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Research on aircraft trajectory optimization based on reducing greenhouse effect[1]

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Abstract. Air transport plays an important role in people's daily life. However, the environmental impact caused by it has become increasingly serious. In order to reduce the greenhouse effect caused by global aviation, the absolute global temperature potential (AGTP) was used for the uniform quantization of aircraft emissions of CO_2 and the generated contrails. Then, considering the control boundary and mobility constraints, the aircraft level optimization model was established with the optimization objectives of minimizing greenhouse effect, and it was verified using the actual radiosonde data and operational data of Guangzhou-Beijing route. Finally in the optimized flight profile, the global surface temperature decreased, in three time level of 25 years, 50 years and 100 years, which was reduced by 36.39 %, 13.98 % and 11.21 %, respectively. Therefore, the optimization model can effectively reduce the greenhouse effect caused by aircraft operation.

Key words. Greenhouse effect, global warming potential, carbon dioxide emission, condensation.

1. Introduction

As a new industry, civil aviation industry has brought convenience, comfort and high efficiency. However, the impact of noise, fuel consumption, and pollution emissions caused by air transport on the environment has attracted more and more

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attention. According to the United Nations Intergovernmental Panel on climate change (IPCC) statistics, 13 % of current fossil fuel is consumed by air transport, in which air transport emissions of carbon dioxide (CO_2) account for 2 % of the total global anthropogenic emissions CO_2 [1]. Another cause of climate impact is the contrail, and the impact of climate warming produced by it is even higher than the aircraft's CO_2 emissions [2]. Aircraft flying at high altitude, long duration, emissions of the gas is difficult to be absorbed compared to the ground, so the impact on the environment is a long process. Environment is a part of the future development of the aviation industry which cannot be ignored, and the altitude layer selection of aircraft is not only to follow the high level of safety and efficiency principles, but also needs to further consider the impact of the environment. Therefore, the establishment of a safe and environmentally friendly aircraft trajectory is one of the main directions of the future development of the aviation industry.

Based on the current situation of the development of Chinese civil aviation, facing to the environmental protection which should be considered in the air traffic operation, according to the characteristics of climate impact of CO_2 and contrail, the absolute global temperature potential (AGTP) [3] climate standard is used to measure the effect of CO_2 and contrail on global surface temperature, establish the weight of CO_2 and contrail, construct the aircraft altitude layer optimization model with the goal of minimizing the greenhouse effect, and compare with the global surface temperature increase value caused by the aircraft flying under the original flight profile, so as to verify that the model can effectively reduce the impact of the environment.

2. Current research status

While consuming a large amount of fuel in the upper air, the aircraft also brings about a lot of pollution to the surrounding environment and the formation of the condensate. High altitude flight usually refers to the flight altitude of 7000 m∼15000 m in altitude. For the aircraft during the height range, due to high altitude, the noise pollution of flight trajectory is negligible, and the aircraft fuel combustion CO_2 is the greenhouse gas, which can absorb and release radiation to affect global climate change, and cause a great threat to human survival. At the same time, the aircraft is easy to generate the contrail, which can block the long wave radiation from the earth's surface in the atmosphere, increasing the greenhouse effect. Therefore, the impact of high altitude flight on the environment is mainly reflected in the CO_2 emission and the contrail.

As for the twenty-first century, the research of reducing the impact of high altitude flight on the environment has been carried out by foreign countries as the following. In 2003, Victoria Williams et al. [4] proposed that the aircraft flying height layer was in favor of reducing the impact of aviation activities on the European climate. In 2008, Klaus Gierens [5] summarized a review of the methods to relieve the contrail. In 2011, Banavar Sridhar et al. [6] combined with upper wind data to optimize the horizontal direction and the height of the routes of the 12 cities in United States, and obtained the flight path with the minimal impact on the environment by solving the nonlinear optimal control problem. In 2012, Chen et al. [7] measured the carbon dioxide and the contrail, and made the artificial determination of weighing coefficient. Although more flexible, it was greatly affected by human factors, which was not easy to unify the specification. In 2014, Manuel Soler et al. [8] described the 4D flight path planning as a multi-stage mixed integer optimization control problem, and replanned the route of the aircraft, so that the impact of contrail on the environment was minimal. In 2015, Antonio Filippone [9] evaluated the reduction measures of all kinds of contrails. There are few related researches in China, currently only focused on research of greenhouse gases on global climate change, less considering the impact of the aircraft operation on the climate, thus not carrying out the research of reducing the impact of aircraft on the aircraft environment by improving the operation. In 2011, Zhang Ruoyu et al. [10] used the assessment method of global warming potential (GWP) to study the effect of greenhouse gases on climate, and the global warming potential of greenhouse gases was reviewed comprehensively. In 2011, Liu Ping [11] pointed out in his article that China promulgated the "guidance on accelerating the work of energy conservation and emission reduction", which could reduce emissions through technology and management innovation. In 2016, Wang Zhongfengyan and others [12] preliminary discussed the aircraft flying height layer distribution program to reduce the greenhouse effect through the establishment of the climate impact assessment method of CO_2 and the contrail.

3. Aircraft trajectory optimization model and its solution

The impact of high altitude flight on the environment is mainly reflected in the formation of CO_2 emission and the formation of contrail. CO_2 emissions depend on fuel consumption and combustion efficiency. The formation of contrail is related to the atmospheric temperature and relative humidity, and the appropriate climate assessment index should be selected to establish the global warming response function. Aircraft trajectory optimization can reduce the impact of aircraft operation on the global temperature change by optimizing the altitude layer of the flight phase, thus forming an environmentally friendly path.

