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ECOLOGICAL OPTIMIZATION OF JET AIRCRAFT FLIGHTS IN VIEW OF CONTRAILS AND CONTRAIL CIRRUS FORMATION

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Keywords: *contrails, contrail cirrus, ecological optimization*

Abstract

Presented in the paper are the results of research carried out in the Gromov flight Research Institute (GFRI) in 2004…2013 on elaboration and approbation of calculation-experimental methodic of evaluation and prediction of formation and existence of condensation trails (contrails) and condensation cirrus clouds during flights of civil aviation jet aircraft and of methodology of ecological optimization of particular aircraft flights on concrete flight routes.

As a result of the research conducted there were obtained and approved the quantitative indices determining a necessary and sufficient conditions of contrails and contrail cirrus formation and existence enabling to evaluate and forecast the ecological optimization of aircraft flights planning along particular flight routes with the aim to reduce the linear contrails (LC) and aviation induced cirrus clouds (AIC) harmful influence on the Earth heat exchange – "greenhouse effect".

1 Quantitative indices, defining the necessary and sufficient conditions of contrails and contrail cirrus formation and existence. Ecological optimization of flights

- *LC* formation boundary altitude (H_b) for concrete aircraft $H_b=f(T_{amb},\varphi_{amb})$ in different atmospheric conditions (ambient air temperature $T_{amb}(H)$ and relative humidity $\varphi_{amb}(H)$ at the altitude *H*) with account of experimental data.
- Deviations of daily and averaged temperature values $T_{amb}(H)$ and relative humidity $\varphi_{amb}(H)$ versus altitude at particular parts of flight route with accounting of time of the year and time of the day.
- Intensity of *LC* and *AIC* formation from concrete aircraft during the day on a particular part of the flight route.
- Air traffic density on a particular part of the flight route, which is defined by the number of aircraft flying through this space versus time of the day.
- *AIC* existence duration (τ_{eAIC}), defined by the time period when ambient air relative humidity is kept ≥100% towards ice (~ 60% towards water) on particular part of flight route.
- Amount of *AIC* from concrete aircraft at a particular flight route during the daytime and night which defines *AIC* influence on the Earth heating and cooling with account of air traffic density on this route.

2 The possibilities of the developed technique implementation

For reliable estimation and prognosis of *LC* and *AIC* formation and existence during specific aircraft flights and carrying out of possible optimization of flights planning on concrete flight routes it was fulfilled:

- Matching of determined contrails formation boundary values $H_b=f(T_{amb},\varphi_{amb})$ for concrete aircraft with experimental data.

Determination of contrails formation boundaries was performed according to GFRI technique with utilization of particular engine characteristics and math model of the flow fields at two-dimensional mixing of engine exhaust jet and atmosphere with account of engine nacelle overflow and velocity of mixed stream variation along mixing distance. The "mixing line" of exhaust jet and atmosphere was proved to be analogous to the "straight line" for uniform mixing for bypath jet engines with various bypath ratio [1], [2]. As quantitative criterion of contrails formation it was used the index of total supersaturation of vapor (h_Σ) towards water comprising two terms:

$$h_\Sigma = h_m + \varphi_{amb} \qquad (1)$$

where:

h_m – maximum humidity supersaturation index towards water while mixing of exhaust jet with «dry» atmosphere (φ_{amb} = 0), depending from engine characteristics, ambient temperature and pressure (flight altitude);

φ_{amb} – partial pressure of water vapor in the atmosphere at flight altitude.

Calculated value of the boundary altitude $H_{b_{calc}} = f(T_{amb},\varphi_{amb})$ was determined from condition of equality to zero of total maximum vapor supersaturation index ($h_\Sigma = 0$), what corresponds to experimental results obtained in flying test-bed Tu-154M FTB and observations of contrails formation from civil aircraft at international routes in Moscow region (see Figure 1, Table 1). Calculations were performed for the case of ambient air temperature (T_{amb}) to be equal to the value corresponding to the International Standard Atmosphere (T_{ISA}).

