WILL CLIMATE CHANGE AFFECT CONTRAIL OCCURRENCE?

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ABSTRACT

Radiative forcing from contrail coverage is an important climate impact of aviation. In this study the conditions that permit contrail persistence and indicate spreading are analysed for a present (1980-2012) and future (2068-2100) climate, based on a high emissions (RCP8.5) scenario, using data from an EC-Earth climate simulation. The analysis is conducted over three areas of aviation and meteorological interest: the North Atlantic region, the South Asia region and the USA region. Changes in the frequency of cold ice-supersaturated regions, the regions where contrails can persist, are used to indicate the changes in frequency of persistent contrails. In the North Atlantic, South Asia and USA regions, a mean change of 1.7%, -7.2% and 0.8% in the frequency of cold ice-supersaturated regions is found from a present to future climate, respectfully. The decrease in the South Asia region in a future climate is a result of increased temperatures while the increase in the North Atlantic and USA regions is a result of increased relative humidity. Changes in the vertical wind shear within cold ice supersaturated regions are used to indicate changes in the extent that contrails spread out horizontally. In the North Atlantic, South Asia and USA regions, a mean change of 0.45 m s\(^{-1}\), 0.04 m s\(^{-1}\) and 0.69 m s\(^{-1}\) in the wind shear is found from a present to future climate, respectfully. The distribution of wind shear is found to change differently in each region, but an increase in the mean wind shear is observed in all three regions. These results suggest that contrail coverage is likely to increase in a future climate in the North Atlantic and USA regions, but likely to decrease in the South Asia region. Future work is recommended to quantify the change in contrail coverage, additionally considering changes in aircraft traffic and technology.
1. INTRODUCTION

A condensation trail, or contrail, is an anthropogenic ice cloud generated behind an aircraft under certain atmospheric conditions. Contrails form in cold ice-supersaturated regions (ISSRs) where the ambient temperature and relative humidity with respect to ice (from here on in just relative humidity) exceed threshold values, but there is a lack of ice nuclei to form natural cirrus. When aircraft fly through ISSRs, particles in the aircraft exhaust act as nuclei for water vapour to condense and instantly freeze around, generating a contrail.

Typically, contrails fall into three categories (Madigan, 2013): short lived contrails which appear as short white lines following along behind an aircraft lasting a few minutes or less, persistent contrails which look like long white lines that remain visible after the aircraft has disappeared and persistent spreading contrails which look like long, broad, fuzzy white lines that can develop to become indistinguishable from natural cirrus. The formation and type of a contrail is dependent on the state of the atmosphere, so variations in atmospheric properties (relative humidity, temperature and wind shear) due to climate change could result in changes to contrail frequency and rate of spreading.

The study of contrails is of importance because contrails are a significant climate impact of aviation, which is calculated to contribute up to 14% of the total radiative forcing (RF) due to all human activities (Shine, 2010). However, estimates in aviation RF are somewhat uncertain, largely because of the uncertainty in aviation-induced cloudiness. Of interest in this study is the direct mechanism of aviation-induced cloudiness: the formation of persistent contrails and spreading of these contrails to produce natural-like cirrus clouds known as contrail-cirrus. The present day RF of these anthropogenic clouds is estimated at 10-80 mW m\(^{-2}\), potentially larger than the impacts from the CO\(_2\) emissions of aviation of about 30 mW m\(^{-2}\) (Lee et al., 2009). Schumann (2005) finds that the contrail-cirrus cover over Europe is about 10 times higher than the line shaped contrail cover, reinforcing the importance of spreading of contrails.

Global air traffic is predicted to grow by 2-5% annually for the next 50 years, leading to large increases in contrail coverage (Minnis et al., 1999) and motivating the study
of a climate-contrail relationship. Considering changes in air traffic, aircraft technology and climate change, Marquart et al. (2003) estimate that global annual mean contrail cover will increase from 0.06% in 1992, to 0.14% in 2015, and to 0.22% in 2050. This corresponds to a RF of 3.5 mW m$^{-2}$ in 1992, to 9.4 mW m$^{-2}$ in 2015, and to 14.8 mW m$^{-2}$ in 2050. They add that the enhancement of contrail cover is dominated by the growth of aviation, although the contrail cover is, additionally, highly affected by climate change in the tropics.

Global contrail RF is extremely inhomogeneous, largely due to the distribution of aircraft traffic. As a result, contrail RF at any given location could be much larger or smaller than the magnitudes presented above. Wilkerson et al. (2010) state that 92.5% of aviation fuel was burned in the northern hemisphere in 2006 with 69% between 30°N and 60°N. They also state that over half of this was distributed amongst 3 regions: United States (25.5%), Europe (14.6%) and East Asia (11.1%). These results imply that particular areas of the world are of greater interest for studying contrails.

Given the known sensitivity of contrail formation, persistence and spreading to atmospheric conditions, their climate impacts and their expected increase in coverage, this study aims to investigate the impact of climate change on contrails. Firstly, this study aims to determine to what extent the frequency of persistent contrails might change under climate change. Secondly, this study aims to determine to what extent the spreading of persistent contrails might change under climate change. Rather than analysing observations or simulations of actual contrails, the work to be reported will analyse the changes in frequency of ISSRs and changes in wind shear within these ISSRs for a present and future climate, indicating a change in the potential for contrail formation, persistence and spreading.

In Section 2 the regions of interest for this study are defined. In Section 3 the frequency of ISSRs are analysed for the present climate using reanalysis data. In Section 4 a similar analysis validates the historical climate simulation data with the reanalysis data. In Section 5 future and historical climate simulation data are compared to identify changes in the frequency of ISSRs. In Section 6 wind shear data from historical and future climate simulations are compared, which is validated against reanalysis data, to identify changes in the wind shear. The results are summarised and conclusions are stated in Section 7.
2. REGIONS OF INTEREST

The first requirement is to define areas that are appropriate for studying contrails. As discussed in Section 1, the global distribution of aircraft traffic is extremely inhomogeneous. To ensure this study produces the most relevant results, data analysis will be focused over areas of particular aviation and meteorological interest. These include areas of high and/or strong growth of air traffic, areas in the tropics where contrail formation has been shown to be most sensitive to climate change (Marquart et al., 2003) and areas dominated by short/long haul flights determining the percentage of the flight time that the aircraft resides at cruise altitude.

