

¹ The dependence of contrail formation on the weather ² pattern and altitude in the North Atlantic

E. A. Irvine,¹ B. J. Hoskins,^{1,2} K. P. Shine¹

B. J. Hoskins, Grantham Institute for Climate Change, Imperial College London, Exhibition Road, South Kensington, London, SW7 2AZ, UK.

E. A. Irvine, Department of Meteorology, University of Reading, Earley Gate, Reading, RG6 6BB, UK. (e.a.irvine@reading.ac.uk)

K. P. Shine, Department of Meteorology, University of Reading, Earley Gate, Reading, RG6 6BB, UK.

¹Department of Meteorology, University of Reading, Reading, UK.

²Grantham Institute for Climate Change, Imperial College London, London, UK.

3 Aircraft flying through cold ice-supersaturated air produce persistent con-
4 trails which contribute to the climate impact of aviation. Here, we demon-
5 strate the importance of the weather situation, together with the route and
6 altitude of the aircraft through this, on estimating contrail coverage. The re-
7 sults have implications for determining the climate impact of contrails as well
8 as potential mitigation strategies. Twenty-one years of re-analysis data are
9 used to produce a climatological assessment of conditions favorable for per-
10 sistent contrail formation between 200 and 300 hPa over the north Atlantic
11 in winter. The seasonal-mean frequency of cold ice-supersaturated regions
12 is highest near 300 hPa, and decreases with altitude. The frequency of oc-
13 currence of ice-supersaturated regions varies with large-scale weather pat-
14 tern; the most common locations are over Greenland, on the southern side
15 of the jet stream and around the northern edge of high pressure ridges. As-
16 suming aircraft take a great circle route, as opposed to a more realistic time-
17 optimal route, is likely to lead to an error in the estimated contrail cover-
18 age, which can exceed 50% for westbound north Atlantic flights. The prob-
19 ability of contrail formation can increase or decrease with height, depend-
20 ing on the weather pattern, indicating that the generic suggestion that fly-
21 ing higher leads to fewer contrails is not robust.

1. Introduction

22 Cold ice-supersaturated regions (ISSRs) are climatically important. An aircraft flying
23 through such regions will form a contrail, which may persist for many hours and even
24 spread to become indistinguishable from natural cirrus. The present-day climate impact
25 of these man-made clouds is estimated to be between 10-80 mW m⁻² [*Lee et al.*, 2009],
26 potentially greater than that of aviation CO₂ emissions (estimated at 28 mW m⁻² [*Lee*
27 *et al.*, 2009]).

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

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

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

53 One, perhaps surprising, difficulty in determining the climate impact of contrails is that
54 an accurate description of where aircraft fly is not readily available. Compiled inventories
55 of aircraft movement often use great circle routes (or assume a simple distribution around
56 them) to approximate true aircraft routes; more recent inventories use radar data where
57 available but must still use great circle routes over areas such as the North Atlantic where
58 there is no radar coverage [*Owen et al.*, 2010; *Wilkinson et al.*, 2010]. Aircraft routes
59 over the North Atlantic vary greatly from day-to-day depending on the strength of the
60 jet stream, and eastbound and westbound routes can differ significantly [*Irvine et al.*,
61 2012]; in Section 3.3 it is demonstrated how this may introduce an error into estimates of
62 contrail coverage which use great circle routes.

