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PAPER

Impact of climate variabilities on trans-oceanic flight times and emissions during strong NAO and ENSO phases

Jung-Hoon Kim[1], Daehyun Kim[2], Dan-Bi Lee[3], Hye-Yeong Chun[3], Robert D Sharman[4], Paul D Williams[5] and Young-Joon Kim[6]

[1] School of Earth and Environmental Sciences, Seoul National University, Seoul, Republic of Korea
[2] Department of Atmospheric Sciences, University of Washington, Seattle, WA, United States of America
[3] Department of Atmospheric Sciences, Yonsei University, Seoul, Republic of Korea
[4] National Center for Atmospheric Research, Boulder, CO, United States of America
[5] Department of Meteorology, University of Reading, Reading, United Kingdom
[6] NOAA/NWS/Analyze, Forecast, and Support Office, Silver Spring, MD, United States of America

E-mail: jhkim99@snu.ac.kr

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Abstract

This study investigates the impact of the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) on trans-oceanic round-trip flight times and consequent CO_2 emissions over the north Atlantic and eastern Pacific regions. For three strongest winter periods of both polarity during 1979–2016, daily mean wind data are used to compute the wind-optimal flight trajectories at cruising altitudes. Results show that intensified upper-level jet streams during the +NAO winters provide stronger headwinds for westbound flights between the eastern US and the western Europe. This causes 4.24 ~ 9.35 min increase in an averaged total round-trip journey time during the +NAO compared to −NAO winters. In the eastern Pacific region, the jet stream is extended eastward towards the southwestern US during the +ENSO period, which lengthens the travel time for westbound flights between Hawaii and the west coast of the US. The increase in travel time of westbound flights is greater than the corresponding decrease in travel time for eastbound flights, resulting in a 5.92 ~ 8.73 min increase of the averaged total round-trip time during the +ENSO compared to the −ENSO periods. Extrapolating these results to overall trans-oceanic air traffic suggests that aircraft will take a total of 1908 ~ 4207 (888 ~ 1309) extra hours during the +NAO (+ENSO) than the −NAO (–ENSO) winters over the North Atlantic (Eastern Pacific) regions, requiring 6.9 ~ 15 (3.2 ~ 4.7) million US gallons of extra fuel burned at a cost of 21 ~ 45 (9.6 ~ 14) million US dollars and 66 ~ 144 (31 ~ 45) million kg of extra CO_2 emissions to all trans-oceanic traffic. In +ENSO and +NAO winters, the chances of a given flight having a slower round-trip flight time with more fuel burn and CO_2 emissions are 2–10 times higher than in a −ENSO or −NAO winter. These results have significant implications for the planning of long-term flight routes with climate variability.

1. Introduction

With recent improvements in observational techniques and advancements of physical parameterizations and dynamical cores in Numerical Weather Prediction (NWP) models, the performance skill in forecasting upper-level winds has been increasing steadily (e.g. Bauer *et al* 2015), providing benefits for the aviation industry in flight planning. For example, the average wind speed errors near the jet stream have decreased by about 45% from 13 m s^{-1} in 1984 to 8 m s^{-1} in 2004, providing less uncertainty in both head and tail winds for long-haul flights, thereby enhancing efficiency of flight route planning, and reducing fuel consumption (e.g. Petersen 2015). Further, due to an increase in demand for longer forecast lead time and better understanding of large-scale and low-frequency climate variabilities (e.g. Kim *et al* 2012, Scaife *et al* 2014, Dunstone *et al* 2016), long-range weather outlooks (seasonal to subseasonal; S2S forecasts) have become more important. However, there are only a few studies that show the linkage between low-frequency climate variabilities and their impacts on aviation operations.

Because of this, it is important to consider seasonal and inter-annual fluctuations in mid-latitude jet stream intensity and position, which are highly modulated by large-scale climate variabilities such as the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) (Wallace and Gutzler 1981, Barnston and Livezey 1987). The NAO in its simplest definition is a fluctuation index in terms of the difference of Sea-Level Pressure (SLP) between the quasi-stationary Icelandic Low (northern side) and the Azores High (southern side) over the North Atlantic Ocean. Larger (smaller) difference in the SLP provides stronger (weaker) jet streams shifted northward (southward), which is calculated as a positive (negative) NAO index (e.g. Wallace and Gutzler 1981). The ENSO is the interaction between the atmosphere and ocean in the tropical Pacific region, which influences the position of deep convection that produces different characteristics of subtropical jet streams. In the positive ENSO phase, the subtropical jet stream is sometimes elongated to the eastern Pacific region in the northern hemisphere (e.g. Barnston and Livezey 1987). While changes in the jet stream associated with the NAO and ENSO have been extensively studied, their effects on flight routes and journey times have received limited attention. Recently, it has been recognized that such large-scale climate variability could have important implications for air travel. For example, Karnauskas *et al* (2015) found that historical round-trip flight times of commercial airliners between the west coast of the US and Hawaii are highly correlated with the strengthening of the Pacific jet, which is mainly driven by the ENSO and Arctic Oscillation (AO). Regarding climate change, Irvine *et al* (2016) and Williams (2016) showed that the North Atlantic upper-level jet is strengthened and shifted northward under future climate scenarios, causing more fuel to be burned and greenhouse gases to be emitted due to the longer round-trip journey time between US and UK. Kim *et al* (2016a) demonstrated that the change of the daily trans-Atlantic flight routes and their potential for encountering clear-air turbulence (CAT) depend on the characteristics of the upper-level jet streams in different NAO phases.

This study builds upon the earlier work of Kim *et al* (2016a) and expands it by testing the robustness of the relationship between the NAO and flight routes for multiple cruising altitudes, and also by examining the effect of another large-scale variability, ENSO. We will demonstrate how different types of the large-scale weather and climate variabilities can affect long-haul trans-oceanic flight routes, journey time, and their greenhouse gas emissions. We focus on the changes in the characteristics of the midlatitude upper-level jet streams over the north Atlantic and the subtropical jet stream over the eastern Pacific, which drive the daily trans-oceanic flight routes and their overall round-trip journey time. Data and methodology used in this study will be introduced in section 2. Results from the experiments will be discussed in section 3, and a summary and conclusions will be followed in section 4.

