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CHARACTERISTICS OF THE TROPOPAUSE AND ITS EFFECT ON OPTICAL IMAGING

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ABSTRACT

This note summarizes the meteorological implications of airborne optical imaging through the tropopause, with specific reference to a series of experiments in New Zealand in September 1971. The general characteristics of the tropopause and lower stratosphere are discussed as they relate to optical propagation. Specific meteorological data pertaining to the experimental flights are presented and discussed.

Accepted for the Air Force
Joseph J. Whalen, USAF
Chief, Lincoln Laboratory Project Office

CHARACTERISTICS OF THE TROPOPAUSE AND ITS EFFECT ON OPTICAL IMAGING

I. INTRODUCTION

A "tropopause experiment" was considered several times during our airborne optical measurements program, which was devoted to missile re-entry observations. By this experiment we have generally meant the operation of optical instruments in a region where the aircraft is clearly within the stratosphere, to distinguish the results from those typically observed within the troposphere. Since the KC-135 jet aircraft we employed was generally limited to altitudes below 12.2 km (40 kilofeet) we could reach the stratosphere only at high latitudes, in either hemisphere. Recently, a series of experimental flights at high southern latitudes, operating from Christchurch, New Zealand, was carried out. The imaging results will be reported by B. Bryant and modulation transfer measurements by D. Kelsall, in separate reports. In the following discussion I shall describe the tropopause and its characteristics, both for the general case and for the experimental flights in New Zealand.

The height of the tropopause is subject to many variations, and is a truly dynamic atmospheric parameter. In general, it is at its lowest altitude (8-10 km) in high latitudes, and in winter, for each hemisphere. Although meteorological data are much richer in detail for the northern hemisphere, there is a considerable body of southern hemisphere data near the 170°E meridian, from the mid-Pacific islands to the southern polar bases, due to fortuitous placement of upper-air stations. Many of these stations were apparently established for the first IGY and have been continued by their respective governments.

The original plan was to conduct a series of flights using Christchurch, New Zealand as a base in August-September of 1971, and then conduct a second series from Fairbanks, Alaska in January-February 1972. However, the aircraft was not available for the latter series and was terminated as an optical platform in June 1972. Thus we were able to conduct optical experiments under documented meteorological conditions in only one of these regions.

II. THE TROPOPAUSE

To aid in discussing the objectives and procedures for this series of measurements we shall briefly review the meteorology of the lower stratosphere, as contrasted with the upper troposphere, and the meaning of the tropopause, which is generally considered to be the boundary between these two regions. In the mean, the temperature in the troposphere decreases with height, while the temperature in the lower stratosphere is nearly independent of height. Thus the tropopause separates two regions which have markedly different vertical temperature gradients and dynamic characteristics. The altitude of the mean tropopause at a given geographical location should be determined by these gradients. In practice, the best description of such boundaries is given by seasonal and geographical averages of the vertical temperature and wind profiles, and most of our knowledge of lower stratospheric circulation is derived from these.

The determination of tropopause altitude at a given location and time may often become rather ill-defined and arbitrary. Individual vertical temperature profiles can show more than one level where an abrupt change in gradient exists. The meteorological services use criteria which depend both upon the existence of such a gradient change and its duration with height in order to define a tropopause for a given atmospheric sounding. Individual deviations from the simple concept of a single boundary are not surprising since the modern view of the tropopause presents a picture of its structure which deviates greatly from an abrupt boundary layer, continuous in time and space.

Recent treatments of the tropopause structure tend to agree that it can be represented on individual days by continuous surfaces which have discontinuities (breaks) at points corresponding to maxima of wind speed for that day. Each hemisphere usually contains two of these wind speed maxima which vary with altitude and latitude, but are more or less continuous around the globe. These are referred to as the "subtropical jet" and the "polar-front jet" and as is well-known from high altitude flying, these jet streams are marked by great variability in time and space.

The classic concept of the tropopause as a continuous surface between two differing atmospheric regions is thus generally held to be true except at these breaks where interchange of air can be carried out. Such a view may be unduly influenced by averaging of the temperature profiles. Detailed studies of the stability parameters of the atmosphere are usually necessary to understand the actual interchange process for given soundings. We shall assume, however, that the picture of the tropopause as a continuous surface with significant, variable break regions is sufficient for our purposes.

