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Ice-supersaturation and the potential for contrail formation in a changing climate

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Abstract

Ice-supersaturation (ISS) in the upper-troposphere and lower stratosphere is important for the formation of cirrus cloud and long-lived contrails. We analyse projected changes to 250 hPa ISS distribution and frequency over the twenty-first century using data from the RCP8.5 simulations of a selection of CMIP5 models. The models show a global-mean annual-mean decrease in ISS frequency of 4 % by the end of the twenty-first century, relative to the present-day period 1979–2005. Changes are analysed in further detail for three sub-regions where air traffic is already high and increasing (Northern Hemisphere mid-latitudes) or expected to increase (tropics and Northern Hemisphere polar regions). The largest change is seen in the tropics, where a reduction of around 9 % in ISS frequency by the end of the century is driven by the strong warming of the upper troposphere. In the Northern Hemisphere mid-latitudes the multi-model mean change is an increase in ISS frequency of 1 %; however the sign of the change is not only model-dependent but also has a strong latitudinal and seasonal dependence. In the Northern Hemisphere polar regions there is an increase in ISS frequency of 5 % in the annual-mean. These results suggest that over the 21st century climate change may have large impacts on the potential for contrail formation; actual changes to contrail cover will also depend on changes to the volume of air traffic, aircraft technology and flight routing.

1 Introduction

Regions of ice-supersaturation (ISS) are a relatively common feature of the upper-troposphere. Aircraft flying through ISS regions may form persistent contrails, which have been shown to contribute to anthropogenic climate change. Because of their potentially large climate impact (e.g. Lee et al., 2009), many studies have considered possible strategies to reduce contrail formation in the future, for example by developments to engine technology (Gierens et al., 2008; Haglind, 2008) or by changing aircraft

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altitude (Williams et al., 2002; Fichter et al., 2005; Mannstein et al., 2005; Rädel and Shine, 2008; Schumann et al., 2011; Deuber et al., 2013) or route (Sridhar et al., 2013; Irvine et al., 2014b; Soler et al., 2014; Zou et al., 2013) to avoid flying through ISS regions. In addition, it is likely that contrail formation will become more frequent due to increased air traffic, and the introduction of newer more efficient engines, which consume less fuel but allow contrail formation to occur at warmer temperatures and so over a wider range of cruise altitudes than at present (Schumann, 2000). Using projected future air traffic scenarios, including an increase in engine propulsion efficiency, but with a present-day climate, Gierens et al. (1999) projected that global-mean contrail cover would increase by a factor of between 3 and 9 by 2050 (depending on the scenario used) relative to 1992.

One additional factor in determining future contrail cover which has received much less attention is how climate change itself may alter the likelihood of contrail formation, by causing changes to the frequency and distribution of ISS regions. Marquart et al. (2003) found that, to 2050, climate change had a smaller impact on contrail cover than increasing air traffic. There was some regionality to the calculated changes in contrail cover; in the tropics the impact of climate change was important but in the Northern Hemisphere mid-latitudes, a region where present-day air traffic is already high, an increase in air traffic was more important than any climate changes. Marquart et al. (2003) combined time-slice simulations from a single climate model with air traffic projections, both for 2050; together these increased the global-mean contrail cover by a factor of 3.7, relative to 1992. This study makes use of the latest climate projections submitted to IPCC (2013), which extend out to 2100, allowing the assessment of changes to ice-supersaturation not only over a longer time period, but also an examination of the time evolution of these changes. Further, by comparing the results from multiple climate models, we can assess the robustness of our conclusions. Unlike the Marquart et al. (2003) and Gierens et al. (1999) studies, we do not attempt to calculate contrail cover using air traffic projections; the focus of this paper is the impact of cli-

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mate change on ISS regions, independent of changes to air traffic, aircraft technology or routing.

Regions of ice-supersaturation are generally shallow and located close to the tropopause, which makes their global distribution highly variable with altitude. They are typically associated with ascending air streams (Gierens and Brinkop, 2012; Irvine et al., 2014a), such as those found in frontal systems and jet streams in the mid-latitudes or deep convection in the tropics (Kästner et al., 1999; Spichtinger et al., 2005; Gettelman et al., 2006; Luo et al., 2007; Irvine et al., 2012), but also around high pressure ridges (Immler et al., 2008; Gierens and Brinkop, 2012; Irvine et al., 2014a). The present-day global distribution of ISS regions, as determined by satellite and aircraft observations, tends to coincide with regions where these features occur. For example, in-situ aircraft and satellite measurements around the highest aircraft cruise altitudes (~ 200 hPa) show the highest frequencies of ISS in the tropics, in regions with deep convection (Spichtinger et al., 2003b; Gettelman et al., 2006; Luo et al., 2007; Lamquin et al., 2012). High frequencies are also found to coincide with the mid-latitude storm tracks, where the frequency is highly variable with altitude (e.g. Irvine et al., 2012; Lamquin et al., 2012), and in high latitude regions, particularly over the Southern Hemisphere polar regions (Gettelman et al., 2006; Lamquin et al., 2012).

The present-day distribution of ISS could be affected by climate change in two ways: firstly, via changes to humidity, and secondly via changes to temperature which may make a region too warm to support contrail formation. In the upper-troposphere and lowermost stratosphere the consensus is that, under climate change, there will be a decrease in relative humidity in the tropics and increases towards the poles, with a transition at mid-latitudes (e.g. Lorenz and DeWeaver, 2007; Wright et al., 2010; Sherwood et al., 2010). This suggests that the pattern of the response of ice-supersaturated regions to climate change will be regional rather than globally uniform. Climate models also predict a general warming of the upper-troposphere with climate change (e.g. Thorne et al., 2011), which is projected to be strongest in the tropics. Due to this warming, and since present-day temperatures at typical aircraft cruise altitudes in

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the tropics are often close to the threshold temperature for contrail formation, it is in the tropics that we might expect to see the largest impact of climate change on contrail cover, as was indeed found by Marquart et al. (2003). The uppermost flight levels used by commercial aircraft are often in the lowermost stratosphere, particularly over the polar regions. Here climate models predict a general cooling, although the impact on contrail formation in the polar regions is likely limited since temperatures are generally well below those required for contrail formation.