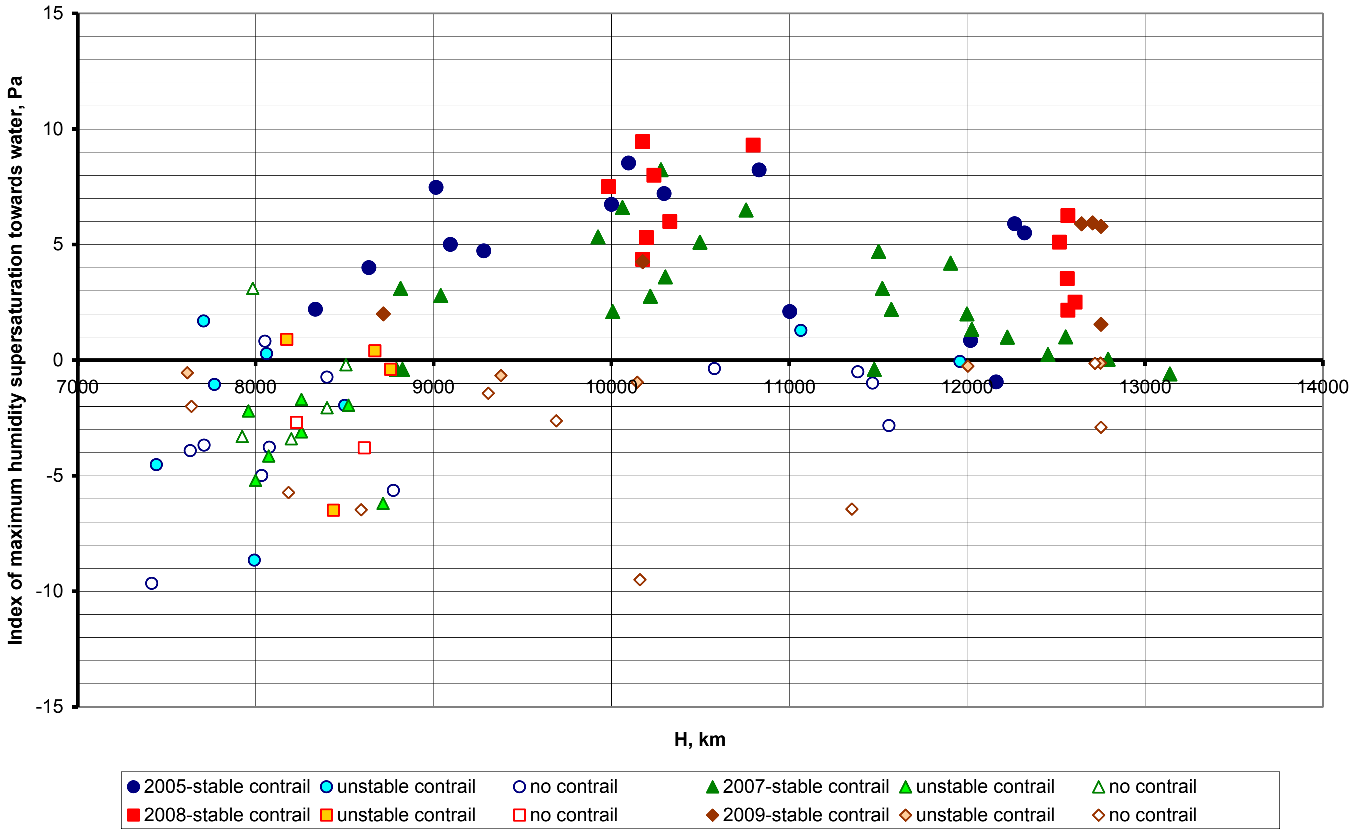

Fig. 1. Variation of maximum humidity supersaturation index h_{Σ} [Pa] versus flight altitude for Tu-154M FTB with D-30KU engines for the cases: Stable *LC*; Unstable *LC* (just formed only); No *LC* (*LC* disappears quickly).

Table 1. Values of $H_{b_{calc}}$ and $H_{b_{exp}}$, obtained for T_{amb} = T_{ISA} and φ_{amb} = 60% towards water.

Aircraft	**Engine Type**	$H_{b_{calc}}$ **km**	$H_{b_{exp}}$ **km**
Tu-154	D-30KU	10,125	10,2
Yak-42	D-36	9,6	9,35
B777	GE90-94B	9,175	9,1
B747	PW4056	9,385	9,5
B747	RB211-524G/H	9,84	9,7
B767	PW4056	9,385	9,15
B757	RB211-524G/H	9,84	9,35
A310, 330	CF6-80	9,45	9,35
B737	CFM56-5B1	9,45	9,85
A340	CFM56-5C4	9,8	
A319	CFM56-5B1	9,45	9,63
A320	CFM56-5B1	9,45	9,65

Analysis of the flight experiment and observations data have revealed that calculated values of $H_{b_{calc}}$ for particular aircraft (Tu-154M, B777, B747, B767, B757, B737, A310, A330, A319, A320, A321, A340) at standard temperature T_{ISA} and relative humidity φ_{amb}=60% towards water practically correspond to experimental values $H_{b_{exp}}$.

- To obtain reliable information on real atmospheric conditions of aircraft operations it was carried out the assessment of atmospheric conditions variations (temperature $T_{amb}(H)$ and relative humidity $\varphi_{amb}(H)$) for altitude range H=8…12 km utilizing data presented in the manual "Global Reference Atmosphere for Altitudes 0 – 120 km for Aerospace Application" [3] and radiosondes measurements.

Evaluations of $T_{amb}(H)$ and $\varphi_{amb}(H)$ variations (daily, seasonal, and annual) based on radiosondes data (year 2008; time of the day - 0, 6, 12 and 18 o'clock) were performed for chosen points of flight routes (a route, passing along latitude ≈N45…55° and the route from North Pole through equator (Bangui) till South Pole) at altitude range H=8…12 km. Examples of average annual atmospheric conditions variations versus altitude in some points of these routes are presented in Figures 2…4.