III. OPTICAL PATHS THROUGH THE ATMOSPHERE

One of the motives for making optical measurements within the lower stratosphere is to see whether disturbances along the optical path in that region can produce the degrading effects which have been observed in the troposphere. An optical difference between the two regions can reasonably be hypothesized since they differ significantly in a meteorological sense. The troposphere is, in the mean, a region of small average stability and positive average baroclinicity, while the stratosphere is characterized by large average stability and negative average baroclinicity.*

*Definitions: Stability-unsaturated air is hydrodynamically stable when the temperature lapse rate is less than adiabatic.

Baroclinicity-air is said to be baroclinic if the isobaric and isosteric surfaces intersect and form "solenoids" of atmospheric circulation.

Although these are differences only in the mean, and do not exclude mass transport of air from one region to the other, certainly the scale of the density variations must also differ in the mean. Since density fluctuations are presumed to be the cause of phase and amplitude fluctuations which disturb traveling wavefronts then we should reasonably expect to measure the effects of these fluctuations. Statistical studies of image formation, amplitude variations, and modulation transfer should reveal the integrated effects of the atmosphere through which the radiation passes, and if we can eliminate the troposphere from this path, net changes in these parameters may be observed.

The relative stability of the lower stratosphere stems from its near-isothermal nature and the decrease of wind speed with height (except in polar regions). Our experience with "seeing" experiments in the troposphere has led us to believe that an optical path which is more homogeneous with respect to temperature and air motion should result in fewer and/or smaller wavefront disturbances. Of course, these parameters again change with height, the temperature and wind both increasing to maxima at about 50-60 km (the stratopause), then decreasing to minima at 80 km (the mesopause). However, the density monotonically decreases with height so that these upper strata have much smaller effects on optical paths than the lower stratosphere and the troposphere.

The primary cause of density fluctuations in the atmosphere is the class of small-scale motions denoted by "turbulence." These include convective cells and storms, small eddies formed by surface winds and upper air variations. Turbulence is usually not considered in theoretical treatments of atmospheric dynamics because the relation of turbulence to the mean properties of the atmosphere is not well understood. It is clear however, that the largest scale effects of turbulence are confined to the "friction layer," or lowest 1 km of the atmosphere, and that in other regions turbulent motions produce mixing or smoothing of atmospheric parameters. Since dynamic meteorology deals principally with large scale motions (weather-map scale: 100-300 km in the horizontal, 1 km in the vertical, 1 hour in time) then turbulent effects are assumed only to increase minimum values and decrease maximum values of meteorological quantities.

For optical propagation through the atmosphere, however, both the spatial and temporal scales of density fluctuations are quite important. A considerable body of literature is available to document the variations and their meaning, both experimentally and theoretically. They are relevant not only to optical imaging but to the transmission of coherent beams through the atmosphere, i.e., laser beam propagation. Density variations are closely related to the velocity field and its fluctuations, which can be characterized as unstable disturbances of laminar flow. Such turbulent flow is dissipative, three-dimensional and nonlinear, resulting in treatments which must be statistical in nature, both due to the complexity of the interactions and the inability to predict the velocity field. The statistical descriptions used in analysis of velocity fluctuations are also used to describe the density (or temperature) fluctuations which affect the refractive index, and thus disturb optical wavefronts.

No attempt will be made here to relate the synoptic meteorological data to these fluctuations in detail. However, an estimation of the overall experimental effects of propagation through the tropopause requires that the optical data gathered by a sensor be correlated with the tropopause location at the time of the observations. Since the four flights made from Christchurch, New Zealand will be compared in this way, the actual atmospheric soundings which are applicable to these flights must be examined in enough detail to ascertain that the planned experimental conditions were achieved.

The principal optical assumption which has been made about the tropopause is that it represents a region where unstable air (troposphere) interacts with stable air (stratosphere) within a shallow layer, causing an increase in density fluctuations at that altitude. Few direct experimental data have been measured at high altitudes, and most of the inferences regarding the source of fluctuations have been estimated from stellar scintillation data and the speeds of disturbances observed from ground points. The most commonly-used model of refractive index fluctuations has been derived by Hufnagel[1]; this model predicts a peak in the value of the refractive index structure constant at the tropopause. Recent measurements by Bufton et al[2] seemed to confirm Hufnagel's model at lower altitudes, but the data did not reach the tropopause.