This study analyses changes in ISS over the twenty-first century in a selection of models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble (Taylor et al., 2012). These data are described in Sect. 2.1. Data from simulations of the 21st century with a high greenhouse gas emissions pathway (named RCP8.5 in the CMIP5 experiments) are compared to simulations of the present-day climate. ERA-Interim re-analysis data are used to evaluate the distribution of ISS in the present-day climate simulations of the CMIP5 models (Sect. 3.1). Changes to the global frequency and distribution of ISS are analysed for an end of century time period. The end-of-century change, as well as the time evolution of this change and its seasonal aspects are analysed further for three regions of interest: the tropics, Northern Hemisphere (NH) mid-latitudes and NH polar regions (Sect. 3.2). Finally, since the daily-mean data used in this study are only available on a single pressure level relevant to contrail formation, monthly-mean data are used to understand whether the conclusions reached from the single-level data might be applicable to the range of aircraft flight altitudes (Sect. 3.3). Conclusions are presented in Sect. 4.

2 Method

2.1 Data

Climate model data from the CMIP5 multi-model archive were used, from two simulations: historical and representative concentration pathway (RCP) scenario 8.5 (Taylor

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et al., 2012). The historical simulation simulates the present-day climate by forcing the models with observed or simulated greenhouse gas and aerosol concentrations; for this study we take data from the historical simulation for the period 1979–2005. The RCP8.5 simulation uses economic scenarios to estimate future emissions of greenhouse gases and the resulting impacts on climate, for the period 2006–2099. RCP8.5 describes a world where there is little mitigation of greenhouse gas emissions, such that by 2100 emissions reach three times their 2000 values (Riahi et al., 2011). This leads to a global-mean radiative forcing of $8.5\,\mathrm{W\,m^{-2}}$ and a surface temperature increase of about 4 °C by 2100 (IPCC, 2013). RCP8.5 has the highest emissions and largest warming of the scenarios considered by IPCC (2013). This implies that we are analysing the maximum likely changes to ISS from climate change; more moderate emissions scenarios cause less warming, particularly in the second half of the 21st century, and therefore an evaluation of these simulations would likely show smaller changes than in the RCP8.5 simulations.

For the purposes of this study, a selection of five CMIP5 models were chosen to analyse. Data were used from EC-EARTH (Hazeleger et al., 2010, 2012), GFDL-ESM2G (Dunne et al., 2012), HadGEM2-CC (Martin et al., 2011; Collins et al., 2011), MIROC5 (Watanabe et al., 2010) and MPI-ESM-MR (Stevens et al., 2013). These models have been shown to have a good representation of key circulation features (Lee and Black, 2013; Davini and Cagnazzo, 2013). In addition, EC-EARTH was chosen because it explicitly represents ice-supersaturation in its cloud scheme (it is based on a similar version of the European Centre for Medium-Range Weather Forecasts (ECMWF) forecast model as ERA-Interim; a description of the model version is given in Hazeleger et al., 2012). The resolution of the CMIP5 models used ranges from 1.2 to 2.0° (Table 1). The majority of this study uses daily-mean global data, for which data are available on a limited number of pressure-levels. Data are used on the 250 hPa level, since this corresponds to typical aircraft cruise altitudes, and so is most appropriate to study changes in ISS that are relevant to aircraft contrail formation. To investigate whether the changes seen at the 250 hPa level might also be observed at other levels, monthly-mean data were used, which are available on seven pressure levels between 500 and 100 hPa (500, 400, 300, 250, 200, 150 and 100 hPa).

As an evaluation of high humidity regions in the historical simulations of the CMIP5 models, re-analysis data from the ECMWF Interim re-analysis (ERA-Interim; Dee et al., 2011) were used. Daily-mean data at a pressure level of 250 hPa, as well as monthly-mean data were used, for the period 1979–2005. The data are available at a horizontal resolution of 0.7°. ERA-Interim is particularly suited to studies of ISS since ISS is explicit within the cloud scheme (Tompkins et al., 2007). This has led to an improved humidity analysis at upper-levels although the analyses show a general dry bias when compared to Atmospheric Infra-Red Sounder satellite measurements (Lamquin et al., 2009); the ISS frequency in the model climate is lower than observed in the tropics, particularly over the Maritime continent, African continent and South America (Tompkins et al., 2007). Forecasts of ice-supersaturated regions produced using the same model version as used to produce the re-analyses also validate well against radiosonde observations and visual observations of contrails (Rädel and Shine, 2010).

In addition to analysing changes to the global frequency and distribution of ISS, regional changes are also analysed. Three sub-regions of interest are defined: the tropics (30° S–30° N), Northern Hemisphere mid-latitudes (40–60° N) and NH polar regions (70–90° N). The choice of these three regions is motivated by the present-day distribution of air traffic and projected changes during the 21st century. Of these three regions, the NH mid-latitude region currently has the highest proportion of global air traffic (e.g. Wilkerson et al., 2010). Air traffic in all three regions is projected to grow, particularly in the tropics; projections in Owen et al. (2010) for the A2 scenario (their Fig. 2) used in the 2007 IPCC assessment (Riahi et al., 2007), which the RCP8.5 scenario is based on, predict five times as much air traffic in some regions in 2050 compared to 2000.

2.2 Definition of ice-supersaturation

Regions of ice-supersaturation are defined using both a relative humidity with respect to ice (RHi) and a temperature threshold. Typically, that the RHi should be greater

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than 100 %, and the temperature below a threshold value of 233 K. This temperature threshold is necessary in order to avoid considering regions where mixed phase or supercooled clouds could form, and is additionally consistent with the threshold temperature for contrail formation, defined by the Schmidt–Appleman criterion (Schumann, 1996). We note that climate models, including the CMIP5 models analysed here, often have large temperature biases in their representation of the upper troposphere in the present-day climate. The use of a fixed temperature threshold may therefore lead to an underestimation or overestimation of the amount of ISS, depending on the direction of the bias, in regions where the true temperature is often close to this temperature threshold. The temperature biases of the CMIP5 models used in this study are analysed in Sect. 3.1.

