GASP Cloud Encounter Statistics: Implications for Laminar Flow Control Flight

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The entire cloud observation archive (88,000 samples) from the NASA Global Atmospheric Sampling Program (GASP), which was conducted in 1975 1979 aboard four commercial Boeing 747 airliners, has been analyzed to obtain summary statistics on the probability of cloud encounter at commercial airliner altitudes, for application in determining the feasibility of employing laminar flow control (LFC) on long range airline routes The probability of cloud encounter is found to vary significantly with altitude latitude and distance from the tropopause, but less significantly with season Several meteorological circulation features, such as the in tertropical convergence zone are apparent in the latitudinal distribution of cloud cover The cloud encounter statistics are shown to be consistent with the classical midlatitude cyclone model with more clouds encountered in highs than in lows Observations of clouds spaced more closely than 90 min are found to be statistically dependent The observations of route averaged time in clouds are found to fit a gamma probability distribution model, which is applied to estimate the probability of extended cloud encounter and the associated loss of LFC effectiveness along seven high density routes The probability is shown to be low

Nomenclature

CIV	= fraction of observations having clouds in vicinity
GASP	= Global Atmospheric Sampling Program
ITCZ	= Intertropical Convergence Zone
JFK	= John F Kennedy International Airport New York
LFC	= laminar flow control
LHR	= London Heathrow International Airport
NMC	= National Meteorological Center
p	= probability
t	= variable of integration
TIC	= fraction of time-in clouds during one ob servation
TIC_f	= average fraction of time in clouds on one given flight along a route
TIC_R	= $\overline{TIC_F}$ = average fraction of time in clouds in a sample of flights along a route
TICIV	= fraction of time actually in clouds during a 256 s cloud detection observation, defined for observa tions having TIC > 0
x	= value of TIC_F in limit of integration [see Eq (3)]
Γ	= gamma function
ζ	= relative vorticity
η	= parameter in gamma probability density function

Introduction

THE purpose of this paper is to present results of analysis of all cloud encounter measurements taken at aircraft flight altitudes as part of the Global Atmospheric Sampling Program (GASP) This paper extends and generalizes the preliminary results given in Nastrom et al [1 2] which were based on a fraction of the GASP data used here The primary motivation for this study is the evidence that the low drag characteristics of laminar flow control (LFC) wings are also lost (albeit temporarily) whenever visible clouds are en countered, and are lost occasionally in cirrus hazes, thereby influencing the economic feasibility of LFC winged air craft [3 4] The research reported here lies within the context of the first of a two part research effort by the NASA to assess the inpact of cloud particles on LFC performance In the first part a climatology of cloud/particle encounters is being developed to address the fundamental questions: What is the probability of cloud encounter on airline routes and what is its variability with altitude season, and location? These climatological data, together with theoretical estimates of the effect of ice crystals on LFC (Ref 4) and USAF data from cirrus cloud particle measurement missions [5 6] have already been used in making preliminary estimates of the portion of time that LFC would be lost in clouds and clear air [7] In the second part of the research effort, the NASA will make precise in situ measurements of the cloud particle en vironment on flights of an LFC winged research aircraft in an attempt to quantify better the effects of clouds on LFC (Ref 8)

The location of clouds and their extent are of interest for several meteorological reasons as well, such as the Earth's radiation balance[9] and the long term (climatic) variations of global temperature;[10 11] thus both the meteorological and LFC applications aspects of cloud encounter results are discussed here This paper begins by describing the data set used in this study and then discuses its climatology in relation to features of the atmospheric circulation We believe this to be the most complete set of cloud encounter data available at aircraft flight altitudes Next the relationship between cloud encounter statistics and relative vorticity is presented and discussed Last a simple empirical model which can be used to estimate the percentage of time that clouds will be en countered along several airline routes is presented and discussed

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Data

The data in this study were collected as part of the NASA Global Atmospheric Sampling Program (GASP) and have been discussed in detail in earlier reports [1 2] Briefly the data acquisition phase of GASP lasted from March 1975 to July 1979 and obtained meteorological and trace constituent data with instruments placed aboard as many as four Boeing 747 airliners in routine commercial service Data collected on these flights should thus be representative of conditions encountered by commercial airliners Observations were recorded at nominal 5 or 10 min intervals at all altitudes above about 20 kft (6 km) Each observation contains the number of seconds, out of the preceding 256 s, that the air plane was "in cloud" The presence of clouds at cruise altitude was determined with a light scattering particle counter A cloud detection threshold was set based on visual observation of a light haze outside the aircraft The same threshold was used for all GASP instruments and resulted in an "in cloud" registration whenever the local aggregate particle number density (for all particles with diameters >3 μm) was greater than 66,000 m^{-3} Meteorological variables not measured by the GASP instruments such as tropopause height and relative vorticity were estimated from gridded analysis products obtained from the National Meteorological Center (NMC)

