.29%	0.34%	89.47%	0.13%	0.19%	71.43%	26,693
Summer (JJA)	0.14%	0.22%	71.43%	0.16%	0.19%	84.62%	29,356
Autumn (SON)	0.13%	0.19%	72.22%	0.11%	0.19%	58.82%	23,316
Annual	0.18%	0.25%	75.36%	0.12%	0.19%	63.16%	25,835

contrail-coverage (cc) of 0.15% is obtained, which rises to 0.22% when only those images with contrails present in them are considered. Out of the 69 morning and 57 evening images, the annual average contrail coverage when present is calculated to be 0.25% and 0.19% respectively. A seasonal breakdown of these values is presented in Table 1. Also shown in Table 1 is the percentage of images in which contrails were positively detected (i.e. contrail-coverage was greater than 0.01%), as well as the seasonal number of overflights through Irish airspace in 2008. The times of AATSR overpasses over Ireland for 2008 are 11:15UTC and 21:45UTC respectively. The morning overpass corresponds to a daily peak in overflights in Irish airspace (i.e. westbound transatlantic flights), while the evening overpass represents a minimum in air-traffic. However the night-time peak in Irish air-traffic, which occurs around 04:00UTC (i.e. eastbound transatlantic flights) was not imaged by AATSR.

Table 1 indicates that spring has the highest daytime cc in 2008 (nearly double that of other seasons), although overflights are highest in summer. Winter presents a much lower average cc relative to other seasons - which is not unexpected considering that winter has the fewest overflights.

The actual averages provide a general overview of the seasonal contrail-coverage. However, as indicated by the haze of cirrus-cloud visible in Figure 1a, the intensity of cc when present is at least as important as the frequency of contrail occurrence.

## 5. DETERMINING VIABLE CONTRAIL-ATMOSPHERIC CONDITIONS

Contrail formation is described thermodynamically by the Schmidt-Appleman Criterion, due to a temporary increase in the local relative humidity to above water saturation in the exhaust plume of jet aircraft. Liquid water particles that form in water-supersaturated air freeze to form icy contrails, which can then persist in ambient air that is only ice-supersaturated. It should be noted that ‘natural cirrus’ clouds cannot form spontaneously under these atmospheric conditions, but contrails that are formed can persist and may develop into ‘contrail cirrus’. The critical temperature threshold for contrail formation is dependent upon ambient pressure, relative humidity and the aircraft’s contrail factor [10]. The Schmidt-Appleman criterion assumes an isobaric mixing process; thus the critical temperature threshold for contrail formation must be calculated independently for each atmospheric pressure layer. Using pressure, temperature and relative humidity data from radiosondes, the susceptibility of the atmosphere to contrail formation and persistence can be determined.

If the atmospheric relative humidity is above ice-saturation, contrails that form will persist under these conditions, as hypothesized for the image in Figure 1. Several studies [11], [12], [5] & [13] have successfully predicted contrail persistence using these criteria with reasonable accuracy. Figure 3 shows a radiosonde ascent from Valentia at 11:15UTC on 17/03/2009 (coincident with the AATSR overpass shown in Figure

1), with the contrail-susceptible layer of the upper atmosphere shown to occur centered around the 200hPa pressure level (which corresponds to approximately 35,000ft – a typical cruising altitude for transatlantic flights). In this instance, the radiosonde’s path might not take it directly through one of the contrails shown on the image in Figure 1 however it does indicate the potential for upper atmospheric conditions to support contrail formation at this time.

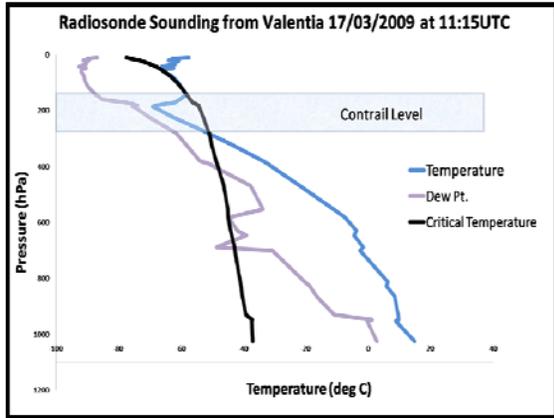


Figure 3: Radiosonde sounding indicating contrail susceptible atmospheric layers for the same date and approx. time as the AATSR imagery in Figure 1.