2. Data and methodology

To understand the effects of the NAO and ENSO on the position and intensity of the upper-level jet stream, we first identify three winter periods that have the highest values of both positive and negative NAO and ENSO indices during 1979–2016. Using the monthly averaged daily values of the standard NAO index data (https://crudata.uea.acuk/cru/data/nao/; Jones *et al* 1997), the +NAO winter periods selected are DJF88-89 (December 1988—February 1989; +3.0), DJF94-95 (+2.9), and DJF15-16 (+2.33), while the −NAO periods are DJF09-10 (–3.34), DJF95-96 (–2.24), and DJF10-11 (–1.07). For the ENSO, daily averaged Sea Surface Temperature anomalies over the tropical Pacific region (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/; Rayner *et al* 2003) are used. The +ENSO periods selected are DJF15-16 (+2.41), DJF82-83 (+2.33), and DJF97-98 (+2.27), and the −ENSO are DJF88-89 (−1.77), DJF07-08 (−1.7), and DJF99-00 (−1.62).

To understand the changes in the daily upper-level jet stream associated with the NAO and ENSO, we then calculate the averaged anomalies for horizontal wind speed at typical cruising altitudes (e.g. 250 hPa) during the selected NAO and ENSO winter periods with 95% significant confidence level (stipples) in Figure 1. Here, anomalies are calculated using daily mean wind data for 28 years (1979–2016) from the European Centre for Medium-Range Weather Forecasts' Re-Analysis Interim (ERA-Interim; Dee *et al* 2011) data on a 1.5 × 1.5 degree global domain. Seasonal mean state of atmospheric circulations such as NAO and ENSO anomalies are somewhat predictable on a timescale of months in advance (Kim *et al* 2012, Scaife *et al* 2014, Dunstone *et al* 2016). These changes in the seasonal mean state accompany systematic changes in daily winds, hence, the daily round-trip flight routes and times. This justifies that seasonal mean indices of NAO and ENSO are a good target for this study.

For the NAO case shown in Figures 1(a) and (b), the midlatitude upper-level jet streams are highly

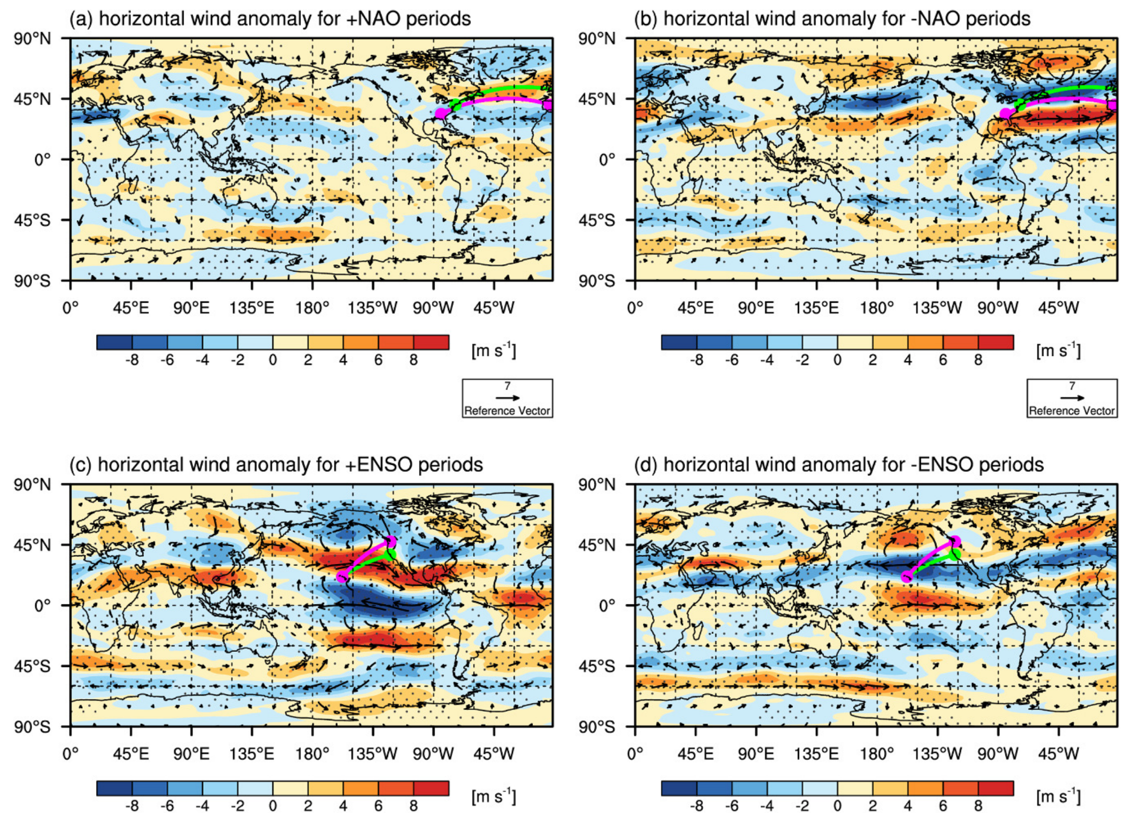

Figure 1. Anomalies of horizontal wind speed (SPD; color shading) and wind vectors (a reference vector is 7 m s^{-1}) at the 250 hPa level for (a) +NAO, (b) −NAO, (c) +ENSO, and (d) −ENSO winter periods using the daily mean wind data during 1979 ∼ 2016. Great circle planes between JFK (ATL) and LHR (MAD) are depicted as green (pink) lines in (a) and (b) over the North Atlantic region, while those between HNL and SFO (SEA) are depicted as green (pink) lines in (c) and (d) over the eastern Pacific region. Significant anomalies (two-tailed t-test with p-value < 0.05) are depicted by stippling.

sensitive to the NAO polarity in the north Atlantic region with strong positive and negative wind anomalies. Note that the areas of strong anomaly are collocated with the Great Circle plane (GC; green solid line in Figures 1(a) and (b)) between New York (John F. Kennedy airport; JFK) and London (Heathrow airport; LHR). For the ENSO case in Figures 1(c) and (d), strong positive and negative anomalies are dominant in wide areas over the eastern Pacific region, which affect flight routes between Hawaii (Honolulu airport; HNL) and the west coast of US (e.g. San Francisco airport; SFO) shown as green solid lines in Figures 1(c) and (d). This implies that the round-trip flight times along those jet routes are strongly influenced by these variant upper-level winds during the NAO and ENSO winter periods.