Before proceeding it is necessary to establish some nomenclature that will be used repeatedly in the analyses to follow First it is convenient to separate GASP observations according to whether the indicated time in clouds during the observation period was equal to or greater than zero The total indicated time in clouds divided by the total observation time gives the fraction of time in clouds (TIC) Those ob servations with TIC$=0$ are termed in clear, and those with TIC>0 (but not necessarily equal to 100%) are interpreted to be those with clouds in the vicinity (CIV) The time in clouds divided by the total observation time for only those ob servations with TIC>0 gives the fraction of time in clouds in the vicinity of clouds denoted TICIV These three quantities are related by the expression:

$$\mathrm{TIC} = \mathrm{CIV} \times \mathrm{TICIV} \tag{1}$$

All of the quantities are expressed as percentages in the analysis It should be noted that CIV is the same as the term P (TIC>0) used in some earlier reports [1 2 7]

Results

Cloud Climatology

Distribution of Observations

Approximately 88 000 cloud detector observations were made during the entire 4 year GASP measurement period Figure 1 shows how these observations are distributed with respect to season latitude height and distance from the tropopause The shaded area in each part of the figure represents the number of observations for which TIC>0 In each case the number above the upper (unshaded) bar represents CIV the percentage of observations within that bar for which TIC>0 This latter percentage is equal to the ratio of the shaded bar to the unshaded bar multiplied by 100

Figure 1a shows that the number of observations is weighted slightly toward winter and spring and that a higher percentage of clouds is observed in winter than in summer Figure 1b shows that most of the data are from the Northern Hemisphere middle latitudes, with approximately three quarters of the data coming from the latitudes 20 60 deg N CIV is seen to be a maximum near the Equator with values reaching 35% Almost 75% of the observations were made between 33 5 kft and 43 5 kft (10 21 and 13 26 km), as shown in Fig 1c The probability of cloudiness (CIV) tends to decrease with increasing height Figure 1d presents a stratification of the data by the distance from the tropopause The tropopause is the boundary between the troposphere where vertical motions are often large and the stratosphere a region of strong thermal stability The tropopause tends to act as a lid on the weather and cloud systems of the troposphere About 40% of the GASP observations come from within 5000 ft (1 52 km) of the tropopause CIV is relatively uniform below the tropopause, with a slight maximum in the region 5 10 kft (1 52 3 04 km) below but it decreases rapidly above the tropopause The number of observations in Fig 1d is smaller (70 000) because the NMC tropopause height was not available for some of the observations

Relation to Global Circulation Features

All of these cloud distribution patterns are consistent with other meteorological observations and global circulation models Most of the GASP cloud encounters occur in the

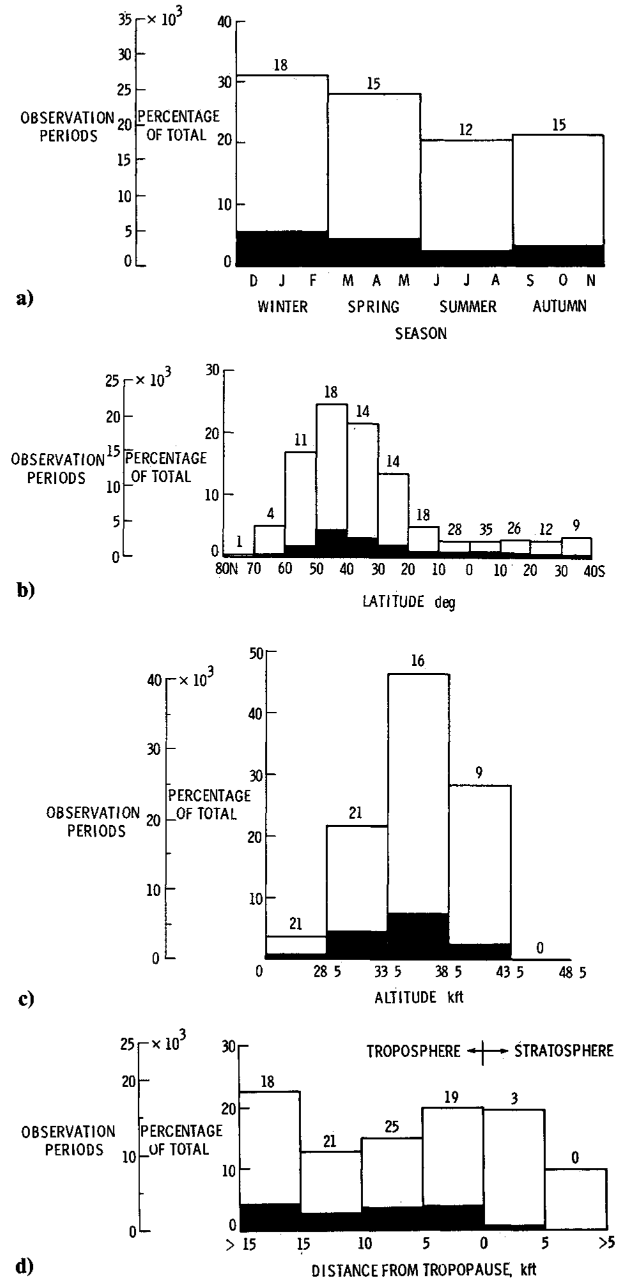

Fig 1 Distribution of cloud detector observations by a) season b) latitude, c) altitude and d) distance from the NMC tropopause Shading represents observations with TIC$>$0 Numbers above bars represent percentage CIV for each interval