## 6. ANALYSIS OF CONTRAIL LAYERS IN VALENTIA RADIOSONDES

Using the modified Schmidt-Appleman criterion [10] and a contrail factor of 0.036 g/kg/K (average for commercial jets, from [13]), it was first determined if the formation criteria for contrails were satisfied. For cases where contrail formation was possible, a second test evaluated if the ice-supersaturation condition was also satisfied (i.e. if contrails that formed would persist). Hence, results presented here represent Contrail favourable Ice-SuperSaturated Layers (CISSLs).

Four times daily radiosonde ascents from the Valentia observatory have been supplied by Met Éireann and are used in this study. All available ascents for 2008 have been analyzed, at standard vertical resolution (on average ~300 m). The CISSL values (Figure 4), were calculated using uncorrected data from the Väisälä RS92 radiosonde, which can result in an overly conservative estimation of CISSL thicknesses as there is a tendency for radiosondes to underestimate atmospheric humidity [11], [14]. However, atmospheric profiles from radiosondes provide an objective method of ground truthing the presence or absence of contrail-favourable atmospheric conditions.

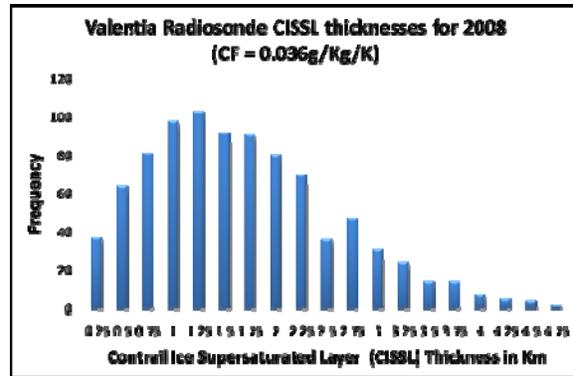


Figure 4: Histogram of CISSL distribution for 2008 from four times daily Valentia radiosondes

77% (i.e. 1114 out of 1449) of radiosonde ascents available for 2008 from Valentia had at least one Contrail Ice-Supersaturated layer (CISSL) present. The modal CISSL thickness (Figure 4) is 1.25km, with the majority lying between 0-2.25km thick. These values are consistent with ice-supersaturated layer thicknesses established from UK radiosonde ascents [11]. However, several cases of extreme CISSL thicknesses are observed in excess of 3.5km and with a maximum of 4.75km; which is highly unusual. The image shown in Figure 1, which demonstrated a scenario of excessive contrail-coverage, was acquired when the atmospheric conditions gave rise to such an exceptionally thick CISSL of about 4.5km in depth.

Plotting the monthly mean thickness of the contrail ice-supersaturated layers for 2008, shows they were thickest at night and in winter (Figure 5).

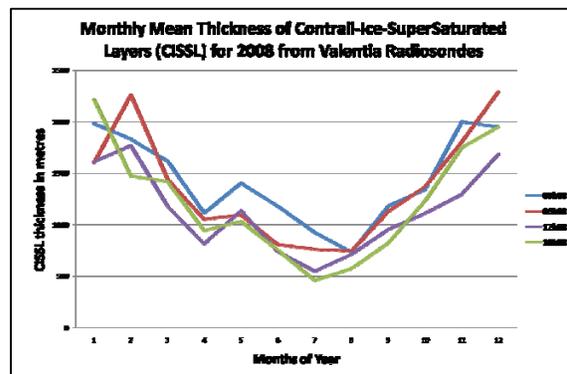


Figure 5: Monthly mean thickness of contrail ice supersaturated layers for 2008 from Valentia radiosondes

## 7. DISCUSSION

Detection of contrails by a fully automated image analysis process has proven to be problematic due to the trade-off that arises when tuning the detection algorithm to minimize the number of false alarms but maximize the number of correctly detected contrails. As demonstrated by Figure 2, the parameters used can significantly impact the results. It is estimated that the CDA detects between 30-50% of those contrails visibly recognizable in the temperature difference image, when tuned to constrict misdetections.

For one year of AATSR data acquired over Ireland, an average contrail-coverage when present of 0.22% was calculated; potentially this number could be as high as 0.4-0.6%. On some occasions excessive contrail coverage is identified (~2%), even with conservative tuning of the algorithm; in reality on such occasions there may be as much as 6% contrail-coverage.

