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Supplement of

Air traffic simulation in chemistry-climate model EMAC 2.41: AirTraf 1.0

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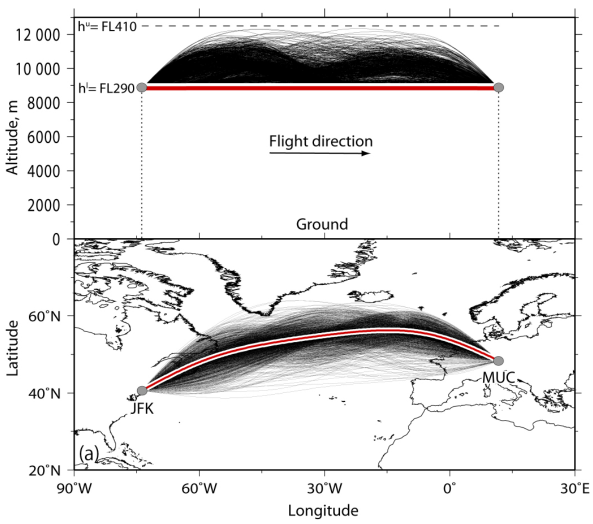

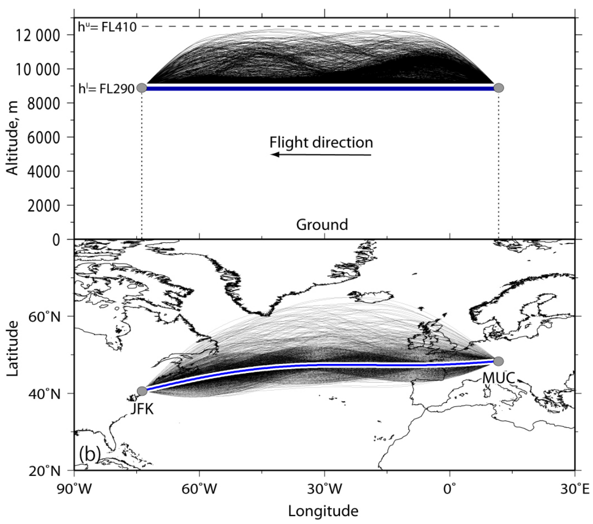

Figure S1. Ten-thousand explored trajectories (black lines) between JFK and MUC in the vertical cross section (top) and projection on the Earth (bottom), including the time-optimal flight trajectories (red and blue lines). **(a)** The eastbound flight from JFK to MUC. **(b)** The westbound flight from MUC to JFK.