3.1. CO_2 emissions model

CO_2 is the main greenhouse gas, accounting for about 75 % of all greenhouse gases, no obstacle to light radiation, but it can absorb infrared and block infrared. CO_2 likes a greenhouse, and energy is easy to into and hard to go out. The more CO_2, the stronger the hindering effect of earth's heat escapes to hinder the atmosphere, so that the global warming effect is stronger. If the CO_2 content is doubled, the global temperature will rise 3∼5 °C, which may be increased by 10 °C in the Polar regions, and the climate will be significantly warmer.

With the rapid development of the global airline industry, if not to take corresponding measures to protect the environment, the proportion of gas emissions produced by air transport over the next 40 years will increase to 3 % of global anthropogenic CO_2 emissions, and the proportion causing the climate change will reach 5 % [13]. CO_2 emissions from engines are mainly derived from fuel combustion, while combustion and combustion efficiency are the decisive factors in determining the total amount and composition of emissions.

The amount of CO_2 gas emitted by the fuel consumed during the aircraft operation can be expressed as:

$$E_{\mathrm{CO_2}} = EI_{\mathrm{CO_2}} \cdot FW \,. \tag{1}$$

In the formula, $E_{\mathrm{CO_2}}$ is the emission of CO_2, and its unit is kg, $EI_{\mathrm{CO_2}}$ is emission index for CO_2, and the emission index of aviation fuel is $EI_{\mathrm{CO_2}} = 3.155\,\mathrm{kg/kg}$. Quantity FW represents the fuel consumption, and its unit is kg.

3.2. The formation model of contrail

For aircraft flying at high altitude, the tail behind will form a cloud band atomization wake. The white cloud belt is produced by condensation of condensed water from the engine and the surrounding cold air. They can be condensed into tiny droplets to form a cloud, so this article will call it the contrail. The contrail can absorb the heat of the ground radiation, thereby "adding fuel to the flames of global warming". Generally, above sea level 8000 m, the temperature is low to minus 40 °C, and the contrail will form. Therefore, the high altitude cruise phase is more likely to form the contrail.

The formation of contrails is related to the atmospheric temperature and relative humidity of the atmosphere. Air humidity refers to the degree of humidity in the air, which means the degree of vapor content in the atmosphere. At a certain temperature, the smaller the air humidity, the faster the water evaporates. Whereas the atmospheric humidity is bigger, water evaporates is more slowly. The high temperature gas discharged by the engine cold air condenses into small droplets, which is not easy evaporation, existing in the atmosphere in the form of cloud, which is the formation of contrails. When the relative humidity (RH_{w}) of ambient air is greater than or equal to a certain humidity, it is easy to form a continuous contrail, and the humidity is defined as the critical relative humidity RH_{critical} [14].

$$RH_{\mathrm{critical}} = \frac{G\left(T - T_{\mathrm{contrail}}\right) + e_{\mathrm{sat}}^{\mathrm{liq}}\left(T_{\mathrm{contrail}}\right)}{e_{\mathrm{sat}}^{\mathrm{liq}}\left(T\right)} \,, \tag{2}$$

$$e_{\mathrm{sat}}^{\mathrm{liq}}\left(T\right) = e_0 \cdot 10^{\frac{aT}{b+T}} \,, \tag{3}$$

$$T_{\mathrm{contrail}} = -46.46 + 9.43 \ln\left(G - 0.053\right) + 0.72 \ln^2\left(G - 0.053\right) \,, \tag{4}$$

and

$$G = \frac{EI_{\mathrm{H_2O}} C_{\mathrm{p}} P}{\varepsilon Q \left(1 - \eta\right)} \,. \tag{5}$$

In the above formulas, $e_{\mathrm{sat}}^{\mathrm{liq}}\left(T\right)$ is the saturated vapor pressure at atmospheric temperature (hPa), e_0 is the saturated vapor pressure at $0\,^\circ$C and its value is 6.11 hPa. For water, $a = 7.5$, $b = 237.3$. Symbol T_{contrail} denotes the critical temperature for the formation of contrail in degrees of Celsius, $EI_{\mathrm{H_2O}}$ represents the emission index of steam, C_{p} is the specific heat capacity of air at constant pressure (J/kg K), P denotes the atmospheric pressure (hPa), ε stands for the ratio of the molecular weight of water to the average relative molecular mass of dry air, Q is the fuel combustion value (J/kg) and η denotes the average propulsion efficiency of engine.

When the relative humidity of the atmosphere RH_{i} is greater than or equal to 100 %, the shape of the contrail can be kept.

$$RH_{\mathrm{i}} = RH_{\mathrm{w}} \frac{6.0612\mathrm{e}^{\frac{18.102T}{249.52+T}}}{6.1162\mathrm{e}^{\frac{22.577T}{237.78+T}}}\,. \tag{6}$$

Therefore, the conditions for the formation of the continuous contrail are as follows: the relative humidity of the water should satisfy $RH_{\mathrm{critical}} \le RH_{\mathrm{w}} < 100\,\%$. And the relative humidity of ice needs to satisfy$RH_{\mathrm{i}} \ge 100\,\%$.