IV. COMPOSITION OF THE LOWER STRATOSPHERE

Two important compositional features of the lower stratosphere which might affect optical experiments within it are its markedly lower water vapor content and the significantly smaller particle densities. A third pronounced difference is in ozone content: it is well known that the ozone density reaches a maximum between 15 and 30 km which is highly variable with latitude and season, and over short periods. Finally, the occurrence of clouds, and their types, make a significant contrast with the tropopause.

A. Water Vapor

The water vapor content in the stratosphere is not routinely measured, so we are dependent upon special research measurements for the data. Several different methods have been used on aircraft and balloons, with general agreement that the mixing ratio (grams of water vapor per kilogram of dry air) decreases as much as two orders of magnitude in the first 10 kilometers above the tropopause. However, above the level at which the water vapor content is a minimum, the mixing ratio increases again to values near that of the upper trosophere. Thus the lower stratosphere is a very dry region, with moist layers both above and below it. Clouds are often observed at 20 to 30 km, in particular geographical regions, but the mechanism of water vapor transport to that altitude is not understood.

B. Particulates

Observations of particulate matter in the stratosphere are also neither routine nor plentiful. From the experiments on particle distribution one can make a few general observations. Small dust particles (radius less than 0.1 micron) have an approximately constant concentration with height a few km below the tropopause, but the concentration decreases rapidly above the tropopause. Most of these particles, which play an important role in condensation and cloud formation, originate at the earth's surface and are transported from the troposphere by convection, at low efficiency.

Larger particles (radius 0.1 to 1.0 micron) show a concentration which goes through a minimum at or slightly below the tropopause, but then increases by as much as an order of magnitude at about 20 km. The absolute density in this weak peak does not exceed 1 particle per $cm.^3$ These particles may originate within the stratosphere by coagulation of ionized molecules.

However, there is some evidence to suggest that particles of all sizes can also be deposited from sedimentation of meteoric material, and be subjected to coagulation and condensation processes as well.

C. Ozone

Vertical profiles of ozone concentration measured during the last decade have revealed a large amount of variability in the distributions, both in altitude and geographical position. These are closely related to the mechanisms of ozone formation and destruction, which are in turn linked to tropopause altitude and to the general circulation of the atmosphere. Since ozone is a gaseous constituent and is transparent at visible wavelengths, it is normally of no consequence to imaging experiments. However, it is an efficient absorber of both infrared and ultraviolet wavelengths, processes which are intimately connected with ozone formation itself and with the stratospheric temperature profile. Thus optical devices which utilize wavelength regions where the ozone absorbs and re-emits radiation would "see" ozone as a cloud layer. As is well known, ozone absorbs in the regions 0.2-0.3, 9-10 and 14-15μ-meters.

Although some detail in ozone structure has been measured in vertical profiles, particularly at middle and high latitudes, it is not clear whether such detailed variations exist in lateral distributions. One would certainly expect the mixing to be such that no small-scale ozone variations could be resolved by optical instruments. In addition, this emission would be added to that of the general atmospheric background and instrument background, leading to an expectation of uniform brightness over the field of view of most instruments.

D. High Altitude Clouds

At the altitudes flown regularly by the KC-135 we are concerned only with clouds above 35,000 feet, or about 11 km. Since these clouds are seldom of any synoptic interest (that is, connected with forecasting of weather disturbances) they are neither reported nor studied in any detail on a regular basis.

As we have often observed from the aircraft, in the tropical latitudes the spreading and trailing of cirrostratus from cumulonimbus development are very common. Quite often, the cirrus persists far beyond and long after the cumulonimbus which generated it, and we see it as high, thin layers at or above KC-135 operating levels. These layers usually have a definite upper boundary, but above it even thinner clouds rise and fall in a random fashion. Cirrostratus clouds of this type may occur up to the tropopause, which rises to as high as 18 km in the winter season at the tropical latitudes.

Clouds of the cirrostratus (ice crystal) type can occur also at other latitudes but where tropopause is lower they tend to be altitude-limited by this air mass barrier. Stratospheric clouds, however, are of two general types: <u>nacreous</u> clouds, probably composed of short-lived water droplets or ice crystals in the one micron range, and noctilucent clouds, composed of meteoric particles in the .01 to 0.1 micron range. The former, also called "mother-of-pearl" clouds, occur at altitudes of 20 to 30 km in particular geographical regions and are rendered visible by sunlight scattered at small angles. These clouds form principally in the lee waves associated with orographic circulations.