To satisfy a mix of these criteria, 3 regions have been selected (Figure 1). The region over the North Atlantic is chosen because of high air traffic, a dominance of long-haul flights and the fact that it represents the mid-latitudes (40°N to 65°N). The region over South Asia is chosen due to strong air traffic growth in this area and the fact that it resides in the tropics (below 23°N). The region over the United States of America (USA) is selected due to very high air traffic and a dominance of short-haul flights in this area.

![Figure 1](image)

*Figure 1:* The three regions this study will focus on based on aviation and meteorological interest are (1) The North Atlantic Flight Corridor (40°N-65°N x 70°W-5°W) (2) South Asia (0°N-23°N x 70°E-105°E) and (3) United States (23°N-50°N x 125°W-66°W).
**3. PRESENT DAY ISSRs**

### 3.0. Data

ERA-interim reanalysis data produced by the European Centre for Medium Range Weather Forecasts (ECMWF) is used in this chapter to analyse ISSRs, the regions that permit contrail formation and persistence. This dataset is created via an unchanging model which ingests all available observations over the period being analysed, providing a dynamically consistent estimate of the state of the atmosphere at each time step in the dataset. The data runs from 1979-present and is available at a horizontal resolution of 0.75° and 60 vertical levels (Dee et al., 2011).

This data is chosen because the formulation of the ECMWF model allows formation of cloud free ISSRs, in contrast to other reanalysis datasets which create clouds once the relative humidity reaches 100%. Satellite data is used in some studies of ISSRs (Spichtinger et al., 2003; Lamquin et al., 2012) but suffers from coarse vertical resolution, particularly in the upper troposphere, is only generally available from the early 1990s onwards containing noticeable gaps. Although the spatial coverage of in-situ measurements is greater now than any time previously, these observations would not allow the analysis of ISSRs over large geographical locations and for climatological time periods in a way that reanalysis data offers. For these reasons, ERA-Interim reanalysis data is well suited to this study.

Here, temperature and humidity are extracted for the three regions of interest at 0000 UTC for each day in January from 1980-2012, and are limited to 4 vertical pressure levels (300, 250, 225 and 200 hPa) that span the range of aircraft cruise altitudes. January is chosen because ISSRs are most frequent at this time of year in the Northern hemisphere due to lower average temperatures, and also because the jet stream is strongest in winter leading to greater vertical shear and contrail spreading.

### 3.1. Mean frequency of ISSRs

To analyse ISSRs the first requirement is to define exactly what an ISSR is. Firstly there must be a temperature dependence as contrails are ice clouds by definition. To ensure only ice is present the temperature threshold is set to less than 235K to
eliminate super-cooled water. Secondly there must be a humidity dependence as contrails can only persist in a sufficiently humid environment. For this persistence to occur, the relative humidity must be greater than 100%. However, in this study it is noted that the reanalysis data are averaged over grid boxes, so locally within a grid box the relative humidity could be greater than 100%, even when the grid box averaged relative humidity is less than 100%. To better capture ISSRs, the relative humidity threshold for ISSRs is therefore set at greater than 98%.

The mean frequency of ISSRs in January for the entire period from 1980-2012 over the North Atlantic region is shown in Figure 2. At the 200 hPa level there are two key features visible. The first feature is the band of relatively high frequencies of ISSRs (values of 15-20%) from roughly 40°N x 33°W to 52°N x 5°W, attributed to the North Atlantic storm track. As the jet stream directs cyclones across the North Atlantic, rising moisture within these systems leads to higher humidities at these upper levels. The other feature is the very low frequencies of ISSRs seen intruding from the north-west of the region. This is due to the presence of the Stratospheric Polar Vortex (SPV). Descending dry stratospheric air in the SPV leads to low humidity values, causing frequency of ISSRs near 0%.

![Figure 2](image-url)

*Figure 2: Mean frequency of ISSRs in January over the North Atlantic region from 1980-2012 at a) 200 hPa, at b) 250 hPa and at c) 300 hPa. Uses ERA-Interim reanalysis data.*
The height of the tropopause is variable, but lies between 200 hPa and 300 hPa for the majority of the time in this region. Therefore, the mean plots in Figure 2 can be interpreted as a transition from the lower stratosphere at 200 hPa to the upper troposphere at 300 hPa. As a result it is seen that the influence of the SPV is decreasing towards the surface, while the influence of the storm track is increasing.

For the South Asia region (Figure 3), at 200 hPa the first thing to note is the sharp boundary in ISSR frequency located between 5°N and 11°N. This shows the maximum extent of the Inter-Tropical Convergence Zone (ITCZ). The Hadley cell circulation causes moist air to rise along the ITCZ, leading to high frequency of ISSRs at high altitudes from convection. To the north of this region the air is in the descending branch of the Hadley cell and is therefore lacking the transport of moisture to high levels, resulting in very low frequency of ISSRs.

As the altitude decreases the mean frequency of ISSRs recedes towards the equator, and at 300 hPa it is very low everywhere. This is a direct result of the temperature threshold of ISSRs. At 300 hPa in the tropics the temperature is very rarely below 235 K (see Section 3.2, Figure 5 (b)). Figure 3 (d) shows this plot without the temperature threshold and it is seen that the frequency of ISSRs does indeed increase near the equator if the temperature threshold is removed.

