NOTES AND CORRESPONDENCE

Frequency Change of Clear-Air Turbulence over the North Pacific under 2 K Global Warming – Ensemble Projections Using a 60-km Atmospheric General Circulation Model

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Abstract

Future changes in the climatological distribution of clear-air turbulence (CAT) and its seasonality over the North Pacific are estimated on the basis of an ensemble of climate projections under warming for the globally averaged surface air temperature of 2 K relative to preindustrial levels, which includes over 3000 years of ensembles using a 60 km atmospheric general circulation model (AGCM). The AGCM outputs are interpolated to a 1.25° horizontal resolution, and the climatological CAT frequency is computed. The CAT broadly decreases in the mid-latitude central to western North Pacific along with the anticyclonic (south) side of its present-day high-frequency band extending from Japan to the eastern North Pacific. Meanwhile, large relative increases are found outside the band, implying an increased risk of CAT encounters. Uncertainty in future CAT changes due to uncertainties in the spatial pattern of sea surface temperature (SST) change is addressed for the first time using six selected Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models. The uncertainty is greatest in the boreal winter and spring over the central North Pacific and is associated with an uncertainty in future changes in the jet stream and upper-level synoptic-scale disturbances.

Keywords clear air turbulence; climate change; ensemble projection database

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1. Introduction

Clear-air turbulence (CAT) accompanies vertical airflows greater than or equal to the size of an aircraft, that is, tens to 2000 m. Aircraft often experience CAT in the tropopause region near jet streams, where environmental conditions frequently satisfy those required for Kelvin–Helmholtz instability. Since CAT is not explicitly resolved by current numerical weather

forecast models, several CAT indices have been developed to diagnose the potential for CAT to occur using synoptic or mesoscale grid point parameters output from forecast models (see Sharman et al. (2006) and the references therein). In a recent paper by Kim et al. (2018), they described the latest development of the Global Graphical Turbulence Guidance (G-GTG), which considers CAT and mountain wave turbulence diagnostics.

From a climatological perspective, Jaeger and Sprenger (2007) reported the climatological distributions of CAT indices in the Northern Hemisphere tropopause region derived from the ERA-40 reanalysis dataset, which was interpolated from a 125 km horizontal resolution to a 1° horizontal resolution, and discussed their relevance to synoptic-scale dynamical and thermal environments (e.g., jet streams and frontal structures near the tropopause). They also discovered an increasing trend in the CAT frequency in the North Atlantic sector. Williams and Joshi (2013) were the first to conduct a study using a coupled atmosphere–ocean climate model to project future changes in the CAT and reported an increase in the CAT in the wintertime North Atlantic sector. Their atmospheric model has a horizontal resolution of $2^\circ \times 2.5^\circ$ in latitude and longitude. Later, Storer et al. (2017) extended this study to estimate the global change in the CAT frequency for all four seasons, as diagnosed by 20 different CAT indices, which were projected using a higher $1.25^\circ \times 1.875^\circ$ horizontal resolution climate model. More recently, Storer et al. (2018) presented a detailed review on aviation turbulence, including its response to climate change.

Following these earlier studies, in the present paper, we report several new aspects of future changes in the CAT frequency. We focus on the geographical patterns of frequency changes in the North Pacific sector, which have not been addressed in detail in previous climate change studies. Unlike earlier studies that compared climates under the preindustrial and double the preindustrial concentrations of CO_2 (Williams and Joshi 2013) or the preindustrial and the late 21st century in the RCP8.5 scenario (Storer et al. 2017), we compare the present-day climate and the climate under 2 K global warming with the preindustrial level. Unlike earlier studies where only a single climate model was considered, we present future CAT changes projected by an atmospheric general circulation model (AGCM) forced with six different SST change patterns (ΔSSTs) obtained from CMIP5 climate models. Unlike earlier studies where 20 years of daily means or 30 years of six-hourly output were used, we use

ensemble projection data from 270 years of six-hourly output for each of the six ΔSSTs . For the CAT indices, we select four from the 20 presented by Storer et al. (2017), which showed a striking dissimilarity with each other, to consider future changes in CAT patterns over the North Pacific.

The data and methodology are described in Section 2, followed by an analysis of the results in Section 3 and a summary and discussion in Section 4.

