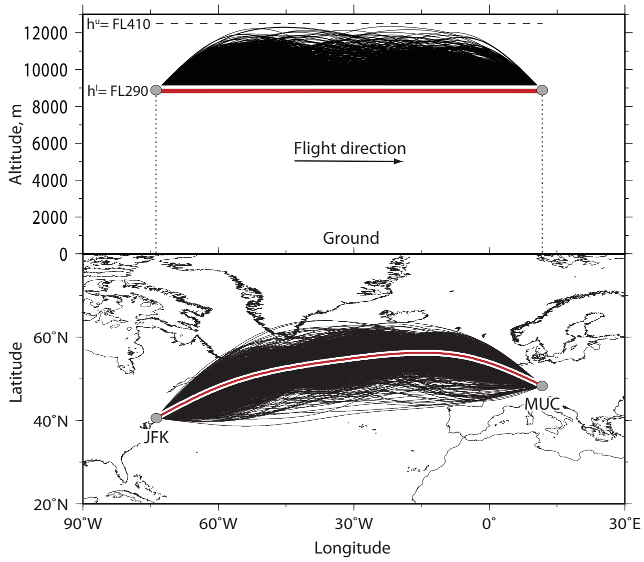
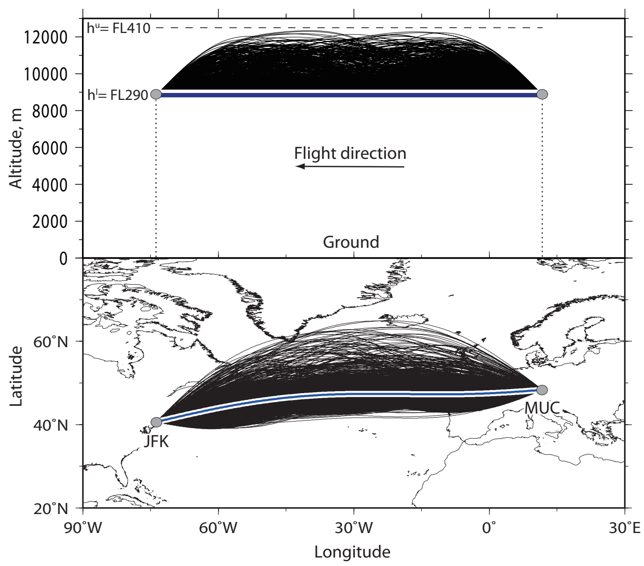
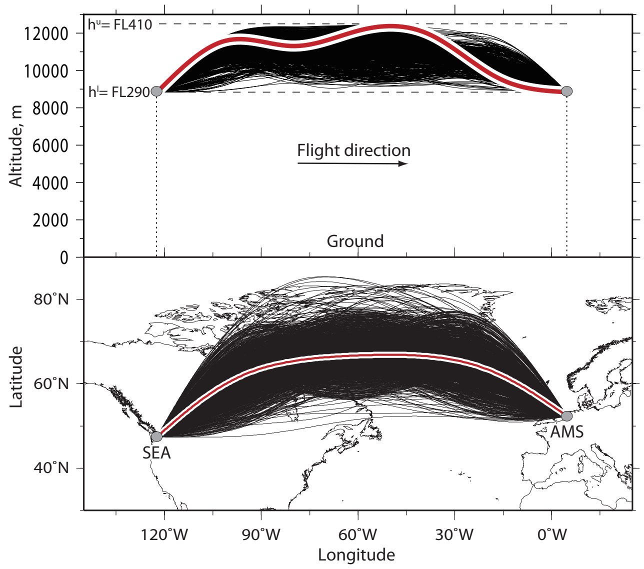


(a)