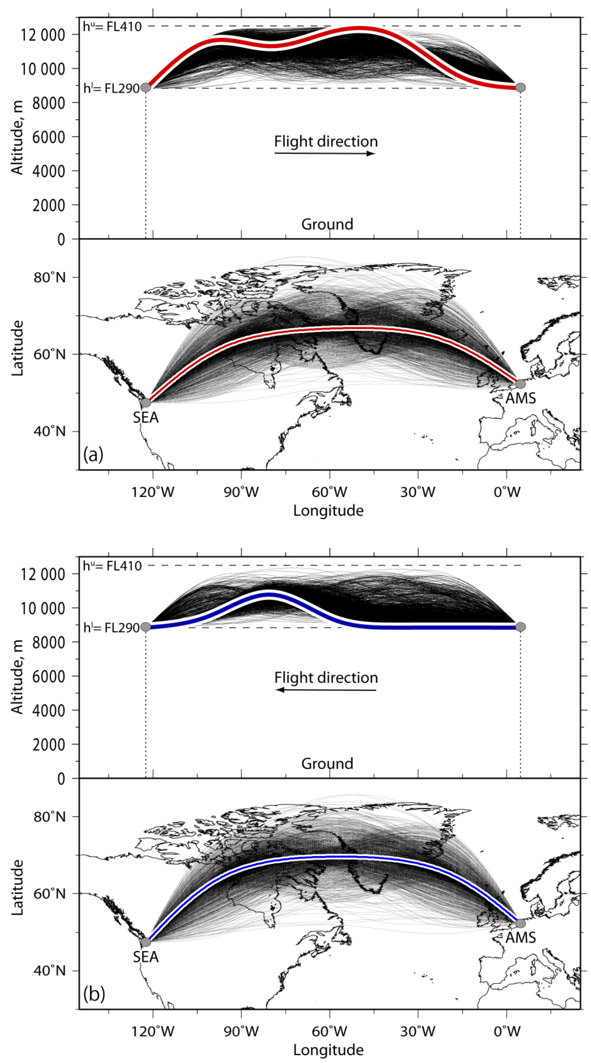

Figure S2. Ten-thousand explored trajectories (black lines) between SEA and AMS in the vertical cross section (top) and projection on the Earth (bottom), including the time-optimal flight trajectories (red and blue lines). **(a)** The eastbound flight from SEA to AMS. **(b)** The westbound flight from AMS to SEA.

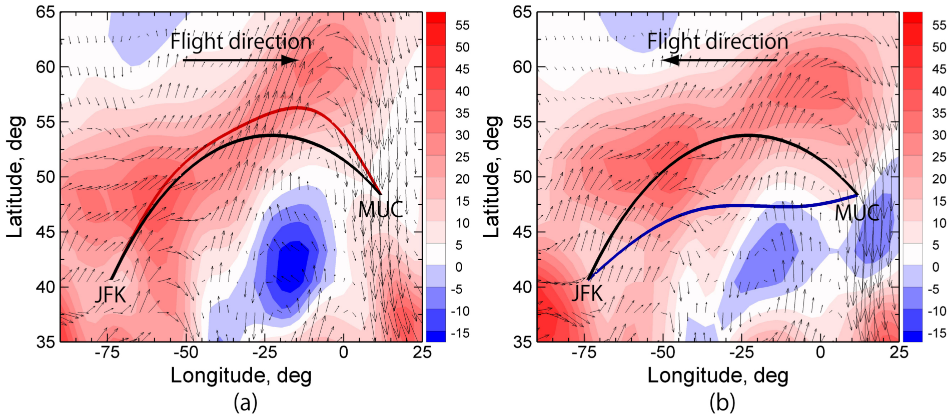

Figure S3. Trajectories for the time-optimal (red and blue lines) and great circle cases (black lines) between JFK and MUC. The contours show the zonal wind speed (u in ms^{-1}); arrows (black) show the wind speed ($\sqrt{u^2+v^2}$) and direction. **(a)** The eastbound flight from JFK to MUC with the wind field at $\overline{h} = 8841$ m at 01:30:00 UTC. **(b)** The westbound flight from MUC to JFK with the wind field at $\overline{h} = 8839$ m at 14:27:00 UTC.

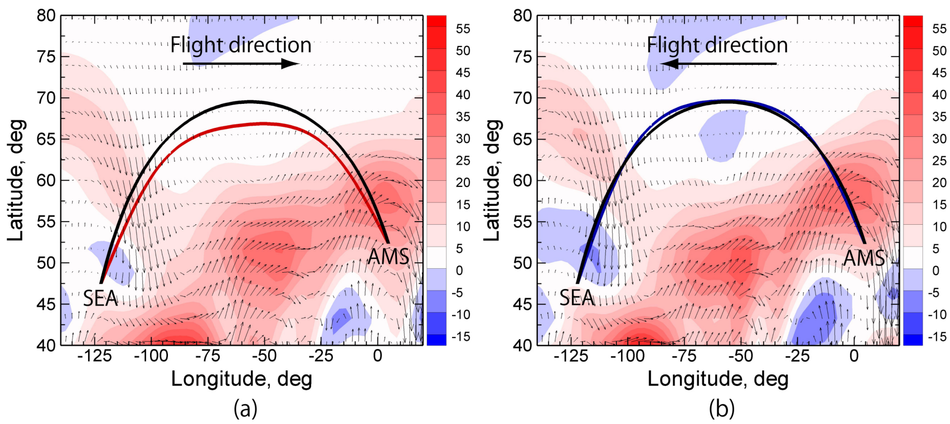

Figure S4. Trajectories for the time-optimal (red and blue lines) and great circle cases (black lines) between SEA and AMS. The contours show the zonal wind speed (u in ms^{-1}); arrows (black) show the wind speed ($\sqrt{u^2+v^2}$) and direction. **(a)** The eastbound flight from SEA to AMS with the wind field at $\overline{h} = 10\,829$ m at 21:05:00 UTC. **(b)** The westbound flight from AMS to SEA with the wind field at $\overline{h} = 9311$ m at 12:30:00 UTC.