2. Data and methodology

In the present study, we use the database for Policy Decision Making for Future Climate Change (d4PDF), produced with a 60 km horizontal resolution AGCM, MRI-AGCM3.2 (Mizuta et al. 2012, 2017). This database includes an ensemble transient historical simulation of the recent past (PAST experiment) and an ensemble time-slice 2 K warming simulation (referred to as the +2 K experiment hereafter). Here, +2 K denotes the 2 K warming of the globally averaged surface air temperature relative to the preindustrial level in the context of the Paris Agreement. See Mizuta et al. (2017) and Fujita et al. (2019) for a detailed experimental design. The ensembles are generated by adding small perturbations to the observed (PAST) or detrended (+2 K) SSTs. To capture the uncertainty in future climate change projections arising from differences between models, the AGCM's +2 K experiment is forced with six different ΔSSTs obtained from selected CMIP5 climate model results. These models are abbreviated as CC (CCSM4: Community Climate System Model version 4), GF (GFDL-CM3: Geophysical Fluid Dynamics Laboratory Climate Model version 3), HA (HadGEM2-AO: Hadley Centre Global Environmental Model version 2 AO), MI (MIROC5: Model for Interdisciplinary Research on Climate version 5), MP (MPI-ESM-MR: Mixed Resolution version of the Max Planck Institute for Meteorology Earth System Model), and MR (MRI-CGCM3: Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model version 3).

The present study uses six-hourly instantaneous three-dimensional horizontal winds in the upper troposphere–lower stratosphere levels, which are interpolated to a 1.25° horizontal resolution to reduce the data volume. The target domain, the North Pacific sector, is defined as $30^\circ\text{--}75^\circ\text{N}$ and $120^\circ\text{E--}120^\circ\text{W}$ and covers the main North Pacific flight routes and some of the domestic flight routes over Japan (Fig. 1). This domain contains $37 \times 97 = 3,589$ grid points.

Here, the disagreement among the changes in the projected patterns of the CAT indices in the North

Fig. 1. Climatological distribution of CAT frequency at 200 hPa in the PAST experiment as diagnosed by T11, Sv, DEF, and rNBE (from top to bottom) in DJF, MAM, JJA, and SON (from left to right), respectively.

Pacific is considered in detail. In Fig. 2 of Storer et al. (2017), the CAT index associated with the deformation of the horizontal flow (DEF), which potentially leads to the spontaneous generation of gravity waves, increases between 30°N and 50°N in the North Pacific. The magnitude of the residuals of the nonlinear balance equation (rNBE), which is a common diagnostic method for the spontaneous generation of gravity waves (e.g., Zhang et al. 2000; Plougonven and Zhang 2014), increases in the same latitude band as the DEF, but its increase in the western Pacific sector is less pronounced. In contrast, the vertical shear magnitude of the horizontal wind (S_v), which is related to the intensity of the CAT, generally decreases in the North Pacific. Variant 1 of Ellrod's turbulence index (TI1), which is defined as the product of the DEF and S_v and has been proven to be skillful in capturing pilot-reported CAT (Ellrod and Knapp 1992), increases between latitudes of 30–35°N around Japan and the central to eastern North Pacific. Averaging these different projections of changes in CAT frequencies diagnosed by different CAT indices may limit our understanding of future changes in aviation risks. Therefore, the present paper focuses on the individual CAT indices. As a first step, we limit the number of CAT indices to the four mentioned above (i.e., TI1, S_v , DEF, and rNBE), which we selected from the 20 considered by Storer et al. (2017).

By definition, S_v , DEF, and rNBE are independent of each other, whereas TI1 is correlated with S_v and DEF. These CAT indices are calculated for the 200 hPa level, using the last 30 years of PAST and +2 K experimental results for d4PDF. S_v is calculated by combining the vertical finite differences among the 150, 200, and 250 hPa horizontal winds as

$$S_v = \sqrt{\left[\frac{1}{2} \left(\frac{u_{150} - u_{200}}{z_{150} - z_{200}} + \frac{u_{200} - u_{250}}{z_{200} - z_{250}} \right) \right]^2 + \left[\frac{1}{2} \left(\frac{v_{150} - v_{200}}{z_{150} - z_{200}} + \frac{v_{200} - v_{250}}{z_{200} - z_{250}} \right) \right]^2},$$

where the subscripts denote the pressure levels and u , v , and z denote the eastward wind component, the northward wind component, and the log-pressure height, respectively. The coarse vertical resolution prohibits the exact estimation of S_v above and below the jet axis, a common deficiency when using pressure level outputs from AGCM and global reanalysis products.

To reduce the uncertainty in the projections arising from natural climate variability, nine ensemble members of the PAST experiment are used in the calculation of the CAT indices. Similarly, nine ensemble members from the +2 K experiment are used for each of the six Δ SST patterns. Thus, the time series of the

Table 1. 99.6th percentile values for CAT indices calculated in the North Pacific sector.