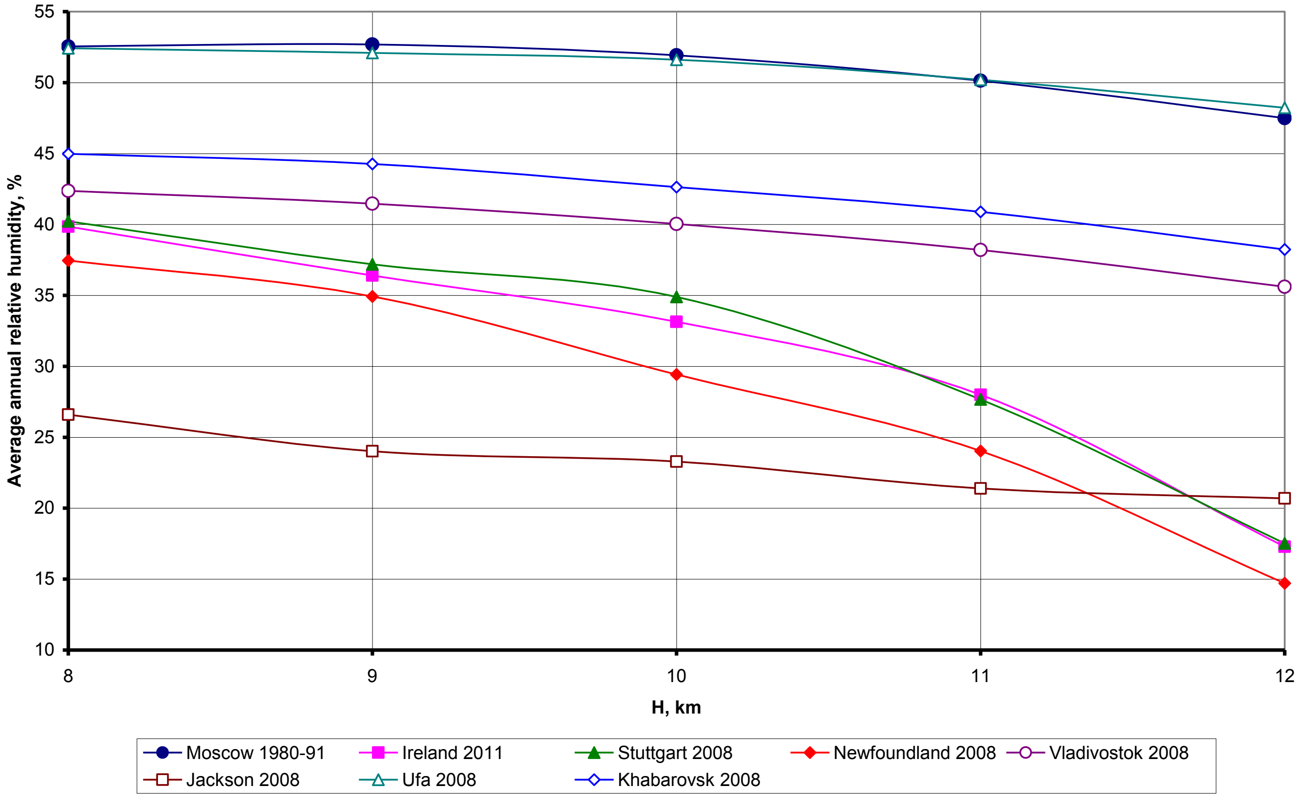

Fig. 2. Variations of average annual relative humidity at 0 o'clock GMT at the route "Stuttgart - Vladivostok" versus altitude.

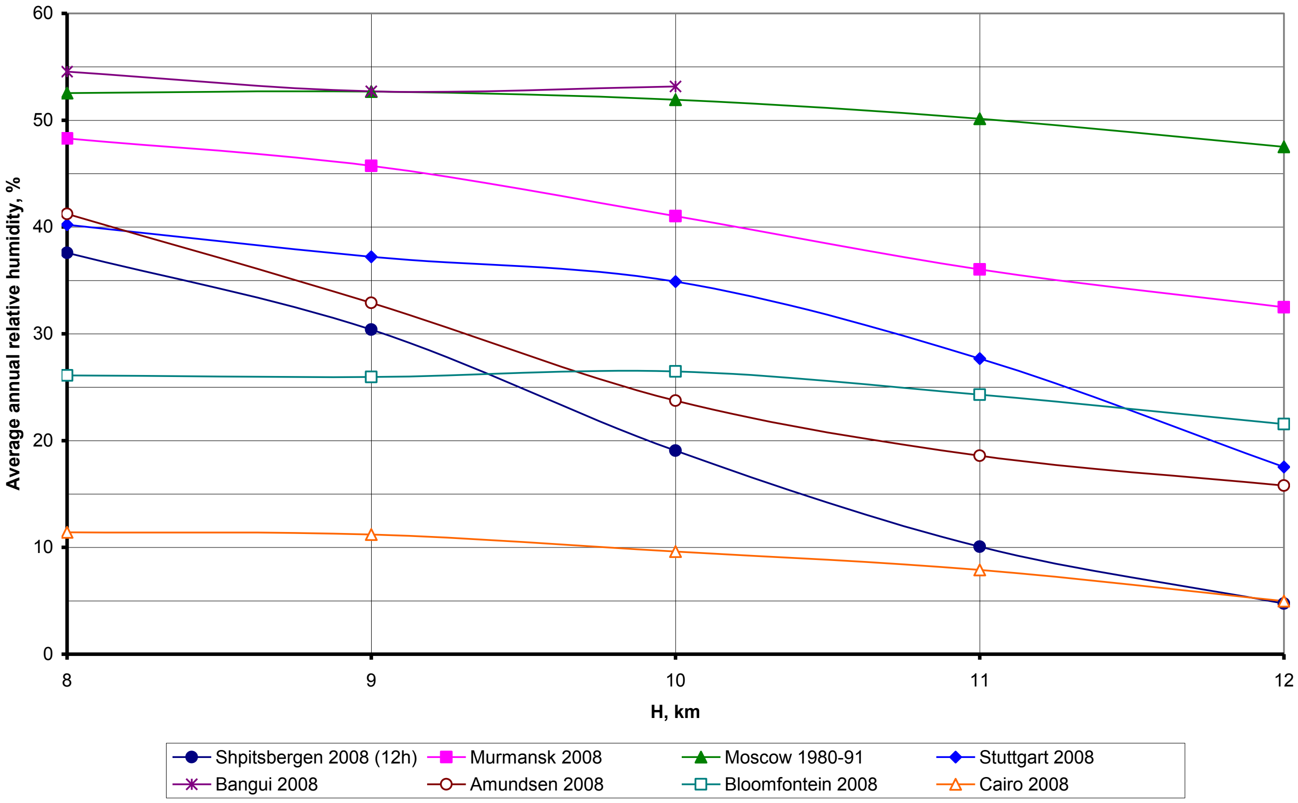

Fig. 3. Variations of average annual values of relative humidity in the route "Spitsbergen-Amundsen".