Figure 3: Mean frequency of ISSRs in January over the South Asia region from 1980-2012 at a) 200 hPa, b) 250 hPa, c) 300 hPa and d) 300 hPa without the temperature dependence. Uses ERA-Interim reanalysis data.
Another two interesting features can be identified in the USA region (Figure 4). The storm track seen in Figure 2 begins off the East coast of the USA. At the north-east corner of the region where the USA region and the North Atlantic region overlap, the higher frequencies of ISSRs associated with the storm track follows on directly between the two regions. Perhaps more surprising is the maximum in ISSR frequency located to the far north-west of the USA. The maximum is evident at all pressure levels but becomes higher in magnitude at lower altitudes. Section 3.4 will analyse this maximum in more detail and attempt to explain its existence.

![Figure 4: Mean frequency of ISSRs in January over the USA region from 1980-2012 at a) 200 hPa, at b) 250 hPa and at c) 300 hPa. Uses ERA-Interim reanalysis data.](image)

In addition to analysing the mean frequency of ISSRs over the three regions of interest, the standard deviation is plotted for each region (not shown). Here the focus is the standard deviation of the monthly mean of each January from the 1980-2012 January mean. In the North Atlantic region there are relatively high standard deviations around the boundary of the SPV, showing there is year-to-year variability in its maximum extent, and also in the storm track as a result of variations in the jet stream position, largely determined by the North Atlantic Oscillation. Relatively high
standard deviations are also seen in the South Asia region where the annual variability is likely due to the influence of the El Niño Southern Oscillation (ENSO), which is discussed in more detail in Section 3.3.

3.2. Probability density functions (PDFs)

Plotting the relative humidity and temperature distributions across each of the regions allows identification of how the data are distributed, and also where the data are distributed in relation to the temperature and humidity thresholds for ISSRs. Analysing PDFs of temperature and relative humidity over the same region, it is then clear to see what dependence is dominating/limiting the occurrence of ISSRs.

The temperature and humidity PDFs for the South Asia region at 300 hPa are shown in Figure 5. The humidity plot, plot (a), shows a bimodal distribution with a maximum at both low humidities (0-20%) and high humidities (100%). This is a typical humidity distribution that is seen across all the regions. The maximum at low humidities is simply a function of the average relative humidity, but the maximum at 100% humidity occurs because the existence of clouds, giving rise to the much sharper peak. Although cloud free ice supersaturation is permitted in the model, whenever a cloud does form, the in-cloud relative humidity is set to 100%. Clouds are relatively common at 300 hPa in the tropics giving rise to a significant peak in this region. The temperature plot, plot (b), shows an approximately normal distribution. The mean temperature is approximately 242 K and is rarely below the 235 K threshold. The area under the curve to the left of 235 K is very small in relation to the area under the curve to the right of 235 K, hence why the mean frequency of ISSRs was ~ 0% (Figure 3 (c)).

![Figure 5: Probability density functions of a) Relative Humidity with respect to ice and b) Temperature in the South Asia region at 300 hPa. Includes all 0000 UTC January data from 1980-2012. Uses ERA-interim reanalysis data.](image)
3.3. Identifying the El Niño Southern Oscillation

The El Niño 3.4 sea surface temperature anomaly, a measure of ENSO strength, from 1980-2012 (NOAA, 2013) is used here to identify years of strong El Niño and strong La Niña. This study will focus on 2 strong El Niño events, 1983 and 1998, and 2 strong La Niña events, 1989 and 2000 identified using this method, which have strong signatures in January. The definition of El Niño has evolved over the years leading to confusion in its use (Trenberth, 1997). For the sake of this study it is important to note that there are relatively warmer sea surface temperatures (SSTs) in the central and eastern Pacific during an El Niño episode, and the relatively warmer SSTs in the western Pacific and surrounding water during a La Niña episode.

A comparison of the plots in Figure 6 reveals that the mean frequency of ISSRs across the South Asia region is higher during a La Niña event, an average of 6.1%, than an El Niño event, an average of 2.3%. As well as the average area mean frequency of ISSRs being higher during the La Niña events, both individual La Niña years had higher area mean frequency of ISSRs than either of the El Niño years. Warmer SST’s occur in this region during La Niña which causes the air directly above to warm,

![Figure 6](image-url)

*Figure 6: Mean frequency of ISSRs at 250 hPa for two strong El Niño years, a) 1983 and b) 1998, and two strong La Niña years, c) 1989 and d) 2000 across the South Asia region. Uses ERA-Interim reanalysis data.*
become more buoyant and drive convection, explaining this pattern. Being a primarily equatorial phenomenon, the influence of ENSO is most easily detected south of 10°N.

3.4. Maximum frequency of ISSRs in the far north-west of the USA

In Figure 4 it was identified that there is an isolated maximum frequency of ISSRs in the north-west corner of the USA. To analyse this isolated maximum, the surrounding area is plotted separately in Figure 7. The plot was purposely extended out into the Pacific in anticipation that the maximum could be related to the Pacific storm track. Figure 7 shows that the maximum ISSR frequency is sharply confined to the coast and just inland at upper levels and extends out into the Pacific and increases in spatial coverage at lower altitudes. This suggests the maximum is related to the end of the Pacific storm track, but the fact that the maximum extends to higher altitudes at the coast remains unknown. Creating the same plots but without a temperature dependence made little difference, confirming temperature was not a limiting factor.

This maximum does not appear to have been identified in other studies of ISSRs. Spichtinger et al. (2003) and Lamquin et al. (2012) use different pressure levels and resolutions, making it impossible to directly compare these results.