CAT index	TI1 (10^{-9} s^{-2})	S_v (10^{-3} s^{-1})	DEF (10^{-6} s^{-1})	rNBE (10^{-12} s^{-2})
99.6 percentile	833.3	10.7	116.7	8750

CAT indices in the individual simulations are calculated using nine ensemble simulations with 30 years of six-hourly data, which consists of about 10^5 time steps per season at each grid point. This is one or two orders of magnitude greater than in previous studies. The larger time steps provide a smoother geographical distribution of CAT frequency and a more reliable estimation of its future change.

Following Williams (2017), the probability distribution of the magnitude of the CAT indices sampled over the target period and the grid points involved in the target horizontal domain are calculated, and the threshold values for the severity classes of the CAT are obtained accordingly. As stated by Storer et al. (2017), moderate or greater (MOG) CAT is defined as values exceeding the 99.6th percentile for each CAT index over the entire 270 years of PAST experimental ensembles, and the same threshold value is applied to the +2 K experiment to diagnose the occurrence of MOG CAT. Table 1 shows the threshold values for the four CAT indices, which are larger than those in earlier studies based on lower-resolution climate model data (e.g., Williams 2017). These threshold values are only valid for a particular model and spatial resolution. The present study focuses on the climatological frequency of MOG CAT, which is represented as a percentage, that is, $100 \times (\text{number of MOG CAT}) / (\text{total time steps})$. These calculations are conducted at each grid point for four seasons, that is, December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON), each of which includes about 360 time steps per year. By definition, a CAT frequency of around 0.28 % ($1/360$) corresponds to a single occurrence of a MOG CAT event at the 200 hPa level in a season. We investigate the relative change in the PAST and +2 K experimental data to understand the response of the CAT frequency to climate change.

The climatological CAT frequency at each grid point is derived from the PAST experimental ensemble (270 years) and the +2 K experimental ensembles forced by the six Δ SSTs (6×270 years), respectively. The horizontal distribution of the climatological CAT frequency in the PAST experimental ensemble cal-

culated as above is validated against that calculated using 30 years (from 1 December 1979 to 30 November 2009) of the Japanese 55-year Reanalysis (JRA-55) data (Kobayashi et al. 2015; Harada et al. 2016). The AGCM used in JRA-55 has the same 60 km horizontal resolution as that used in the present study, and the outputs are interpolated to the same 1.25° horizontal resolution (Japan Meteorological Agency 2013).

3. Results

3.1 Present-day climatology of CAT distributions

Figures 1 and 2 compare the climatological seasonal evolution of the CAT frequency at 200 hPa diagnosed by the TI1, S_v , DEF, and rNBE derived from the PAST experiment and JRA-55, respectively. The geographical distributions of the CAT frequency in the PAST experiment generally agree with those in JRA-55 and are smoother owing to the larger sample size. The TI1 distribution shown here qualitatively agrees with that shown by Jaeger and Sprenger (2007), although some differences are apparent since they analyzed a longer period and included multiple altitudes near the tropopause.

The CAT frequency diagnosed by the four indices shows a distinct seasonal variation; TI1 and S_v peak in the boreal spring and autumn and have their minima in the summer, whereas the DEF (rNBE) peaks in the summer (winter). The seasonal variations in TI1 and S_v in the PAST experiment seem to be associated with variations in the activity of upper-level synoptic-scale disturbances, which are diagnosed by the eddy kinetic energy (EKE) due to the 2–8-day component at the same 200 hPa level (Fig. 3). We define EKE as $0.5(u'^2 + v'^2)$, the 2–8-day eastward and northward wind components are extracted using a temporal filter following Inatsu and Hoskins (2004). Here, we assume that EKE cascades into turbulence through a wide variety of processes around the meandering jet-front system. TI1 and S_v have broad peaks coinciding with the cyclonic side of the EKE maximum, which migrates northward from DJF to SON. In particular, S_v exhibits a maximum in the midlatitude central to eastern North Pacific where synoptic-scale meandering of the jet stream frequently occurs. In contrast, the DEF peaks over the subtropical western North Pacific and aligns with the cyclonic side of the subtropical jet (Fig. 4). It is revealed from a six-hourly diagnosis that the DEF shows a distinct peak in the summer over Japan and further downstream in the jet stream, because of the frequent passage of sub-synoptic-scale disturbances associated with the Baiu front accompanying large DEF and relatively small S_v . These sub-

