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Aircraft flying through cold ice-supersaturated air produce persistent contrails which contribute to the climate impact of aviation. Here, we demonstrate the importance of the weather situation, together with the route and altitude of the aircraft through this, on estimating contrail coverage. The results have implications for determining the climate impact of contrails as well as potential mitigation strategies. Twenty-one years of re-analysis data are used to produce a climatological assessment of conditions favorable for persistent contrail formation between 200 and 300 hPa over the north Atlantic in winter. The seasonal-mean frequency of cold ice-supersaturated regions is highest near 300 hPa, and decreases with altitude. The frequency of occurrence of ice-supersaturated regions varies with large-scale weather pattern; the most common locations are over Greenland, on the southern side of the jet stream and around the northern edge of high pressure ridges. Assuming aircraft take a great circle route, as opposed to a more realistic time-optimal route, is likely to lead to an error in the estimated contrail coverage, which can exceed 50% for westbound north Atlantic flights. The probability of contrail formation can increase or decrease with height, depending on the weather pattern, indicating that the generic suggestion that flying higher leads to fewer contrails is not robust.

1. Introduction

Cold ice-supersaturated regions (ISSRs) are climatically important. An aircraft flying through such regions will form a contrail, which may persist for many hours and even spread to become indistinguishable from natural cirrus. The present-day climate impact of these man-made clouds is estimated to be between 10-80 mW m^{-2} [*Lee et al.*, 2009], potentially greater than that of aviation CO_2 emissions (estimated at 28 mW m^{-2} [*Lee et al.*, 2009]).

Ice-supersaturation is a relatively common feature of the upper troposphere; in-situ measurements of relative humidity from specially-instrumented commercial aircraft found ice-supersaturation in 13.5% of the data, with a mean supersaturation of 15% [*Gierens et al.*, 1999]. Satellite data provide a global view of the distribution of ISSRs, revealing maxima in the storm track regions and near the tropopause at high latitudes [*Spichtinger et al.*, 2003a; *Lamquin et al.*, 2012].

The motivation for this study is to link the distribution of ISSRs to specific large-scale weather patterns. Previous studies show that ISSRs may be found in anticyclonic flow [*Kästner et al.*, 1999; *Immler et al.*, 2008], above a warm conveyor belt of a cyclone [*Spichtinger et al.*, 2005a] or caused by gravity waves [*Spichtinger et al.*, 2005b]. These observationally-based studies necessarily use small local domains and short observational time periods or individual case studies and therefore the results may not be representative of larger mid-latitude regions. A climatological assessment of the occurrence of cold ISSRs over the north Atlantic region is presented Section 3.1; this is related to large-scale weather patterns in Section 3.2.

Previous work has investigated the possibility of mitigating the climate impact of contrails by changing aircraft cruise altitudes [*Williams et al.*, 2002; *Mannstein et al.*, 2005; *Fichter et al.*, 2005; *Rädel and Shine*, 2008]. This is based upon ISSRs being shallow features; radiosonde observations of ISSR depth over the United Kingdom show a peak value of 50 m [*Rädel and Shine*, 2007]. For the northern hemisphere mid-latitudes, increasing the cruise altitude of aircraft on average reduces the number of contrails that would be formed [*Fichter et al.*, 2005], as more flights then occur in the comparatively dry stratosphere; however, in Sections 3.2 and 3.3 we show that it is important to consider both the altitude and the weather pattern together with the likely path of the aircraft to determine whether a change in altitude will reduce or increase the probability of contrailing.

One, perhaps surprising, difficulty in determining the climate impact of contrails is that an accurate description of where aircraft fly is not readily available. Compiled inventories of aircraft movement often use great circle routes (or assume a simple distribution around them) to approximate true aircraft routes; more recent inventories use radar data where available but must still use great circle routes over areas such as the North Atlantic where there is no radar coverage [*Owen et al.*, 2010; *Wilkerson et al.*, 2010]. Aircraft routes over the North Atlantic vary greatly from day-to-day depending on the strength of the jet stream, and eastbound and westbound routes can differ significantly [*Irvine et al.*, 2012]; in Section 3.3 it is demonstrated how this may introduce an error into estimates of contrail coverage which use great circle routes.