![Figure 7](image-url)

*Figure 7: Mean frequency of ISSRs in January surrounding the north-west USA maximum (170°E - 110°W x 25°N-60°N) from 1980-2012 at a) 200 hPa, at b) 225 hPa, at c) 250 hPa and at d) 300 hPa. Uses ERA-Interim reanalysis data.*
4. VALIDATION OF EC-EARTH DATA FOR ANALYSIS OF ISSRS

4.0. Data

In this chapter EC-Earth climate simulation data from the CMIP5 archive, also based on ECMWF’s forecasting model, is compared to the ERA-interim reanalysis data used in Section 3 to investigate how well the climate simulation captures the present conditions (1980-2012). EC-Earth generates predictions and projections of global climate change, aiming to simulate climatic conditions. This is unlike the reanalysis data which aims to simulate the exact conditions at a given time. As a result, it is possible to compare climate patterns between the two datasets, but impossible to compare the two datasets over shorter time scales (eg. individual days). The EC-Earth data are available at a horizontal resolution of 1.125° and 62 vertical levels (Hazeleger et al., 2012).

As the EC-Earth data are also generated from the ECMWF model, it also allows formation of cloud free ISSRs. As a result, the variables of interest for studying ISSRs can be extracted and compared with the reanalysis data, easily identifying any bias between the two datasets. This makes EC-Earth climate simulation data well suited for this study.

The variables extracted from the EC-Earth data are temperature and specific humidity. The relative humidity with respect to ice is then calculated using the exact formula used in the ECMWF model, allowing direct comparison with the ERA-Interim data. The variables are extracted for the three regions of interest as daily mean values for each day in January from 1980-2012, the same time period as the reanalysis data. Here, the data are extracted at a single typical aircraft cruise altitude of 250 hPa.

4.1. Temperature and relative humidity PDFs

A first step in comparing the two datasets is to plot PDFs of the temperature and relative humidity over each of the three regions. This shows how the data are distributed on average over each region for the entire period 1980-2012.
Figure 8 shows the distribution of relative humidity in each region. The EC-Earth data appears to follow the shape of the ERA-Interim data distribution well, replicating the bimodal distribution identified in Section 3. There is a particularly good agreement at the lower humidity peak. A bias appears to be present across all three regions at the peak in humidity values near 100%. The ERA-Interim data shows a stronger peak at 100%, whereas the EC-Earth data shows a weaker peak and more frequent ice supersaturation, significantly so in the South Asia region. The disparity at this peak in humidity near 100% suggests cloud processes are not being captured well by the model, which are being corrected by observations in the reanalysis data.

Figure 9: Probability density functions of temperature in the a) North Atlantic, b) South Asia and c) USA region for ERA-Interim reanalysis data (blue) and EC-Earth climate simulation data (green). Includes all January data from 1980-2012 at 250 hPa.

The temperature distributions of the two datasets for each region are shown in Figure 9. A bias in temperature is much simpler to identify here as the temperature distributions are approximately Gaussian distributions. A shift in the peak of the distribution therefore represents a shift in the mean temperature. Seen across all three
regions is a systematic shift to colder temperatures in the EC-Earth data, and again significantly so in the South Asia region. In the North Atlantic and USA regions the difference in mean temperature between the two datasets is 2-3°C, compared with approximately 4°C in the South Asia region. This is a well-documented bias (Hazeleger et al., 2012), common in climate simulations, due to climate models not capturing cloud processes accurately. Convective clouds are more common in the tropics which explains why this error is greater in the South Asia region.

4.2. Specific humidity PDFs

The relative humidity from the EC-Earth data is calculated using the specific humidity and temperature data. The systematic cold bias identified in the EC-Earth data therefore introduces a bias in the relative humidity calculations. This could explain the disparity seen in relative humidity between the two datasets near 100%, or it could be due to the moisture content. Here the moisture content is examined by plotting PDFs of the specific humidity for each region using both datasets (Figure 10).

The specific humidity distributions over the North Atlantic region (Figure 10 (a)) are similar for both datasets. The peak in specific humidity occurs at slightly lower humidities in the EC-Earth data, but the peak is sharper. Additionally, the ERA-Interim data shows a greater spread with higher frequency at higher specific humidities. The higher frequencies of more moist air in the reanalysis data can be explained by the temperature biases, shown in Figure 9, arising because warmer air can hold more moisture.

![Figure 10: Probability density functions of specific humidity in the a) North Atlantic, b) South Asia and c) USA region for ERA-Interim reanalysis data (blue) and EC-Earth climate simulation data (green). Includes all January data from 1980-2012 at 250 hPa.](image-url)
Figure 10 (b) shows the specific humidity distributions over the South Asia region, where both datasets show a secondary peak in the data at higher specific humidities and are less similar. These peaks again occur at lower humidities in the EC-Earth data and the ERA-Interim data again shows higher frequencies at higher specific humidities, due to the temperature bias. This bimodal distribution implies sharp gradients between dry and moist regimes in space and time which is typical in the tropics (Zhang et al., 2003).

In the in the USA region, Figure 10 (c), the distributions of specific humidity are a very similar shape to the North Atlantic region. Both datasets are well correlated with a single peak in the distribution, which is stronger in the EC-Earth data, and a higher spread in the reanalysis data, resulting from the temperature bias.

4.3. Mean frequency of ISSRs

Figure 8, 9 and 10 give an idea of how the temperature and humidity data are distributed on average over each region, but show nothing about the spatial distribution of the data within each region. To determine the distribution within each region, the mean frequency of ISSRs within each region is shown in Figure 11.

Figure 11: Mean frequency of ISSRs in January over the a) North Atlantic, b) South Asia and c) USA region from 1980-2012 at 250 hPa. Uses EC-Earth climate simulation data.
Comparing Figure 11 (a) with Figure 2 (b) it is seen that the EC-Earth model captures the pattern of the frequency of ISSRs well in the North Atlantic region. The band of high frequencies from north-east USA to north-west Europe, associated with the North Atlantic storm track, is clearly evident. Likewise, the low frequencies of ISSRs to the east of North America, associated with the SPV, are also seen. However, the mean frequency of ISSRs over the region is 10.4%, as opposed to 15.3% for the reanalysis data. This under-prediction appears to be evenly distributed across the region as both the storm track and SPV features have lower frequencies, relative to the reanalysis data. The temperature is not a limiting factor for ISSR formation in this region, so it is the differences in moisture content causing this under-prediction.