3.3. Linear climate model

3.3.1. Absolute global temperature potential (AGTP). The radiative forcing and lifetime of different greenhouse gases are different, and the effect of increasing temperature is not the same. AGTP [15] is the change in global mean surface temperature caused by instantaneous or continuous release of a greenhouse gas in a future given time. In order to measure the effect of aircraft operation on the global climate, AGTP is used as the evaluation index to establish the global warming response function of the air exhaust and contrail by the linear system, so as to quantify the change of global average surface temperature by the aircraft operation. The following equation is established through the convolution from $t_0 = 0$ to $t = H$:

$$\mathrm{AGTP}(H) = \int_0^H R\,(H-\zeta)\,\Delta F\,(\zeta)\;\mathrm{d}\zeta\,. \tag{7}$$

Here, $R\,(H-\zeta)$ is the impulse response function, which represents the change of the global surface temperature within the H time due to the radiative forcing of $\Delta F\,(\zeta)$ at time ζ.

AGTP is divided into two kinds: one is the absolute global temperature change potential pulse discharge, recorded as pulse discharge AGTP, the other is the absolute global warming potential of continuous emissions, recorded as a continuous emission AGTP. Because the continuous emission of AGTP considers the influence of the gas on the surface temperature changes in the case of continuous emission, the instantaneous emission of CO_2 and the critical of the aircraft during the flight are discussed in this paper. Therefore, using the pulse emission AGTP to measure the effects of CO_2 and the critical, the effects of CO_2 and the critical are transferred to the global surface temperature change.

3.3.2. Pulse discharge AGTP of CO_2 . Pulse emission AGTP model of CO_2 describes the change of CO_2 concentration due to the transport and absorption of land and sea, which can be calculated as follows:

$$\Delta F^{CO_2}(t) = A^{CO_2}\left(a_0 + \sum_{i=1}^{3} a_i e^{-\frac{t}{\alpha_i}}\right). \tag{8}$$

The global surface temperature response to the radiative forcing of the unit pulse is modeled using a quadratic linear model, and the impulse response function is

$$R(t) = \sum_{j=1}^{2} \frac{c_j}{d_j} e^{-\frac{t}{\alpha_i}}. \tag{9}$$

In the above formula, A^{CO_2} is the radiative forcing of concentration change of 1 kg CO_2, $A^{CO_2} = 1.82 \times 10^{-15}$ Wm^{-2}/kg. The values of a_i, α_i, c_j, d_j, which are the given calculation parameters, are shown in Table 1.

Table 1. Parameter values of the impulse response function of CO_2 concentration

No. of variable	0	1	2	3
a_i (dimensionless)	0.217	0.259	0.338	0.186
α_i (year)		172.9	18.51	1.186
c_j (Km^2/W)		0.631	0.429	
d_j (year)		8.4	409.5	

From formulae (7)–(9), it can be seen that the pulse discharge AGTP of 1 kg CO_2 within H time level is as follows:

$$\mathrm{AGTP}^{CO_2}(H) =$$

$$= A^{CO_2} \sum_{j=1}^{2}\left[a_0 c_j\left(1 - e^{-\frac{H}{d_j}}\right) + \sum_{i=1}^{3} \frac{a_i \alpha_i c_j}{\alpha_i - d_j}\left(e^{-\frac{H}{\alpha_i}} - e^{-\frac{H}{d_j}}\right)\right]. \tag{10}$$

The value of the parameters is added into the formula (10). The calculation shows that the value of the pulse emission AGTP^{CO_2} at different times is only related to time level. The MATLAB is used to draw the function curve, with the step size of 0.1, and the change trend of pulse discharge AGTP^{CO_2} with the time level is shown in Fig. 1.

3.3.3. Pulse discharge AGTP of the contrail. The AGTP modeling of the pulse discharge contrail is the same with the CO_2. The pulse discharge AGTP of the

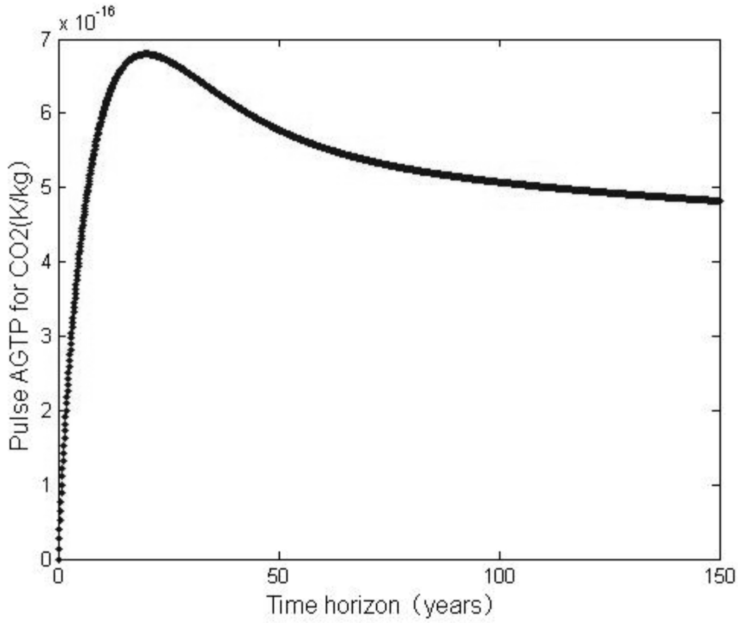

Fig. 1. Pulse AGTP for CO_2

contrail can be simply regarded as the impulse response. It is calculated as follows:

$$\mathrm{AGTP}^{\mathrm{Con}}(H) = \int_0^H R(H-\zeta)\,\delta(\zeta-0)\,\mathrm{d}\zeta = R(H)\,. \tag{11}$$