Karnauskas *et al* (2015) clearly showed that there is a close relationship between the measured round-trip flight time and climate variability between Hawaii and the west coast of US. But a historical record of actual flight time data can include other factors such as systematic changes in traffic, aircraft, and policy in addition to day-to-day weather conditions. To isolate the impact of climate variability (wind variation) on the long-haul flight time, we employed a simplified 2-D (horizontal) flight trajectory model for cruising mode (e.g. Williams 2016; Kim *et al* 2016b, Irvine *et al* 2013, 2016) because they are normally long-haul flights that they spend most of their flight times at their cruising altitudes. We calculated two different types of flight trajectories [the Great Circle Route (GCR) and Wind-Optimal Route (WOR)] at three levels [300, 250, and 200-hPa levels ($\sim z = 9 \sim 11$ km or 30 000 ∼ 35 000 ft)] using the daily mean wind data from the ERA-Interim reanalysis data. This will be a bottom line for strategic flight planning only focus on the relationship between the large-scale climate variability and flight time (hence fuel consumption and CO_2 emissions), which will be extended to consider more factors such as other emissions (SO_x, NO_x, water vapor, and contrails; Grewe *et al* 2017) as well as air capacity/traffic density for more realistic and climate optimal aviation operations.

For the selected NAO and ENSO winter periods, the GCR and WOR daily flight trajectories are computed separately accounting for the winds in spherical earth geometry by integrating the time evolution ($\Delta t = 1$ min) of the heading angle (HA) of the aircraft from departure to destination. The HA of the GCR changes at each time step depending on the location of the aircraft as it is displaced by wind variations. The HA of the WOR at each time step is determined by an analytic cost function that minimizes total flight time between city pairs (e.g. Sridhar *et al* 2011a; Kim *et al* 2015, Williams 2016). Then, the shooting method for the integration of the candidate trajectories with various initial HAs finally gives an optimal WOR from a departure to a destination for a given daily wind condition, which is called the minimum-time route. Detailed information about this method can be found in previous studies (Kim *et al* 2015, 2016a, 2016b, Williams 2016). For the selected NAO winter periods, we have total of 810 trajectories (90 d × 3 layers × 3 years) separately for the GCR and WOR between the JFK and LHR. The same number of trajectories are also obtained for the ENSO case between the HNL and SFO in the eastern Pacific region. In this way, we consider two possible scenarios (either the GCR with winds or WOR) of day-to-day flight planning, which provides more realistic ranges of possible round-trip flight times between the city pairs (e.g. Ng *et al* 2012).

Figure 2 shows the example envelope of daily GCR and WOR trajectories at 250 hPa for +NAO and ENSO winter periods between two city pairs (JFK and LHR, and HNL and SFO). There are three interesting features here. First, the GCRs (blues and greens) are slightly off the GC plane (black line). At every point on the GCR trajectory, the heading angle is chosen such that the aircraft is pointing directly towards the arrival airport. If the winds were zero, this approach would take the aircraft along the GC plane between the two airports, but the winds blow it off the course such that GCRs with winds are not the same as GC plane. Second, HA of the WORs is actively changed at each time step, so that their overall envelopes of the WORs are wider and broader compared to the GCRs. Third, when we compare the eastbound (EB; top) and westbound (WB; bottom) WORs, the overall envelope of the WB WORs is wider than that of the EB WORs because they try to avoid the strong headwinds of the jet stream, which lengthens the WB WORs significantly although they are faster than the WB GCRs. This is consistent with previous studies (e.g. Irvine *et al* 2013, 2016, Williams 2016, Kim *et al* 2016a, 2016b).

3. Results

Figure 3 shows the same anomalies as in Figure 1, but zoomed in over the north Atlantic region (top) and the eastern Pacific region (bottom). It is found that the upper-level jet stream between the Icelandic Low and the Azores High is strengthened, causing strong positive anomaly wind (the maximum of +6 m s^{-1} in this region) between the eastern US [New York (JFK) and Atlanta (ATL)] and western Europe [London (LHR) and Madrid (MAD)] during the +NAO winter phase (Figure 3(a)). During the −NAO period, on contrary, the jet stream is moved southward (35 ∼ 40 N latitude band), providing strong negatively anomalous winds (the minimum of −10 m s^{-1}) in the north Atlantic region (Figure 3(b)). For the selected ENSO periods, the Pacific jet is elongated eastward toward the southwestern US during the +ENSO phase, which gives strong positive anomalous winds (up to +14 m s^{-1}) between HNL and SFO (Figure 3(c)). On the other hand, during the −ENSO period negatively anomalous winds (up to −12 m s^{-1}) are dominant in this area (Figure 3(d)). These characteristics of the upper-level jet related to NAO and ENSO are consistent with the results of previous studies (e.g. Woollings *et al* 2010; Irvine *et al* 2013, Karnauskas *et al* 2015).

The position and intensity of the upper-level jet stream anomalies shown in Figure 3 are very important for trans-oceanic flights. In general, the EB flights take advantage of the strong tailwinds to arrive at the destination earlier, reducing fuel consumption. Although the WB WORs try to avoid the jet stream areas to mitigate the strong headwinds (Figure 2), they still face wide areas of strong headwinds (Figure 3) that produce delays of the round-trip flight times, which could be increased even more during the +NAO and +ENSO periods (e.g. Irvine *et al* 2013, 2016, Williams 2016, Kim *et al* 2016a, 2016b). To understand the dependence of tailwinds and headwinds on the upper-level jet stream patterns, histograms of the zonal wind at cruising altitudes (200, 250, and 300 hPa levels) between North America and the western Europe over the north Atlantic region (40–60° N and 30–50° W) and between Hawaii and the west coast of US over the eastern Pacific region (25–35° N and 130–150° W) are calculated for the selected positive and negative NAO and ENSO winter periods separately (Figure 4). The averaged zonal wind the North Atlantic region in Figure 4 is significantly increased from 16.36 m s^{-1} in −NAO to 30.4 m s^{-1} in +NAO (p-value ∼ 10^{-12}; n = 158 760). The averaged zonal wind in the eastern Pacific region in Figure 4 is also significantly increased from 14.65 m s^{-1} in −ENSO to 37.7 m s^{-1} in +ENSO (p-value ∼ 10^{-30}; n = 79 380). This confirms that these distributions are significantly different. Figure 4 clearly shows that the +NAO and +ENSO phases provide significantly enhanced headwinds for the WB flights, and consequently longer journey times with more fuel burned and enhanced emissions in +NAO and +ENSO periods than in −NAO and −ENSO periods in the north Atlantic and eastern Pacific regions, respectively.