upper troposphere, where the primary sources of clouds are extratropical cyclones and the glaciated (i.e., ice crystal) remnants of thunderstorms, which may persist long after the liquid portion of the clouds has evaporated. The higher incidence of cloud probability in the winter is a reflection of the higher frequency and larger areal extent of cyclones during this season.

The mean height of the tropopause ranges from about 25 kft (7.62 km) near the poles to 50 kft (15.24 km) at the Equator Thus, at high latitudes most of the GASP observations came from the stratosphere, while most observations at low latitudes were made in the troposphere. The relatively high values of CIV at low latitudes correspond to the presence of the Intertropical Convergence Zone (ITCZ) caused by the convergence of the Northern and Southern Hemisphere trade winds.[12] The clouds associated with the ITCZ are of the convective type and tend to form a concentrated, but by no means continuous, belt of clouds around the Earth. The subtropical high-pressure belt that is typically centered between 15 and 35 deg from the Equator is manifest in the minima in CIV in Fig. 1b. The local maximum in CIV between 40 deg N and 50 deg N is caused primarily by the clouds associated with the extratropical cyclones of midlatitudes.

During the course of the year the center of the general circulation shifts toward the summer hemisphere. This is illustrated in Fig. 2, which presents the GASP statistic CIV as a function of latitude for three height intervals in winter and in summer. In winter (Fig. 2a), the maximum equatorial cloudiness occurs between 5 deg N and 15 deg S. There is some dependence on height. The minimum cloudiness, associated with the subtropical highs, is at 15 deg N. The higher values of CIV centered around 45 deg N are associated with the midlatitude cyclones. The smaller values of CIV at the upper height ranges are due to the low wintertime tropopause and the fact that the aircraft were often in the cloud-free stratosphere.

Figure 2b shows that the maximum CIV has generally moved north of the Equator in the Northern Hemisphere summer. The plotted points with boxes around them represent fewer than 100 observations and can be regarded as being less reliable. The minimum in CIV has moved north to about 35 deg N, and the midlatitude cloudiness is less pronounced than in winter, probably due to the general lack of well-developed cyclones during summer. A larger proportion of the summer cloudiness at midlatitudes is due to the smaller-scale convective storms.

For additional analyses, similar to those just presented, of CIV and other GASP statistical quantities, comprehensive summaries of all the GASP cloud statistics, stratified by latitude, longitude, season, height, distance from the tropopause, and covering the portion of the data from December 1975 through December 1977 are available (see Ref. 1).

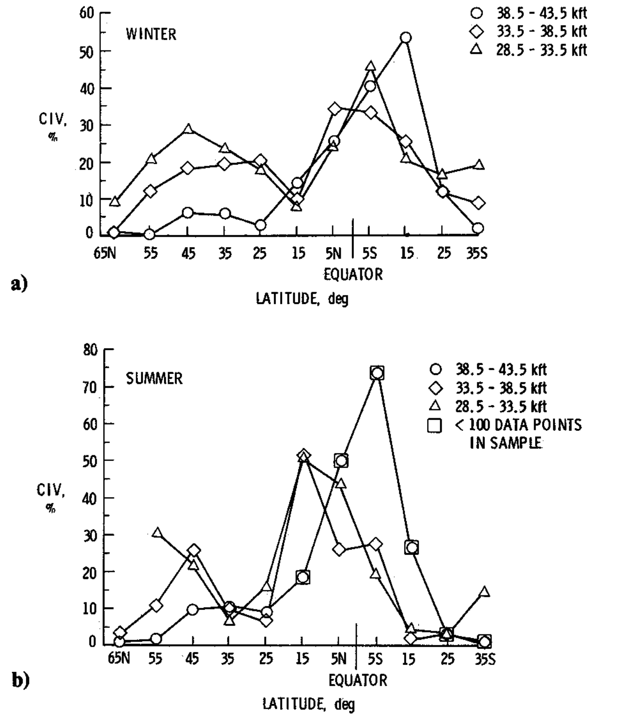

Fig. 2 Probability of cloud encounter as a function of latitude for three height intervals in a) winter and b) summer.