The above formula shows that $\mathrm{AGTP}^{\mathrm{Con}}(H)$ means the pulse discharge AGTP of the contrail, and its value is equal to the impulse response function $R(H)$. Net radiative forcing (RF_{net}) of the contrail includes long wave radiative forcing (RFLW) and short wave radiative forcing (RFSW):

$$RF_{\mathrm{net}} = RF_{\mathrm{LW}} + RF_{\mathrm{SW}}\,. \tag{12}$$

In the above formula, the radiative forcing has a unit of $\mathrm{W/m^2}$, which means the energy produced by the condensation in each unit area. In general, the value of RF_{net} is from $10\,\mathrm{Wm^{-2}}$ to $30\,\mathrm{Wm^{-2}}$. Due to the linear cloud of the contrail, the expression of the contrail is optimized. Optimization is for the energy generated by the unit of flight distance, and the total energy EF (GJ) of the contrail in unit length within the life cycle is calculated as follows:

$$EF = \int_{\mathrm{lifetime}} RF_{\mathrm{net}}(\zeta)\,W_{\mathrm{c}}(\zeta)\,\mathrm{d}\zeta\,. \tag{13}$$

In this formula, W_{c} is the width of the contrail, and its unit is meter.

Through formula (11)–(13), it can be seen that the pulse discharge AGTP of 1 kg

CO_2 within H time level is as follows:

$$\mathrm{AGTP}^{\mathrm{Con}}(H) = \int_0^H R(H-\zeta)\,\delta(\zeta-0)\,\mathrm{d}\zeta =$$

$$= \sum_{j=1}^{2} \frac{c_j}{d_j} \mathrm{e}^{-\frac{c_j}{d_j}} \cdot \frac{EF}{\text{Global surface area} \times \text{A year}}\,. \tag{14}$$

In general, the value of RF_{net} [14] is during $10\,\mathrm{Wm}^{-2}$–$30\,\mathrm{Wm}^{-2}$. And this article assumes that $RF_{\mathrm{net}} = 10\,\mathrm{Wm}^{-2}$, the width of the contrail is $W_{\mathrm{c}} = 1000\,\mathrm{m}$, life is $10000\,\mathrm{s}$, and then $EF = 100\,\mathrm{GJ}$. The value of the parameters is added into the formula (14). The calculation shows that the value of the pulse emission $\mathrm{AGTP}^{\mathrm{CO_2}}$ at different time is only related to time level. The MATLAB is used to draw the function curve, with the step size of 0.1, and the change trend of pulse discharge $\mathrm{AGTP}^{\mathrm{CO_2}}$ with the time level is shown in Fig. 2.

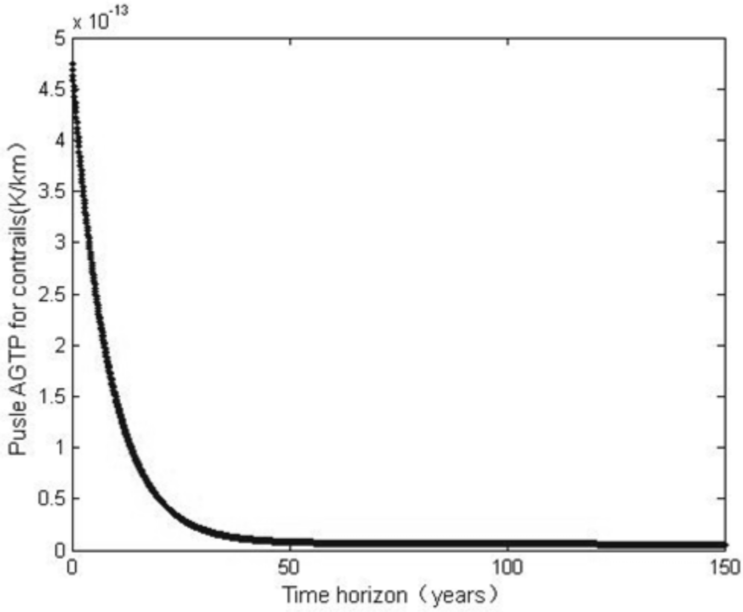

Fig. 2. Pulse AGTP for contrails

Three time levels of 25 years, 50 years and 100 years are analyzed and the $H = 25$, $H = 50$, $H = 100$ are brought into the formula (10) and (14) in this paper. The results are shown in Table 2. Comparative analysis shows that the change of global surface temperature 1 km of the contrail is the same as the effects of 44.6 kg, 12.1 kg and 9.9 kg emissions of CO_2 on the global surface temperature in 25 years, 50 years and 100 years.

Table 2. AGTP values for CO_2 and contrails at different time horizons

Time horizon H (years)	25	50	100
$\mathrm{AGTP}^{\mathrm{CO_2}}(H)$ (K/kg)	$6.73 \cdot 10^{-16}$	$5.76 \cdot 10^{-16}$	$5.13 \cdot 10^{-16}$
$\mathrm{AGTP}^{\mathrm{Con}}(H)$ (K/km)	$3.0 \cdot 10^{-14}$	$6.98 \cdot 10^{-15}$	$5.10 \cdot 10^{-15}$

3.4. Locus model

Previous studies have indicated that only changing the cruising altitude can we reduce the impact of aircraft flying on the environment during the flight phase effectively. To reduce the height of the cruise is conducive to the elimination of the contrail under normal circumstances, it is contrary to the corresponding economic cruising altitude. Therefore, it is necessary to optimize the height layer to reduce the influence of the aircraft operation on the global temperature change so as to form an environment friendly path.