Finally, we calculate the minimum, maximum, and average total flight times of the EB and WB trans-oceanic GCRs and WORs at three levels for the selected strong NAO and ENSO winter periods (Figure 5). There are several important findings: (1) As expected, the mean flight time for the EB flights is shorter

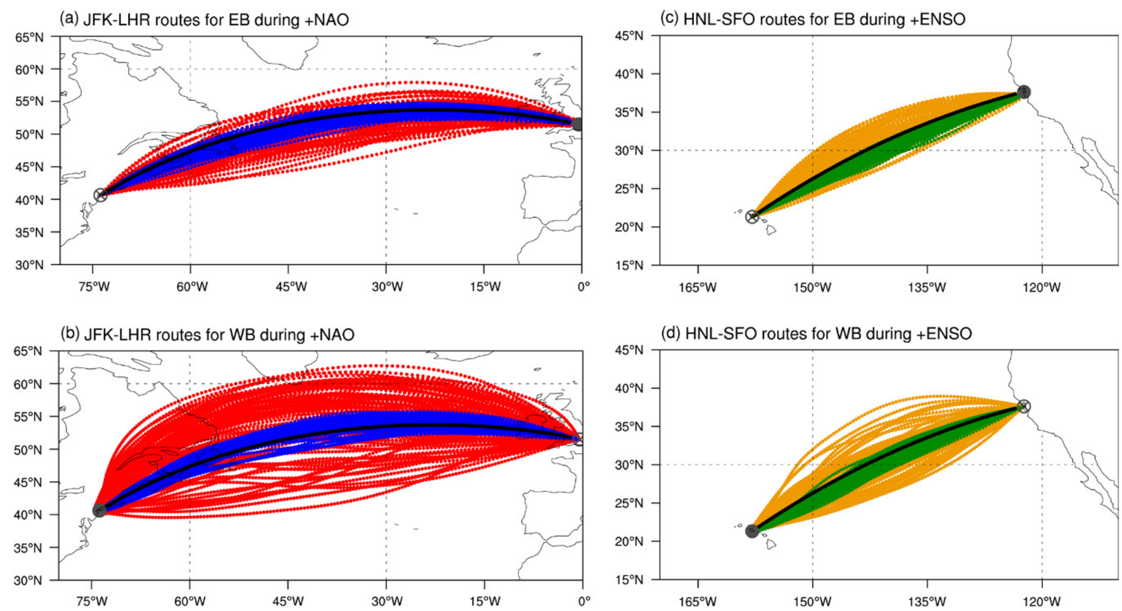

Figure 2. Daily Great Circle Routes (GCRs) (blues and greens) and Wind-Optimal Routes (WORs) (reds and yellows) for eastbound (top) and westbound (bottom) at 250 hPa between JFK and LHR (left) during the +NAO wintertime (DJF88-89) and between HNL and SFO during the +ENSO wintertime (DJF15-16), derived using the ERA-Interim data. Black thick lines denote the great circle plane (GC) between the two city pairs.

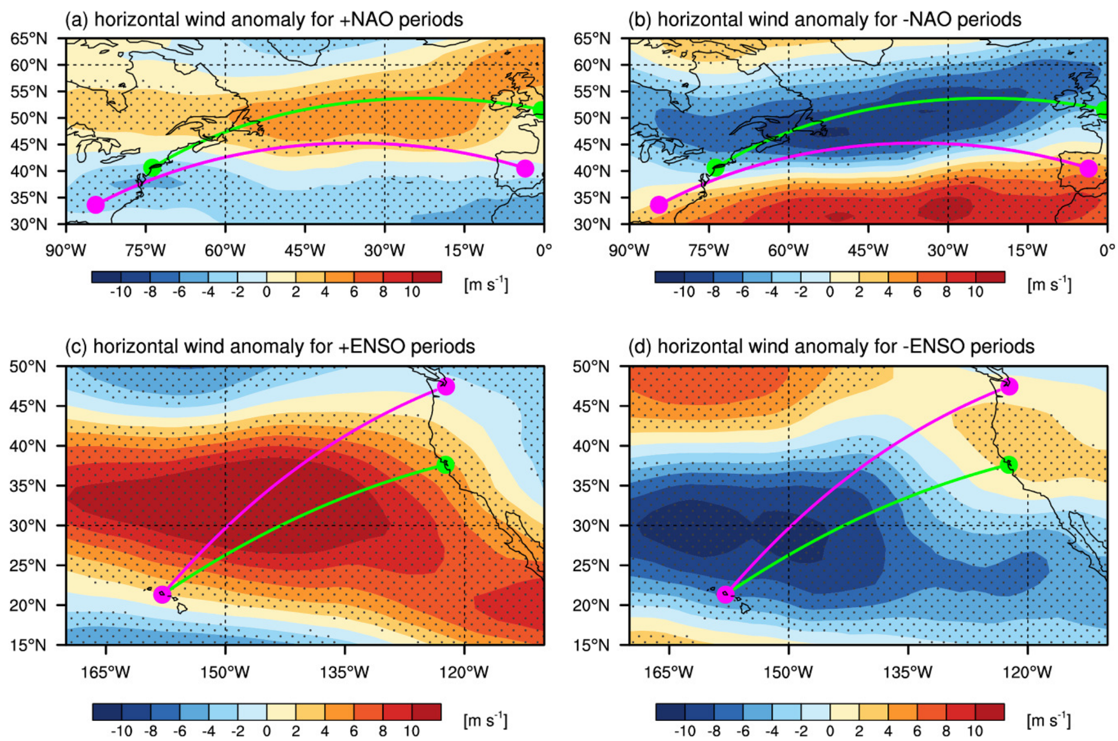

Figure 3. The same as Figure 1 except zoomed in to the north Atlantic Ocean for the NAO case (top) and in the eastern Pacific Ocean for the ENSO case (bottom) with the Great Circle planes (GCs; green lines) between the JFK and LHR (top) and between the HNL and SFO (bottom). The GCs between ATL and MAD (top) and between HNL and SEA (bottom) are also depicted as pink lines. Significant anomalies (two-tailed t-test with p-value < 0.05) are depicted by stippling.