For studies based on model data, it is appropriate to select an RHi threshold below 100 %, to account for sub-gridscale variability in the humidity field, and the relatively coarse horizontal resolution of the model data in comparison to typical sizes of ISS regions. For example, the horizontal grid spacing of the CMIP5 models used here (Table 1) is of similar size to the mean size of ISS regions, of 150 km, reported by in-situ aircraft measurements (Gierens et al., 2000). However we find it problematic to use a single RHi threshold to define ISS at a single level for a set of models that have varying horizontal resolution, model parameterisations and biases. For example, using a RHi threshold of 90 % gives annual-mean global-mean ISS frequencies ranging from 1 to 19 % (compared to 11 % for ERA-Interim) for the historical period for the five CMIP5 models used here. This vast range makes it difficult to compare the ISS distributions between the models. The model range of ISS frequencies is likely because of different representations of cloud processes and water vapour transport. These lead to distinctly different RHi distributions between the models (Fig. 1); GFDL-ESM2G and HadGEM2-CC have a higher proportion of lower RHi values than ERA-Interim, whereas MPI-ESM-MR has a higher proportion of very high RHi values.

To enable a fair comparison between the CMIP5 models, instead of using a fixed RHi threshold we chose to use a threshold that varied by model. This is justified since we

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do not seek to quantify the frequency of ISS in each model for a particular region or time; rather we are interested in comparing the spatial distribution of ISS between the models, and quantifying the change in ISS frequency between the future and historical simulations of the same models. The threshold was defined as follows: for each model, we calculated the cumulative probability distribution of RHi (Fig. 1) using RHi data directly from each model, and found the RHi value corresponding to the 90th percentile of RHi. The resulting model-dependent RHi thresholds are given in Table 1. For ERA-Interim the RHi threshold is 92 %, and for the CMIP5 models the thresholds range from 72 % (GFDL-ESM2G) to 98 % (EC-EARTH).

Using the 233 K temperature and model-dependent RHi thresholds specified above, the global-mean annual-mean 250 hPa ISS frequency over the period 1979–2005 is 8.1 % in ERA-Interim, and varies between 10.1 and 12.1 % in the historical simulations of the CMIP5 models (Table 1). Applying this threshold ensures that the global-mean ISS frequency is close to the "observed" frequency, without constraining the regional distribution of ISS frequency.

3 Results

3.1 Ice-supersaturation in the present-day climate

The annual-mean distribution of ISS at 250 hPa in the present-day climate for the period 1979–2005 is shown for ERA-Interim in Fig. 2a. At this pressure level, there are high frequencies of ice-supersaturation over the tropics, although as previously noted ERA-Interim is known to underestimate ISS in this region (Tompkins et al., 2007). The distribution of high ISS frequencies in the tropics is not uniform and is linked to regions of deep convection; high frequencies are observed in particular over the northern Indian ocean and Maritime continent and also parts of central Africa, in agreement with in-situ aircraft measurements (Luo et al., 2007). Some of the highest frequencies of ISS in ERA-Interim are in the Southern Hemisphere polar region, south of 70° S. These

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are also observed by satellite measurements (e.g. Gettelman et al., 2006; Lamquin et al., 2012), but the future evolution of these are of little interest to this study because of the lack of air traffic in this region. There are also elevated frequencies in the mid-latitude regions and over Russia. In particular, regions of high frequencies of ice-supersaturation are found in the north Atlantic and north-west Pacific regions; their location and south-west to north-east tilt suggest they are related to the storm-tracks in these regions (e.g. Irvine et al., 2012).

The distribution of ISS in the historical simulations of the CMIP5 models for the same time period are shown in Fig. 2b–f. These can be qualitatively compared to the distribution in ERA-Interim (Fig. 2a) in order to assess the performance of each model in simulating ISS in the present-day climate. There are differences in the distribution of ISS between the CMIP5 models, even though the way the RHi threshold for ISS has been defined means that the global-mean annual-mean ISS frequency in each model is similar. All models qualitatively reproduce the main features of the ERA-Interim ISS distribution although with varying frequencies; all models have high frequencies of ISS in the tropics, and mid-latitude storm tracks. EC-EARTH (Fig. 2b), GFDL-ESM2G (Fig. 2c) and MPI-ESM-MR (Fig. 2f) also have high ISS frequencies in the Southern Hemisphere polar region, in similar locations to ERA-Interim; EC-EARTH and MPI-ESM-MR also have high ISS frequencies over Russia, which are missing from GFDL-ESM2G at this level. HadGEM2-CC (Fig. 2d) has somewhat lower frequencies of ISS over Antarctica and Russia at this level than ERA-Interim. Of the five CMIP5 models analysed, the MIROC5 model distribution of ISS (Fig. 2e) has the largest differences from ERA-Interim outside the tropics: the ISS frequency in the mid-latitudes is the highest of any of the models, while the ISS frequencies in the southern polar region are very low.

There are several reasons why we might expect to find differences between the distribution of ISS in ERA-Interim and the CMIP5 models. The use of a single pressure level to analyse ISS is one factor since regions of ISS are typically shallow, and located close to the tropopause (Spichtinger et al., 2003a; Rädel and Shine, 2007). Satellite-derived climatologies of ISS frequencies show significant differences in ISS frequency and dis-

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tribution at different levels in the upper-troposphere (e.g. Spichtinger et al., 2003b; Lamquin et al., 2012). Hence any bias in tropopause height in the models, particularly in the mid-latitudes where the 250 hPa level is often close to the tropopause, would bias the resulting ISS frequencies. Since the CMIP5 data archive retains model data on only a limited number of pressure levels in the upper-troposphere, we do not attempt to compute a bias in tropopause height for each model.

An additional reason for the differences between the models in Fig. 2 is that the CMIP5 models exhibit substantial temperature biases at the 250 hPa level when compared to ERA-Interim. Figure 3a, c and e shows pdfs of temperature for ERA-Interim and each CMIP5 model for the three sub regions of interest. The size of the temperature bias varies by model and region, but is typically a few Kelvin in magnitude, with almost all models and regions biased cold. Since a region is only considered as ice-supersaturated if the temperature is below the 233 K threshold (shown as a dashed line on Fig. 3), a cold bias could lead to an overestimation of ice-supersaturation in regions where the temperature is often close to this threshold. Figure 3 shows that for the NH mid-latitude (Fig. 3c) and polar (Fig. 3e) regions, the temperature threshold is at the upper-limit of the temperature pdf in the present-day climate, and so the bias will have little impact on ISS frequency. However in the tropics, the 250 hPa temperature in ERA-Interim is often around the 233 K threshold, but in the CMIP5 models it is almost always below the threshold in the present-day climate (Fig. 3a), and so could impact the ISS frequency. Additionally, since relative humidity is exponentially related to temperature through the saturation vapour pressure, a cold temperature bias will cause a high relative humidity bias (for the same specific humidity). In the CMIP5 models, however, the cold temperature bias is accompanied by a dry bias in the specific humidity. Pdfs of specific humidity (Fig. 3b, d and f) show mean biases of the order of 10^{-2} g kg^{-1} in the tropics and NH mid-latitude regions, and 10^{-3} g kg^{-1} in the NH polar regions. In all regions, the CMIP5 models typically have a higher proportion of points with low specific humidity than in ERA-Interim, and fewer with high specific humidity in the tail of the distribution.