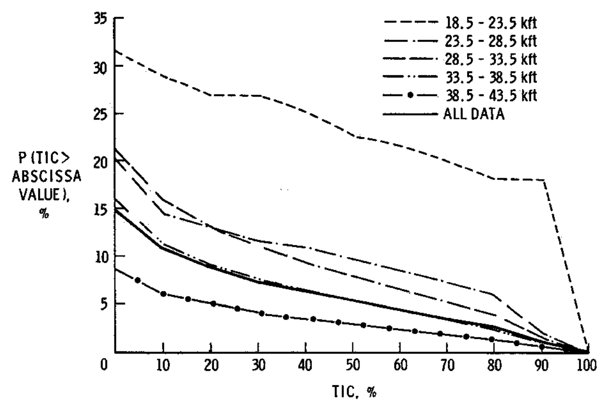

Fig. 3 Probability of exceedance of time-in-clouds values within three different altitude bands.

Analysis of Independence of Observations

Cloud encounter data are presented in this paper just as reported, with all observations given equal weight. Figure 3 presents the probability that any given TIC value will be exceeded in an observation, stratified by 5000-ft (1.52-km) altitude bands between 18.5 and 43.5 kft (5.64 and 13.26 km). From the figure, P(TIC>0) (the probability of cloud encounter itself) is seen to decrease from 32% for the 18.5-23.5-kft (5.64-7.16-km) band to around 8% for the 38.5-43.5-kft (11.73-13.26-km) band. From the curve for all data, it is seen that clouds are present in about 15% of the observations in the GASP cloud encounter archive, but that in only 7% of cases was TIC greater than 50%. Because general cloudiness (or the lack thereof) is associated with large-scale weather systems, clear and cloudy areas tend to have appreciable areal extent, i.e., successive observations are not independent.[2] In order to perform statistical significance tests with the cloud encounter data, the number of observations was reduced to account for this dependence, or "memory," between observations. Statistical analysis showed that, with respect to the presence of clouds, data separated by 90 min or more of flight time were independent.

Analysis of Statistical Significance of Zonal Mean Values

An analysis was performed on zonal mean values of TIC, TICIV and CIV to test for statistically significant variations as a function of season, latitude, and height (or distance from the tropopause). The methodology was an analysis-of-variance procedure[13] implemented through a well-proven software package.[14] The tests were performed using the number if independent observations from all three altitude bands as a parameter. The analysis was restricted to the latitude range 30-60 deg N, where this number was always greater than 90.

This analysis was performed with the data stratified by height; the following results were found:

1) Variations of TIC with respect to altitude, season, and latitude are significant at the 99% confidence level. Taken