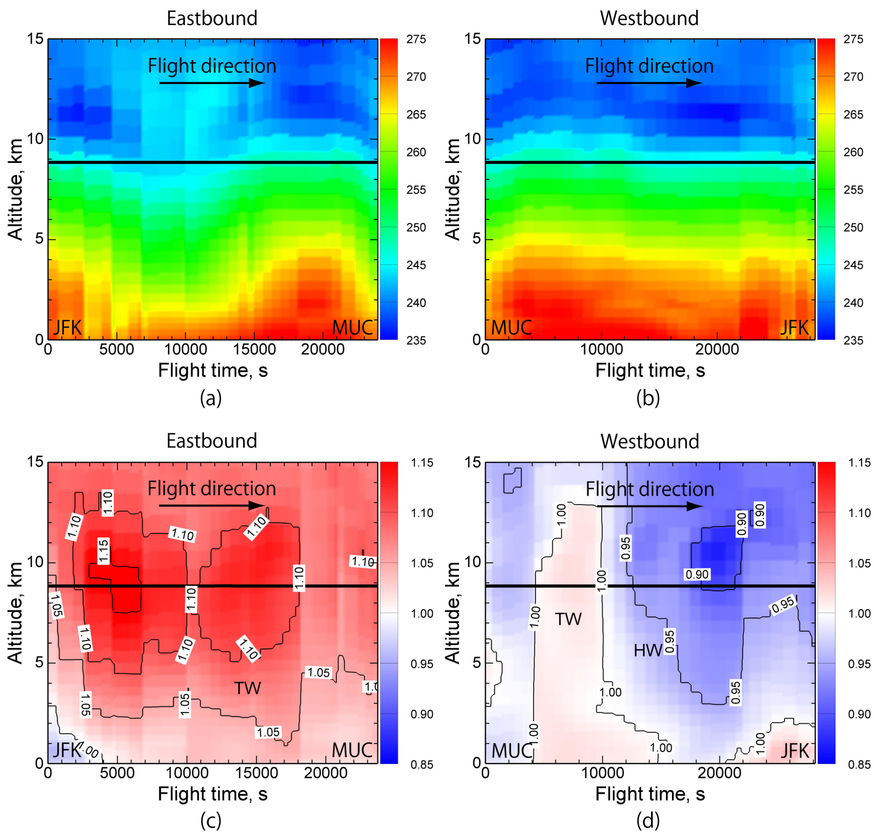

Figure S5. Altitude distributions of the true air speed V_{TAS} in ms^{-1} **(a, b)** and the tail wind indicator $V_{\text{ground}}/V_{\text{TAS}}$ **(c, d)** along the time-optimal flight trajectories (black line) between JFK and MUC. Note that $(V_{\text{ground}}/V_{\text{TAS}}) \geq 1.0$ means tail winds (TW, red), while $(V_{\text{ground}}/V_{\text{TAS}}) < 1.0$ means head winds (HW, blue) in the flight direction. The contours were obtained at the departure time: 01:30:00 UTC (eastbound, **a**, **c**); 14:27:00 UTC (westbound, **b, d**).