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3.2 Changes to ice-supersaturation over the twenty-first century

Changes to the ice-supersaturation frequency and distribution over the twenty-first century are now investigated, using the RCP8.5 simulations of the CMIP5 models. The annual-mean global-mean change in 250 hPa ISS frequency by the end of the twenty-first century is shown in Table 1, calculated as the average frequency over the period 2073–2099 minus the average over 1979–2005 (from the historical simulation). All models predict a decrease in the annual-mean global-mean ISS frequency by the end of the twenty-first century, relative to the present-day. The multi-model mean decrease is 4 % with a range of 3.3 to 4.9 % decrease over the individual models. This is a relatively narrow range, given the differences in the spatial distribution of ISS in the models in the present-day climate.

The spatial distribution of the change in 250 hPa ISS frequency due to climate change is shown in Fig. 4 for each of the CMIP5 models, using the same time periods as above. The present-day distribution of ISS in each model is shown by black contours, in order to see the relationship between the present-day distribution of ISS and future changes to it. There are several features common to all five models. Firstly, all models predict strong decreases in the frequency of ISS in the tropics; the regions of strongest decrease correlate well with the regions of highest frequency of ISS in the present-day climate. All models show an increase in ISS frequency in both the northern and southern high-latitudes, although the size of the change varies between models. The largest differences between the models are found in the mid-latitudes. This is not surprising, given that the 250 hPa level is very close to the tropopause in the mid-latitudes, as previously discussed, and so the ISS frequency will be very sensitive to small changes in tropopause height. ISS in the mid-latitudes is often linked to the storm track regions; maxima in ISS frequency coincide with the location and orientation of the storm track in all major basins. In the annual-mean, all the models studied predict a small northward shift in jetstream location over the north Atlantic (Irvine et al., 2015), for example, but the change to ice-supersaturation frequency in the models in this region varies. For example GFDL-ESM2G (Fig. 4b) suggests a northward shift in the ISS frequency maxima in both north Atlantic and Pacific storm track regions, whereas most other models the change appears to be a decrease in the strength of the ISS maxima in these regions.

Figure 5 shows a time series of the multi-model mean change in ISS frequency, from 1979 to 2100, i.e. from the historical period through the RCP8.5 period. The change in frequency is calculated separately for each CMIP5 model as the annual-mean frequency in each year minus the 1979–2005 average. The individual time series are then averaged together to provide a multi-model mean (plotted). There is considerable interannual variability in the ISS frequency, particularly on seasonal timescales, and so the multi-model mean time series has been smoothed with a 10 year running mean to allow the long-term trends in the multi-model mean to be more clearly seen. The time series are shown separately for each region, and the mean changes in that region from the historical period to mid-century (2030–2056) and late century (2073–2099) periods are given separately for each model as well as the multi-model mean in Table 2.

For the NH polar regions, the time series shows an increase in ISS frequency through the 21st century. The rate of increase is faster over the second half of the 21st century than the first half; the multi-model mean increase in annual-mean ISS frequency is 1.7 % (range 0.9–2.2 %, Table 2) by mid-century and 4.9 % (range 2.8 to 6.2 %) by the end of the century. There is a strong seasonality to the changes; the largest changes are in the autumn (September, October and November) and smallest in the spring (March, April and May) (not shown). At these latitudes, 250 hPa is certainly in the stratosphere and the water vapour content of the air is very small, as shown by the small values of specific humidities in the pdfs in Fig. 3f. Any contrails forming in this region may have small optical depths such that their impact on climate is lower than contrails formed in other regions with higher water vapour contents. Thus the increase in ISS frequency shown here may be less significant in terms of persistent contrails and their climate impact than for the other regions studied.

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In the NH mid-latitude region there is little change in the annual-mean ISS frequency over the 21st century (Fig. 5). The multi-model mean change by mid-century and end of century are comparable, at 0.7 and 0.9 % increase respectively. Moreover, there is some disagreement between the models on the sign of the change. MIROC5 predicts small decreases in ISS frequency by both mid-century and end of century time periods. EC-EARTH and MPI-ESM-MR predict no change by the end of the 21st century whereas GFDL-ESM2G and HadGEM2-CC predict small increases. This spread in model behaviour is likely linked to the different jet stream and tropopause height climatologies in the models, since in this region 250 hPa is often close to the tropopause, and regions of ISS are often associated with the position of the jet stream in the model. There is some seasonality to the ISS changes shown; the multi-model mean shows an increase of around 3 % in winter (December, January and February, DJF), and a decrease of around 2 % in summer (June, July and August, JJA) by the end of the 21st century (Fig. 5). At this altitude, the ISS frequency is higher in summer than winter in the re-analysis data (not shown).

In the tropics there is a strong decrease in annual-mean ISS frequency throughout the 21st century. The decrease is strongest through the middle of the century, and begins to level-off by 2080. The multi-model mean change is a decrease of 3.3 % by mid-century (range 2.6 to 5.6 %, Table 2), and 8.8 % by the end of the century (range 6.1 to 11.5 %). Given the nature of ISS regions in the tropics, and that we are averaging over both northern and Southern Hemisphere portions of the tropics, it is unsurprising that there is little seasonality to this change. The main factor driving the large decrease in ISS frequency in the tropics is temperature. Figure 6 shows a timeseries of average change in tropical ISS frequency for each model, with colours used to indicate the fraction of all tropical points in each model which are below the 233 K temperature threshold used to define an ISS region. During the historical period this is always above 0.9, therefore it is almost always sufficiently cold for contrail formation, so that the limiting factor determining the ISS frequency would be the humidity. This fraction begins to decrease in the 2030s and by 2080 it has dropped below 0.2; this low fraction means

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that regardless of the humidity, over most of the tropics it is too warm to meet the definition of an ISS region. This explains the sharp decrease in ISS frequency predicted by the models. Note that the changes during the historical period, a decrease in ISS frequency, are very small in comparison to the predicted changes over the 21st century.