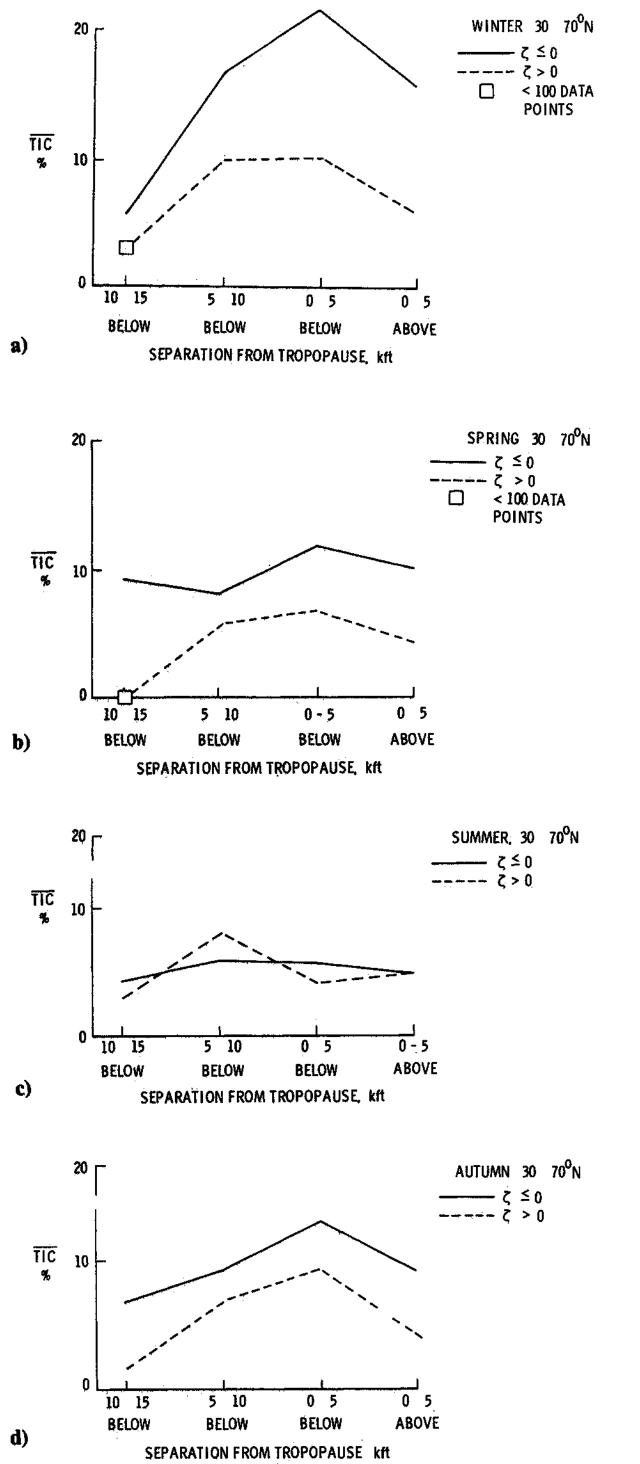

Fig. 4 Average time in-clouds in cyclones and anticyclones as a function of distance from the NMC tropopause in a) winter b) spring c) summer, and d) autumn

individually, the lowest values of TIC correspond to higher altitudes, to summer, and to latitudes poleward of 45 deg It is noted that, even though the equatorial areas were not included in this statistical testing due to small sample sizes, the data suggest that TIC increases with height in this region This is likely due to the high tropical tropopause, which is often several kilometers higher than the aircraft flight level This result is consistent with other studies,[15] which showed that cirrus consistently occurs 5 km or more beneath the tropical tropopause

2) Variations of CIV with respect to altitude and latitude are also significant at the 99% level The variation in CIV with respect to season, however is not significant at the 95% level The fact that the tropopause moves up and down through the height intervals, both with the passage of highs and lows and on a seasonal time scale tends to mask the seasonal differences The fact that TIC varied significantly with respect to season appears to be due to the different structure of cloud systems between summer and winter

3) Variations of TICIV are significant with respect to season and latitude at the 99% confidence level

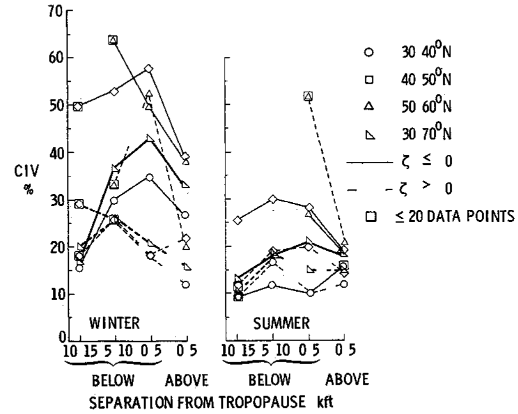

Fig 5 Probability of cloud encounter as a function of distance from the NMC tropopause by latitude and sign of relative vorticity ζ in winter and summer

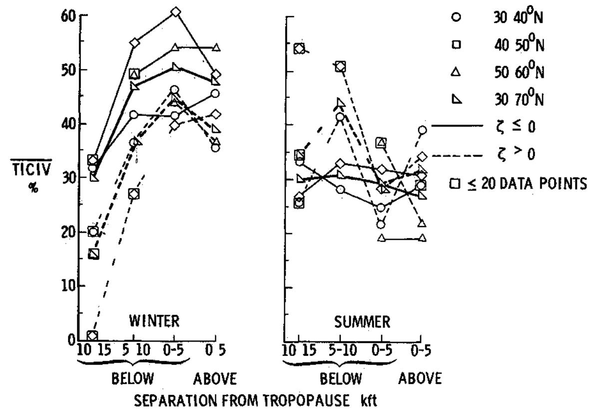

Fig 6 Average time in clouds in the vicinity of clouds as a function of distance from the NMC tropopause, by latitude and sign of relative vorticity ζ, in winter and summer

Clouds and Vorticity

As noted earlier, the extent of cloudiness is related to large scale cloud systems (a general model can be found in Ref 16) An objective variable often used for separating the two fundamental dynamic regimes cyclones (i e low pressure systems) and anticyclones (highs) is the relative vorticitiy Cyclonic motion is associated with positive and anticyclonic with negative, relative vorticity In earlier analyses of the GASP data [1 2] significant differences were found when the cloud statistics were stratified by the relative vorticity An extension of these analyses is given next

Figure 4 presents TIC as a function of the distance from the tropopause and the algebraic sign of the relative vorticity for each of the seasons From this figure, the following con clusions can be drawn:

1) For winter, TIC is substantially larger for negative vorticity than for positive vorticity, particularly near the tropopause The maximum occurs in the layer immediately below the tropopause This at first appears surprising,