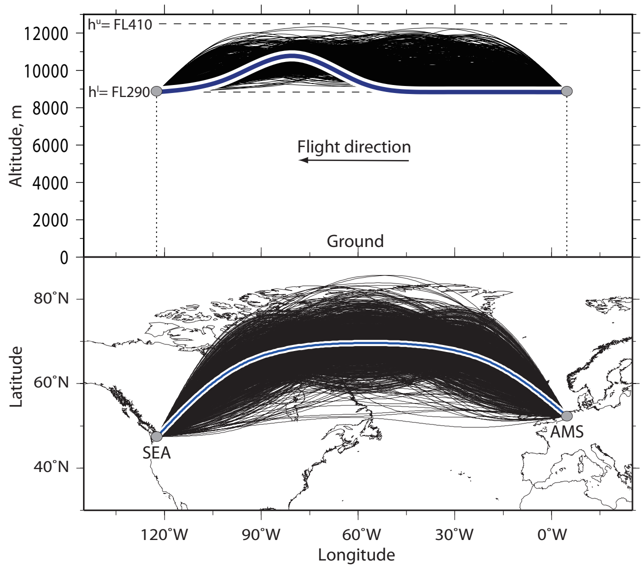


(b)

Figure S1. 1,000 explored trajectories (black lines) between JFK and MUC as longitude vs altitude (top) and as location (bottom), including time-optimal flight trajectories (red and blue lines). (a) The eastbound flight from JFK to MUC. (b) The westbound flight from MUC to JFK.

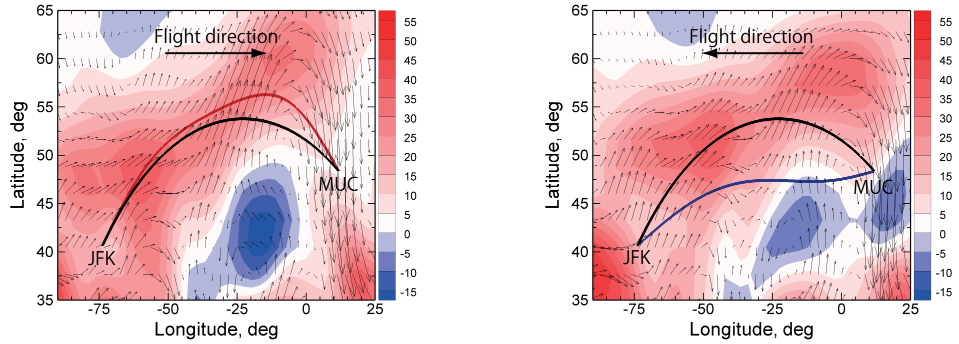


(a)



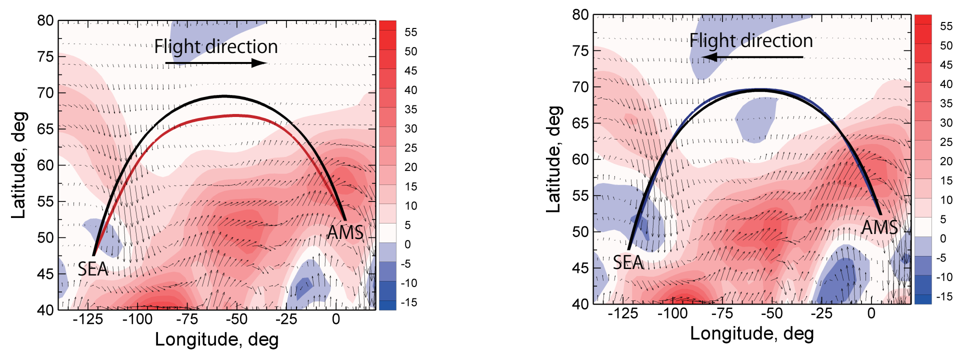
(b)

Figure S2. 1,000 explored trajectories (black lines) between SEA and AMS as longitude vs altitude (top) and as location (bottom), including time-optimal flight trajectories (red and blue lines). (a) The eastbound flight from SEA to AMS. (b) The westbound flight from AMS to SEA.



(a) (b)

Figure S3. Comparison of trajectories for the time-optimal (red and blue lines) and the great circle cases (black lines) between JFK and MUC. The contours show the zonal wind speed (u); 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 $\overline{h} = 8{,}841$ m at 01:30:00 UTC. (b) The westbound flight from MUC to JFK with the wind field at $\overline{h} = 8{,}839$ m at 14:27:00 UTC.