3.3 Extension of results to multiple levels

The analysis of ISS regions has so far concentrated on the 250 hPa level, for which daily-mean data are available. In order to assess whether the changes in ISS frequency over the twenty-first century can be generalised to levels other than 250 hPa, monthly-mean data are analysed. Given the relatively small-scale and short time-scale nature of ISS regions, it would not be particularly meaningful to try to define regions of ISS using monthly-mean data. Instead, we use the annual-mean zonal-mean differences between the RCP8.5 and historical simulations of the CMIP5 models, to analyse the vertical structure of changes in mean relative humidity and temperature. These are shown separately for each CMIP5 model, as the average over 2073–2099 minus the average over 1979–2005, in Fig. 7. The latitudinal bounds of the tropical, NH mid-latitudes and NH polar regions are also given, along with the range of typical cruise altitudes of commercial aircraft (approximately 300–200 hPa).

There is generally good agreement on the vertical structure of zonal-mean temperature and relative humidity changes between the models. For the NH polar regions, the models agree on an increase in mean relative humidity over the altitude range of interest, which suggests that the increase in ISS frequency predicted in this region will be observed at other levels. Mean temperature changes in this region are irrelevant for ISS frequency, since the temperatures at flight level are well below the 233 K threshold. For the NH mid-latitude region, there is less agreement between models; the mean changes are more dependent on altitude and latitude. However, all models agree on an increase in relative humidity at altitudes above 250 hPa, with the largest changes at the highest flight levels. It is possible that there will be a decrease in ISS regions at low mid-latitudes and flight levels, from a combination of the decrease in

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relative humidity and increase in temperature (which will increase the number of days where the temperature is above the 233 K threshold). In the tropics, all models except GFDL-ESM2G (Fig. 7b) predict a decrease in mean relative humidity; this decrease in relative humidity has been found by many previous studies (e.g. Lorenz and DeWeaver, 2007; Wright et al., 2010; Sherwood et al., 2010) and is considered a robust signal of climate change. All models predict a strong warming over the altitude range of interest in the tropics; most importantly, this has the effect of pushing temperatures above the 233 K threshold and so reducing the potential for contrail formation, regardless of any changes in relative humidity. This effect is strongest at the 250 hPa level in the models, but all levels show some reduction. The effect is smaller at higher altitudes where temperatures are colder and the warming is not sufficient to result in temperatures above the 233 K theshold. At lower altitudes where it is warmer, in the present-day climate much of the temperature pdf is already above the 233 K threshold, so any warming has a smaller effect on the ISS frequency.

4 Conclusions

The evolution of meteorological conditions controlling persistent contrail formation during the 21st century are investigated. Specifically, the frequency and distribution of ice-supersaturation are analysed in simulations from a selection of models in the CMIP5 multi-model archive, using a model-dependent RHi threshold defined using the cumulative probability distribution of RHi in each model.

The present-day simulations from the CMIP5 models qualitatively reproduce the main features of the ISS distribution seen in ERA-Interim re-analysis data: high frequencies of ISS in the tropical regions, mid-latitude storm tracks, and most models also simulate high frequencies in the southern high-latitude regions. At the 250 hPa level analysed, all models have cold biases of a few Kelvin in the tropics. This is particularly significant as in this region observed temperatures are close to the temperature

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threshold for ISS; ISS frequencies in the tropics may be overestimated for the present-day climate by the CMIP5 models as a result.

To analyse the impact of climate change on ISS frequency, RCP8.5 simulations were used. This scenario has the highest greenhouse gas concentrations and therefore largest temperature changes of the different scenarios considered by the 2013 IPCC report. Globally, the CMIP5 models predict a decrease in ISS frequency by the end of the 21st century, of average 4 % over the models analysed here. However, this change is not uniform globally, and both the sign and magnitude of the change in ISS varies by region. The largest contribution to the global-mean decrease is the strong decrease in ISS frequency in the tropics, of 8.8 % in the multi-model mean by the end of the 21st century. The rate of decrease is strongest in the mid-century, and levels-off by the late century. The decrease in ISS frequency is mainly due to the strong warming at the 250 hPa level, which shifts the temperature pdf from below the 233 K temperature threshold to above it. There is less consensus between the models on the sign and magnitude of the change in the NH mid-latitudes at the 250 hPa level. The multi-model mean annual-mean change is around 1 % by 2100, and seasonally-dependent; models show small increases in ISS frequency in winter and decreases in summer. The models agree on an increase in ISS frequency over the NH polar regions in all seasons, reaching approximately 5 % by 2100.

The CMIP5 zonal-mean monthly-mean relative humidity and temperature projections suggest that the changes projected at the 250 hPa level are applicable to other levels, perhaps with the exception of the NH mid-latitudes where the sign of any change in ISS frequency is more dependent on latitude and altitude. In the tropics, the largest change in the CMIP5 models is at 250 hPa, which is in the middle of the range of permitted cruise altitudes. However, since the models have a cold bias, relative to the re-analyses, the level at which the maximum change is seen may actually be higher than this.

The projected changes to ice-supersaturation frequency over the twenty-first century have implications for contrail cover, and consequently contrail climate impact. Persis-

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tent contrails form when aircraft fly through the ISS regions analysed here; making projections of actual contrail cover for the 21st century would require combining the climate model data with estimates of the amount and distribution of air traffic throughout this time period of the climate model simulations, as well as accounting for improvements to aircraft engine technology. Here we provide a discussion of the possible impact of the ISS changes on contrail cover, given projections of air traffic demand and increasing aircraft engine efficiency. In the NH mid-latitudes where there is already a high volume of air traffic, climate models predict small increases in ISS frequency, particularly in winter. This suggests that there could be small increases in contrail cover from the combination of increased ISS frequency and increased air traffic. Increases in engine efficiency are likely to have only minor impacts on contrail cover in this region since temperatures are normally well below those required for contrail formation. In the tropics, the reduction in ISS frequency is in opposition to the predicted growth in aviation and increase in engine efficiency. It seems likely however, that a factor of 2–5 increase in air traffic from 2000 to 2050 (Owen et al., 2010) along with an increase in engine efficiency will outweigh the few percent decrease in ISS frequency shown here, leading to an increase in contrail cover. In the NH polar regions, the situation is similar to the NH mid-latitudes, but with more confidence in larger increases in ISS frequency due to climate change. The predicted increases in ISS frequency presented here, as well as a possible factor of 2 increase in air traffic (Owen et al., 2010) suggest an increase in contrail cover. The climate significance of this is less obvious, since any contrails formed at high latitudes are likely to be very thin, and the level of air traffic is likely to remain far below that of the mid-latitude or tropical regions. Overall, global contrail cover seems likely to increase over the twenty-first century, with climate change acting to increase contrail cover in the mid-latitude and polar regions and constraining changes in contrail cover in the tropics.