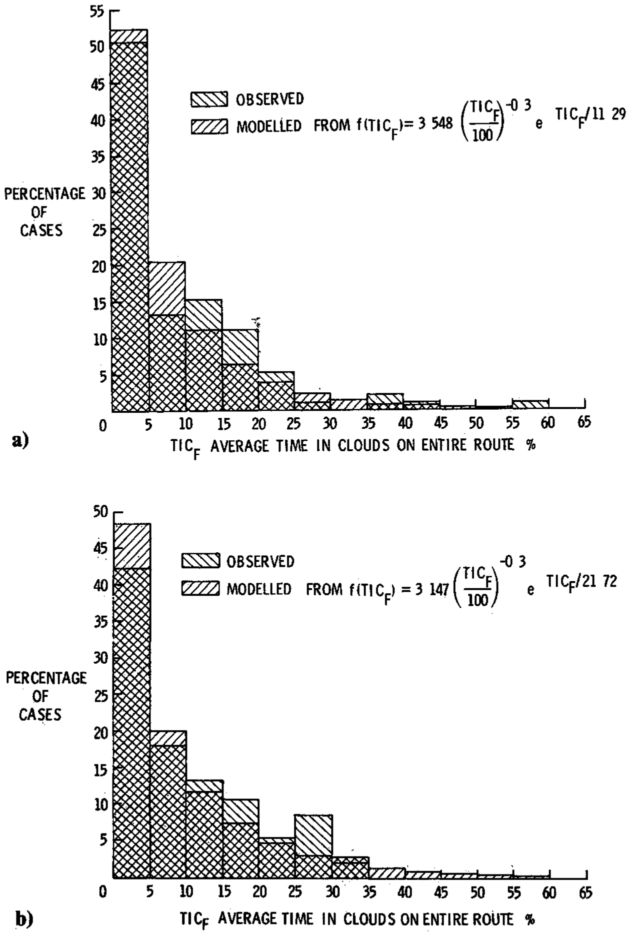

Fig 7 Comparison of observed and theoretical frequency distributions of route averaged time in clouds on GASP flights between the U S East Coast and Northwest Europe having a) an average altitude between 33 5 and 38.5 kft (99 flights in sample) and b) an average altitude between 28 5 and 33 5 kft (38 flights in sample)

because most readers are accustomed to associating positive vorticity with lows and their associated cloudiness, which is indeed the case at the surface Because of the vertical structure of the atmosphere and the tilting of the presure systems with respect to height, however, the opposite tends to be true at aircraft flight levels, as high pressure areas aloft overly lows at the surface and vice versa

2) During summer, TIC is near 5%, independent of the vorticity and distance from the tropopause This is consistent with the seasonal model of fewer and weaker cyclones in summer, with more of the clouds, relatively, stemming from convective storms, as discussed in the previous section

3) The spring and autumn panels show behavior representative of transition periods between winter and summer

Figure 5 presents CIV as a function of vorticity and distance from the tropopause, latitude, and season (winter and summer) The following characteristics are observed in this figure:

1) The differences in the mean values of CIV between positive and negative relative vorticity is greatest in the winter and for heights near the tropopause As mentioned before positive vorticity and clouds are positively correlated in the lower atmosphere, and this is consistent with the crossover of the curves at 10 15 kft (3 05 4 57 km) below the tropopause in winter

2) For the case of negative vorticity, winter values of CIV are much larger than summer values

3) In winter, the maximum is at 0 5 kft (0 1 52 km) below the tropopause when the relative vorticity is negative and at 10 15 kft (3 05 4 57 km) below the tropopause when positive

4) For both seasons and both signs of relative vorticity, CIV tends to be smaller for latitudes 30 40 deg N than for higher latitudes

Figure 6 presents TICIV as a function of vorticity and distance from the tropopause, latitude, and season (winter and summer) The following characteristics are observed in this figure:

1) In winter, TICIV is consistently larger at all heights when the relative vorticity is negative This is consistent with earlier discussions

2) In winter, the maximum in TICIV occurs 0 5 kft (0-1 52 km) beow the tropopause

3) There is an extremely sharp drop off of TICIV in winter for both signs of relative vorticity for heights greater than 10 kft (3 05 km) below the tropopause

4) There is no distinguishable pattern between TICIV and distance from the tropopause in summer although the mean value for positive vorticity tends to be larger than the mean value for negative vorticity

This section has shown that relative vorticity can be a useful variable in stratifying cloud encounter statistics These results may be used to estimate the probability of cloud encounter purely from meteorological parameters such as distance from the tropopause and voriticity

Application to Airline Route Studies

The preceding sections have shown that cloud encounter statistics have seasonal, geographical, and altitudinal variabilities that can be explained in terms of well-known meteorological models It is important to realize, however, that these statisitcs pertain to the ensemble behavior of 256 s observations within each cell in a latitude longitude-season-altitude grid [2] In earlier reports, the gridded data were used directly in a first attempt to provide an estimate of cloud encounter statistics along several routes and altitudes [1 2 7] However, because weather systems have appreciable horizontal extent, a high or low pressure system can cover several cells, so the data from adjacent cells are not in dependent Thus, there are problems in using cell statistics to estimate the probability of encountering a given average amount of cloudiness along an airline route that traverses one or more cells—the estimate that is needed in assessing the feasibility of employing LFC on transport routes

A more direct approach is to compute the cloud encounter statistics for routes of interest by studying the frequency distribution of route averaged time in cloud values for all flights on a given route A model using this approach was developed as follows:

1) The ensemble of flights on each city pair (e g JFK LHR) was collated and each flight placed into one of three altitude band sets (28 5 33 5, 33 5 38 5, and 38 5 43.5 kft) according to the average altitude along the entire route

2) For each flight in a city pair and altitude band, an average value of TIC_F was computed, i e , the average percentage time in clouds along the route for *that* flight.