2. Data

Cold ISSRs are identified as regions with a relative humidity with respect to ice above 100% and a temperature below 233K (to avoid regions of supercooled water clouds). Such a temperature threshold is broadly consistent with the Schmidt-Appleman criterion [*Schumann*, 1996] for contrail formation for an aircraft engine with an efficiency of 0.3. For this study, ISSRs were identified in the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis Interim data (ERA-Interim; *Dee et al.* [2011]) over the north Atlantic flight corridor (here taken to be the area 35-75°N, 0-70°W). The data were used at 0.7° horizontal resolution on four pressure levels (300, 250, 225 and 200 hPa) that span the range of permitted aircraft cruise altitudes. For the climatological analysis (Section 3.1), ISSRs are identified in the 0000 UTC analyses for the period 1989-2010; the weather pattern analysis (Sections 3.2 and 3.3) uses data for three winters (December - February) for which optimal route data were available. The use of re-analysis data allowed the analysis of ISSRs over a larger geographical region and for a climatological time period that would not be possible with direct observations. ERA-Interim data are particularly suited to this study as the model cloud scheme permits ice-supersaturation [*Tompkins et al.*, 2007], although the analyses suffer from a dry bias [*Lamquin et al.*, 2009] and have had limited validation against observational data.

True aircraft flight paths across the Atlantic are approximated using daily time-optimal route data, which are representative of the location of north Atlantic air traffic [*Irvine et al.*, 2012]. These routes minimise the flying time between London and New York, taking into account the winds at 250 hPa and assuming the aircraft flies at a constant speed and pressure. The data were generated using the Met Office optimal routing software [*Lunnon*, 1992] that was run on 40 km resolution Met Office Unified Model forecasts. An eastbound (at 0000 UTC) and a westbound (at 1200 UTC) route are provided for each day of three winters, 2004-05 2008-09 and 2009-10, which were chosen for their different jet stream behavior and correspond respectively to positive, neutral and negative seasonal-mean phases of the north Atlantic oscillation (NAO).

3. Results

3.1. Climatological Frequency of ISSRs

In the north Atlantic region in winter, the mean frequency of cold ISSRs is 7.1%, with an overall decrease in frequency with altitude from 8.7% at 300 hPa to 5.2% at 200 hPa (the mean values are obtained by averaging over the north Atlantic region shown in Figure 1). This decrease above 300 hPa is in agreement with *Fichter et al.* [2005].

Figure 1 shows spatial variations in the long-term winter-mean frequency of cold ISSRs in the north Atlantic. Maxima in the frequency of cold ISSRs are found in the storm track regions and are particularly noticeable at 200 and 250 hPa in the ERA-Interim data. The higher frequencies at higher altitudes are consistent with the ISSRs occurring south of the jet stream where the tropopause is higher.

The largest frequency of cold ISSRs is over Greenland. This maximum is absent at 200 hPa (Figure 1(a)), presumably because at this high latitude air is generally further into the relatively dry stratosphere. Local maxima in ISSR frequency along the coast of Greenland match the location of maxima in gravity wave stress as represented in the ECMWF system (not shown), suggesting that ISSRs may be formed by the lifting of air past saturation by orographically-generated gravity waves. The minimum in ISSRs at

200 hPa over Newfoundland coincides with the climatological position of the stratospheric polar vortex, which is often elongated over this region in winter.

In all seasons (not shown) the same features predominate although their frequency varies; in particular the maxima associated with the storm track and 200 hPa minima associated with the stratospheric polar vortex are less visible in summer. Additionally, in summer there are fewer cold ISSRs at 300 hPa in the south of the study region where the ambient temperature exceeds the threshold for contrail formation. The highest overall frequency of cold ISSRs is observed in winter, therefore this study concentrates on the winter season only.