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which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

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Table 1. Characteristics of the CMIP5 models used in this study. The ISS threshold is the threshold RHi value used in the calculation of the annual-mean global-mean ISS frequency at 250 hPa in the present-day climate (note a temperature threshold of 233 K is also applied). The change in ISS frequency is calculated as the global-mean annual-mean ISS frequency in the RCP8.5 simulation over the period 2073–2099 minus that in the historical simulation over the period 1979–2005.

Model	Centre	Horizontal resolution	ISS threshold (%)	ISS frequency 1979–2005 (%)	Change in ISS frequency (%)
ERA-Interim re-analysis	**European Centre for Medium-Range Weather Forecasts**	**0.7°**	**92**	**8.1**	**–**
EC-EARTH	EC-EARTH consortium	1.125°	98	10.1	−3.6
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	2.0° lat, 2.5° lon	72	10.8	−3.3
HadGEM2-CC	Met Office Hadley Centre	1.25° lat, 1.875° lon	78	12.1	−4.9
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, Japan Agency for Marine-Earth Science and Technology	1.4°	93	11.1	−3.5
MPI-ESM-MR	Max Planck Institute for Meteorology	1.875°	97	10.5	−4.7

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Table 2. Changes to the annual-mean frequency of ISS at 250 hPa from the RCP8.5 simulation minus the historical simulation, for the sub-regions of interest. The change is shown for two time-periods: middle of the 21st century, and end of the 21st century.

Model	Change in ISS frequency (2030–2056) – (1979–2005) (%)			Change in ISS frequency (2073–2099) – (1979–2005) (%)		
	Tropics	NH Midlats	NH Polar	Tropics	NH Midlats	NH Polar
EC-EARTH	−2.6	0.4	1.8	−7.6	0.2	4.5
GFDL-ESM2G	−2.6	1.5	1.6	−9.5	3.8	6.0
HadGEM2-CC	−5.6	1.8	2.2	−11.5	2.4	6.2
MIROC5	−2.7	−0.5	2.0	−6.1	−1.8	5.0
MPI-ESM-MR	−3.2	0.2	0.9	−9.2	0.1	2.8
Multi-model mean	−3.3	0.7	1.7	−8.8	0.9	4.9

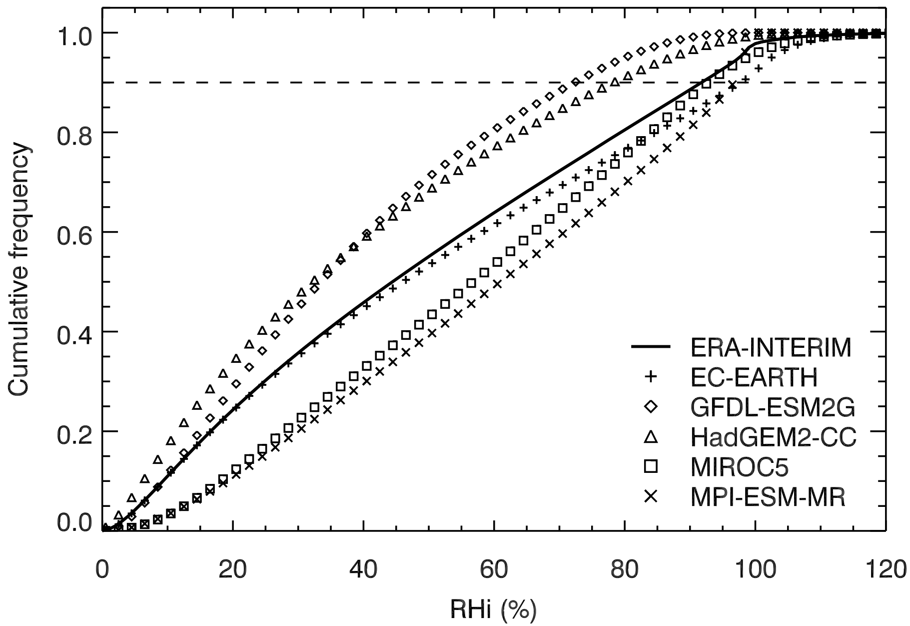

Figure 1. Cumulative frequency distribution of 250 hPa relative humidity with respect to ice for ERA-Interim (thick solid line) and the CMIP5 models (symbols). Global daily data over the period 1979–2005 is used. The dashed line marks the 90th percentile of the RHi distribution, used to define the model-dependent RHi threshold for ice-supersaturated regions.

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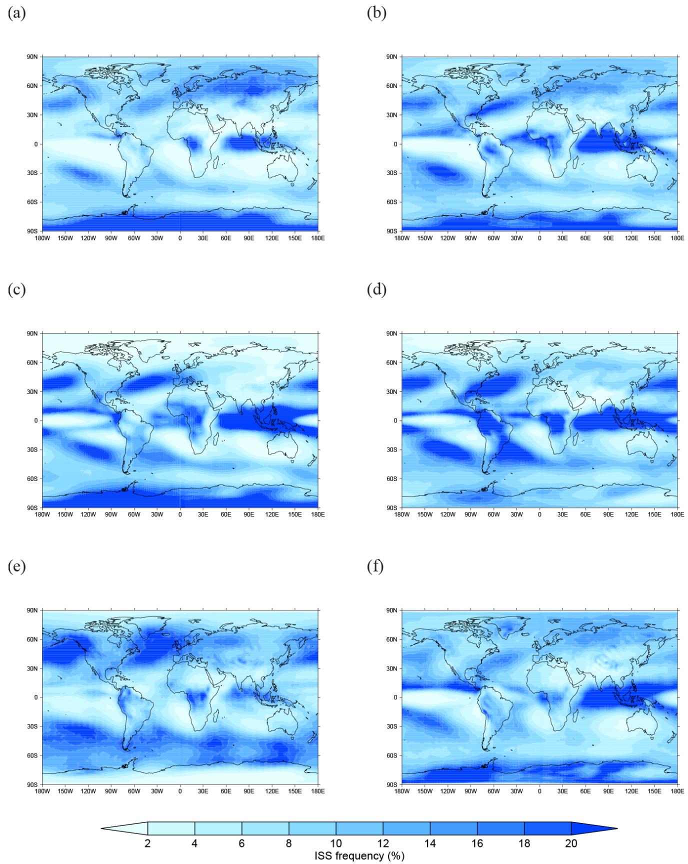

Figure 2. Annual-mean ISS frequency at 250 hPa over the present-day period 1979–2005 for **(a)** ERA-Interim re-analysis and the CMIP5 models **(b)** EC-EARTH, **(c)** GFDL-ESM2G, **(d)** HadGEM2-CC, **(e)** MIROC5 and **(f)** MPI-ESM-MR.