(a) (b)

Figure S4. Comparison of trajectories for the time-optimal (red and blue lines) and the great circle cases (black lines) between SEA and AMS. The contours show the zonal wind speed (u); 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 $\overline{h} = 9{,}311$ m at 12:30:00 UTC.

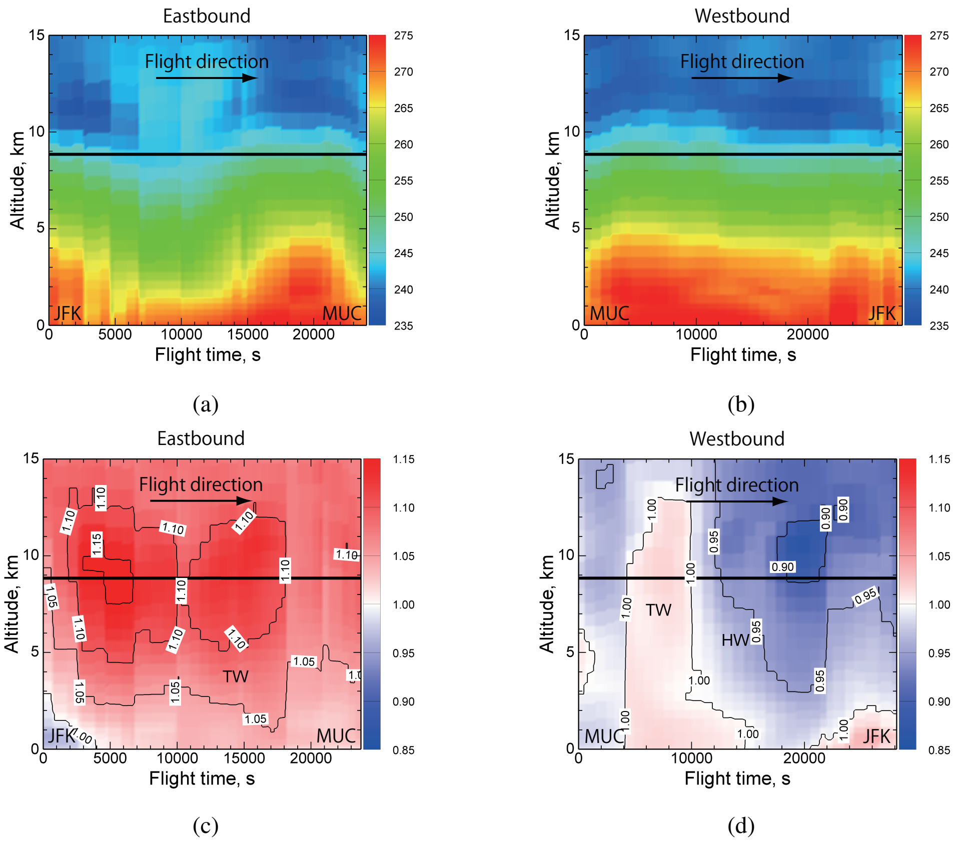


Figure S5. Altitude distributions of the true air speed V_{TAS} (a and b) and the tail wind indicator V_{ground}/V_{TAS} (c and d) along the time-optimal flight trajectories (black line) between JFK and MUC. Note, $(V_{ground}/V_{TAS}) \geq 1.0$ means tail winds (TW, red), while $(V_{ground}/V_{TAS})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