3.4.1. Objective function. In order to ensure the safety and economic operation of the aircraft, it is necessary to make the following assumptions to simplify the problem:

1) Aircraft study is considered to be a moving particle, without considering the volume change of route and sector and airspace resources is adequate.

2) The assumption that Beijing time 20:00 to the next day 8:00 meteorological conditions are unchanged.

3) The meteorological data is not accurate enough in the process of changing the height layer, so the formation of the contrail is not considered.

4) Climbing or falling in the previous time slot are completed in the height of the conversion process.

The flight operation of an aircraft in the air route is assumed to be: climbing or descending. The objective function is constructed to minimize the global surface temperature variation caused by aircraft operation. The following expression is established:

$$\min T^{\mathrm{env}} = \mathrm{AGTP}^{\mathrm{CO_2}} \cdot EI_{\mathrm{CO_2}} \cdot \left(FW_m^{\mathrm{cr}} + FW_m^{H}\right) + r_l \gamma_{m,l} \mathrm{AGTP}^{\mathrm{Con}} L_{\mathrm{Con}} a, . \quad (15)$$

Here, r_l and $\gamma_{m,l}$ are decision variables, which are shown as follows:

$$r_l = 1$$

when the height layer l meets the conditions of the formation of the condensation layer and

$$r_l = 0 \quad (16)$$

when the height layer l does not meet the conditions of the formation of the condensation layer.

$$\gamma_{m,l} = \begin{cases} 1, & \text{Aircraft } m \text{ flies on the altitude layer } l. \\ 0, & \text{Aircraft } m \text{ does not fly on the altitude layer } l. \end{cases} \quad (17)$$

Quantities FW_m^{cr} and FW_m^H are the fuel consumption of cruise and altitude adjusted and they are calculated as follows:

$$FW_m^{\mathrm{cr}} = FF_m^{\mathrm{cr}} \cdot t_m^{\mathrm{cr}} \tag{18}$$

$$FW_m^H = \chi_m^n \cdot \left[FF_m^{\mathrm{cl}} \cdot t_m^{\mathrm{cl}} + FF_m^{\mathrm{des}} \cdot t_m^{\mathrm{des}} + (FF_m^{\mathrm{cr}} + \Delta FF_m^{\mathrm{cr}} \cdot \Delta H_m) \cdot t_m^{\mathrm{ncr}}\right] . \tag{19}$$

Here,

$$\chi_m^n = \begin{cases} 1, & \text{Height adjustment}, \\ 0, & \text{No height adjustment}. \end{cases} \tag{20}$$

Further, FF_m^{cl} and FF_m^{des} are the fuel flow of climbing and falling and the model data can be obtained from the BADA3.12, t_m^{cl} and t_m^{des} are the times of climbing and descent processes, ΔH_m and $\Delta FF_m^{\mathrm{cr}}$ are the height of the aircraft changes m and fuel flow rate changes. Finally, t_m^{ncr} is a new height layer cruise time.

3.4.2. Constraint conditions. 1. Control boundary constraints
The height of an aircraft m cannot be above the boundary of the control area:

$$FL_{\min} \le FL_m \le FL_{\max} . \tag{21}$$

2. Height layer uniqueness constraint
Each aircraft m must and can only be assigned a height layer l:

$$\sum_{n=1}^{l_x} \gamma_{m,l} = 1,\ l = 1, \ldots, l_x . \tag{22}$$

3. Mobility constraints
Up or down of aircraft m there can only change a height layer at most:

$$\Delta H_m \le |600| . \tag{23}$$

4. Aircraft performance constraints
In addition to ensure flight safety, civil aviation also needs to take into account the comfort of passengers. Therefore, the aircraft's rate of climb and descent cannot exceed the maximum rate of climb and descent:

$$\mathrm{ROC} \le \mathrm{ROC}^{\max} , \tag{24}$$

$$\mathrm{ROD} \le \mathrm{ROD}^{\max} . \tag{25}$$

Here, ROC and ROD are the rate of climb and descent, respectively. $\mathrm{ROC}^{\max}$ and $\mathrm{ROD}^{\max}$ are the aircraft's maximum rate of climb and the maximum rate of decline, respectively.

4. Example analysis and discussion

This article selects Beijing - Guangzhou route and the CA1336 flight from Guangzhou to Hong Kong in January 2rd, 2016 20:38 of Beijing time as the research object. Arrival time in Beijing is 23:17 and the route points are: Chenzhou, Changsha, Yueyang, Wuhan, Zhumadian, Zhengzhou, Handan and Tianjin. Horizontal track, height profile and velocity profile are shown in Figs. 3–5.