2. Data

63 Cold ISSRs are identified as regions with a relative humidity with respect to ice above
64 100% and a temperature below 233K (to avoid regions of supercooled water clouds).
65 Such a temperature threshold is broadly consistent with the Schmidt-Appleman criterion
66 [*Schumann, 1996*] for contrail formation for an aircraft engine with an efficiency of 0.3.
67 For this study, ISSRs were identified in the European Centre for Medium-Range Weather
68 Forecasts (ECMWF) Re-analysis Interim data (ERA-Interim; *Dee et al. [2011]*) over the
69 north Atlantic flight corridor (here taken to be the area 35-75°N, 0-70°W). The data were
70 used at 0.7° horizontal resolution on four pressure levels (300, 250, 225 and 200 hPa)
71 that span the range of permitted aircraft cruise altitudes. For the climatological analysis
72 (Section 3.1), ISSRs are identified in the 0000 UTC analyses for the period 1989-2010;
73 the weather pattern analysis (Sections 3.2 and 3.3) uses data for three winters (December
74 - February) for which optimal route data were available. The use of re-analysis data
75 allowed the analysis of ISSRs over a larger geographical region and for a climatological
76 time period that would not be possible with direct observations. ERA-Interim data are
77 particularly suited to this study as the model cloud scheme permits ice-supersaturation
78 [*Tompkins et al., 2007*], although the analyses suffer from a dry bias [*Lamquin et al., 2009*]
79 and have had limited validation against observational data.

80 True aircraft flight paths across the Atlantic are approximated using daily time-optimal
81 route data, which are representative of the location of north Atlantic air traffic [*Irvine*
82 *et al., 2012*]. These routes minimise the flying time between London and New York, taking
83 into account the winds at 250 hPa and assuming the aircraft flies at a constant speed and
84 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

105 200 hPa over Newfoundland coincides with the climatological position of the stratospheric
106 polar vortex, which is often elongated over this region in winter.

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

114 The frequencies of ISSRs reported here are likely to be lower bounds, due to the known
115 dry bias in ERA-Interim (discussed in Section 2). Whilst the frequencies of ISSRs in
116 ERA-Interim are smaller than those reported by observational studies [*Gierens et al.*,
117 2000; *Lamquin et al.*, 2012], the locations agree well. This supports the use of ERA-
118 Interim data to link ice-supersaturation to large-scale weather patterns.

3.2. Frequency of ISSRs by Weather Type

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

124 There is a maximum in ice-supersaturation over Greenland in all synoptic conditions,
125 although the maximum is less distinct in weather types 4 (Figure 2(c)) and 5. Maxima in

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

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

145 ISSRs have been observed to be shallow features [Rädel and Shine, 2007; Spichtinger
146 *et al.*, 2003b]; in the limited altitude range considered here, 57-63% of ISSRs are observed
147 at a single pressure level, depending on the weather type. This indicates that within

148 the range of aircraft cruise altitudes, small changes in altitude may be sufficient to avoid
149 forming a contrail, corroborating *Mannstein et al.* [2005].

3.3. Application to Quantifying Aircraft Climate Impact

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

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

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

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

4. Discussion and Conclusions

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

185 The probability of contrailing along a route is 1-10%, and importantly, can either in-
186 crease or decrease with altitude, depending on weather pattern. Even climatologically,
187 although the mean frequency of cold ISSRs over the north Atlantic decreases with altitude
188 in the range 200-300 hPa, this is location dependent; the maximum over Greenland de-

189 creases with altitude but storm track maxima increase with altitude. This indicates that
190 there is no generic (e.g. ‘fly higher’) solution to mitigating the climate effects of contrails;
191 any such mitigation decisions would have to be dependent on the weather situation.