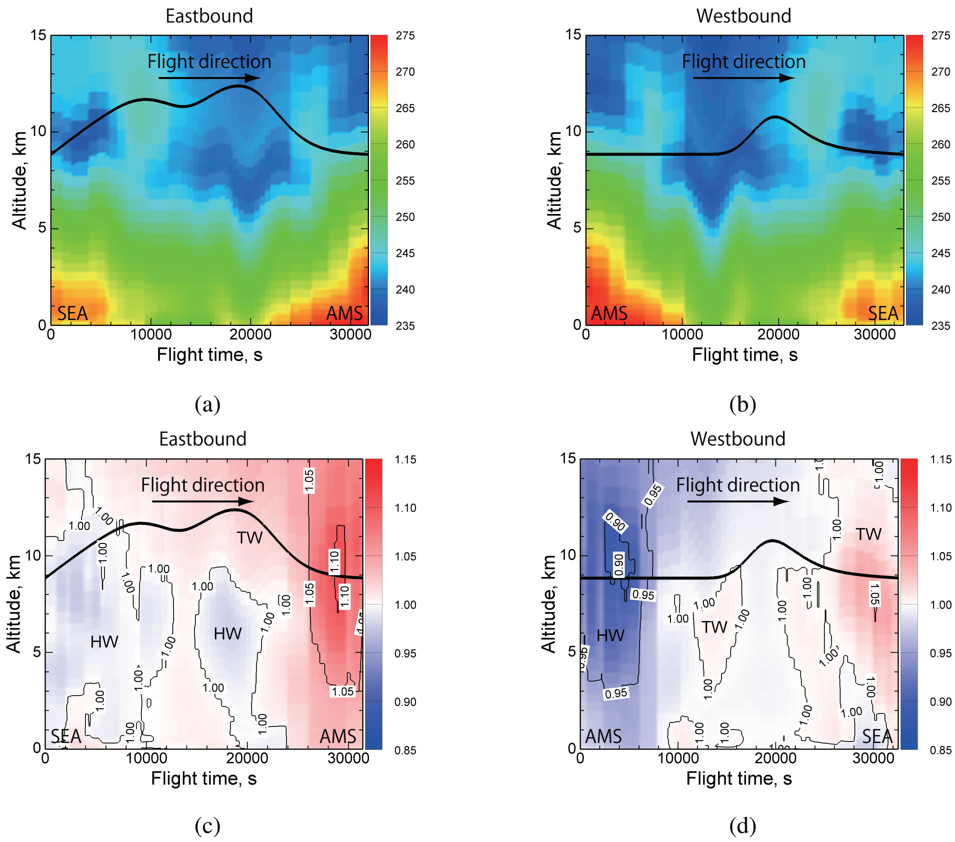


Figure S6. Altitude distributions of the true air speed V_{TAS} (a and b) and the tail wind indicator V_{ground}/V_{TAS} (c and d) along the time-optimal flight trajectories (black line) between SEA and AMS. Note, $(V_{ground}/V_{TAS}) \geq 1.0$ means tail winds (TW, red), while $(V_{ground}/V_{TAS})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

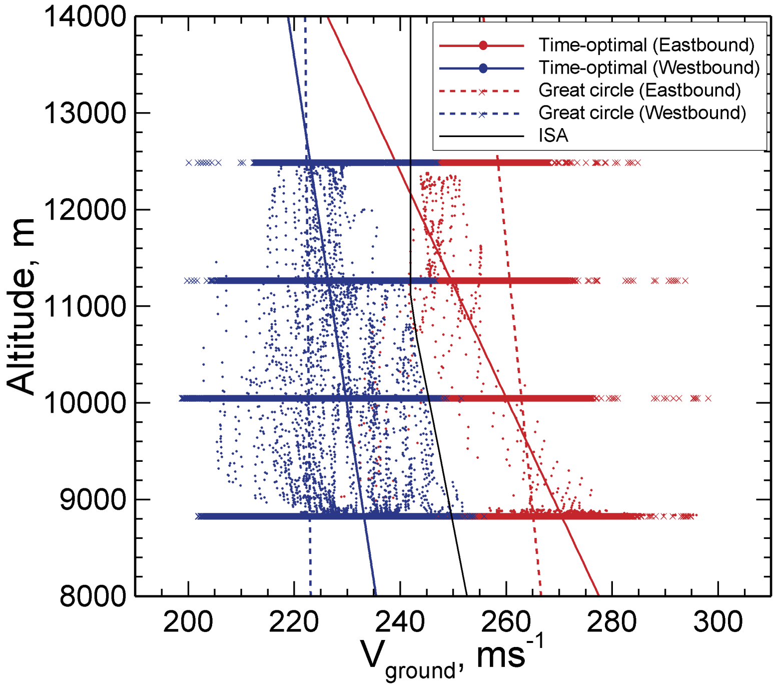
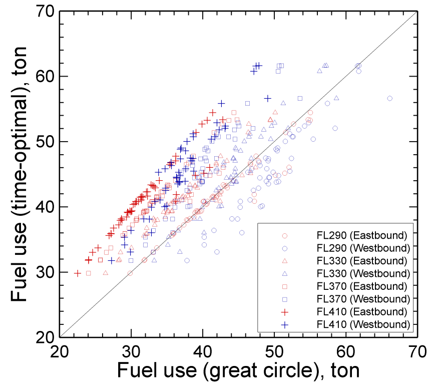
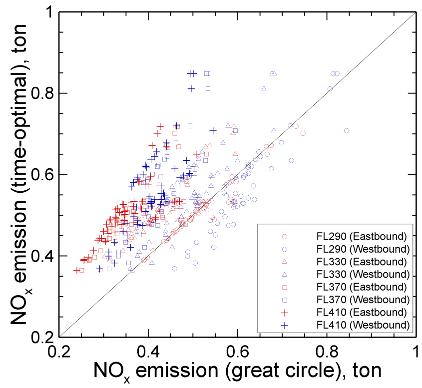