The frequencies of ISSRs reported here are likely to be lower bounds, due to the known dry bias in ERA-Interim (discussed in Section 2). Whilst the frequencies of ISSRs in ERA-Interim are smaller than those reported by observational studies [*Gierens et al.*, 2000; *Lamquin et al.*, 2012], the locations agree well. This supports the use of ERA-Interim data to link ice-supersaturation to large-scale weather patterns.

3.2. Frequency of ISSRs by Weather Type

Irvine et al. [2012] identified a set of five frequently-occurring characteristic weather types for the north Atlantic winter season, defined according to the pattern of geopotential height at 250 hPa. Three of these weather patterns (types 1, 2 and 4), along with the frequency of ice-supersaturation in each pattern are shown in Figure 2 (the other weather patterns, types 3 and 5, are shown in the auxiliary material).

There is a maximum in ice-supersaturation over Greenland in all synoptic conditions, although the maximum is less distinct in weather types 4 (Figure 2(c)) and 5. Maxima in the regions south of the jet stream are also evident, particularly for types 2 (Figure 2(b)) and 3 where the jet stream is located further north; this suggests that the ISSRs are caused by the slantwise ascent of the warm air in the storms that grow on the jet. Averaged over all the weather types this gives the general storm track region maximum seen in Figure 1. In type 4, where the ridge over the Atlantic is most pronounced, high frequencies of ice-supersaturation are found in the anti-cyclonic flow. This is consistent with the fact that air travelling northwards around a ridge ascends up the isentropic surface and this can lead to saturation.

Clearly, in different weather types the frequency of cold ISSRs does not always decrease with height. Over Greenland it decreases with height, for all weather types except type 4 where the high frequency of cold ISSRs in the ridge over Greenland exhibit little change with height. However, the frequency of cold ISSRs south of the jet stream increases with height; this is clear in type 2, where there is a tilted jet across the Atlantic, and a higher tropopause south of the jet stream. This is particularly important as it shows that whilst earlier results indicating that flying higher produces fewer contrails may be true climatologically, the results do not hold for individual weather patterns. The differences in the distributions of ISSRs for the various weather types show little relationship with the corresponding differences in the mean tropopause locations obtained using a blended tropopause definition [*Wilcox et al.*, 2012].

ISSRs have been observed to be shallow features [*Rädel and Shine*, 2007; *Spichtinger et al.*, 2003b]; in the limited altitude range considered here, 57-63% of ISSRs are observed at a single pressure level, depending on the weather type. This indicates that within the range of aircraft cruise altitudes, small changes in altitude may be sufficient to avoid forming a contrail, corroborating *Mannstein et al.* [2005].

3.3. Application to Quantifying Aircraft Climate Impact

The probability of forming a contrail flying at a particular altitude in a weather pattern is shown in Figure 3, for both great circle and time-optimal routes. This is the fraction of the total route distance in a cold ISSR, averaged over all days belonging to that weather type. For great circle routes (Figure 3(a)) the probability of contrailing at a particular altitude is 1-10%, and there is a range of behavior with height for the different weather patterns. We note that these probabilities are likely to be biased low, as previously discussed.

In reality, jet stream winds heavily influence the route location, so that it is more appropriate to use time-optimal routes to approximate flight paths across the north Atlantic. Figure 2 shows the mean and standard deviation of the time-optimal routes across the Atlantic, for each weather type: eastbound routes take advantage of strong tailwinds in the jet stream whereas westbound routes are located away from the strong headwinds.

As the jet stream often lies close to the New York - London great circle route, the location of eastbound time-optimal routes and therefore the probability of forming a contrail along the route (Figure 3(b)) are similar to great circle routes (Figure 3(a)). The greatest probability of contrail formation is in types 2 and 3, with an increase with height up to 225 hPa. For types 4 and 5 the probability of contrailing exhibits little change with height, in contrast to type 1 which shows a strong decrease with height.