synoptic-scale disturbances are reproduced by the 60 km resolution AGCM, which is an advantage of using the d4PDF to study the CAT in this region. The wintertime peak rNBE band extends from Japan to the eastern North Pacific and migrates northward from DJF to SON. rNBE is closely related to the spontaneous generation of gravity waves in the jet-front system (e.g., Zhang et al. 2000; Plougonven and Zhang 2014), and its seasonal variation is strongly associated with the strength and location of the subtropical jet (Fig. 4). In addition, divergent flows associated with large-scale mountain waves enlarge the rNBE, generating hot spots over mountains. Because the accuracy of the resolved mountain waves in the AGCM is limited because of its horizontal resolution and the downsampling (i.e., 1.25° by 1.25°), we avoid discussions on future changes in rNBE over land.

3.2 Changes in +2 K climate

Figure 5 shows the horizontal distribution of the percentage change of the CAT frequency diagnosed by the TI1 in the +2 K experiment with the six CMIP5 Δ SSTs, relative to the PAST experiment, that is, $100 \times (+2 \text{ K} - \text{PAST})/\text{PAST}$. Figures 6, 7, and 8 show a similar percentage change in the distributions of S_v , DEF, and rNBE, respectively. First, we overview the characteristic morphology of the change in the projected patterns. For TI1 and S_v , the most prominent feature is a decrease of over 25 % in the midlatitude central to western North Pacific along with the anticyclonic (south) side of the present-day maximum (Figs. 5, 6). In contrast, the DEF and rNBE show a broad increase of 25–100 % in the eastern North Pacific, which is outside the present-day high-frequency band (Figs. 7, 8). Large relative increases are commonly seen for all CAT indices surrounding the present-day envelope of the CAT frequency maximum (e.g., subtropical, coastal, and continental regions). To allow a more practical evaluation of these large relative increases, which may be exaggerated by the relatively low frequency observed in the PAST experiment, the light (dark) gray shading in Figs. 5–8 indicates regions where the CAT frequency diagnosed by each index is less than 0.1 % (0.01 %) in the +2 K experiment, roughly corresponding to once every three (30) years.

There are several interesting features in the seasonality of the projected CAT change and its dependency on the SST change. The most striking Δ SST dependency can be found in DJF, when two or three of the six Δ SST ensembles, depending on the index, project

Fig. 2. Same as Fig. 1 but for JRA-55 data.

Fig. 3. Top row: climatological distribution of EKE at 200 hPa (EKE200) at synoptic scales (2–8 days) in the PAST experiment for DJF, MAM, JJA, and SON (from left to right), respectively. Second to seventh rows: future changes in EKE200 in +2 K ensembles forced by six different Δ SSTs (see Section 2). Contours show EKE200 in +2 K ensembles.

Fig. 4. Same as Fig. 3 but for 200 hPa horizontal wind speed.

Fig. 5. Top row: climatological distribution of CAT frequency at 200 hPa in the PAST experiment diagnosed by TII in DJF, MAM, JJA, and SON (from left to right), respectively. Second to seventh rows: future changes in +2 K ensembles forced by six different Δ SSTs (see Section 2), displayed as relative changes in percent: $100 \times (+2 \text{ K} - \text{PAST})/\text{PAST}$. The light- and dark-gray shading indicate regions where the CAT frequency in the 2 K ensembles is less than 0.1 % and 0.01 %, respectively. The black shading indicates grid boxes where no CAT is diagnosed throughout the analysis period (270 years) either in the PAST or in the +2 K experiment.

Fig. 6. Same as Fig. 5 but for S_v .

Fig. 7. Same as Fig. 5 but for DEF.

Fig. 8. Same as Fig. 5 but for rNBE.

a broad increase in the CAT frequency near the Aleutian Low. Another interesting feature in DJF is that S_v and DEF, whose future changes are not positively correlated in the other three seasons, both decrease near Japan and further downstream in the jet stream. Indeed, future changes in these two indices are not as strongly correlated with each other in individual Δ SST ensembles, whereas their product, TI1, shows a robust reduction among all Δ SSTs. This future decrease in the CAT frequency in TI1 near Japan is not consistent with the results of Storer et al. (2017), which showed increases in all four indices (i.e., TI1, S_v , DEF, and rNBE). In the eastern Pacific, DEF and rNBE show a similar increase in DJF to that shown by Storer et al. (2017), except that their DEF shows a wider extension. Because the present result shows a large inter- Δ SST variation in DJF, the differences between the two studies may also be related to differences in SST change patterns.