The performance of the EC-Earth model at predicting the frequency of ISSRs in the South Asia region is analysed by comparing Figure 11 (b) with Figure 3 (b). Again, the pattern matches up well, with both datasets showing a clear north-south divide in the frequency of ISSRs corresponding to the rising and descending branches of the Hadley cell. The latitude where the frequency of ISSRs rapidly changes from low to high values is approximately 10°N in the EC-Earth data, which is slightly further north than the reanalysis data, which is approximately 8°N. This results in the mean frequency of ISSRs over the region increasing from 9.51% to 12.58% for the EC-Earth data because the higher frequency zone covers a larger proportion of the region.

For the USA region, Figure 11 (c) and Figure 4 (b) are analysed to identify differences in the spatial distribution of the frequency of ISSRs. In this region both the location and magnitude of the storm track is very similar for both datasets. The width of the storm track is approximately 15° in both plots, and the peak frequency of ISSRs at the centre of the storm track is around 20%. One difference is a small maximum above the states of Louisiana and Mississippi in the EC-Earth data that does not appear to be present in the reanalysis data. As mentioned, the frequency of ISSRs in the region where the SPV resides is lower in the EC-Earth data, which explains why it is more evident in Figure 11 (c). Interestingly, the maximum in the far north-west of the USA region, which was identified in Section 3, again is present in the EC-Earth data. However, this maximum is significantly lower in magnitude, reaching only around 16% frequency of ISSRs, as opposed to a large region in the reanalysis data exceeding 20%.
5. A CHANGE IN THE FREQUENCY OF ISSRS BETWEEN A PRESENT DAY AND FUTURE CLIMATE

5.0. Data

By comparing historical EC-Earth and reanalysis data in Section 4, it was established that the EC-Earth model output captures the conditions for ISSRs well, with the exception of a systematic cold bias in the EC-Earth data. In this chapter EC-Earth climate simulation data are compared for present conditions (1980-2012) and future conditions (2068-2100) to analyse changes with climate in the frequency of ISSRs over the three regions of interest. The future data are for a high emissions representative concentration pathway (RCP8.5) which represents a radiative forcing of 8.5 W m\(^{-2}\) relative to pre-industrial values, equivalent to an increase in CO\(_2\) concentration by a factor of 2.4 (Stocker et al., 2013). As for the historical data, the future EC-Earth data are available at a horizontal resolution of 1.125° and 62 vertical levels (Hazeleger et al., 2012). Using the same model to look at data from two different time periods ensures that the physics are consistent and therefore any changes seen can only be attributed to a shift in climate.

The variables extracted from the future EC-Earth data are temperature and specific humidity. The relative humidity with respect to ice is then calculated in the same way as for the historical data before comparison. The variables are extracted for the three regions of interest as daily mean values for each day in January from 2068-2100, the same length of time (33 years) as the historical data. Here, the data is extracted at a single typical aircraft cruise altitude of 250 hPa.

5.1. Temperature and relative humidity PDFs

To analyse the changes in ISSRs with climate, PDFs of temperature and relative humidity can be examined for both historical and future climates. This provides an overview of the average conditions over each region and how they might change. These PDFs also show if the change in the frequency of ISSRs is a result of a change in temperature, a change in moisture content of the air, or both.
Figure 12 shows PDFs of relative humidity across each region for both the historical and future datasets. It is seen in Figure 12 that there are no substantial changes in relative humidity in any of the three regions. The shape of the PDFs are similar in the future climates, with the bimodal distribution remaining present in all three regions. Additionally, the weighting between each of the peaks is similar in the historical and future climates, with only minor changes in each region.

The mean relative humidity decreases by 7.8% in the South Asia region and increases by 4.7% in the North Atlantic and 4.5% in the USA regions in a future climate. Figure 13 shows the change in relative humidity per Kelvin of surface warming averaged over several climate models (Sherwood et al., 2010). Although this is zonally
averaged data, it gives an idea of the sign of the change that is typically found in climate models and can be used to validate the data in this study. The sign of the change matches well with the data here, showing close to zero/decrease in the relative humidity in the tropics, and close to zero/increase in the mid latitudes. However, these are mostly in regions where less than 90% of the models agree on the sign of change.

Figure 14 shows PDFs of temperature for historical and future climates in the three regions. There is a systematic shift to warmer temperatures across all three regions. This is consistent with the warming expected as greenhouse gases continue to be released into the atmosphere. The spread of data is similar for both climates.

![Figure 14](image)

Figure 14: Probability density functions of temperature in the a) North Atlantic, b) South Asia and c) USA region for future (RCP8.5) and historical EC-Earth climate simulation data. Includes all January EC-Earth data from 2068-2100 (blue) and 1980-2012 (green) at 250 hPa.

The shift to warmer temperatures in a future climate is largest in the South Asia region. The change in the mean temperature is approximately 5°C, as opposed to 4°C in the USA region and 3°C in the North Atlantic region. Figure 15 shows the zonal average temperature change from a present day climate to a 4xCO₂ climate (Hazeleger et al., 2012). RCP8.5 represents an increase in CO₂ concentration by a factor of 2.4 relative to pre-industrial values (Stocker et al., 2013), so for the purpose of this study, Figure 15 gives an idea of the relative magnitudes of the changes in temperature associated with the three regions for an increase in atmospheric CO₂. It is seen that the most extreme temperature change at 250 hPa occurs in the tropics, which is in agreement with what is seen in this study, and decreases poleward because the higher latitudes are close to the boundary where warming (in the troposphere) turns to cooling (in the stratosphere).
Note that in the North Atlantic and USA regions, the shift to warmer temperatures does not increase the probability density above the temperature threshold of 235 K. However, in the South Asia region, the distribution above 235 K has increased. In the historical climate the distribution remained almost entirely below 235 K, but in the future climate, a large proportion of the data are now above this value. This will reduce the frequency of ISSRs in the South Asia region for the future climate because the temperature is now a limiting factor for many days, as discussed in Section 5.3.