The westbound time-optimal routes (Figure 3(c)) show very different behavior from the great circle routes, both in their location and likelihood of contrail formation. For westbound routes there is a smaller probability of contrailing, 1-6%, and there are smaller differences between the weather types. The formation of persistent contrails is almost equally likely at each altitude for all weather types except type 1, where contrails are more likely to form at lower altitudes.

4. Discussion and Conclusions

This study provides a unique assessment of the occurrence of cold ISSRs, where persistent contrails form, at three levels of detail: a climatology for the north Atlantic region, the link to frequently occurring large-scale weather patterns and for individual flights through these weather patterns. The climatological assessment shows the preferred locations for ISSRs are linked to the orography of Greenland and the time-mean location of the jet stream. Individual weather patterns show maxima on the southern side of the jet stream where the tropopause is higher, over Greenland and around the northern edge of synoptic ridges. A caveat to these results is that ERA-Interim suffers from a documented dry bias, due to a lack of spin-up time [*Lamquin et al.*, 2009] and therefore the frequencies of ice-supersaturation reported here likely underestimate the true values, although the locations agree well with satellite-based studies [*Lamquin et al.*, 2012].

The probability of contrailing along a route is 1-10%, and importantly, can either increase or decrease with altitude, depending on weather pattern. Even climatologically, although the mean frequency of cold ISSRs over the north Atlantic decreases with altitude in the range 200-300 hPa, this is location dependent; the maximum over Greenland decreases with altitude but storm track maxima increase with altitude. This indicates that there is no generic (e.g. 'fly higher') solution to mitigating the climate effects of contrails; any such mitigation decisions would have to be dependent on the weather situation.

In the north Atlantic, the jet stream variability can lead to routes different from the great circle. Whilst the probability of contrailing along an eastbound route is similar to a great circle route, using a great circle route to approximate the path of a westbound flight can overestimate the probability of contrail formation by over 50% for some commonly occurring weather patterns. This demonstrates the importance of accurate inventories of air traffic movement data, particularly over large oceanic regions with little radar coverage. The lack of such data forces climate impact studies to make assumptions about aircraft routes, which is a source error in the estimation of the resulting climate impact.

Whilst this study focused on the north Atlantic region, the results are relevant to other mid-latitude regions, particularly those with strong day-to-day variation in the upper-level winds, such as the north Pacific.

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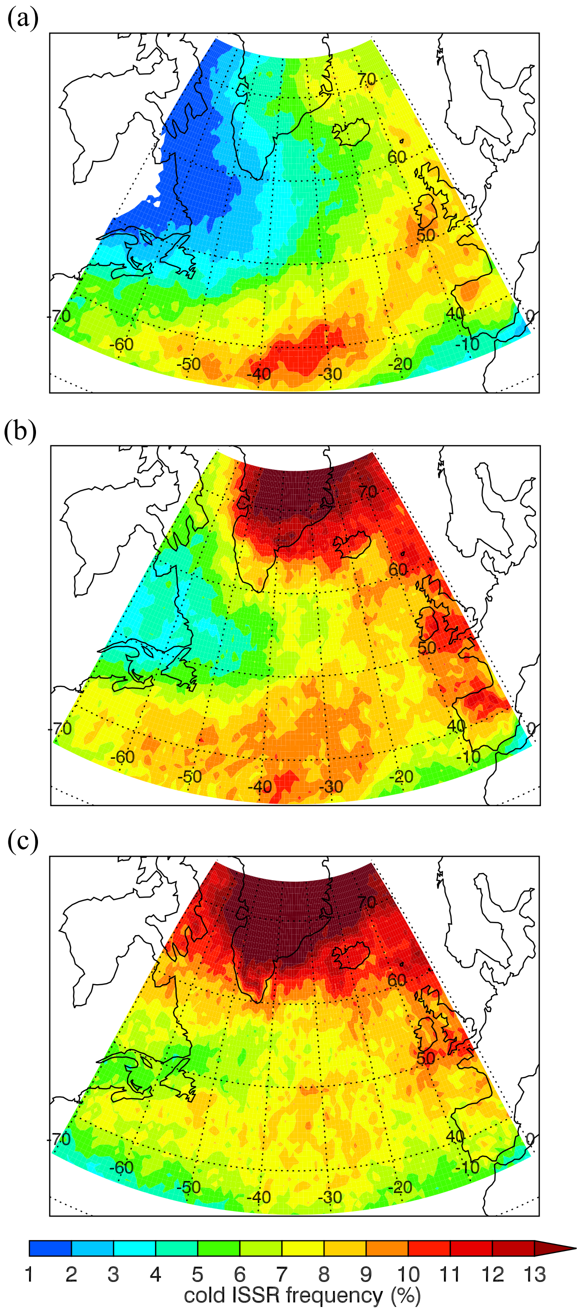