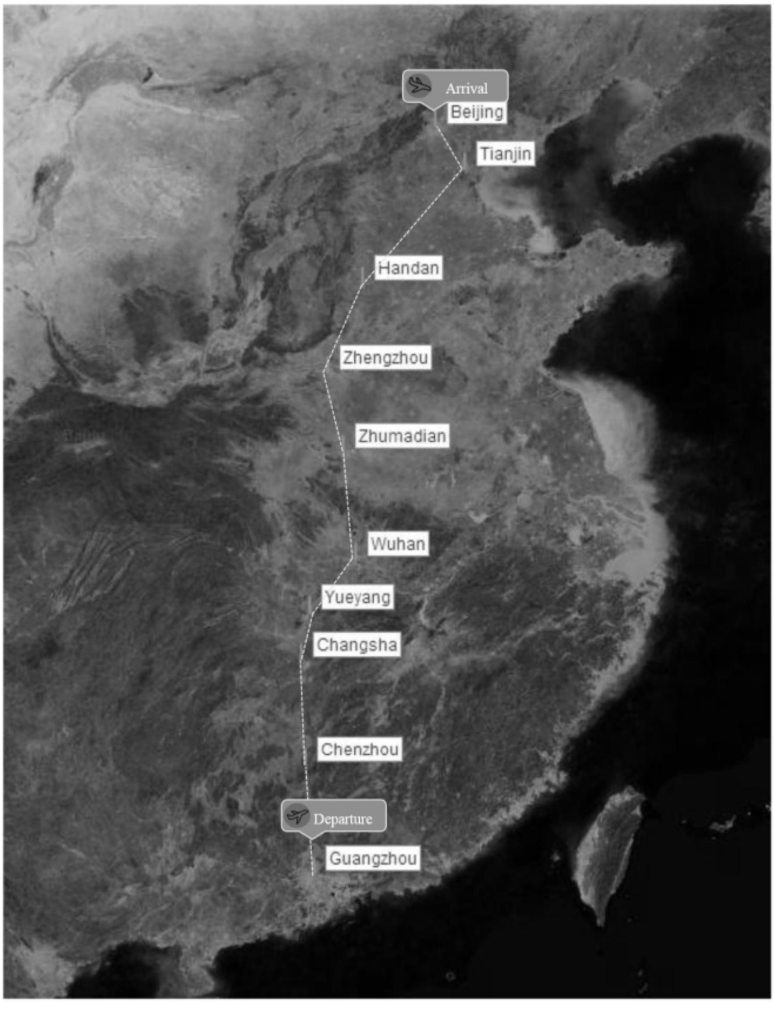

Fig. 3. Horizon track from ZGGG to ZBAA

The difference between the 3 sample points around the insertion point is treated and the power exponent is 2 in the method of inverse distance weighting by means of the available meteorological data from the University of Wyoming (Upperair air data) according to the latitude and longitude information of route point. The esti-

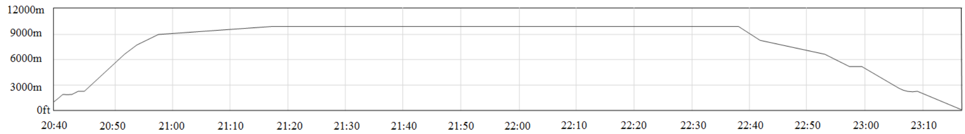

Fig. 4. Altitude profile from ZGGG to ZBAA

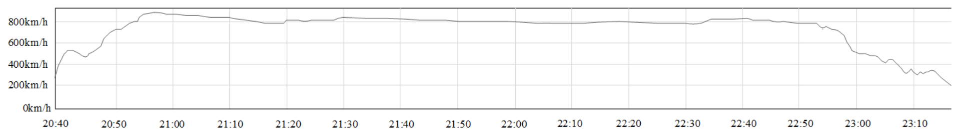

Fig. 5. Velocity profile from ZGGG to ZBAA

mated value of the insertion point is calculated is follows:

$$Z = \left(\sum_{n=1}^{3} \frac{Z_n}{s_n^2}\right) \Bigg/ \left(\sum_{n=1}^{3} \frac{1}{s_n^2}\right). \tag{26}$$

Here, Z_n is the measured value of the first n sample point and s_n was the distance between the first n sample and the point to be inserted in the formula. The weather information of the aircraft flying over the route point is estimated from the known meteorological site information. 118 national meteorological sounding station distributions are known and the route is divided into different layers when conducted subtraction operation. Three characteristic values are used for a single sample point: geographic longitude, latitude and air pressure (or temperature or relative humidity). For example, the difference calculation is conducted according to the distance and the selection principle of Yichang, Wuhan, Changsha radiosonde meteorological information, and meteorological information when calculating the way of Yueyang. The calculation results are shown in Table 3.

The weather information of route point can be calculated by interpolation method. Aircraft flying height layer is a single layer according to the requirements of the Chinese flying height layer due to the route direction is from east to west. The formation of the condensate at different points in different height layers was determined by using formulae (25)–(6) and the results are shown in Table 4. ("$\surd$"represents formation of the contrail, and "$\times$" indicates not generating the contrail).

The flight model of CA1336 is A321-231 and Table 5 is $M = 0.78$. FFcr, FFcl, ROC, FFdes and ROD are as follows when the models are at different heights (Data source come from BADA3.12).

We can check the time and altitude of the flight path according to the ADS-B FlightAware real-time position report and the statistics are shown in Table 6.

It can be seen from the above calculation that the environmental impact of the contrail generation and CO_2 emission is different due to different time levels. But reducing the formation of contrail plays a major role in reducing greenhouse effect.

Data of Yichang, Wuhan, and Changsha in Table 3 are derived from the China Meteorological data network, and the value of Yueyang is calculated by formula (26).