Comparing radiosonde-derived contrail layers with the nearest time-coincident AATSR image, shows that for 72.6% of occasions there is agreement between these two datasets as to the presence/absence of atmospheric contrail layers and the satellite-derived contrail-coverage (or lack thereof). Examination of the incidences of mismatch between the satellite and radiosonde contrail-coverage suggested both a spatial and temporal explanation. In 13.4% percent of cases, the CDA identified contrails over Ireland when radiosonde analysis indicated that atmospheric conditions were unsuitable for their persistence at Valentia. Further investigation, based on visual inspection of the satellite imagery and the contrail masks produced by the CDA, found that the causes for these disagreements were spatial in nature; i.e. contrails detected on the imagery were at locations other than Valentia. There was no instance in which contrails were detected at Valentia in atmospheric conditions which could not support them.

In the remaining 14.0% of comparisons (i.e. when atmospheric conditions were favourable for contrail formation but no contrails were detected) only 7.3% of daytime images indicated such an occurrence as opposed to 20.7% of evening images. Although the daytime overpass of AATSR is close to the midday radiosonde launch, the evening image acquisition tends to precede the launch by about 3 hours; during which time atmospheric conditions may change. Furthermore, a greater number of mismatches of this type occurred in winter months (and in evenings) when there are fewest overflights or on other occasions when contrail layers were relatively thin. Therefore, this is not necessarily a failing of the algorithm.

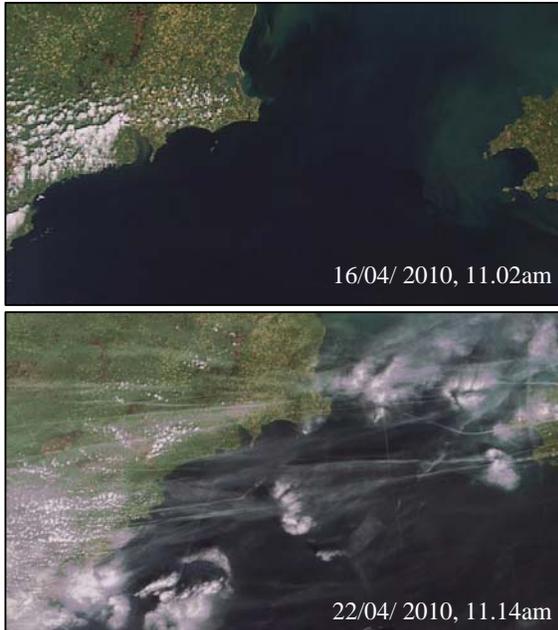
To date only radiosonde launches from Valentia in west Ireland have been examined. Atmospheric conditions may be very variable across Ireland, thus explaining why contrails may be found along the east coast at times when the humidity and temperature on the west coast would not suggest the persistence of contrails. To overcome the lack of spatial coincidence between the satellite and radiosonde ascents, ERA Interim data are being analyzed in conjunction with Valentia-CISSLs. It should be noted as well that the location of the Valentia observatory is at the westernmost tip of Europe, where an increase in humidity compared to more continental locations may contribute to cases of extreme CISSL thickness observed.

AATSR acquires one, or at most two, images of Ireland within a 24 hour period, which severely limits the formation of a complete contrail climatology. The morning overpass (around 11:00UTC) is coincident with one of the busiest flight periods with transatlantic aircraft travelling west over Ireland from European airports. However the influx of aircraft in an easterly direction, which occurs at around 04:00UTC, is not detected by AATSR. Moreover, the 00:00UTC and 06:00UTC radiosonde ascents generally have the thickest CISSLs, indicating the greatest potential for contrails to form and persist at this time. To address this issue it is hoped to augment the AATSR database with imagery from AVHRR, which typically passes over Ireland up to 8 times in a 24 hour period and thus provides a much more comprehensive depiction of diurnal contrail coverage. However, previous work that has compared AVHRR imagery to AATSR [9] suggests that AVHRR has a much higher false alarm rate for a similar detection efficiency as AATSR. Comparing contrail coverages from different instruments and satellites can be problematic as minor differences in the calibration of the thermal channels influence the detection capabilities of the CDA. This is the case even when comparing imagery for the same sensor flying on different satellites [9].