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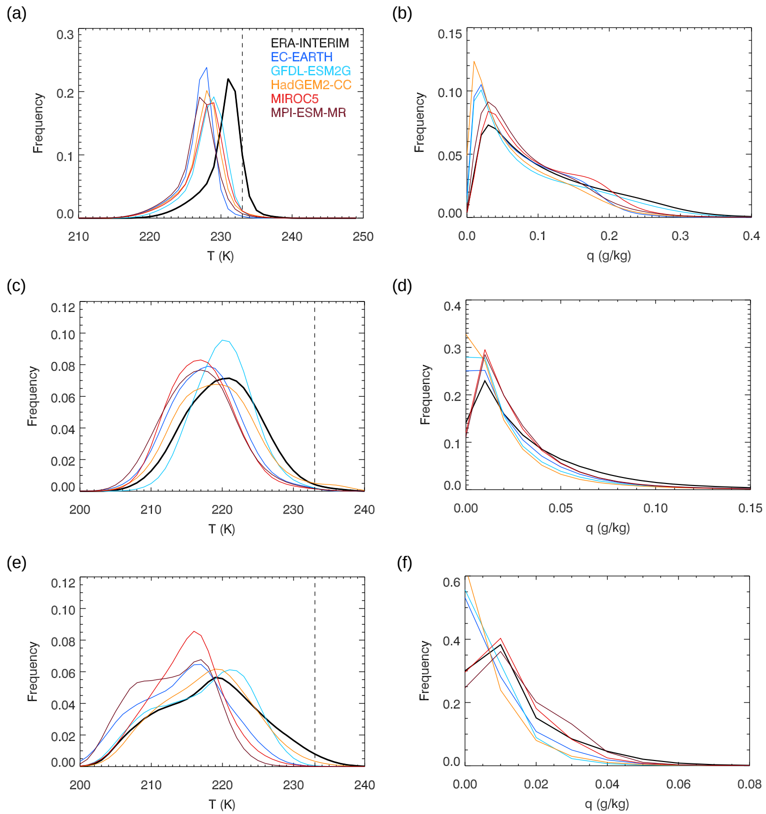

Figure 3. Pdfs of temperature, T (left column) and specific humidity, q (right column) at 250 hPa in the present-day climate (1979–2005) in three regions: (**a** and **b**) the tropics, (**c** and **d**) the NH mid-latitudes and (**e** and **f**) the NH polar regions. Shown for ERA-Interim re-analysis (thick black line) and CMIP5 models EC-EARTH (dark blue), GFDL-ESM2G (light blue), HadGEM2-CC (orange), MIROC5 (red) and MPI-ESM-MR (dark red). The 233 K temperature threshold is marked by the dashed line on panels (**a**, **c** and **e**).

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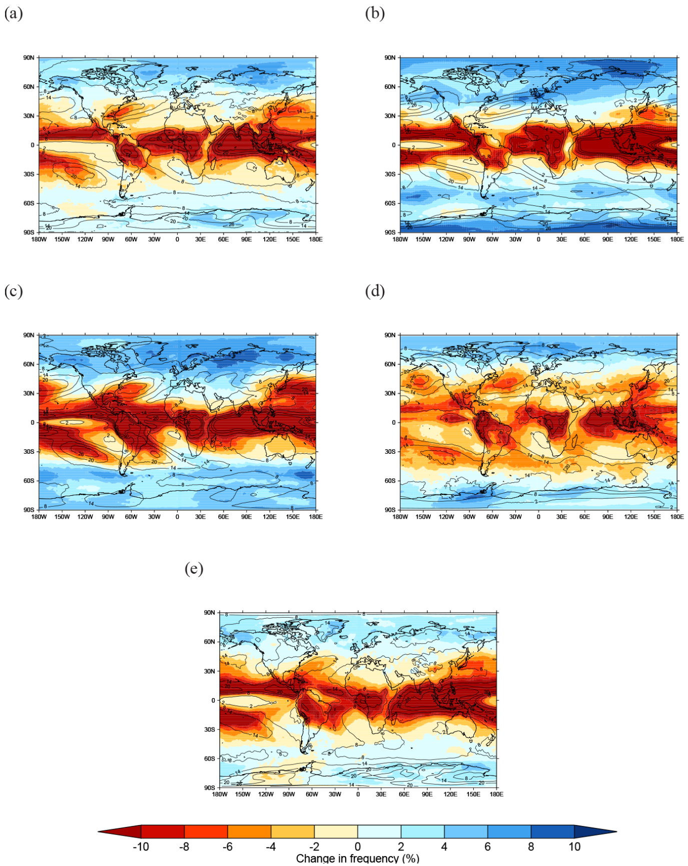

Figure 4. Change in mean ISS frequency at 250 hPa (colours) between the RCP8.5 simulation (average over 2073–2099) and historical simulation (average over 1979–2005) for the CMIP5 models **(a)** EC-EARTH, **(b)** GFDL-ESM2G, **(c)** HadGEM2-CC, **(d)** MIROC5 and **(e)** MPI-ESM-MR. The mean ISS frequency (in %) in each model over the historical period 1979–2005 is overlaid (black contours).