5.2. Specific humidity PDFs

As seen in Figure 12, relative humidity remains fairly constant with only small changes between the historical and future climate. It was seen that there are relatively large changes in temperature, so this implies the moisture content of the air is changing for the relative humidity to remain fairly constant. To analyse changes in moisture content of the air, PDFs of specific humidity have been generated.

Figure 16 shows that in a future climate, the data spreads to larger specific humidities, with a higher mean specific humidity. These plots look very similar to those in Figure 10 for exactly the same reason. In the future climate, the air has a higher temperature and therefore can hold more water vapour. The reason the plots in Figure 16 resemble those in Figure 10 is because the cold bias in the EC-Earth historical data relative to
the ERA-Interim reanalysis data is almost identical to the magnitude that the EC-Earth historical data is colder than the EC-Earth future data.

Figure 17 presents the difference in the mean frequency of ISSRs between a future climate and the present climate. Positive values show an increase in the frequency of ISSRs in a future climate. Figure 17 (a) shows an increase of 1.7% in the average frequency of ISSRs across the North Atlantic region. However, the patchy nature of these increases suggests that the overall increase cannot be associated with changes in specific features which have previously been identified (e.g., the North Atlantic storm track and SPV). This is because the increases are not uniform where these features occur. The increases at approximately 46°N x 20°W and 40°N x 60°W do coincide with the position of the storm track. Since Figure 14 shows temperature is not a limiting factor for ISSRs in this region, these increases are due to changes in the relative humidity. This suggests the possibility of local increases in storm activity at these locations. The other notable maximum is located at approximately 65°N x 55°W, which is directly above Greenland. It has been suggested that ISSRs over Greenland could be due to gravity waves generated by mountains (Irvine et al., 2012). It is therefore possible that the increase in the frequency of ISSRs at this location is linked to changes in the gravity waves.

A decrease in the frequency of ISSRs of 7.2% is seen over the South Asia region in Figure 17 (b). The decrease is not uniform across the region with the areas of strongest decrease in the region of high frequency of ISSRs in Figure 11 (b). It was

5.3. Mean frequency of ISSRs
noted that in Figure 14 (b) the future temperature distribution shifted over the 235 K threshold temperature for ISSRs, while the relative humidity did not significantly change. Therefore the decrease in the frequency of ISSRs is a result of it often being too warm for ISSRs to form in the future climate.

Figure 17 (c) shows a much smaller change with an increase of 0.8% in the mean frequency of ISSRs over the USA region. The pattern of increases and decreases is again patchy. The temperature distribution shown in Figure 14 (c) reveals that temperature is not a limiting factor for ISSRs in this region either. This suggests local changes in moisture content give rise to the increases above the South West of the USA and above the east coast of the USA. These maxima coincide with the location of the jet stream but again are not uniform along its path.

A statistical significance test is used to show if the changes identified in the frequency of ISSRs in each region are significant. A change is deemed significant if the change in the mean frequency is larger than the standard deviation of the frequency of ISSRs in the present climate (the control period). It is found that the changes reported are not significant in any of the regions.

![Figure 17](image)

*Figure 17: Mean frequency of ISSRs in January from 2068-2100 minus mean frequency of ISSRs in January from 1980-2012 over the a) North Atlantic, b) South Asia and c) USA region. Uses EC-Earth data at 250 hPa. Note the different colour bar scale in the South Asia region.*
6. WIND SHEAR WITHIN ISSRS

6.0. Data

In this chapter vertical wind shear data extracted from the EC-Earth climate model are compared for a present (1980-2012) climate and a future (2068-2100) climate, based on a high emissions (RCP8.5) scenario. First the historical data are validated against reanalysis data over the same period before analysing the changes in the vertical wind shear within ISSRs with climate change.

The variables extracted from the EC-Earth and reanalysis data are temperature, specific humidity, zonal wind speed and meridional wind speed. Horizontal winds in the ECMWF model have been shown to agree well with observations (Houchi et al., 2010). In contrast to previous chapters, the variables are extracted for the three regions of interest as monthly-mean values for each January from 1980-2012 for historical and reanalysis data and from 2068-2100 for future data. Monthly-mean values are used as opposed to daily-mean values because the wind speed data is not available at the 200 and 300 hPa level as daily-mean values from the CMIP5 database. Here, the data is extracted at a single typical aircraft cruise altitude of 250 hPa for analysing ISSRs and at 200, 250 and 300 hPa for analysing the vertical wind shear associated with these ISSRs.

6.1. Validation of monthly-mean data

Before examining the wind shear with these datasets, it is important to ensure that the monthly-mean frequency of ISSRs shows the same features that were identified in the daily data. To do this, the mean frequency of ISSRs is plotted over each region with monthly-mean data (not shown), and compared to the identical plots for the daily data. The first thing to note is that the threshold relative humidity for ISSRs has to be reduced for the monthly-mean data. This is because ice-supersaturation is a relatively infrequent phenomena, so once the relative humidity has been averaged over a month, the ice-supersaturation cannot be seen. To obtain plots that are comparable between daily and monthly-mean data, the relative humidity threshold for the monthly data is reduced until the region mean frequency of ISSRs is similar. This has the result of a reduced relative humidity threshold of 64% in the North Atlantic region, 74% in the
South Asia region and 73% in the USA region. It is found that the main features previously identified in each region are replicated in the monthly data. In the North Atlantic region the signals associated with the storm track and SPV are observed, in the South Asia region the position of the north-south divide of ISSRs matches well and in the USA region the jet stream signal and the maximum in the far north-west of the region are also seen. As a result, it is safe to proceed with the monthly-mean data if suitable relative humidity thresholds are chosen.