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

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

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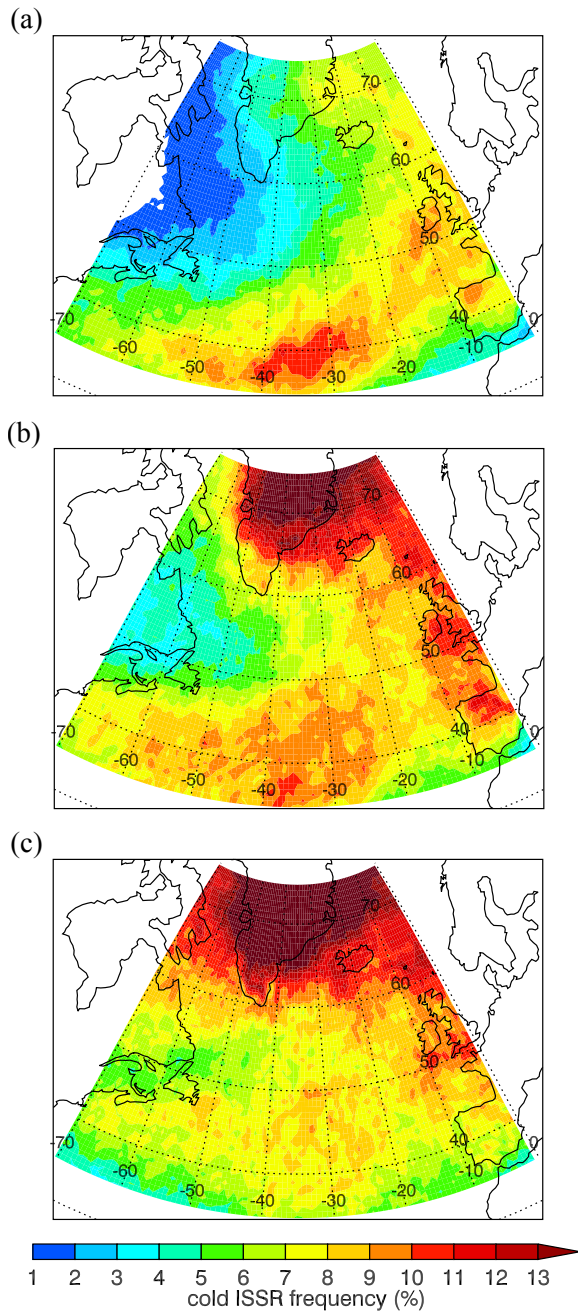


Figure 1. Mean frequency of cold ISSRs at (a) 200 hPa, (b) 250 hPa and (c) 300 hPa, averaged over all winters in the period 1989 - 2010.