Noctilucent clouds occur at much higher altitudes, 65 to 95 km, and are seen only when the sun is a few degrees below the horizon. Recent measurements and indirect evidence have led to the conclusion that these clouds are composed only of dust particles accumulated from small meteorites, or from the debris from larger meteors traversing the atmosphere.

The above cloud types are those which are visible, at least under special conditions, and thus have been classified. We do not yet know whether other small-scale variations of composition may exist, sufficient to attenuate or emit radiation in non-visible spectral regions, and where they might be located.

V. THE MEAN TROPOPAUSE AT 40°-50°S, 170°E

To prepare for the series of flights from Christchurch a brief survey of upper atmospheric conditions in the general area was conducted. In addition to the general climatic surveys,[3,4] and standard sources on the upper atmosphere,[5,6] a study of the temperature cross-sections along the 170°E meridian by Taylor[7] was found to be particularly useful.

From these data and studies we expected that the polar tropopause during August and early September would be well developed and reasonably low most of the time at the latitude of Christchurch. We planned to restrict our flights to the region between 40° and 50°S latitude, where the tropopause is near 250 mb, with the tropopause "break" expected at the sub-tropical jet stream well to the north of the flight trajectory. Statistical data for an 8 year period indicated[3] that the tropopause at Christchurch (43.5°S) occurred below 11.3 km (37,000 ft) 90% of the time and below 8.2 km (27,000 ft) 10% of the time, during the late August-early September period. At Invercargill (46.6°S), which was near the southern limit of our flight paths, the mean tropopause was slightly higher (about 0.2 km), but the range of variation was roughly the same.

The New Zealand Meteorological Service has published[8] a summary of radiosonde data for the period 1956-1961 from its several reporting upper air stations. One of the tables gives the statistical mean tropopause height for each month, and another tabulates the distribution of heights for each month at each station, along with pressure and temperature data. Three of these stations are pertinent to the radiosonde data which we recorded and used during the period of the optical flights. Some of these data are summarized in Table I.

TABLE I - New Zealand Tropopause Data, 1956-1961

Month		Christchurch (Lat 43° 29' S) (Long 172° 33' E)			Chatham Island (Lat 43° 57' S) (Long 176° 34' W)			Invercargill (Lat 46° 25' S) (Long 168° 20' E)		
		Height (m)	Temp (°C)	Pressure (mb)	Height (m)	Temp (°C)	Pressure (mb)	Height (m)	Temp (°C)	Pressure (mb)
August	Mean	10061	-58.2	257	10086	-57.9	256	10141	-60.3	252
	Std. Dev.	952	5.1	35	868	5.0	32	1052	5.3	37
	Number	151	151	151	151	151	151	153	153	153
September	Mean	10326	-57.6	251	10268	-57.2	252	10327	-58.5	248
	Std. Dev.	968	5.2	36	858	4.3	30	998	5.5	35
	Number	146	146	146	150	150	150	146	146	146

TABLE II - Summary of Flight Data

Flight Number	Date (GMT)	Time (GMT)	Aircraft Flight Levels (km)		Tropopause	
			Low	High	Pressure (mb)	Height (km)
1	4 Sept. 1971	0700-1050	8.8	11.6	280 ± 12	9.5 ± .3
2	5 Sept. 1971	1415-1730	8.2	11.0	260 ± 25	10.0 ± .6
3	8 Sept. 1971	1500-1845	9.8	12.0	220 ± 15	11.2 ± .4
4	12 Sept. 1971	0700-1100	7.0	11.3	320 ± 60	8.5 ±1.5

VI. METEOROLOGICAL CONDITIONS DURING THE OPTICAL FLIGHT PERIOD

The experimental flights were carried out during the period 4-12 September 1971, operating from Christchurch International Airport. During the 13 day period just prior to this, the tropopause pressure had averaged 263 mb at both Christchurch and Invercargill, which is slightly higher (or 0.3 km lower in height) than the averages in Table I, but well within the standard deviation. Radiosonde ascents at all the New Zealand and surrounding stations, as well as detailed consultations on the meteorological situation, were made available by the Meteorological Office at Christchurch airport, under the direction of Mr. Alan P. Ryan. In addition to collecting all of these data for later analysis, we attempted to plan the flights according to both the pertinent radiosonde ascents and the astronomical sources used for imaging so that we could obtain data on each flight below and above the tropopause.