Figure 1. Mean frequency of cold ISSRs at (a) 200 hPa, (b) 250 hPa and (c) 300 hPa, averaged over all winters in the period 1989 - 2010.

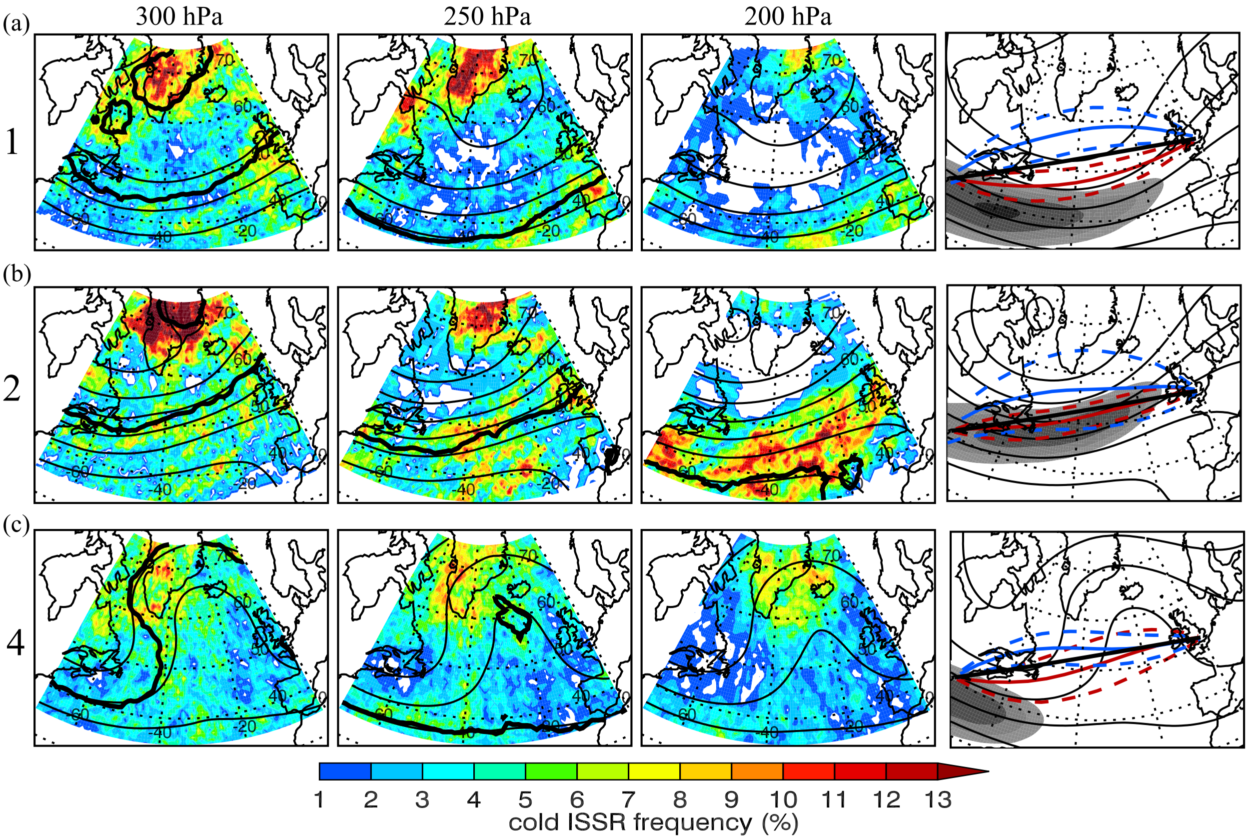

Figure 2. Mean frequency of cold ISSRs, composite geopotential height (thin contours) and tropopause location (thick contour) for days belonging to three of five winter weather types defined in *Irvine et al.* [2012]: (a) type 1, (b) type 2 and (c) type 4 at 300 hPa, 250 hPa and 200 hPa. The final column shows the mean 250 hPa geopotential height (black contours) and wind speed above 40 m s^{-1} (gray shading, darker shading indicating higher windspeeds, with a contour interval of 3 m s^{-1}), with the great circle (black line), eastbound time-optimal (red) and westbound