3) Frequency distributions of TIC_F were prepared for each route and altitude band An average value of TIC_F for the route, TIC_R, was then computed by averaging all the values of TIC_F from all flights along the route

4) For each of several routes where a relatively large number of flights (i e , more than 30) were in the sample the frequency distribution was plotted and its character studied This study disclosed that for all routes the most frequent TIC_F value was 0%; i e , that flight in clear air at these altitudes is the most frequent experience, that a TIC_F value of 100% was never obtained, and that the frequency of TIC_F values usually decreased monotonically as TIC_F increased This behavior suggested that the observations for each route could perhaps be modeled by either a negative exponential or gamma probability density function Further study showed that a gamma probability density function

$$f(t) = \exp(-t)\,(t)^{\eta - l}/\Gamma(\eta) \qquad (2)$$

where $t = 0\ 7\mathrm{TIC}_F/\mathrm{TIC}_R$ and $\eta = 0\ 7$, $0\% < \mathrm{TIC}_R$ $\mathrm{TIC}_F \le 100\%$ gave a good fit to all of the distributions studied As an example Fig. 7a shows a histogram frequency plot of TIC_F for the 99-flight sample of GASP flights between the East Coast of the U S and Northwest Europe where the average cruise altitude lay in the 33 5 38 5 kft (10 21 11 73-km) band, and Fig 7b shows a plot for the same region of the 38 flights in the 28 5 33 5 kft (8.69 10 21 km) band On each figure, both the observed and gamma density modeled histogram plots are shown The apparent agreement of observed and modeled plots on each figure was verified by chi squared goodness of fit testing at the 95% confidence level Similar good agreement was obtained in other cases as well Therefore, Eq (2) was used to model the distribution of time in cloud for all cases using the sample value $t = 0\ 7\mathrm{TIC}_F/\mathrm{TIC}_R$ appropriate to each route/altitude combination. The probability of encounterng a value of TIC_F that equals or exceeds a value x is found by integrating Eq (2):

$$P(\mathrm{TIC}_F \ge x) = P(t \ge 0\ 7x/\mathrm{TIC}_R) = \int_{0\ 7x/\mathrm{TIC}_R}^{\infty} f(t)\,\mathrm{d}t \qquad (3)$$

which does not exist in closed form and must be computed by numerical methods

This model was used in generating Table 1, which presents the resulting parameter values for seven high-density routes For each route/altitude band, parameter values are given for the number of flights actually in the sample; the sample average percentage time in clouds for the route, TIC_R; the probabilities that the average time in clouds will be below 1% and 5% [$P(\mathrm{TIC}_F < 1\%)$ and $P(\mathrm{TIC}_F < 5\%)$, respectively]; and the probabilities that the route-averaged time in clouds will equal or exceed 5%, 10%, 25%, and 50% [$P(\mathrm{TIC}_F \ge 5\%)$, $P(\mathrm{TIC}_F \ge 10\%)$, $P(\mathrm{TIC}_F \ge 25\%)$, and $P(\mathrm{TIC}_F \ge 50\%)$ respectively] All probabilities are expressed here as percentages Conclusions reached from studying Table 1 are as follows:

1) TIC_R, $P(\mathrm{TIC}_F \ge 5\%)$, $P(\mathrm{TIC}_F \ge 10\%)$ $P(\mathrm{TIC}_F \ge 25\%)$ and $P(\mathrm{TIC}_F \ge 50\%)$ all generally decrease with height for all routes except Australia to Southeast Asia For that and other subtropical routes the tropopause lies well above the aircraft cruise altitude, and TIC increases with height, as remarked earlier

2) The abnormally low value of TIC_R for the 33 5 38 5 kft (10 21 11 73-km) altitude band on the West Coast to North west Europe route reflects the low tropopause height at the high latitudes traversed on this route

3) There is a statistically significant difference in TIC_R values between flights from the West Coast to Japan and those in the opposite direction This is because flights on the pairing are routed to take account of the strong west to east North Pacific jet stream; the higher TIC_R on the west to east route, where the jet stream is utilized for a tail wind, probably reflects the increased cloudiness from the cirrus shield that typically accompanies the jet stream