Table 3. Atmospheric data after differential processing in some regions at 20:00 on 2 Jan 2016

Altit. (m)	Yichang			Wuhan			Changsha			Yueyang		
	atm. press.	temp. (°C)	rel humid. (%)	atm. press.	temp. (°C)	rel humid. (%)	atm. press.	temp. (°C)	rel humid. (%)	atm. press.	temp. (°C)	rel. humid. (%)
8100	357.9	-35.1	8.1	361.0	-33.7	83.3	363.3	-33.5	16.2	361.8	-33.8	33.4
8900	318.9	-40.5	7.0	345.8	-36.3	81.8	348.2	-36.0	16.6	346.7	-36.3	33.1
9500	292.2	-43.2	7.0	321.6	-40.3	78.4	324.1	-39.3	16.9	322.5	-39.8	32.2
10100	267.3	-45.9	7.0	307.7	-42.5	75.7	310.3	-39.4	17.0	308.8	-40.7	31.6
10700	255.4	-47.2	7.0	294.2	-44.6	72.5	296.9	-39.9	16.3	295.4	-41.7	30.3
11300	243.9	-48.7	7.0	281.4	-46.0	66.6	284.2	-40.8	14.3	282.7	-42.9	27.5
11900	232.8	-50.1	7.0	269.0	-47.8	61.8	271.8	-42.3	13.8	270.3	-44.4	25.9
11900	222.2	-51.6	7.0	257.0	-48.1	58.8	259.9	-44.1	14.8	258.4	-45.7	25.7

Table 4. The contrail-favorable regions at different level from ZGGG to ZBAA

Altit. (m)	Guangzhou	Chenzhou	Changsha	Yueyang	Wuhan	Zhumadian	Zhengzhou	Handan	Tianjin	Beijing
8100	√	×	×	√	√	×	×	×	×	×
8900	×	×	×	√	√	×	×	×	×	×
9500	×	×	×	√	√	×	×	√	×	×
10100	×	×	×	√	√	√	√	√	√	×
10700	√	×	×	×	√	√	√	√	√	√
11300	√	×	×	×	√	√	√	√	√	√
11900	√	×	×	×	√	√	√	√	√	√
12500	√	×	×	×	√	√	√	√	√	√

Table 5. The fuel flow of A321-231 at different level

Altitude(m)	FF^{cr} (kg/s)	FF^{cl} (kg/s)	ROC (m/s)	FF^{des} (kg/s)	ROD (m/s)
8100	1.88275	2.99884	7.4	0.28557	9.8
8900	1.77090	2.83641	6.3	0.27475	10.0
9500	1.67235	2.63490	7.8	0.26393	14.3
10100	1.58691	2.42395	6.8	0.25311	13.5
10700	1.51445	2.23507	5.7	0.24230	12.9
11300	1.45724	2.04132	4.1	0.23148	11.4
11900	1.41602	1.84244	2.9	0.22066	11.1
12500	1.38789	1.66448	1.7	0.20984	11.0

Table 6. Live flight tracker of Flight CA1336 on 2 Jan. 2016

Waypoint	Latitude	Longitude	Time(CST)	Altitude(m)
Chenzhou	27.644	113.5167	21:26:32	10089
Changsha	28.225	113.5673	21:31:12	10089
Yueyang	28.88	113.5503	21:36:32	10089
Wuhan	30.593	114.3052	21:52:50	10089
Zhumadian	33.815	114.7294	22:17:54	10089
Zhengzhou	34.752	114.8201	22:25:39	10089
Handan	36.667	115.1591	22:41:29	10089
Tianjin	39.09	116.5129	23:04:16	5090

The aircraft is regarded as a moving particle and an aircraft trajectory optimization model based on the reduction of the greenhouse effect is established in this study. The basic modeling ideas are as follows: the vertical section of the aircraft is divided into $k \times l$ two-dimensional grid according to the route points and the height layers. Among them, $k = 1, 2, \ldots, kx$ represents the first k route points and l is the height layer. Firstly, to check whether the condensate is formed at the end of the first grid (k, l), that is to check the contrail generation coefficient $r_{k,l}$. When $r_{k,l} = 0$, there is no need to convert the height layer at the current grid without a condensation ending. While when $r_{k,l} = 1$, it generates the contrail of the current grid. And then to check the adjacent height layer of the contrail of the formation coefficient, the aircraft can only be converted to a height layer by the aircraft mobility constraints. Therefore, we consider only adjacent height layer $l + 1$ or $l - 1$. If the coefficient of condensation at the end of the high layer $l + 1$ or $L - 1$ is 0, the aircraft is moved to the high layer, and if the height of the $l + 1$ or $l - 1$ the contrail of the formation of the coefficient are both 0, the calculation does not generate the contrail of the total height of the global surface temperature T^{env} and moves the aircraft to the minimum height layer of T^{env}. However, if the adjacent height layer the contrail generation coefficient $r_{k,l+1}$ and $r_{k,l-1}$ are 1, then the adjacent height layer is formed by the contrail and then the height layer is not converted. The flow chart is shown in Fig. 6.

Comparison between the optimized flight profile and the original flight profile is shown in Fig. 7. The real-time position report shows that CA1336 began to reach the altitude of 10700 m from Chenzhou. Route points are: Changsha–Yueyang–Wuhan–Zhumadian–Zhengzhou–Handan–Tianjin–Chenzhou. It does not form the contrail due to the height of the arrival of Tianjin has been reduced to 5090 m and there is no need to optimize the height of the route point. Therefore, it is only necessary to optimize the remaining 7 point height and the height of the optimized layer are: 10700 m–10700 m–10700 m–10100 m–9500 m–9500 m–8900 m. Comparison of global surface temperature changes before and after CA1336 trajectory optimization is shown in Table 7.

It can be seen from Table 7 that the use of a high degree of adjustment can reduce the global surface temperature changes greatly. The global surface temperature changes are different at different time levels. Global surface temperature decreases at 36.39 %, 13.98 % and 11.21 % in 25, 50 and 100 years, respectively.