time-optimal (blue) routes (both the mean location as solid lines and standard deviation as dashed lines) from days corresponding to each weather type. Calculated using data from winters 2004-05, 2008-09 and 2009-10.

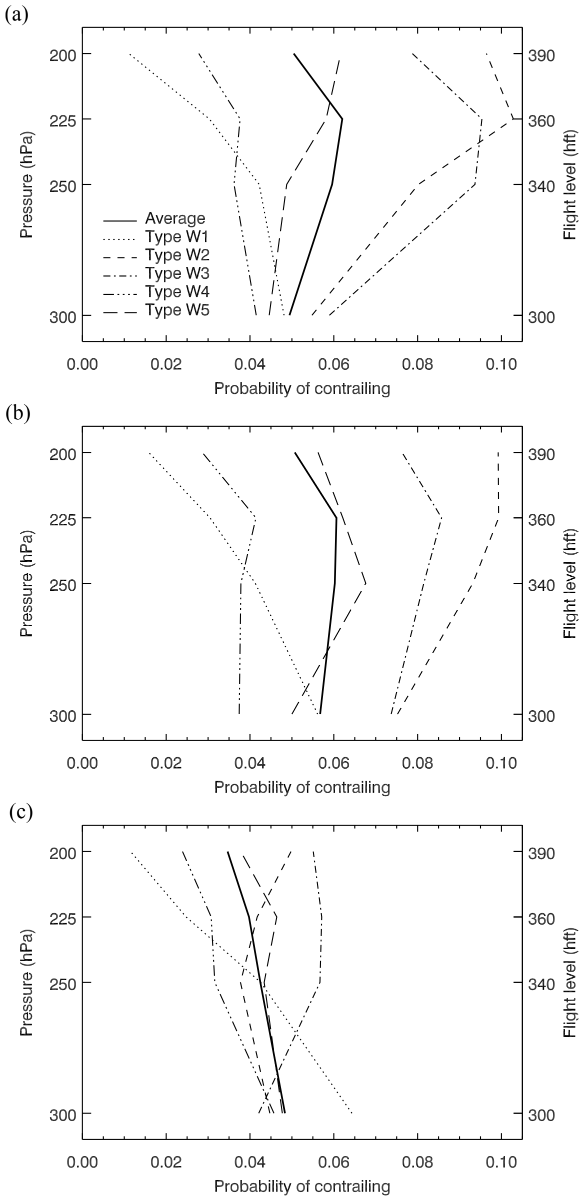

Figure 3. For (a) great circle, (b) eastbound time-optimal and (c) westbound time-optimal routes, the mean probability of making a persistent contrail along the route at different altitudes, averaged over all routes from days corresponding to winter weather type 1 (dotted line), type 2 (short dashed line), type 3 (dash-dot line), type 4 (dash-triple dot line), type 5 (long dashed line) and averaged over all days (solid line). Calculated using data from winters 2004-05, 2008-09 and 2009-10.