The inter- Δ SST variation of the projected change in the CAT frequency in MAM is smaller than that in DJF, but larger than that in JJA and SON. Three of the six ensemble members project a reduction of over 25 % for TI1 and S_v near Japan, and two of them project an increase in the frequency in the central North Pacific. An increase in TI1 of more than 25–50 % over Japan is projected only in JJA, whereas TI1 is projected to decrease (increase) in the northern (southern) part of Japan and further downstream in the jet stream in SON. Wider reductions (increases) are commonly seen in the six Δ SSTs for S_v (DEF and rNBE) in JJA and SON. Interestingly, despite the small inter- Δ SST variation for all CAT indices in these seasons, the future changes in the jet stream (represented by the 200 hPa wind speed $|V|$) and the activity of upper-level synoptic-scale disturbances (represented by the 200 hPa EKE with 2–8-day components) show a relatively large variation depending on Δ SST (Figs. 3, 4). The reason for this is unclear and is left for future studies. On the other hand, the inter- Δ SST variation of $|V|$ and EKE sometimes coincides with that of the CAT indices. For example, the largest changes in the CAT indices in DJF for one Δ SST ensemble (+2 K_MI) might be attributable to the largest poleward shift of the jet stream and associated enhancement of synoptic-scale disturbances over the North Pacific. A similar example is found in MAM for another Δ SST ensemble (+2 K_CC) that shows a unique large reduction in the activity of synoptic-scale disturbances, which leads to common reductions in all CAT indices. These examples demonstrate the possibilities and limitations in attributing CAT frequency

changes to changes in the climatological distribution of the jet stream and activity of upper-level synoptic-scale disturbances.

4. Summary and discussion

The climatological distribution and future changes of CAT over the North Pacific have been investigated using the PAST and +2 K ensembles in the d4PDF. The present-day climatology of the CAT distribution at 200 hPa and its seasonality derived from the PAST experiment in d4PDF agree with those for the JRA-55 data. The CAT frequency in the +2 K experiment decreases in the midlatitude central to western North Pacific along with the anticyclonic side of its present-day maximum, whereas it increases outside the present-day high-frequency band. This decrease is one of the key findings in the present study that has not been uncovered in previous studies based on different models and combinations of present and future scenarios, as well as the selection of CAT indices (Storer et al. 2017).

The uncertainty in the projected CAT changes due to the Δ SST patterns from six selected CMIP5 climate models has been addressed for the first time. The uncertainty is maximized in the boreal winter and spring over the central North Pacific and is associated with uncertainties in future changes in the jet stream and the activity of upper-level synoptic-scale disturbances. Meanwhile, the inter- Δ SST variation of CAT changes is minimized in SON, and a robust reduction of the CAT frequency is projected in the midlatitude central to western North Pacific.

The relative increase of the CAT frequency outside the present-day high-frequency envelope may also have implications for aircraft operations, because aircraft may experience CAT in different locations other than the ones at present. Two of the CAT indices, DEF and rNBE, show a remarkably broad increase over the eastern North Pacific, which may imply more frequent and spontaneous generation of small-scale gravity waves. The increase in the CAT frequency over the southern part of Japan and around the Bering Sea may also affect future aircraft operations. Future studies should investigate the model and scenario dependency of the findings in the present study. The High Resolution Model Intercomparison Project (HighResMIP) would provide the first opportunity to estimate these dependencies (Haarsma et al. 2016). The most serious limitation of the present study is the number of CAT indices considered, and these calculations should be repeated in future work using all 20 indices used in previous works (e.g. Williams 2017; Storer et al.

2017).

The present study focused on the climatological distribution of the CAT frequency and the projected changes for four seasons over the North Pacific. Using large ensembles of d4PDF, in future studies, it may become possible to investigate more localized changes (e.g., along flight routes) in the probability distributions of the CAT intensity (e.g., Williams 2017). Furthermore, it would be informative to investigate the interannual variability of CAT arising from natural climate variability and its future changes (e.g., Kim et al. 2016). The d4PDF also provides 20 km resolution ensemble projections over East Asia centered on Japan, which have been produced by downscaling the 60 km AGCM ensembles using a nonhydrostatic regional climate model, MRI-NHRCM20 (Sasaki et al. 2011; Murata et al. 2013). Using the high-resolution ensembles and further turbulent indices, we will be able to produce projections of aviation relevant turbulence including those generated by other mechanisms (e.g., mountain waves and convection) at multiple flight levels.

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