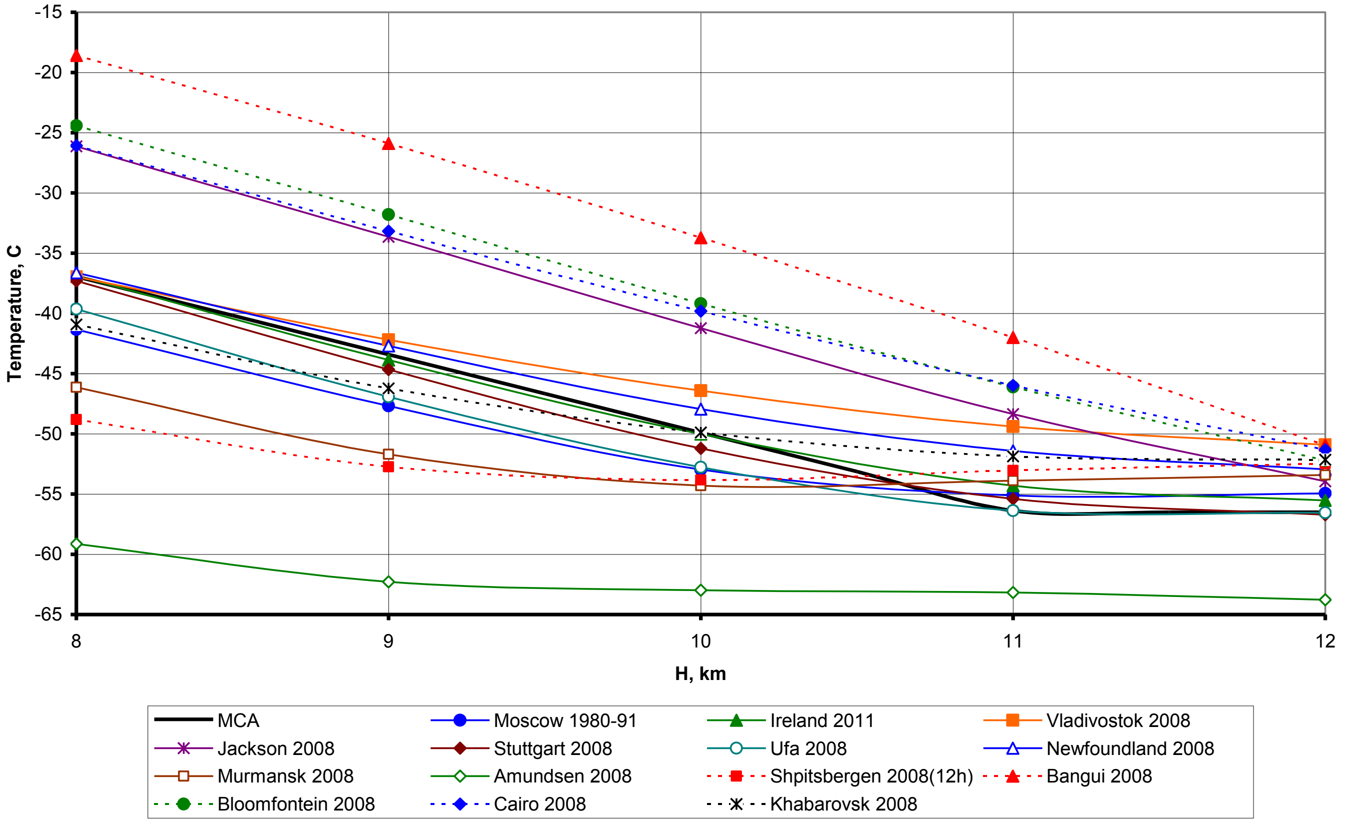

Fig. 4. Variations of average annual values of ambient air temperature in some points of the chosen routes.

The analysis of atmospheric conditions variations in some points of the routes has shown the following:

- Magnitudes of averaged values of ambient air temperature at constant altitude *H*=const depend upon the region (part of the route), time of the year and almost don't change versus time of the day (±0,5°C - average annual values; ±1,5°C – daily);
- Magnitudes of averaged values of ambient air relative humidity at constant altitude *H*=const depend on the region (part of the route), time of the year and time of the day (change with a period of 24 hours). At the same time averaged values of relative humidity generally don't exceed 100% towards ice (60% towards water) what prevents from determination of *AIC* formation ($\varphi_{amb} \geq 100\%$ towards ice). That's why the assessment of *AIC* formation intensity was carried out with the use of relative humidity daily measurements.

Presence of quantitative indices of *LC* formation boundaries for concrete aircraft and $T_{amb}(H)$ and $\varphi_{amb}(H)$ variations on particular part of the route makes it possible to evaluate the intensity of *LC* and *AIC* formation (average monthly and average annual number of days, %) and existence (time τ_{ex}, hours) versus time of the day for given altitude.

Comparative variations of *LC* and *AIC* formation intensity for B777 aircraft versus time of the day over Moscow and Valencia (Ireland) at altitudes 9…12 km are shown on the Figures 5 and 6.