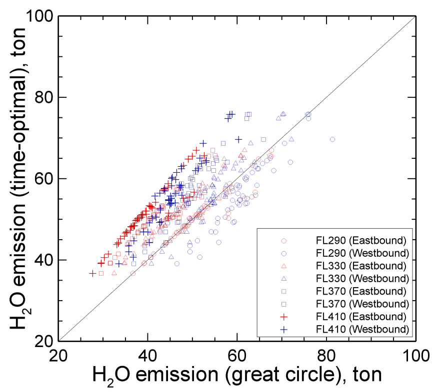
Figure S7. Values of the ground speed V_{ground} at waypoints for the time-optimal and the great circle flights. Linear fits of the time-optimal (solid line, red (eastbound) and blue (westbound)) and that of the great circle cases (dashed line, red (eastbound) and blue (westbound)) are included. V_{TAS}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



(a)



(b)



(c)

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 the great circle flight. 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 $n_p = 100$ and the generation number $n_g = 100$. The difference in flight time between the optimal solution f and the true-optimal solution f_{true} is calculated as $\Delta f = f - f_{true}$ ($f_{true} = 25,994.0$ s). The flight time is minimal for the Solution 9, which corresponds to the best solution shown in Figs. 8 to 11. 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. 12 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	8,840.1	8,840.1	8,840.2	8,839.4	8,841.9	25,996.8	2.8
2	5.11	53.47	31.94	54.36	57.38	49.56	8,844.8	8,841.0	8,840.2	8,839.5	8,847.4	25,996.8	2.8
3	5.10	53.45	31.86	54.37	57.39	49.54	8,839.3	8,839.4	8,839.9	8,839.9	8,839.4	25,996.7	2.7
4	4.61	53.25	29.83	54.52	56.83	49.86	8,841.7	8,840.8	8,839.3	8,841.0	8,839.2	25,996.8	2.8
5	4.61	53.26	30.41	54.53	57.20	49.77	8,839.3	8,839.6	8,839.8	8,839.5	8,840.2	25,996.6	2.6
6	5.88	53.57	32.74	54.29	57.39	49.50	8,840.5	8,839.4	8,839.2	8,839.4	8,839.3	25,997.2	3.2
7	5.27	53.43	31.20	54.36	56.85	49.78	8,846.7	8,847.8	8,847.7	8,841.7	8,845.8	25,997.2	3.2
8	5.55	53.33	29.90	54.41	56.53	50.04	8,844.1	8,840.1	8,840.0	8,840.5	8,839.2	25,997.8	3.7
9 (Best solution)	4.84	53.31	31.60	54.38	57.39	49.54	8,839.6	8,839.5	8,839.4	8,839.2	8,840.4	25,996.6	2.5
10	4.88	53.33	31.53	54.40	57.38	49.59	8,841.9	8,841.0	8,840.1	8,839.5	8,840.3	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 generation number n_g $(10, 20, \cdots, 100)$. The definitions of $\overline{\Delta f}$ and $s_{\Delta f}$ are given in the caption in Fig. 12.

Population size n_p	Generation number 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)