4) For the routes/altitudes shown in Table 1, in all cases, the probability of encountering clouds on more than 10% of a route is less than 33%. The probability of encountering clouds on more than 25% of a route is less than 10%; and the probability of encountering clouds on more than 50% of a route is less than 2%

Effect of Clouds on LFC

The impact of the above results on the feasibility of LFC for long range transports may be estimated as follows: if it is assumed that LFC is totally lost within clouds and that it is totally effective outside of clouds, then the fractional effectiveness of LFC on a route is equal to the fraction of the

Table 1 Probability of encountering various levels of average cloudiness on seven long range airline routes, as estimated using a gamma probability distribution

Code: first column of each band: No of flights; TIC_R,%; $P(\mathrm{TIC}_F < 1\%)$,%; $P(\mathrm{TIC}_F < 5\%)$,%. Second column of each band: $P(\mathrm{TIC}_F \ge 5\%)$,%; $P(\mathrm{TIC}_F \ge 10\%)$,%; $P(\mathrm{TIC}_F \ge 25\%)$,%; $P(\mathrm{TIC}_F \ge 50\%)$,%

Altitude band, kft:	28 5 33 5		33 5 38 5		38 5 43 5	
California	22	52 4	177	37 2	2	
Hawaii	9 4	32 5	5 5	17 4	–	–
	17 3	8 9	24 7	2 1	–	–
	47 6	1 2	62 8	~0	–	–
East Coast-	3	–	58	46 2	13	14 0
West Coast (U S A)	–	–	7 5	25 9	2 4	2 8
	–	–	20 1	5 3	41 3	~0
	–	–	53 8	0 4	86 0	~0
West Coast	6	53 8	26	16 9	26	17 8
Northwest Europe	9 9	34 0	2 7	4 0	2 8	4 4
	16 7	9 9	38 6	0 1	37 7	0 1
	46 2	1 4	83 1	~0	82.2	~0
East Coast	38	52 1	99	47 7	24	23 1
Northwest Europe	9 3	32 2	7 9	27 4	3 4	7 1
	17 5	8 7	19 5	6 0	33 5	0 3
	47 8	1 1	52 3	0 6	76 9	~0
Australia	16	49.4	20	51.0	–	–
Southeast Asia	8 4	29 2	8 9	30 9	–	–
	18.7	7 0	18 0	7 9	–	–
	50 6	0 7	49 0	0 9	–	–
West Coast to	4	–	30	26 2	14	12 1
Japan	–	–	3 8	9 1	2 2	2 1
	–	–	31 3	0 5	43 5	~0
	–	–	73 8	~0	87 9	~0
West Coast from	–	–	12	51 0	29	24 7
Japan	–	–	8 9	30.9	3 6	8 1
	–	–	18 0	7 9	32 2	0 3
	–	–	49 0	0 9	75 3	~0

route that is flown in clear air It is estimated[3] that use of LFC will result in a 30% drag reduction outside of clouds Therefore, the net drag reduction over a route ranges from the full 30%, for a case where no clouds are encountered on the route down to 0%, for a case when the route lies totally within clouds By this reasoning, for example, on a route that is 25% cloud covered, the net effectiveness of LFC is decreased to 75% of 30%, or 22 5% Combining this reasoning with the results in conclusion 4 above it is concluded that the probability of losing 10% or more of LFC effectiveness is less than 33% Similarly the probability of losing 25% or more of LFC effectiveness is less than 10%, and the probability of losing at least 50% of LFC is less than 2% Therefore, it is concluded that for these routes/altitudes the probability of encountering extensive cloud cover on long routes is not large enough, of itself, to make LFC impractical Study is continuing for other routes and altitudes

Summary

This paper has presented results from a valuable and unique set of data. To our knowledge this is the most complete set of cloud encounter data available at aircraft flight altitudes These results can be used in estimating the probability of cloud encounter over a seasonal altitudinal, and geographic grid, and have been applied in assessing the economic feasibility of LFC-equipped aircraft along particular routes

Several meteorological features are readily apparent in the data. In particular, the tropical circulation and its seasonal migration are clearly shown Also, characteristics of the midlatitude circulation regime, such as large scale traveling cyclones in the winter and increased convective activity in the summer, can be isolated in the data

The cloud encounter statistics were also shown to be consistent with the classical midlatitude cyclone model By stratifying the data by the sign of the relative vorticity and plotting the results as a function of distance from the tropopause, the relationship between atmospheric dynamics and clouds becomes apparent

Finally, the relationship of the gridded data to cloud encounter statistics over airline routes was discussed. A statistical model was developed from empirical frequency distributions of the average cloudiness enroute between several city pairs The model takes the form of a gamma probability density function that may be used to assess the economic feasibility of LFC flight along different routes analytically Results from applying this model to seven long range routes suggest that the probability of encountering extended cloud encounter is not large enough to make LFC impractical by reasons of extended cloud cover alone

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