Figure 1 shows the flight paths followed on each of the four experiments and the location of the radiosonde stations in the area. The tropopause pressures and heights experienced on each flight, together with the data-taking altitudes, are summarized in Table II. The tropopause data are estimated on the basis of the applicable radiosonde ascents and the on-board temperature measurements made during the flight, later corrected for air speed.

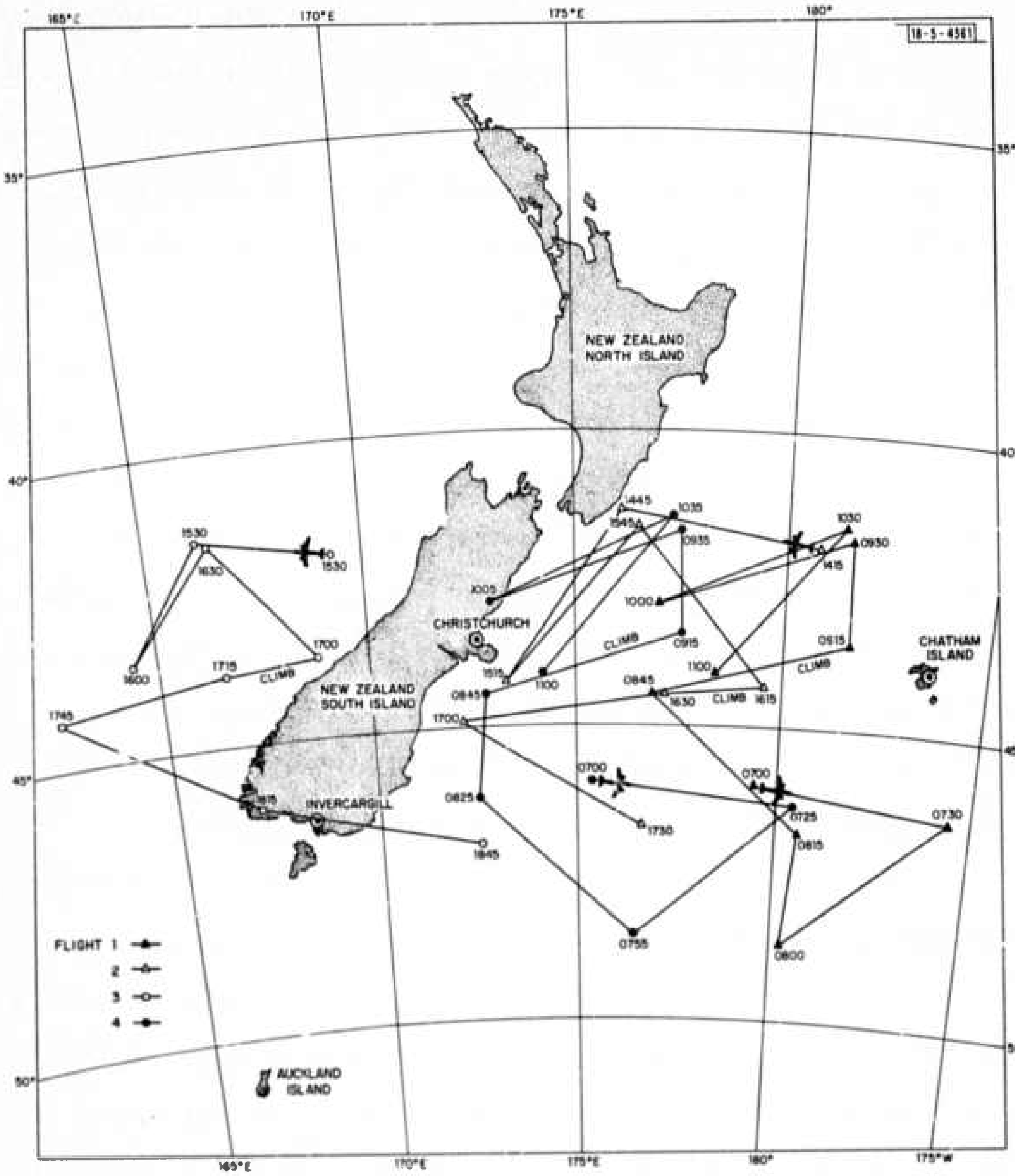

Fig. 1. Map of New Zealand area, with flight paths.