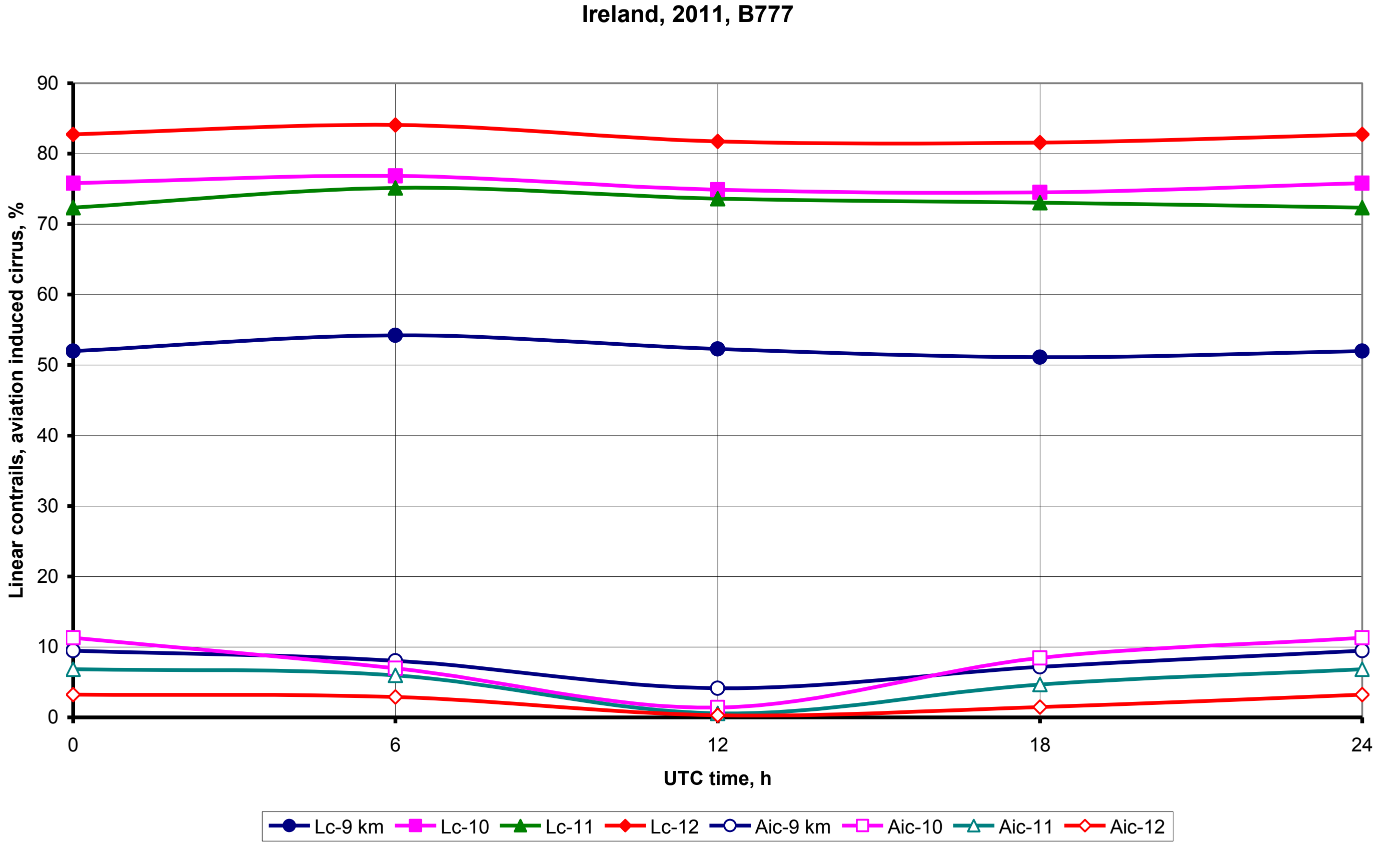

Fig. 5. Variations of average annual number of days with *LC* and *AIC* from B777 over Valencia (Ireland) for altitudes 9…12 km versus time of the day in 2011.

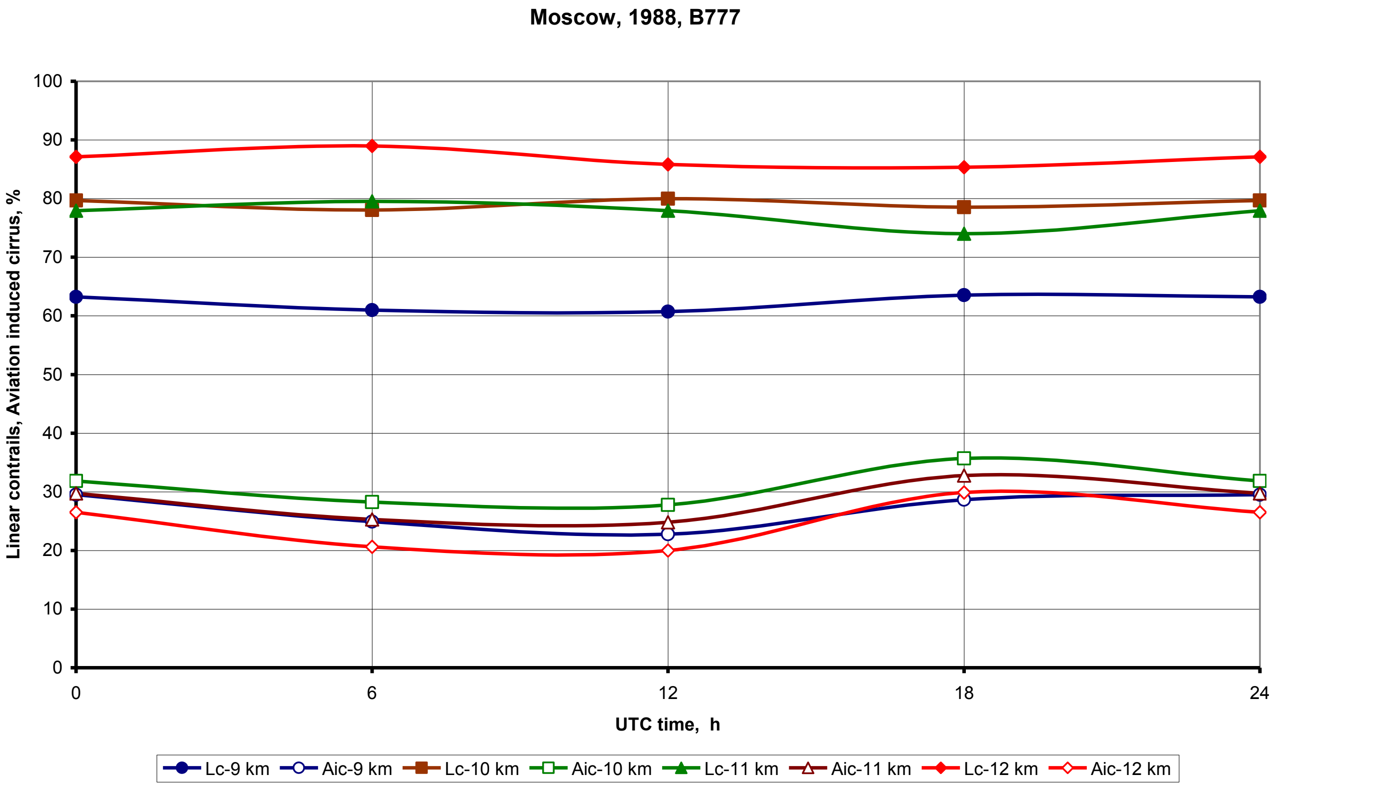

Fig. 6. Variations of average annual number of days with *LC* and *AIC* from B777 over Moscow for altitudes 9…12 km versus time of the day in 1988.

Aircraft wake vortex may influence engine LC formation and existence in different atmospheric conditions. The stable long existent LC could occur if engine exhaust jet is mixed with aircraft wake vortex and is captured by it nucleus. Interaction of wake vortex with LC could result in either LC destruction if formed LC is captured by external flow of wake vortex or LC preservation if it penetrates into internal area of the wake. LC penetrations into wake vortex nuclei most frequently take place for aircraft with 4 engines installed on the wings.