than that for the WB flights in all cases because the EB flights take advantage of the prevailing westerly winds in the northern hemisphere, while the WB flights are slowed by the dominant headwinds. (2) For the EB (WB) flights, the flight time is shorter (longer) in the +NAO and +ENSO than in the −NAO and −ENSO phases because the tailwinds (headwinds) are stronger in the +NAO and +ENSO periods. Therefore, the gap between the EB and WB flight times is larger in the +NAO and +ENSO phases than those in the −NAO and −ENSO phases. We also conducted statistical tests to ensure that the calculations

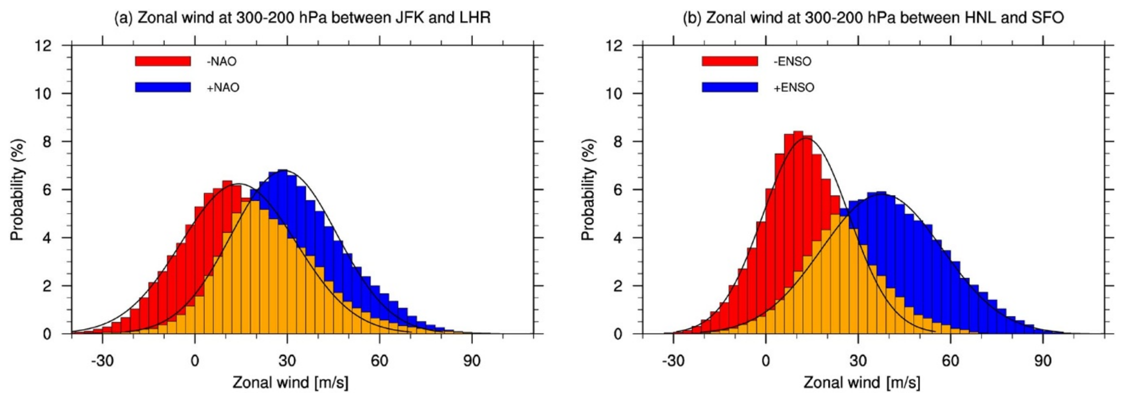

Figure 4. Histograms of zonal wind (m s^{-1}; positive is westerly, and negative is easterly) at 200–300 hPa (cruising altitudes) within (left) 40–60° N and 30–50° W between JFK and LHR during the selected NAO winter periods, and (right) 25–35° N and 130–150° W between HNL and SFO during the selected ENSO periods. The bin interval is 3 m s^{-1}, and blue and red bars are for + and − phases, respectively, and orange bars are overlapped bins for both phases.

of the flight times in Figure 5 are significantly different between + and − phases of the NAO and ENSO winter periods. All of the statistical tests reject the null hypothesis (i.e. all of the tests have p-values lower than 0.05), implying that the differences in flight times during the + and − phases are statistically significant. For example, at 200 hPa the mean EB GCR (323.45 min) between JFK and LHR in the +NAO is significantly shortened by 17.75 min with a 95% confidence interval ranging 16.51 and 19.0 min from its −NAO value (341.20 min). And, the mean WB GCR (418.36 min) is significantly lengthened by 26.31 min with a 95% confidence interval ranging 24.15 and 28.46 min from its −NAO value (392.05 min). We have tabulated the statistical information in Tables S1 and S2. 3 (available online at stacks.iop.org/ERL/15/105017/mmedia) The delay of WB flights is more significant in the +NAO and +ENSO winter periods than the negative ones, which eventually ended up increasing the averaged round-trip flight time in both north Atlantic and eastern Pacific regions, which will be shown in histograms of total round-trip flight times in Figures 6 and 7. Note that there is no significant difference for different cruising altitudes.

When we calculate the daily total round-trip flight journey time, the decreased times of the EB flights and increased times of WB flights do not simply cancel out, but rather lead to an overall increase in the total round-trip journey time (e.g. Williams 2016) during the +NAO and +ENSO periods. Figure 6 shows histograms of daily total round-trip flight times for the GCRs and WORs between two city pairs (JFK–LHR and ATL–MAD shown, respectively, in Figures 3(a) and (b)) during the selected ±NAO winter periods. In general, stronger headwinds in the northern Atlantic region delay the WB flights significantly during +NAO winter periods, which results in a greater round-trip journey time (right shifted blue bars) in the +NAO compared to the −NAO winter periods (left shifted red bars). This separation is more significant in the routes between JFK and LHR than those between ATL and MAD, because the route between JFK and LHR spends more time across strong positive anomalies of upper-level winds (i.e. headwinds for the WB) shown in Figure 3(a).

Consequently, as shown in Figure 6(a) the mean round-trip flight time for the GCR between JFK and LHR in the +NAO (741.42 min) is significantly lengthened by 7.87 min with a 95% confidence interval ranging from 6.69 to 9.05 min from its −NAO value (733.55 min). If an aircraft actively changes its HA to minimize total flight time (Figure 6(b)), the averaged total round-trip flight time of the WOR is reduced to 731.28 min in the +NAO winter period, but it is still significantly lengthened by 5.09 min with a 95% confidence interval ranging from 3.85 to 6.34 min from its −NAO value (726.19 min). For the route between ATL and MAD, in Figure 6(c) the GCR also takes 4.24 min longer in the +NAO than the −NAO with a 95% confidence interval ranging from 2.97 to 5.52 min, which is also seen in the WOR case (9.35 min longer in the +NAO than in the −NAO with a 95% confidence interval ranging from 7.5 to 11.2 min) (Figure 6(d)). These results are summarized in Table S3.