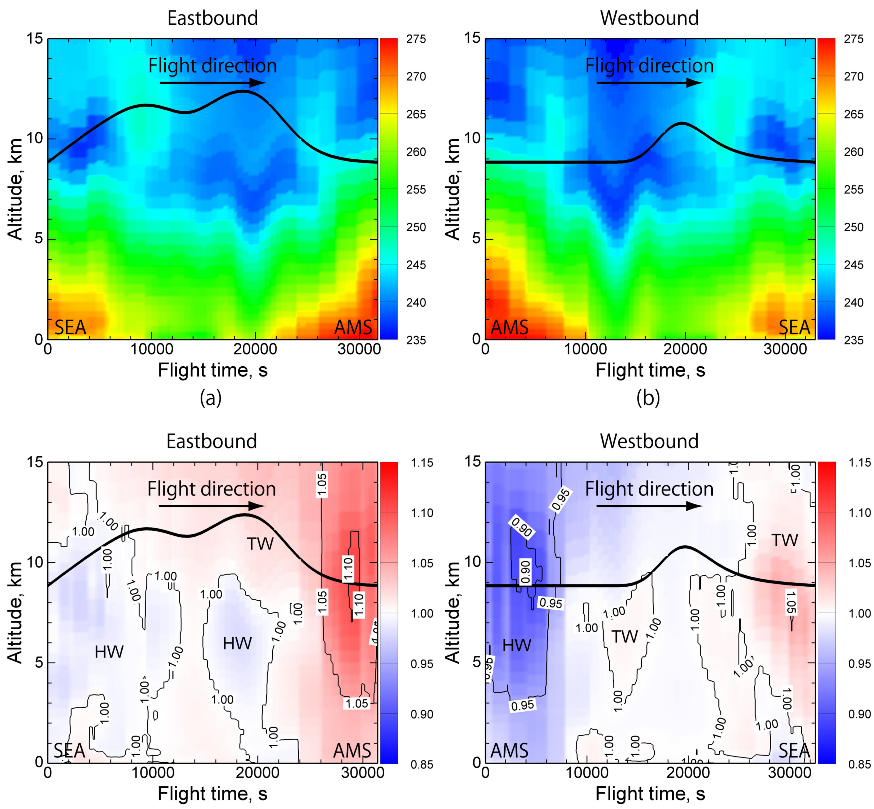

Figure S6. Altitude distributions of the true air speed V_{TAS} in ms^{-1} **(a, b)** and the tail wind indicator $V_{\mathrm{ground}}/V_{\mathrm{TAS}}$ **(c, d)** along the time-optimal flight trajectories (black line) between SEA and AMS. Note that $(V_{\mathrm{ground}}/V_{\mathrm{TAS}}) \geq 1.0$ means tail winds (TW, red), while $(V_{\mathrm{ground}}/V_{\mathrm{TAS}}) < 1.0$ means head winds (HW, blue) in the flight direction. The contours were obtained at the departure time: 21:05:00 UTC (eastbound, **a, c**); 12:30:00 UTC (westbound, **b, d**).

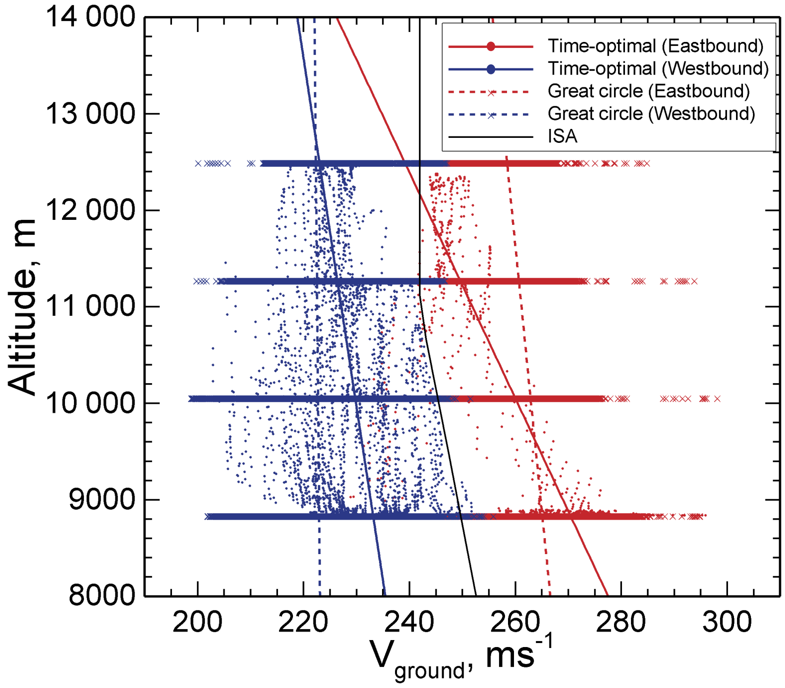

Figure S7. Values of the ground speed V_{ground} at waypoints for the time-optimal and great circle flights. Linear fits of the time-optimal (solid line, red (eastbound) and blue (westbound)) and great circle cases (dashed line, red (eastbound) and blue (westbound)) are included. V_{TAS} of the international standard atmosphere (ISA) is given (solid line, black) provided by the BADA atmosphere table (Eurocontrol, 2010).