On the first three flights the tropopause pressure was within one standard deviation of the mean values shown in Table I, and the high altitude flow was generally westerly with no marked frontal disturbances. Flight 4 was delayed due to a period of low tropopause heights to the south of New Zealand which were caused by a cold polar outbreak and deep trough at 300 mb which developed to the southwest. This trough produced a large amount of high altitude cloudiness and made it difficult to plan a single flight trajectory which would both span the tropopause position and also be free of clouds for star observation. By 12 September the cloud sheet was far enough to the east to permit a successful flight. It was carried out by lowering the altitude of the troposphere portion of the flight to 7.0 km, well under the tropopause on the southern leg.

The radiosonde ascents which were particularly applicable to each flight, in time and location, as well as the on-board temperature readings made during the troposphere - stratosphere transition, are shown in Figures 2, 3, 4 and 5. As can be seen, the "low" and "high" flight altitudes bracketed the estimated tropopause height in each case. The altitude separations from the tropopause varied from 0.7 to 2.8 km, with an average of 1.5 km.

VII. CONCLUSIONS

The foregoing discussions and data are offered in support of the optical experiments conducted in New Zealand. Our aim was

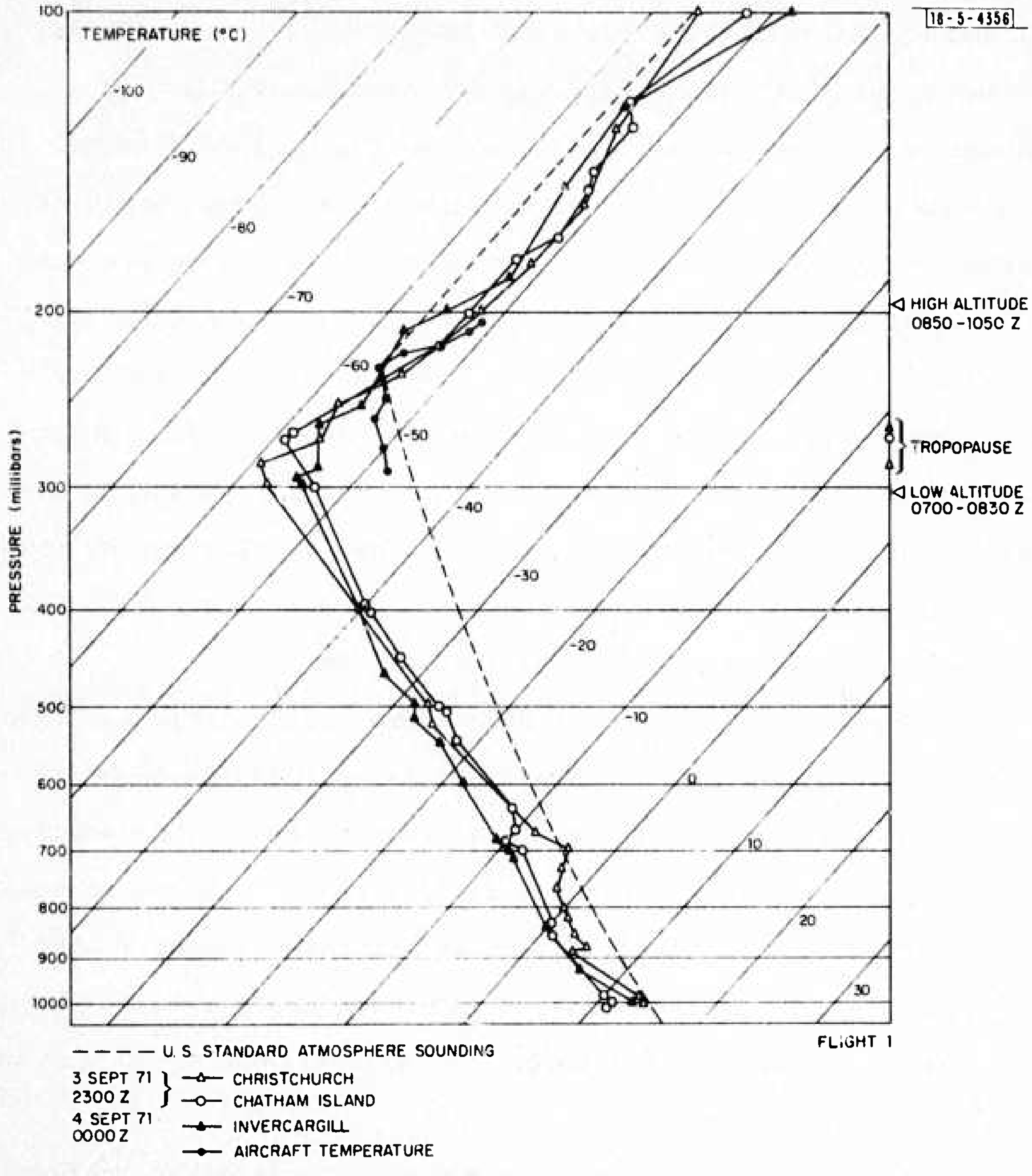

Fig. 2. Atmospheric soundings, 4 September 1971-Flight 1.

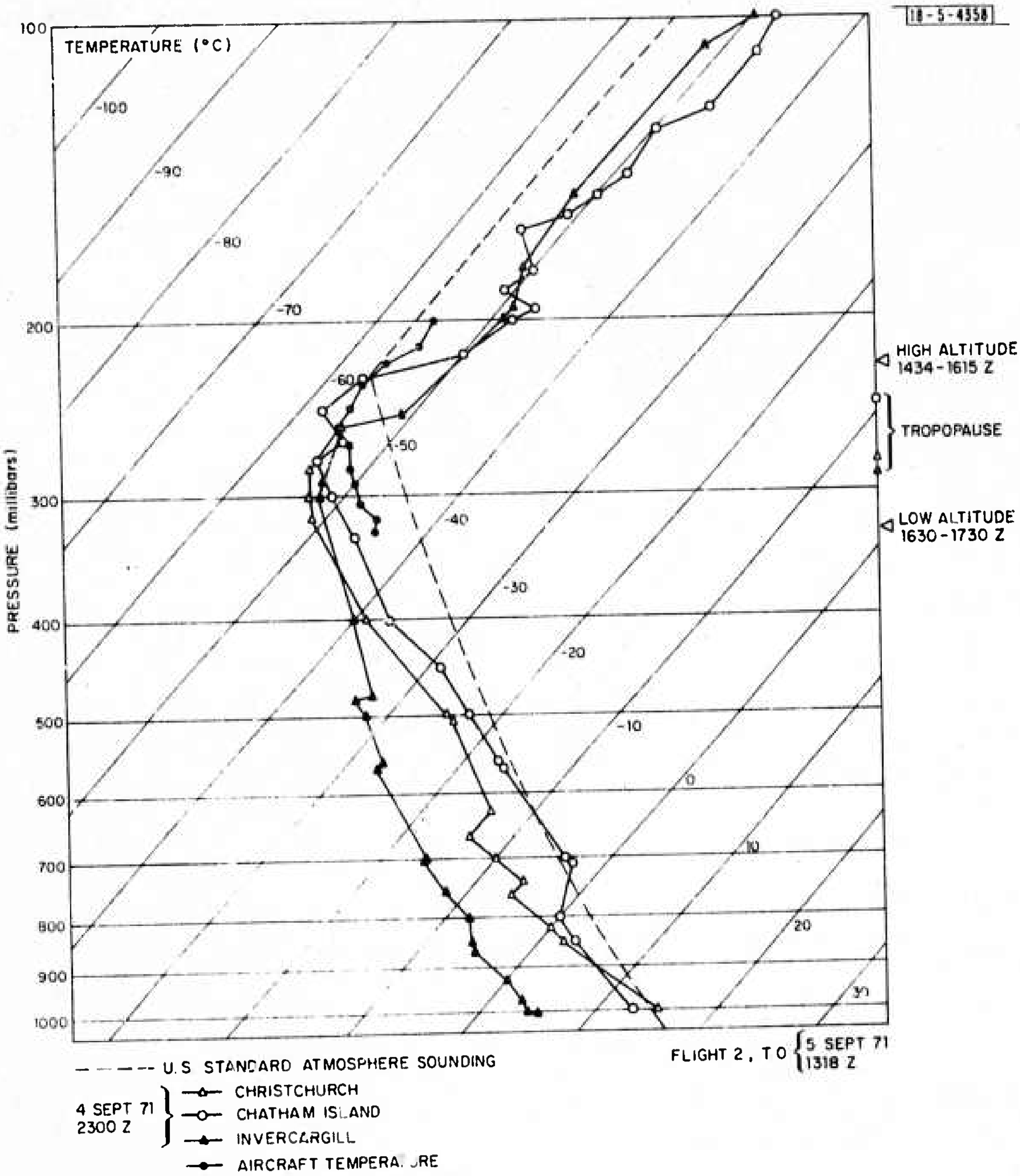

Fig. 3a. Atmospheric soundings, 4 September 1971-Flight 2.