Similar features are found in the eastern Pacific region as shown in Figure 7. In this area, the stronger wind anomalies are dominant over most flight routes between Hawaii and the west coast of the US (see Figures 3(c) and (d)), so that the climate variability affects the delay of WB flights more significantly. The GCR (WOR) between HNL and SEA takes 6.7 (5.92) min longer in the +ENSO of 576.84 (569.98) min than in the −ENSO of 570.14 (564.06) min with a 95% confidence interval ranging 5.82 and 7.58 (4.81 and 7.03) min in Figures 7(a) and (b). The GCR (WOR) between HNL and SFO takes 8.73 (6.51) min longer in the +ENSO of 517.01 min (510.29 min)

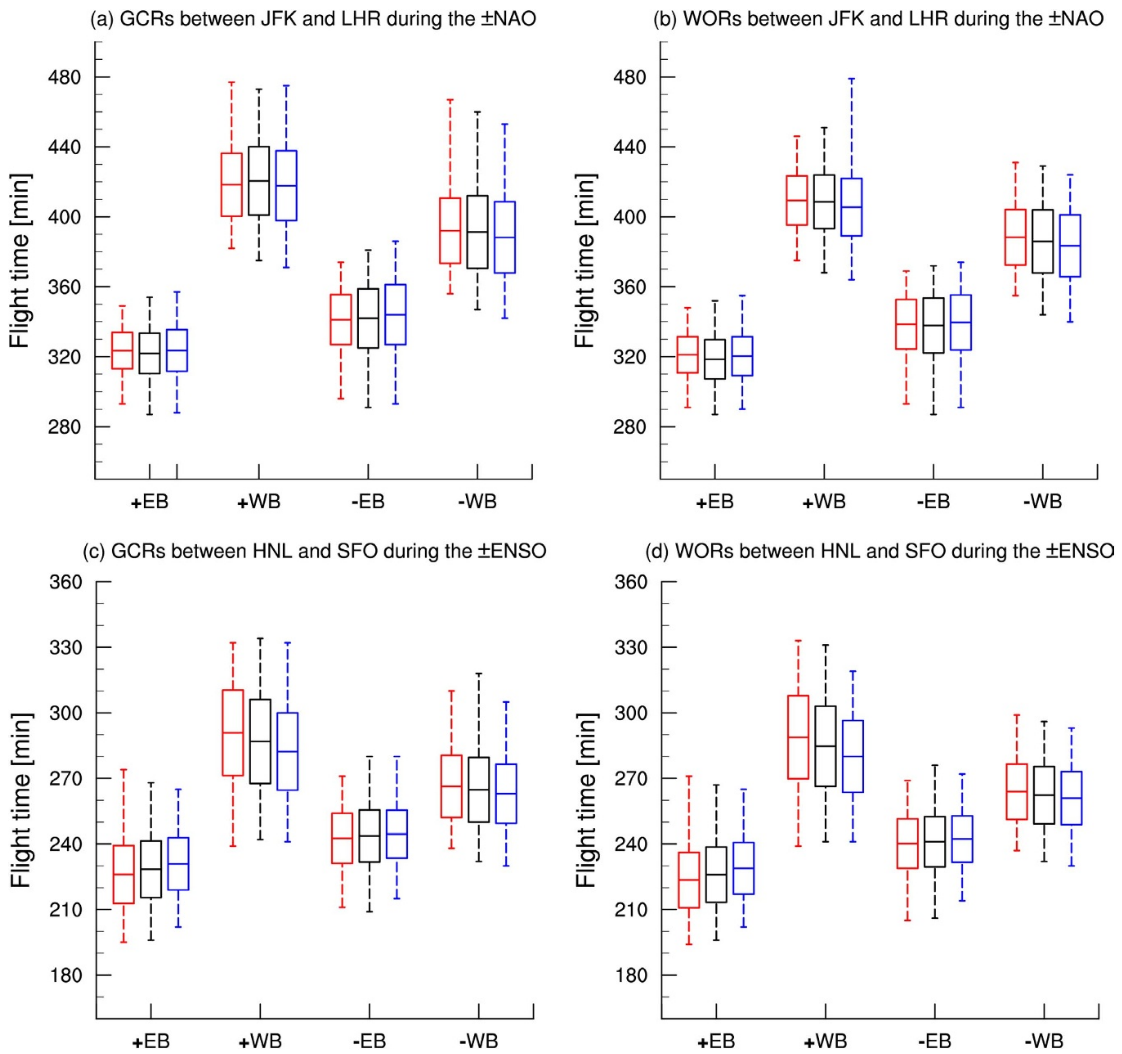

Figure 5. Box plots of the minimum, maximum, mean, and mean ± standard deviations of the daily flight times along the GCRs (left panels) and WORs (right panels) for eastbound (EB) and westbound (WB) flights at the 200 (red), 250 (black), and 300 (blue) hPa levels between JFK and LHR (top panels) during the ±NAO winter periods, and between HNL and SFO (bottom panels) during the ±ENSO winter periods.

than in the −ENSO of 508.28 (503.78) min with a 95% confidence interval ranging 7.62 and 9.83 (5.33 and 7.7) min in Figures 7(c) and (d). Results are summarized in Table S4. This confirms that over the eastern Pacific region the climate variability can provide significant impact on long-term flight route planning, which is also consistent with a previous study (Karnauskas *et al* 2015).

As in previous studies, we extrapolate these results to overall air traffic in the Atlantic region and in the Pacific region. Assuming 300 round trips each day in the north Atlantic traffic region (e.g. Irvine *et al* 2013, Williams 2016) and 100 round trips each day in the eastern Pacific traffic region [Here, 100 comes from the annual (2018) total number of scheduled and delayed direct flights for the top three city pairs between three Hawaiian Islands (HNL in Oahu, Kahului airport in Maui, and Kona airport on the Island of Hawaii), and the west coast of the US (SEA, SFO, and LA) from http://www.transtats.bts.gov], our results suggest that aircraft spend an extra 1908 ∼ 4207 h in the +NAO winter season than −NAO in the Atlantic region and an extra 888 ∼ 1309 h in the +ENSO winter season than the −ENSO in the eastern Pacific region. Using a fuel burn rate of 1 US gal s^{-1}, an average jet-fuel cost of 3 US dollar gal^{-1}, and CO_2 emissions of 9.6 kg gal^{-1} (e.g. Boeing 2010, Karnauskas *et al* 2015; Williams 2016, ICCT 2017, ICAO 2018), airliners will consume about 6.9 ∼ 15 million gallons of extra fuel, spend an extra 21 ∼ 45 million US dollars for fuel, and emit about 66 ∼ 144 million kg of extra CO_2 in the +NAO wintertime than those in the −NAO winter season in the north Atlantic region. In the Pacific region, about 3.2 ∼ 4.7 million gallons more fuel is consumed, corresponding to an extra 9.6 ∼ 14 million US dollars, and 31 ∼ 45 million kg of CO_2 emissions in the +ENSO wintertime than in the −ENSO winter period. Note that the extra costs for fuel are obviously dependent on the price of the jet-fuel