6.2. Present-day wind shear

To analyse wind shear the first requirement is to decide how wind shear will be defined here. If the zonal and meridional winds at a lower altitude are \( U_L \) and \( V_L \) and at an upper altitude are \( U_U \) and \( V_U \) then the wind shear, \( d_u \), is defined in this study to be

\[
d_u = \sqrt{(U_U - U_L)^2 + (V_U - V_L)^2}
\]

(1)

By defining the wind shear in this way, a change in the wind magnitude and wind direction with height are taken into account, both of which influence the rate at which contrails spread.

Figure 18: Mean wind shear (m s\(^{-1}\)) from 200 to 300 hPa over the a) North Atlantic, b) South Asia and c) USA region in January from 1980-2012. Uses monthly-mean ERA-Interim reanalysis data.
Using (1), the mean wind shear between the 200 and 300 hPa levels for each region is plotted with reanalysis data (Figure 18). In the North Atlantic region it is seen that there is a band of minimum wind shear at the location of the high frequency of ISSRs associated with the North Atlantic storm track. This feature seems unusual because this is the area where the jet stream resides, so it is expected that larger shear values would be found here. It is possible that this is because the 300-200 hPa layer is too deep (of the order of a few kilometres). If the jet core is typically located between these two pressure levels it will not be identified. To test this, the wind shear over the North Atlantic region is plotted for the intermediate layers, 300-250 hPa and 250-200 hPa, in Figure 19. It is seen that a maximum in the storm track can be identified in the layer 250-200 hPa but not in the layer 300-250 hPa. The 300-200 hPa level will continue to be used for when ISSRs occur at 250 hPa, but this highlights the importance of vertical resolution and shows that the results should be interpreted with caution. In the South Asia region the mean wind shear is larger than in the North Atlantic region (4.3 m s$^{-1}$ as opposed to 2.4 m s$^{-1}$) and is relatively constant throughout the region. The mean wind shear over the USA region is higher still (5.2 m s$^{-1}$) but has a much larger variation over the region, with a strong north to south gradient.

Figure 20 shows the same as Figure 18, but for historical EC-Earth data. In the North Atlantic region the well-defined minimum band of wind shear seen in the ERA-Interim data (Figure 18 (a)) is not replicated in the EC-Earth data. Instead the low wind shear values extend further north and south, resulting in the mean wind shear over the region decreasing by 0.48 m s$^{-1}$. In the south Asia region, the wind shear matches well between both datasets. The only feature not replicated by the EC-Earth
data is the higher magnitudes of wind shear to the far north of the region, resulting in the region mean decreasing by 0.33 m s\(^{-1}\). The north-south wind shear gradient in the USA region matches well between both datasets. The EC-Earth data slightly underestimates the high wind shear values to the south of the USA region resulting in a decrease in the region mean by 1.42 m s\(^{-1}\). In summary, the EC-Earth data predicts the distribution of wind shear well, but slightly underestimates the magnitude.

The plots thus far have shown wind shear over each region without taking ISSRs into account. Since contrails can only persist in ISSRs, what is actually of most interest here is the wind shear only when ISSRs are present. Figure 21 shows PDFs of wind shear in the 300-200 hPa layer, only when ISSRs are present at 250 hPa, for both ERA-Interim and EC-Earth data. In the North Atlantic region the EC-Earth data shows a broader distribution with a weaker peak, but generally very closely matches both the mean and spread of the ERA-Interim data. In the South Asia region the EC-Earth data does not spread to as high wind shear as the ERA-Interim data resulting in a reduced mean of 1.3 m s\(^{-1}\), but the peak of the distribution matches well. In the USA region the peak of the distribution is lower in the EC-Earth data, decreasing the mean by 1.1 m s\(^{-1}\). This is because the biggest difference in the wind shear between the two

\[ \text{Figure 20: Mean wind shear from 200 to 300 hPa over the a) North Atlantic, b) South Asia and c) USA region in January from 1980-2012. Uses monthly-mean EC-Earth climate simulation data.} \]
datasets occurs in the south of the region (Figure 18 (c), Figure 20 (c)), which coincides with the areas of high frequency of ISSRs (Figure 4 (b), Figure 11 (c)). In summary, it is seen that the wind shear within ISSRs is represented well by EC-Earth data, with a slight underestimation of high wind shear in the South Asia and USA regions.

6.3. Changes in wind shear between a present day and future climate

To analyse the changes in wind shear with climate, plots of the difference in wind shear between a historical and future climate can be examined. Figure 22 shows the difference in mean wind shear, defined as future minus historical mean wind shear, over each region. In the North Atlantic region the largest change occurs to the south of the storm track, which is greater than 2 m s\(^{-1}\) to the far south west of the region. A slight decrease is observed in the mid North Atlantic. Overall there is an increase in wind shear over the region of 0.61 m s\(^{-1}\). In the South Asia region there is relatively little change throughout the majority of the region, except for a large decrease in the south of the region, centred at approximately 83°E, and a large increase in the far north-west of the region. The decrease dominated the regional-mean change reducing the wind shear by 0.25 m s\(^{-1}\) in a future climate. In the USA region the vast majority of the region shows an increase in wind shear. The largest changes coincide with the location of the jet stream, where the highest frequency of ISSRs occur, exceeding an increase of 2 m s\(^{-1}\) over large areas. The area-mean increase in the USA region is 1.43 m s\(^{-1}\). The relative magnitude of the change in each region is in agreement with a previous study of the EC-Earth model, which shows a higher increase in wind speed at the 200 hPa level, relative to the 300 hPa level in the mid latitudes for a 4xCO\(_2\).
climate (Hezeleger et al., 2012). Figure 15 shows an increase in the temperature gradient between the equator and poles at 250 hPa for the 4xCO₂ climate, which is the likely driver of the increased wind speeds in the mid-latitudes at this level.