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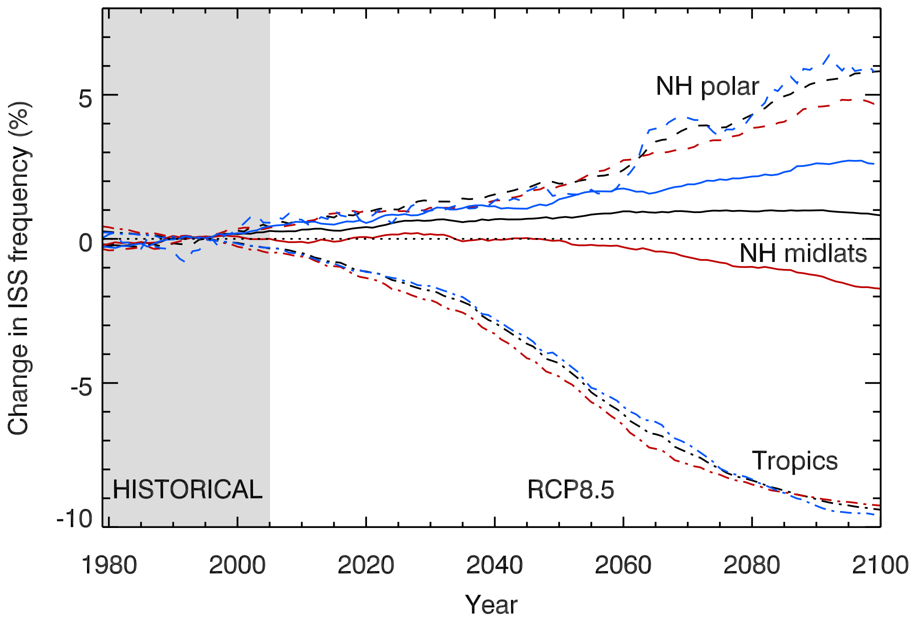

Figure 5. Time series of the multi-model mean change in ISS frequency at 250 hPa from 1979 to 2099, calculated for each year as the mean ISS frequency minus the 1979–2005 average (the historical period, shown by grey shading). The change is calculated separately for the tropics (dashed-dotted lines), NH mid-latitudes (solid lines) and NH polar (dashed lines) regions, for the annual (black lines), DJF (blue lines) and JJA (red lines) mean changes. The changes are calculated separately for each CMIP5 model and averaged to provide a multi-model mean; a 10 year running mean has been applied to each time series before plotting.

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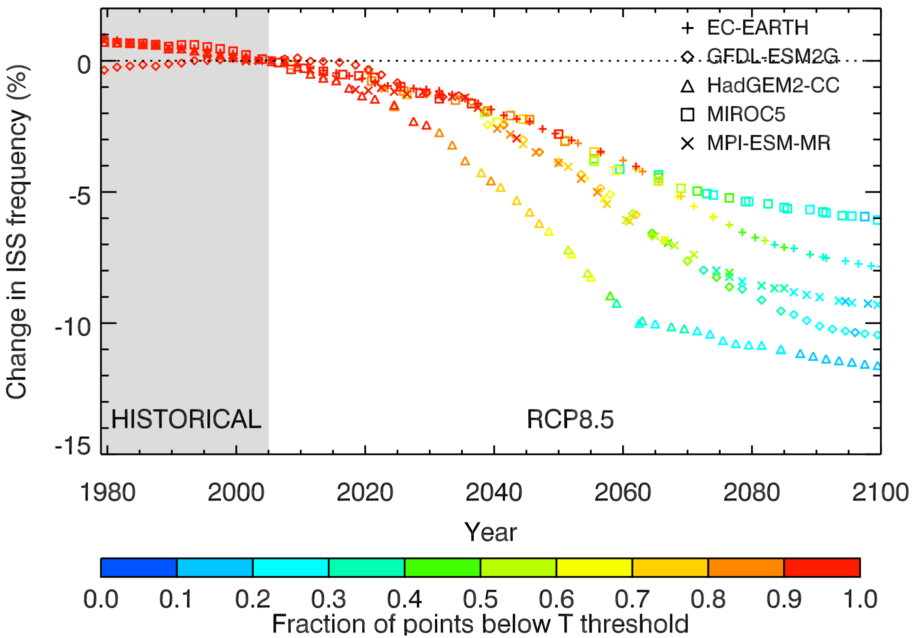

Figure 6. Time series of the change in 250 hPa ISS frequency in the tropics in the CMIP5 models (symbols) from 1979 to 2099, calculated for each year as the annual-mean ISS frequency minus the 1979–2005 average (the historical period, shown by grey shading). The colour of the points shows the fraction of points in the tropics which are below the 233 K temperature threshold for ISS. A 10 year running mean has been applied to each time series before plotting.

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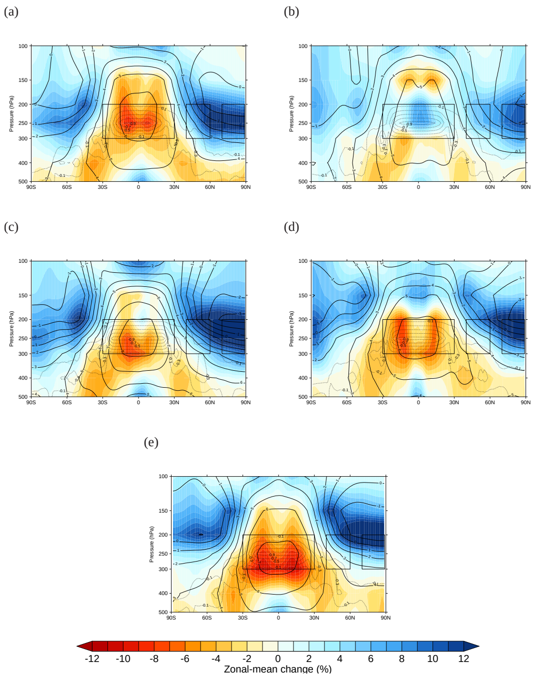

Figure 7. Zonal-mean change in annual-mean RHi (colours), temperature (solid black lines) and fraction of points below the 233 K temperature threshold (dotted black lines) as a function of pressure for the CMIP5 models **(a)** EC-EARTH, **(b)** GFDL-ESM2G, **(c)** HadGEM2-CC, **(d)** MIROC5 and **(e)** MPI-ESM-MR. The changes are calculated using monthly-mean data, as the average over 2073–2099 (RCP8.5 simulation) minus the average over 1979–2005 (historical simulation). The sub-regions of particular interest are highlighted by black boxes: the tropics, Northern Hemisphere mid-latitudes and Northern Hemisphere polar regions. The vertical range of these boxes is 200–300 hPa, spanning the range of typical cruise altitudes for commercial aircraft.

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