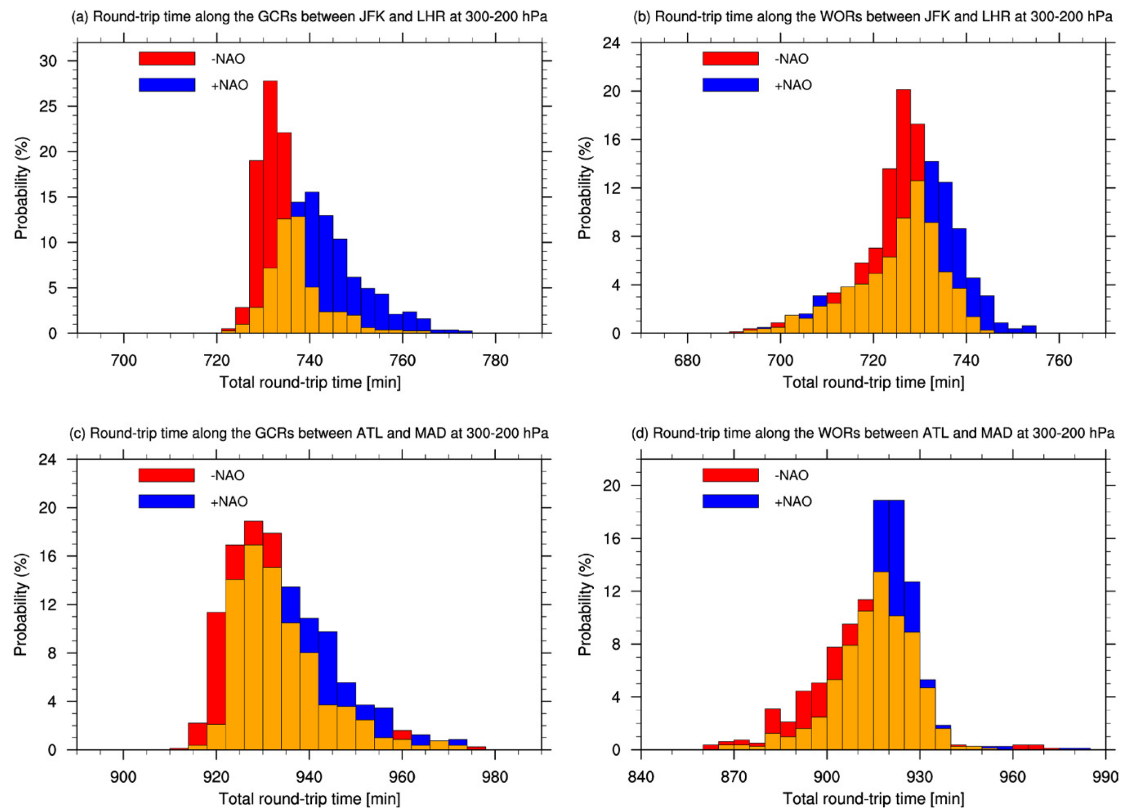

Figure 6. Histograms for the total round-trip flight journey time (minutes) along the (a) and (c) GCRs and (b) and (d) WORs (a and b) between JFK and LHR, and (c) and (d) between ATL and MAD at 300–200 hPa levels during the selected ±NAO periods. Blue and red bars are for + and − phases, respectively, and orange bars are overlapped bins for both phases.

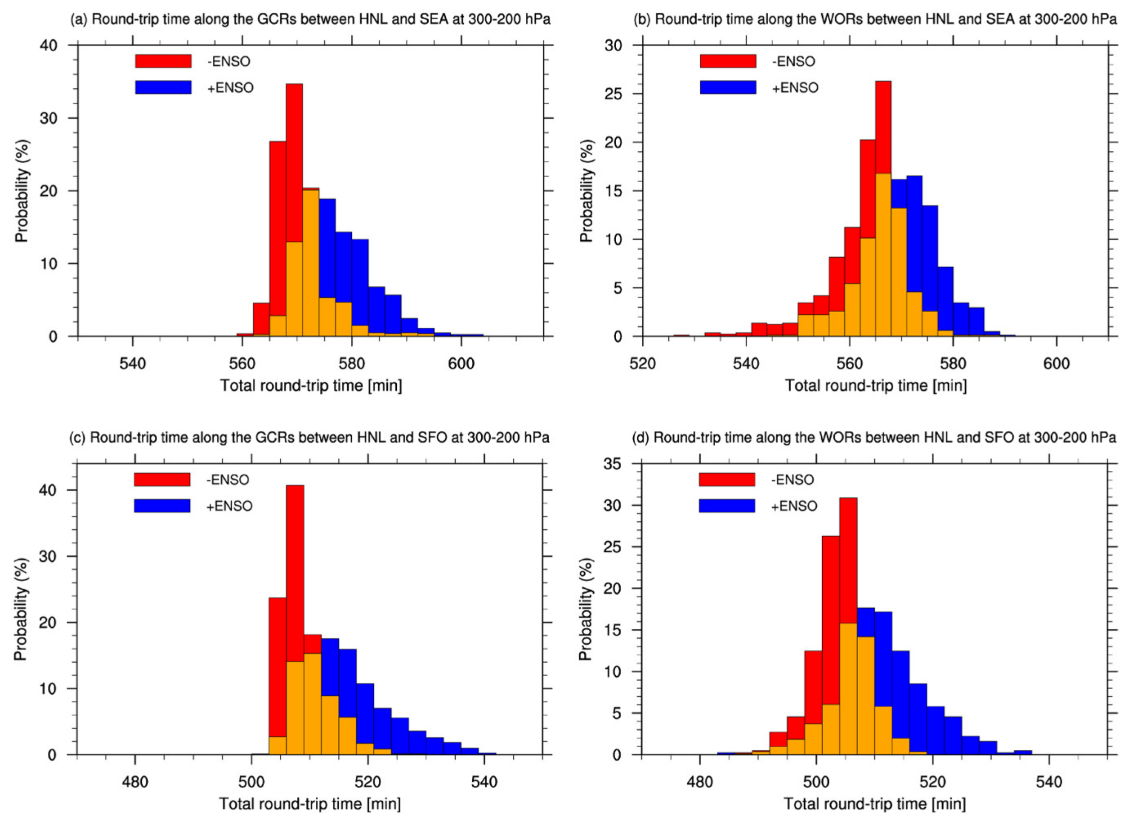

Figure 7. The same as Figure 6 except for (a) and (b) between HNL and SEA (c) and (d) between HNL and SFO during the selected ±ENSO winter periods.