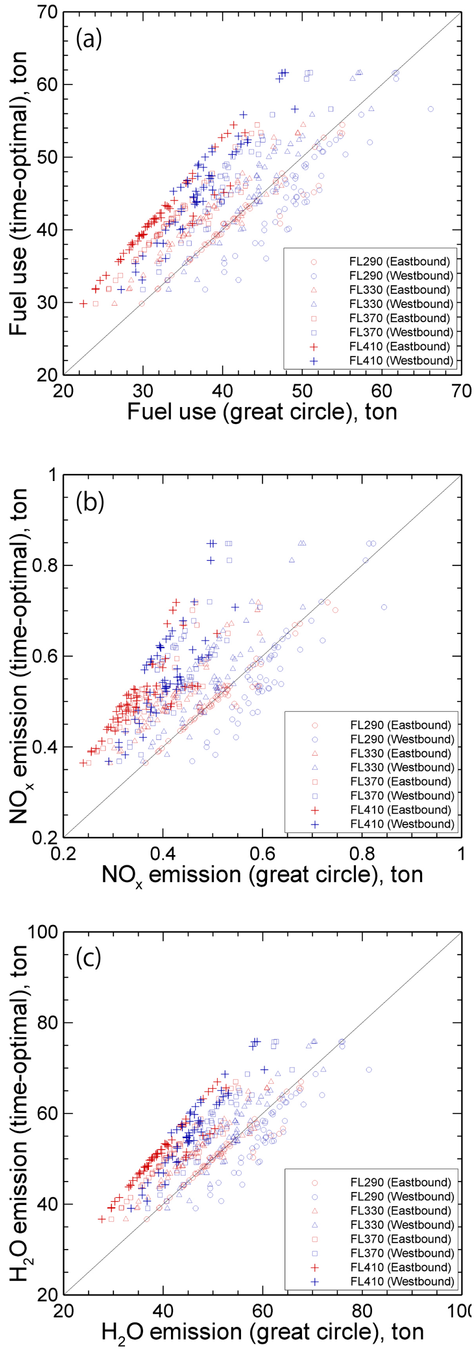

Figure S8. Comparison of the fuel use **(a)**, NO_x **(b)** and H_2O **(c)** emissions for individual flights. A symbol indicates the value for one airport pair, corresponding to the time-optimal and great circle flights. If the value for the time-optimal flight is the same as that of the great circle flight, the symbol lies on the 1:1 solid line.

Table S1. Obtained design variables $x_j (j = 1, 2, \cdots, 11)$ and objective function f (= flight time) for 10 optimal solutions. The solutions were calculated with different initial $populations$ for the $population$ size $n_\mathrm{p} = 100$ and the number of $generations$ $n_\mathrm{g} = 100$. The difference in flight time between the optimal solution f and the true-optimal solution f_true is calculated as $\Delta f = f - f_\mathrm{true}$ ($f_\mathrm{true} = 25\,994.0$ s). The flight time is minimal for the Solution 9, which corresponds to the best solution shown in Figs. 7 to 10. The mean value and the standard deviation of the 10 objective functions are expressed by $\overline{\Delta f}$ and $s_{\Delta f}$, respectively (see caption in Fig. 11 for more details).