To overcome this instrument-dependant bias, an evaluation of the detection efficiency and false alarm rate of the CDA for each instrument will be made using an interactive contrail assessment tool [15] to provide a more diurnally consistent bias-corrected contrail-coverage. As a result, it will be possible to more accurately evaluate the regional climatic effects of the contrails, given that the net radiative forcing effect of daytime contrails is negative, but that of night-time contrails is positive - leading to a net annual warming due to the presence of contrails [1],[2].

The impact of contrails on the skies of north-western Europe was highlighted in April 2010 when air-spaces were closed to commercial jet aircraft for 5 days

following the injection of ash into the atmosphere from the Eyjafjallajokull volcano in Iceland. Figure 6 illustrates the difference in contrail and (potentially) contrail-induced-cirrus as observed by MERIS on 16<sup>th</sup> April (the first day of the flight ban) and 22<sup>nd</sup> April (the day after flights resumed) over the southern Irish Sea. Both images were acquired shortly after 11am, and the midday radiosonde launch for those dates showed very similar atmospheric conditions for contrail formation on both occasions, namely a region of the atmosphere approximately 1.4 km thick at an altitude where jet aircraft would be cruising.



*Figure 6: MERIS images of the southern Irish Sea region during and immediately after the flight ban over north-western Europe in April 2010*

The effect of the closure of Irish air-space, and the impact of the resultant lack of contrails on the Irish climate is unclear. In theory, an increase in the surface diurnal temperature range (DTR) may be observed, as was the case in the USA during the air-traffic shutdown from 11-14<sup>th</sup> September 2001 [16]. However, it is important to note that volcanic eruptions exhibit a substantial but short-lived perturbation of the radiative energy budget. For example, the 1991 eruption of Mt. Pinatubo, which forms the basis of model studies of radiative forcing due to volcanoes, resulted in a temporary radiative forcing of  $-3 \text{ Wm}^{-2}$  [1]. This substantial cooling effect is likely to obscure any small contribution of contrails to the radiative budget on these days, therefore it may not be possible to draw any definitive conclusions regarding contrail climate effects from analysis of the surface temperature records on these dates. Indeed, analysis of surface DTRs at

Valentia during the shutdown does not yield any conclusive results. However, as shown in Figure 6, the impact of aircraft on days which were atmospherically similar is clear and the effect of absent contrails should be considered in any radiative budget calculations of the Eyjafjallajokull volcanic emissions.

## 8. CONCLUSIONS

An automated Contrail Detection Algorithm (CDA), which identifies contrails on the basis of their different properties at the 11 and 12  $\mu\text{m}$  wavelengths, has been applied to one year of AATSR imagery over Ireland. The average annual contrail-coverage when present for 2008 was 0.22%. However, these AATSR-derived contrail-coverages do not take into account the nighttime peak in transatlantic air-traffic crossing Ireland in the early hours of the morning, when Contrail Ice-SuperSaturated Layers are thickest. Nor do these figures take into account that the CDA is conservatively tuned such that there are very few false alarms but typically only 30-50% of those contrails visible in the temperature difference image are detected. As demonstrated by the case study of 17<sup>th</sup> March 2009, there are occasions when the meteorological conditions in the upper atmosphere over Ireland support unusually deep layers in which contrails may form and persist, with eventual dispersion into high level cirrus cloud. As shown by Figure 3 the atmospheric conditions are conducive to contrail formation at an altitude commensurate with transatlantic aircraft, supporting the results of the CDA. However, Figure 4 indicates that such an instance of extreme CISSL thickness is not a unique occurrence. In fact, several cases of extreme CISSL thickness are found in radiosonde ascents from Valentia during 2008 - although it is not currently clear how representative these results are for the rest of Ireland. ERA Interim data will be analyzed in comparison with radiosonde CISSLs and additional satellite imagery to provide further insights. AVHRR thermal imagery is being incorporated to supplement contrail observations to provide a more complete assessment of contrail-coverage trends, with appropriate care taken to consider the different detection capabilities of the CDA across different instruments [9],[15]. This will enable diurnal cycles in contrail coverage to be much more clearly distinguished, and together with information on the contrail optical depths [8] their radiative forcing effect on the regional climate can be evaluated.

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