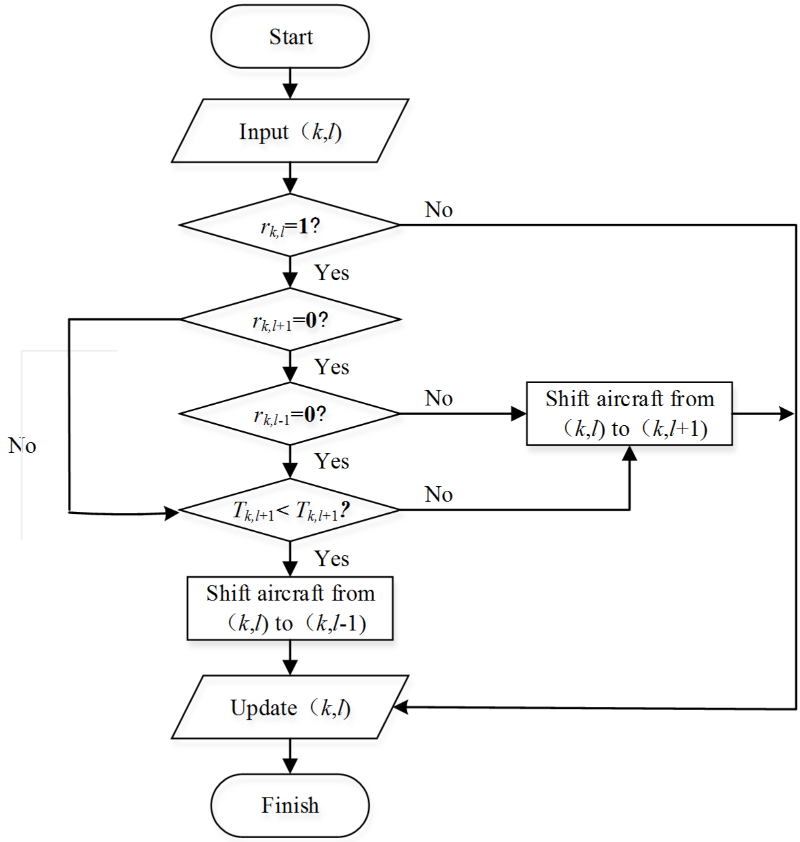

Fig. 6. Flow chart of aircraft trajectory optimization

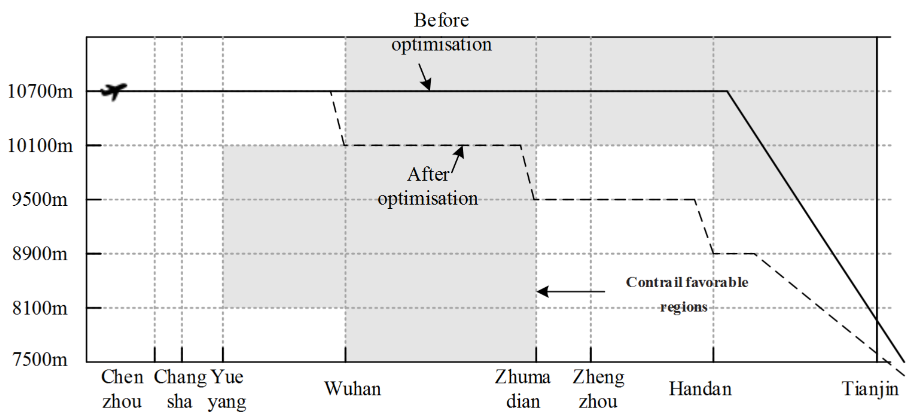

Fig. 7. The flight profile comparison before and after optimization

Table 7. The global temperature change due to flight CA1336 at different time horizons

	$H = 25$	$H = 50$	$H = 100$
The global temperature change due to flight CA1336 before optimization (K)	3.52×10^{-11}	1.72×10^{-11}	1.46×10^{-11}
The global temperature change due to flight CA1336 after optimization (K)	2.24×10^{-11}	1.48×10^{-11}	1.29×10^{-11}
The change rate of global temperature after optimization	-36.39 %	-13.98 %	-11.21 %

5. Conclusion

Aircraft altitude layer optimization is studied by using simulation and optimization algorithms based on the model of the contrail generation and the linear climate relying on the Guangzhou–Beijing route sounding data and flight data in order to reduce the impact of air transport on the environment. The main conclusions of this paper are as follows:

(1) The effect of the condensation and CO_2 emission on the environment is different at each time level, which causes that the global surface temperature increase is also different, but the reduction of the contrail formation plays a major role in reducing the greenhouse effect.

(2) The height of the flight after optimization are: 10700 m-10700 m-10700 m-10100 m-9500 m-9500 m-8900 m. The optimized height layer can eliminate the contrail by reducing the cruise height and reach to the economical cruising altitude as close as possible in order to reduce the influence of the aircraft operation on the global temperature change.

(3) The use of a high degree of adjustment can reduce the global surface temperature change greatly, and the different time levels of the global surface temperature change are different. The global surface temperature decreases by 36.39 %, 13.98 % and 11.21 %, respectively, within 25 years, 50 years and 100 years.

The aircraft trajectory optimization problem is studied and some useful conclusions are obtained combining with the simulation data. But in view of the complexity of the problem, the following issues needed further research: to deepen the research of multi-flight collaborative operation trajectory optimization, to consider the limit of the actual operation, such as route capacity and airspace structure, and to carry out the optimization research on the rising and falling stage of the aircraft trajectory.

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