(https://www.iata.org/en/publications/economics/fuel-monitor/). These 3.2 ∼ 14 million gallons of extra fuel in the +NAO and +ENSO winter times are about 0.1% of total annual fuel consumption [10 252 million gallons in 2018 (http://web.mit.edu/airlinedata/www/Expenses&Related.html) by 7 major airliners in US].

For a relative comparison, we look at the tail of the probabilities (shown in Figures 6 and 7) of the flight times that is directly (linearly) related to the fuel burn. As a result, relative percentage of total round-trip flight times for the GCR (WOR) between JFK and LHR longer than 745 (737) min is only 5% in the −NAO, which increases significantly to 30% (26.6%) in the +NAO, implying that they have about 6 times more chances having a slower round-trip journey time with extra fuel, costs, and emissions in the +NAO winter than the −NAO (Figures 6(a) and (b)). This is similar for the route between ATL and MAD where the round-trip flight times exceeding 949 (932) min for the GCR (WOR) nearly doubled from 5% (5%) to 12.9% (8.6%) (Figures 6(c) and (d)). In the Eastern Pacific region, it is more significant that the round-trip flight times longer than 578 (572) min for the GCR (WOR) between HNL and SEA during the −ENSO winter are dramatically increased from 5% (5%) to 41.4% (42.1%) in the +ENSO winter. The route between HNL and SFO is the worst in this study that the round-trip journey times for the GCR (WOR) taking over 515 (510) min significantly increase from 5% (5%) to 55.7% (52.3%), implying that +ENSO winter has about 10 times more chances to have extremely slowed flight (8.73 min increase in average round-trip flight time) with subsequent fuel, costs, and emissions than −ENSO winter (Figures 7(c) and (d)). In +ENSO and +NAO winters, the chances of a given flight having a slower round-trip flight time with more fuel burn and CO_2 emissions are 2–10 times higher than in a −ENSO or −NAO winter. This study demonstrates how interannual climate variability can be translated into information that is useful for routing decision-making procedures. These results also provide further evidence that large-scale weather patterns have aviation impacts, which feeds back to the environment to create a two-way interaction between climate and aviation (e.g. Irvine *et al* 2013, Williams and Joshi 2013, Karnauskas *et al* 2015, Williams 2017, Storer *et al* 2017).

4. Summary and conclusions

As an extension of the previous study by Kim *et al* (2016a), we investigated the impacts of large-scale climate variabilities (viz. the NAO and ENSO) on long-haul trans-oceanic flight routes and their total round-trip journey time in the eastern Pacific (Hawaii-San Francisco) and the north Atlantic (New York-London) regions. We selected three winter periods of the strongest positive and negative NAO and ENSO phases based on the indices of the NAO and ENSO during 1979–2016. We used daily mean wind fields from the ERA-Interim data to obtain the GCRs and WORs at cruising altitudes during the winter months of strong NAO and ENSO events. From the global map of averaged anomalies for upper-level winds during the NAO and ENSO winter periods, we found strong variabilities in upper-level winds in the north Atlantic and eastern Pacific regions, which could significantly affect the characteristic of the flights there. We examined the characteristics of the upper-level jet stream and trans-oceanic flight routes between the strong positive and negative NAO (ENSO) events in the north Atlantic (eastern Pacific).

Our results confirm that, in the north Atlantic corridor, the strengthened upper-level jet stream between the Icelandic Low and Azores High in the +NAO winters creates stronger headwinds for the WB flights between Western Europe and North America. This causes a systematic increase in the averaged round-trip journey time between the two city pairs by 4.24 ∼ 9.35 min for the +NAO phase when compared to the −NAO winters. In the eastern Pacific region, the eastward extension of the enhanced subtropical Pacific jet also provides a similar condition of stronger headwinds for the WB flights between Hawaii and west coast of the US, which increases +ENSO round trip times by 5.92 ∼ 8.73 min, compared to the −ENSO winters. These increases in the round-trip flight time are statistically significant and have a huge impact when the overall traffic is considered in both regions. Finally, these results extrapolated to overall trans-oceanic air traffic suggest that a significant amount of extra time would be required for round-trip flights during the strong +NAO (+ENSO) winters than strong −NAO (–ENSO) winters in North Atlantic (Eastern Pacific) regions. This subsequently leads to significant amounts of extra fuel burned, with increased costs and greenhouse gas emissions for all trans-oceanic traffic. This also shows that they have about 2 ∼ 10 times more chances to have extremely slowed flight (5.92 ∼ 8.73 min increase in average round-trip flight time) with extra fuel, costs, and CO_2 emissions in the +NAO/ENSO than −NAO/ENSO winter periods.

This study strongly suggests that changes in the seasonal mean state of large-scale climate variabilities (NAO and ENSO) are accompanied by changes in daily wind, hence, flight times and emissions. These anomalies of NAO and ENSO are predictable with a few to several months of forecast lead time (seasonal-to-subseasonal; S2S), which can be useful for decision-making because airlines estimate fuel requirements and delayed arrivals several weeks/months in advance to aid in planning. Future studies could be further refined and improved by taking into account subseasonal and intraseasonal (order of 10 d) variabilities on a zonal extension/retraction of the Pacific jet (e.g. Otkin and Martin 2004, Athanasiadis *et al* 2010, Jaffe *et al* 2011, Griffin and Martin 2017). Furthermore, because of significant improvements in representing major climate modes and variabilities in state-of-the-art climate models during the past decades, the latest operational climate models now show skill at predicting such major climate modes up to 6–9 months in advance (e.g. Kim *et al* 2012, Scaife *et al* 2014, Dunstone *et al* 2016). The aviation industry would be able to take advantage of these factors to create probabilistic forecasts of S2S changes in flight time, fuel consumption, and greenhouse gas emissions, which will be a useful tool for future versions of aviation decision support tools. It will be also interesting to see how other emissions like NO_x, O_3, water vapor, and contrails change along the flight routes depending on the climate variabilities like the NAO and ENSO, which will be useful for climate optimal route planning (e.g. Mannstein *et al* 2005, Sridhar *et al* 2010; 2011b, Schumann *et al* 2011, Grewe *et al* 2014a, 2014b).

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Jung-Hoon Kim
https://orcid.org/0000-0002-5336-9536
Hye-Yeong Chun
https://orcid.org/0000-0002-2014-4728
Paul D Williams
https://orcid.org/0000-0002-9713-9820

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