As discussed in Section 6.2, it is only the changes in wind shear within ISSRs that can change the rate at which contrails spread. Figure 23 shows probability distribution functions of wind shear in the 300-200 hPa layer, only when ISSRs are present at 250 hPa, for a present and future climate (not density functions as before because the number of data between a present and future climate can now be different). Figure 23 (a) shows that in the North Atlantic region the distribution has shifted to higher wind shear. There is a lower frequency of low wind shear and a higher frequency of high wind shear, apart from above 6.5 m s⁻¹. This results in the mean wind shear increasing by 0.45 m s⁻¹ in a future climate, an increase of 15.3%.

In the South Asia region (Figure 23 (b)) the most obvious change is that there is an increase in the spread of the distribution. The standard deviation of wind shear in the future climate is 1.4 m s⁻¹, as opposed to 0.9 m s⁻¹. The mean wind shear only increases by 0.04 m s⁻¹, an increase of 0.89%. However, the wind shear is seen to
increase in ISSRs across the South Asia region, whereas in Figure 22 (b) a decrease over the region was observed when not taking ISSRs into account.

Figure 23 (c) shows another very different change in distribution between a present and future climate for the USA region. Here the maximum and minimum wind shears are similar, but the peak of the distribution has shifted towards higher wind shears for a future climate. As a result the mean wind shear has increased by 0.69 m s\(^{-1}\), an increase of 13.2%. In summary, when ISSRs are present, wind shear increases in all regions, more so in the North Atlantic and USA regions, indicating the spreading of contrails will increase in all regions in a future climate.

A statistical significance test is used to show if the changes identified in the wind shear within ISSRs in each region are significant. A change is deemed significant if the change in the mean wind shear is larger than the standard deviation of the wind shear in the present climate (the control period). It is found that the changes reported are not significant in any of the regions.

**Figure 23**: Probability distribution functions of wind shear from 200 to 300 hPa within ISSRs in the a) North Atlantic, b) South Asia and c) USA region. Includes all January monthly-mean historical EC-Earth climate data from 2068-2100 (blue) and future (RCP8.5) EC-Earth climate data from 1980-2012 (green) when ISSRs are present at 250 hPa.
7. CONCLUSIONS

This study has provided an original analysis of how the conditions that permit contrail persistence and indicate the degree of spreading might change between a present (1980-2012) and future (2068-2100) climate, based on a high emissions (RCP8.5) scenario. From analysis of results from one climate model, for three areas of aviation and meteorological interest: the North Atlantic region, South Asia region and USA region, it is found that the conditions for persistent contrails are likely to become more frequent in a future climate in two of the three regions, and the conditions that lead to spreading of persistent contrails increase in all three.

Changes in the frequency of ISSRs, the regions where contrails can persist, are used to indicate the changes in frequency of persistent contrails, at a typical aircraft cruise altitude of 250 hPa. In the North Atlantic, South Asia and USA regions, a mean change of 1.7%, -7.2% and 0.8% in the frequency of ISSRs is found, respectfully. It is found that the decrease in the South Asia region in a future climate is result of increased temperatures to the point where temperature becomes a limiting factor of ISSRs. The decrease is predominantly observed in the south of the region where the highest frequency of ISSRs are observed in the present climate. In the North Atlantic and USA regions temperature is not a limiting factor, therefore the increase in the frequency of ISSRs in these regions is attributed to an increase in the relative humidity in a future climate. The increases within these regions are patchy and cannot be linked with dynamical features of the atmosphere. The changes reported do not show statistical significance in any of the regions.

Changes in the 300-200 hPa vertical wind shear, a factor that strongly influences why contrails spread horizontally, is used to determine changes in the extent that contrails could spread. In the North Atlantic, South Asia and USA regions, a mean change of 0.45 m s$^{-1}$, 0.04 m s$^{-1}$ and 0.69 m s$^{-1}$ in the wind shear is observed, respectfully. In the South Asia region, the standard deviation of the wind shear distribution in a future climate increases from 0.9 m s$^{-1}$ to 1.4 m s$^{-1}$, caused by an increase in the frequency of both higher and lower wind shear magnitudes. In the North Atlantic and USA regions, the standard deviation of the wind shear distribution between a present and future climate is similar. However, the increase in the mean frequency is caused by a shift of
the entire distribution to higher wind shear magnitudes in the North Atlantic region, whereas in the USA region the increase is caused by an increase only in the peak of the distribution. The changes reported do not show statistical significance in any of the regions.

The results presented in this study are somewhat limited by the data that was available. It is found that the resolution of the monthly-mean wind shear data is too coarse, both in time and space. As a result, relative humidity thresholds were adapted to allow the regional-mean frequency of ISSRs to become similar to daily-mean values. The best vertical resolution available across the 250 hPa level was 200-300 hPa. It is shown that for the North Atlantic region the jet core resides between these two layers, leading to an underestimation of the wind shear in the region of the jet stream.

Although the conditions for contrail persistence and spreading have been analysed in detail, there has been no effort to combine these effects during this study. Future work would include combining these effects to estimate a total change in contrail coverage between a present and future climate. A change in radiative forcing between a present and future climate could then be calculated, the prime motivation for studying contrails.

Throughout this study a single climate model has been used with a single future emissions scenario, and there has been no estimate of the confidence in the results presented. Future work would include repeating these results with different climate models to compare the results. It would also be useful to repeat the results for different emissions scenarios to determine how sensitive the results are to the emissions path taken. This would provide an understanding of the uncertainty associated with the results presented here.

Contrails are only one climate impact of aviation. On a broader scale, these results could be considered alongside other aviation factors which have been shown to impact climate including emission of sulphate and soot particles, emission of greenhouse gasses (CO₂, NOₓ and H₂O), and the influence of sulphate aerosols on low level clouds (Lee et al., 2009; Shine, 2010). Along with these impacts, the results from this project could help to bring together a total climate impact of aviation.
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