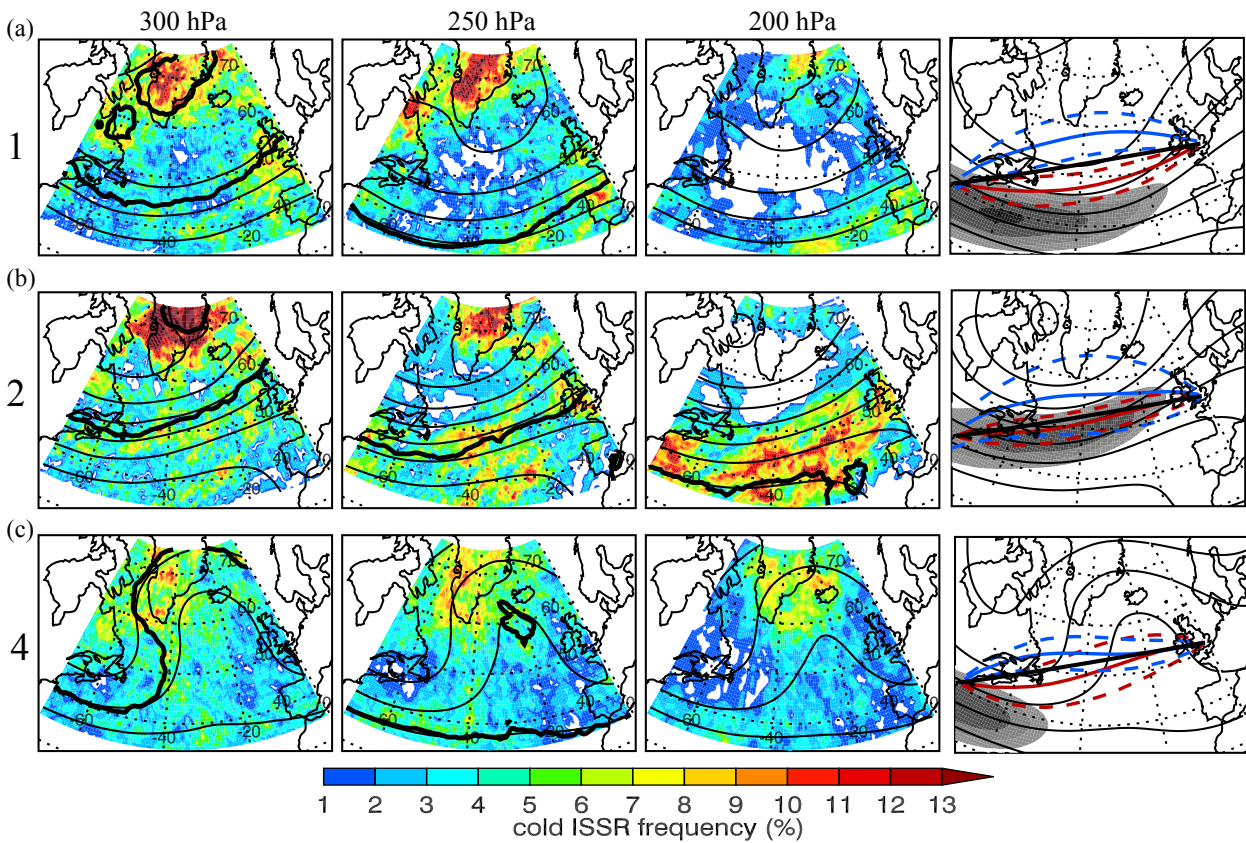


Figure 2. Mean frequency of cold ISSRs, composite geopotential height (thin contours) and tropopause location (thick contour) for days belonging to three of five winter weather types defined in *Irvine et al.* [2012]: (a) type 1, (b) type 2 and (c) type 4 at 300 hPa, 250 hPa and 200 hPa. The final column 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.

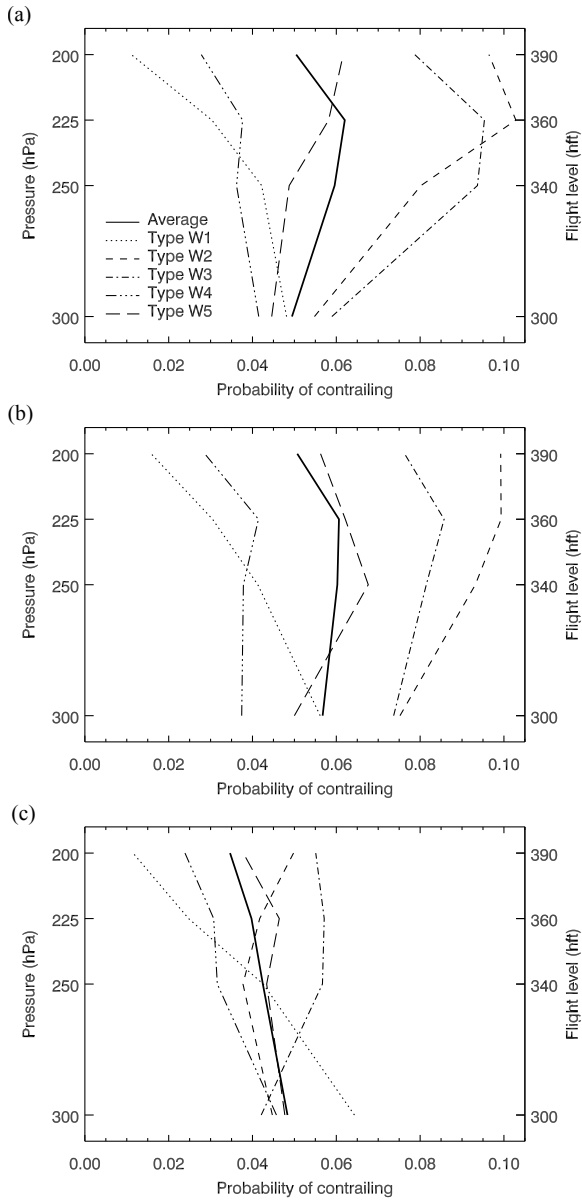


Figure 3. For (a) great circle, (b) eastbound time-optimal and (c) westbound time-optimal routes, the mean probability of making a persistent contrail along the route at different altitudes, averaged over all routes from days corresponding to winter weather type 1 (dotted line), type 2 (short dashed 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.