Solution	x_1, °W	x_2, °N	x_3, °W	x_4, °N	x_5, °W	x_6, °N	x_7, m	x_8, m	x_9, m	x_{10}, m	x_{11}, m	f, s	Δf, s
1	5.18	53.48	31.72	54.41	57.38	49.60	8840.1	8840.1	8840.2	8839.4	8841.9	25 996.8	2.8
2	5.11	53.47	31.94	54.36	57.38	49.56	8844.8	8841.0	8840.2	8839.5	8847.4	25 996.8	2.8
3	5.10	53.45	31.86	54.37	57.39	49.54	8839.3	8839.4	8839.9	8839.9	8839.4	25 996.7	2.7
4	4.61	53.25	29.83	54.52	56.83	49.86	8841.7	8840.8	8839.3	8841.0	8839.2	25 996.8	2.8
5	4.61	53.26	30.41	54.53	57.20	49.77	8839.3	8839.6	8839.8	8839.5	8840.2	25 996.6	2.6
6	5.88	53.57	32.74	54.29	57.39	49.50	8840.5	8839.4	8839.2	8839.4	8839.3	25 997.2	3.2
7	5.27	53.43	31.20	54.36	56.85	49.78	8846.7	8847.8	8847.7	8841.7	8845.8	25 997.2	3.2
8	5.55	53.33	29.90	54.41	56.53	50.04	8844.1	8840.1	8840.0	8840.5	8839.2	25 997.8	3.7
9 (Best solution)	4.84	53.31	31.60	54.38	57.39	49.54	8839.6	8839.5	8839.4	8839.2	8840.4	25 996.6	2.5
10	4.88	53.33	31.53	54.40	57.38	49.59	8841.9	8841.0	8840.1	8839.5	8840.3	25 996.6	2.6
Mean ($\overline{\Delta f}$)												25 996.9	2.9
Standard deviation ($s_{\Delta f}$)												0.4	0.4

Table S2. Values of $\overline{\Delta f}$ (in %) and $s_{\Delta f}$ (in %, in parentheses) for all the combinations of *population* size n_{p} $(10, 20, \cdots, 100)$ and number of *generations* n_{g} $(10, 20, \cdots, 100)$. The definitions of $\overline{\Delta f}$ and $s_{\Delta f}$ are given in the caption in Fig. 11.

Population size n_{p}	Number of generations n_{g}									
	10	20	30	40	50	60	70	80	90	100
10	0.25 (0.112)	0.12 (0.032)	0.08 (0.022)	0.07 (0.020)	0.06 (0.019)	0.05 (0.015)	0.04 (0.013)	0.04 (0.013)	0.04 (0.013)	0.04 (0.012)
20	0.14 (0.097)	0.06 (0.016)	0.05 (0.014)	0.05 (0.012)	0.04 (0.012)	0.04 (0.012)	0.03 (0.011)	0.03 (0.010)	0.03 (0.008)	0.03 (0.006)
30	0.09 (0.043)	0.06 (0.021)	0.04 (0.020)	0.04 (0.018)	0.03 (0.017)	0.03 (0.014)	0.02 (0.013)	0.02 (0.011)	0.02 (0.010)	0.02 (0.009)
40	0.06 (0.011)	0.04 (0.010)	0.04 (0.010)	0.03 (0.009)	0.03 (0.007)	0.02 (0.006)	0.02 (0.006)	0.02 (0.004)	0.02 (0.004)	0.02 (0.003)
50	0.06 (0.016)	0.04 (0.009)	0.03 (0.007)	0.03 (0.007)	0.02 (0.006)	0.02 (0.006)	0.02 (0.005)	0.02 (0.005)	0.01 (0.004)	0.01 (0.004)
60	0.06 (0.012)	0.04 (0.008)	0.03 (0.007)	0.02 (0.005)	0.02 (0.004)	0.02 (0.004)	0.02 (0.004)	0.01 (0.003)	0.01 (0.003)	0.01 (0.003)
70	0.06 (0.016)	0.04 (0.014)	0.03 (0.011)	0.03 (0.009)	0.02 (0.007)	0.02 (0.006)	0.02 (0.005)	0.02 (0.004)	0.02 (0.004)	0.01 (0.003)
80	0.06 (0.009)	0.04 (0.008)	0.03 (0.007)	0.02 (0.006)	0.02 (0.005)	0.02 (0.005)	0.02 (0.004)	0.01 (0.003)	0.01 (0.003)	0.01 (0.003)
90	0.05 (0.008)	0.04 (0.007)	0.03 (0.006)	0.02 (0.006)	0.02 (0.004)	0.02 (0.004)	0.02 (0.003)	0.01 (0.002)	0.01 (0.002)	0.01 (0.002)
100	0.05 (0.011)	0.04 (0.010)	0.03 (0.007)	0.02 (0.005)	0.02 (0.005)	0.02 (0.003)	0.01 (0.003)	0.01 (0.002)	0.01 (0.002)	0.01 (0.001)