3 Assessment of the possibility of flight planning optimization for particular aircraft in view of greenhouse effect diminishing

3.1 Technique [4]

The following is sequentially calculated:

- average annual (average monthly) number of days when *AIC* are formed at given part of the flight route for specified aircraft type with account of air traffic density:

$$A(\tau) = D_{AIC}(\tau) \cdot N(\tau) \qquad (2)$$

Where:

τ - time of the day, [o'clock];

$N(\tau)$ – air traffic density versus time of the day at given part of the flight route, [number of flights / (km·h)]

- average annual (average monthly) amount of formed *AIC* versus time of the day under condition that *AIC* don't disappear during time period ($\tau_1 \; ... \; \tau_i$) at given altitude (S_{fAIC}, [% of days·number of flights/km]):

$$S_{fAIC}(\tau) = \int_{\tau_1}^{\tau_i} A(\tau) d\tau \qquad (3)$$

- average annual (average monthly) amount of disappeared *AIC* versus time of the day at given altitude, i.e. *AIC* were formed and then disappeared after definite time period τ_{exAIC}:

$$S_{dAIC}(\tau) = \int_{\tau_1}^{\tau_i} A(\tau - \tau_{exAIC}) d\tau \qquad (4)$$

- average annual (average monthly) amount of existing *AIC* versus time of the day at given altitude under condition that *AIC* have formed and are existing for a definite time period τ_{exAIC}:

$$S_{exAIC}(\tau) = S_{fAIC}(\tau) - S_{dAIC}(\tau) \qquad (5)$$

Next there are determined the parameters of heat exchange due to *AIC* presence at given part of flight route for aircraft of specified type on definite altitude with account of air traffic density. For that purpose there are calculated the following: average annual (average monthly) amount of existing *AIC* during day time – quantitative parameter of the Earth cooling ($P_{exAICday}$, [% of days·number of flights·hour/km]) due to *AIC* presence and average annual (average monthly) amount of existing *AIC* during night time – quantitative parameter of the Earth heating ($P_{exAICnight}$) due to *AIC* presence under condition that *AIC* formed and exist for a definite time period τ_{exAIC}:

$$P_{exAICday} = \int_{\tau 1}^{\tau 2} S_{exAIC}(\tau) d\tau \qquad (6)$$

Where τ_1 and τ_2 – the beginning and the end of day time;

$$P_{exAICnight} = \int_{\tau 3}^{\tau 4} S_{exAIC}(\tau) d\tau \qquad (7)$$

Where τ_3 and τ_4 – the beginning and the end of night time;

$$P_{exAICtotal} = P_{exAICday} + P_{exAICnight} \qquad (8)$$

Calculated quantitative indices of *AIC* availability during the day define formed *AIC* influence on the Earth cooling and heating and possibility of ecological optimization of annual (monthly) flight schedule planning with account of minimization of greenhouse effect due to *LC* and *AIC* formation and existence from aircraft with jet engine of particular type at civil aircraft cruse flights altitudes on specified parts of flight routes.

3.2 Technique approbation

As an example of the technique approbation here are considered the values of quantitative indices of *AIC* availability during the day from B777 aircraft with GE90-94B engine at the altitude H = 11 km over Valencia city (Ireland). These indices are expressed by amount of existing *AIC* during day and night time with account of air traffic density and *AIC* existence time. The indices under consideration are applied for assessment of possible ecological optimization of daily aircraft flights in view of greenhouse effect minimization.

Air traffic density ($N_{ini}(\tau)$ – initial air traffic density, see Figure 7) presented in this example corresponds to air traffic density in the part of the route over North Atlantic with coordinates: 45°W-10°W, 45°N-55°N [5].

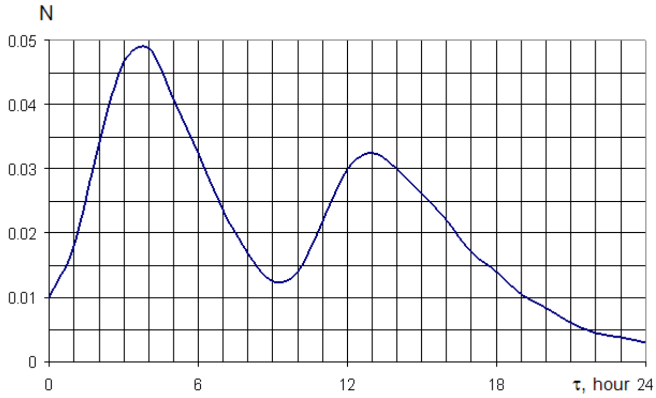

Fig. 7. Variation of initial air traffic density $N_{ini}(\tau)$ (number of flights / km·h) versus time of the day.

Quantitative indices of *LC* formation boundary altitude H_b for aircraft under consideration versus ambient air temperature deviations from standard atmosphere values $\Delta T_{amb\,b} = T_{amb} - T_{ambISA}$ and values of ambient air relative humidity in the range of φ_{amb} = 0…100% are depicted in the Figure 8.

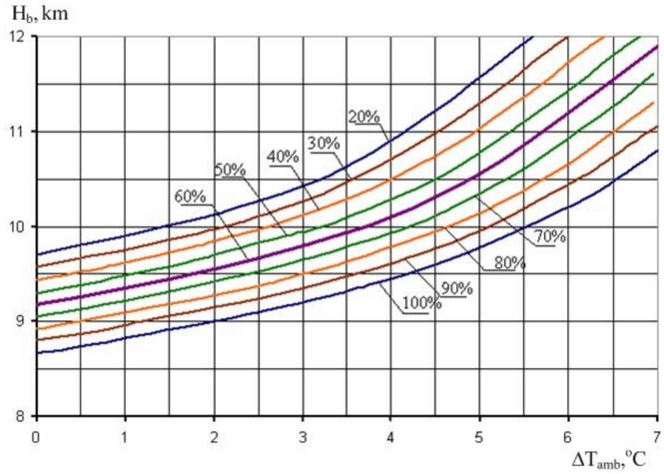

Fig. 8. Determination of $H_b = f(\Delta T_{amb_b}, \varphi_{amb})$ for B777 aircraft.

Results of daily temperature ($T_{amb_{daily}}$) and relative humidity ($\varphi_{amb_{daily}}$) measurements carried out by radiosondes (4 times a day at 0, 6, 12, 18 o'clock GMT) during year 2011 were considered. Basing on these data there were determined deviations of daily values of temperatures ($\Delta T_{amb_{daily}}$) from standard values ($T_{amb_{ISA}}$) and relative humidity ($\Delta\varphi_{amb_{daily}}$) from 60% towards water:

$$\Delta T_{amb_{daily}} = T_{amb_{daily}} - T_{amb_{ISA}} \quad (9)$$

$$\Delta\varphi_{amb_{daily}} = \varphi_{amb_{daily}} - \varphi_{amb_{ISA}} \quad (10)$$

at this altitude at 0, 6, 12, 18 o'clock GMT for each day of radiosondes launches. Next the following data were calculated:

- number of days in the year ($D\varphi$, [% of days]) with humidity $\varphi_{amb} > 60\%$;
- number of days in the year with *LC* (D_{LC} [% of days]);
- number of days in the year with *AIC* (D_{AIC} [% of days]);

Results of these calculations are shown in Figures 9…11.

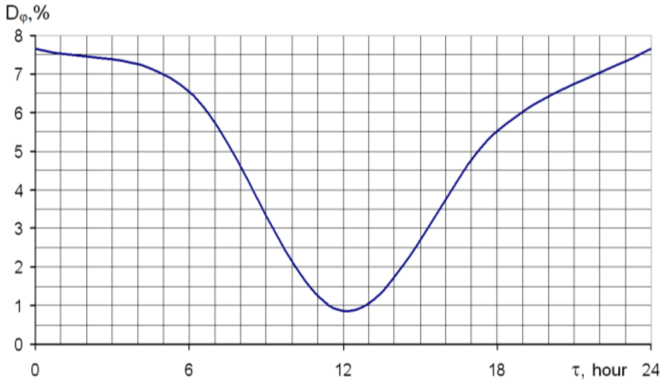

Fig. 9. Variation of average annual number of days with relative humidity more than 60% ($D\varphi(\tau)$, [% of days]) at chosen hours for altitude H = 11 km in chosen part of the flight route.

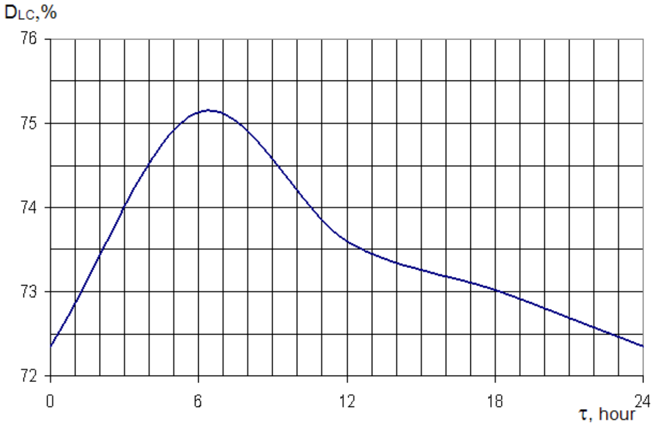

Fig. 10. Variation of average annual number of days with *LC* (D_{LC} [% of days]) at chosen hours for altitude H = 11 km in chosen part of the flight route.

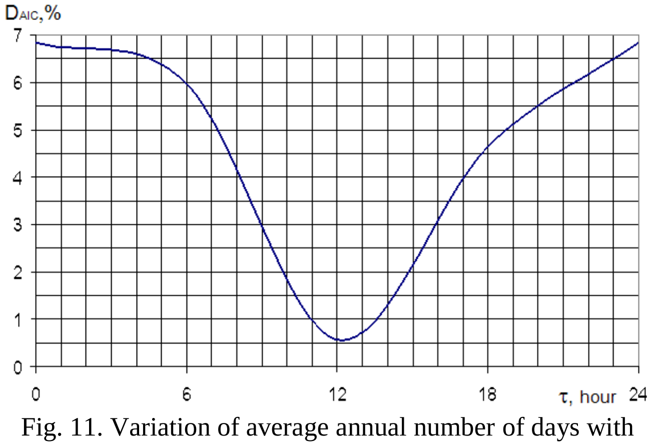

Fig. 11. Variation of average annual number of days with *AIC* (D_{AIC} [% of days]) at chosen hours for altitude H = 11 km in chosen part of the flight route.

Then there were calculated the average annual numbers of days with *AIC* in dependence from time of the day at the altitude H = 11 km with account of initial air traffic density (Fig. 7) at this part of the flight route using the formula (2), where τ - time of the day (0, 6, 12, 18 o'clock).

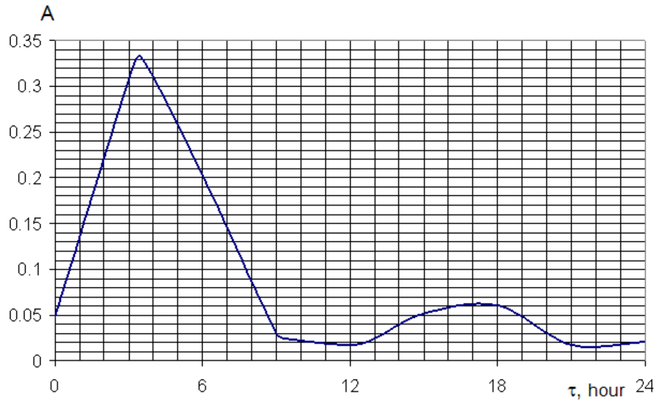

Figure 12. Variation of average annual number of days with *AIC* at chosen part of the flight route A(τ) [(% of days)·number of flights / km·h] with account of initial air traffic density at this part of the route at chosen hours for altitude H = 11 km.

Calculation results on assessment of quantitative indices of *AIC* availability versus time of the day for it existence time 4 hours (in accordance with the evaluation performed the *AIC* existence time generally is less than 6 hours) for initial air traffic density ($N_{ini}(\tau)$) and air traffic densities shifted for 3 ($N_1(\tau)$) and 6 ($N_2(\tau)$) hours in case of equal duration of day time and night time are presented in Figures 13 and 14 and Tables 2 and 3.

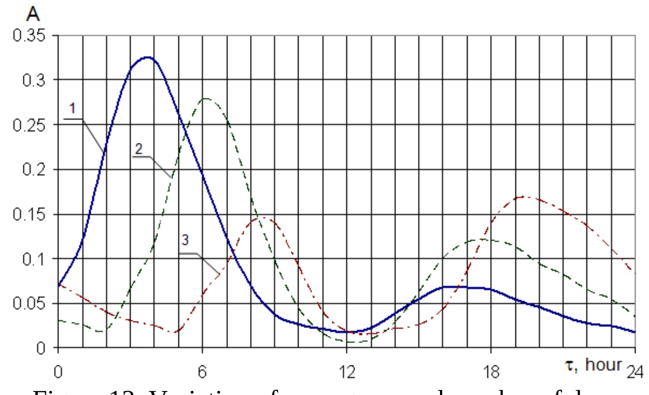

Figure 13. Variation of average annual number of days with *AIC* at chosen part of the flight route A(τ) [(% of days)·(number of flights) / km·h] with account of initial air traffic density at this part of the route at chosen hours for altitude H = 11 km (curve 1) and air traffic densities shifted for 3 (curve 2) and 6 (curve 3) hours.

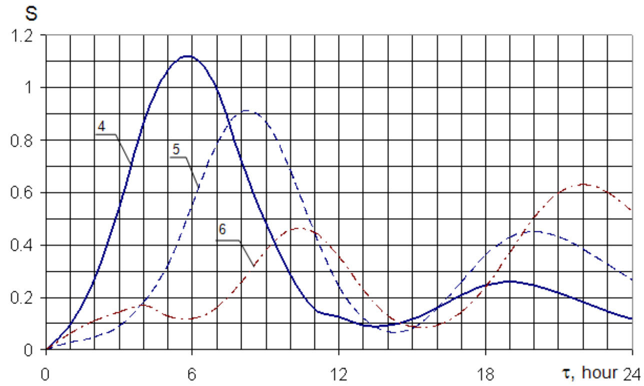

Figure 14. Variation of average annual amount of existing *AIC* ($S_{exAIC}(\tau)$ [(% of days)·number of flights / km]) at chosen hours for altitude H = 11 km in chosen part of the flight route for air traffic densities $N_{ini}(\tau)$ (curve 4), $N_1(\tau)$ (curve 5) and $N_2(\tau)$ (curve 6) under condition that *AIC* have been formed and existed for 4 hours.

Table 2. Values of quantitative indices of *AIC* availability for initial and shifted air traffic densities.

Air traffic density $N(\tau)$	$P_{exAICday}$	$P_{exAICnight}$	$P_{exAICtotal}$
	(% of days)·(number of flights)·hour/km		
$N_{ini}(\tau)$	4,089	4,632	8,721
$N_1(\tau)$	5,034	3,242	8,276
$N_2(\tau)$	2,857	3,749	6,606

Table 3. Change of quantitative indices of *AIC* availability for initial and shifted air traffic densities.

$\frac{P_{exAICtotal}(N_1(\tau))}{P_{exAICtotal}(N_{ini}(\tau))}$	$\frac{P_{exAICtotal}(N_2(\tau))}{P_{exAICtotal}(N_{ini}(\tau))}$	$\frac{P_{exAICday}(N_{ini}(\tau))}{P_{exAICnight}(N_{ini}(\tau))}$	$\frac{P_{exAICday}(N_1(\tau))}{P_{exAICnight}(N_1(\tau))}$	$\frac{P_{exAICday}(N_2(\tau))}{P_{exAICnight}(N_2(\tau))}$
0,95	0,76	0,88	1,55	0,76

As it follows from the Tables 2 and 3 the change of air traffic density at maintaining the total daily number of flights could result in changing of daily ($P_{exAICtotal}$), day ($P_{exAICday}$) and night ($P_{exAICnight}$) amounts of existing *AIC*:

- amounts of $P_{exAICtotal}$ for initial and shifted for 3 hours air traffic densities $N_{ini}(\tau)$ and $N_1(\tau)$ are almost equal, shift of air traffic density for 6 hours results in $P_{exAICtotal}$ diminishing for 24%;
- amount of $P_{exAICday}$ which determines reduction of the Earth heating, for initial and shifted for 6 hours air traffic densities ($N_{ini}(\tau)$ and $N_2(\tau)$) is less than amount of $P_{exAICnight}$ which determines reduction of the Earth cooling. The values of it relation are 0,88 and 0,76 correspondingly (i.e. < 1) as it follows from the Table3. The amount $P_{exAICday}$ is greater than the amount $P_{exAICnight}$ for 55% for air traffic density shifted for 3 hours.

These data demonstrate the possibilities to reduce the “greenhouse” effect from *AIC* formation because of their influence on the Earth cooling during day time (at air traffic density shifted for 3 hours – $N_2(\tau)$) that was noted earlier in [6].

4 Conclusions

The technique developed makes it possible under condition of availability of the following valid information on:

- characteristics of particular aircraft (engines);
- atmospheric conditions (daily, average monthly and average annual dependences of air temperature and relative humidity versus altitude and time of the day) along concrete flight route;
- air traffic density along flight route;
- time of *AIC* existence

to perform with utilization of quantitative indices developed the evaluation and prognosis of *LC* and *AIC* formation and existence and to conduct the ecological optimization of flights planning along particular flight routes with the aim of diminishing of harmful influence of *LC* and *AIC* on the Earth heat exchange – “greenhouse effect”.

For ecological optimization of aircraft flights with utilization of the quantitative indices it is necessary to have the reliable long-term prognosis of atmospheric conditions variations determining *AIC* existence ($\varphi_{amb_{daily}} \geq$ 100% towards ice) along flight routes of concrete aircraft flights.

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