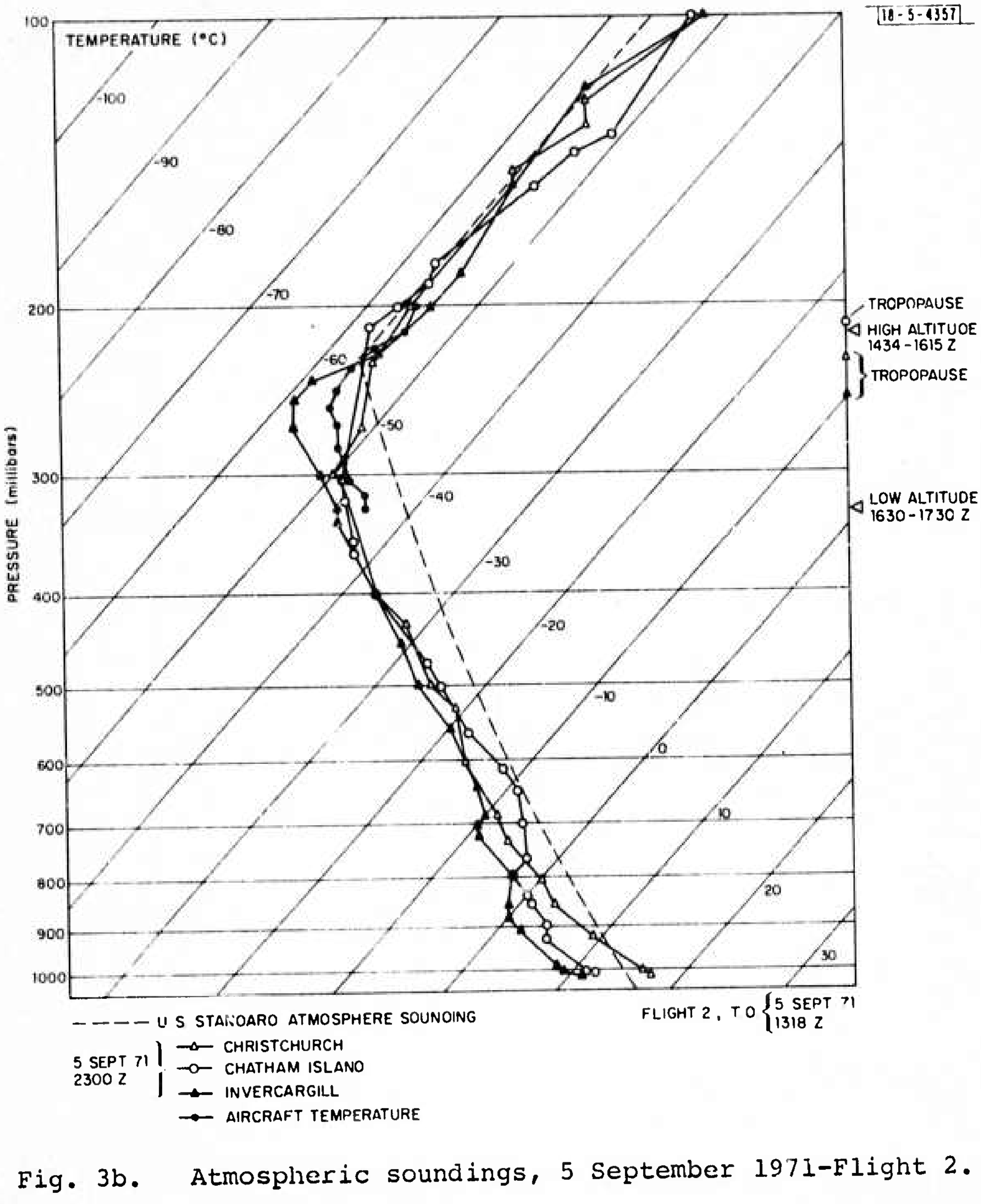

Fig. 3b. Atmospheric soundings, 5 September 1971-Flight 2.

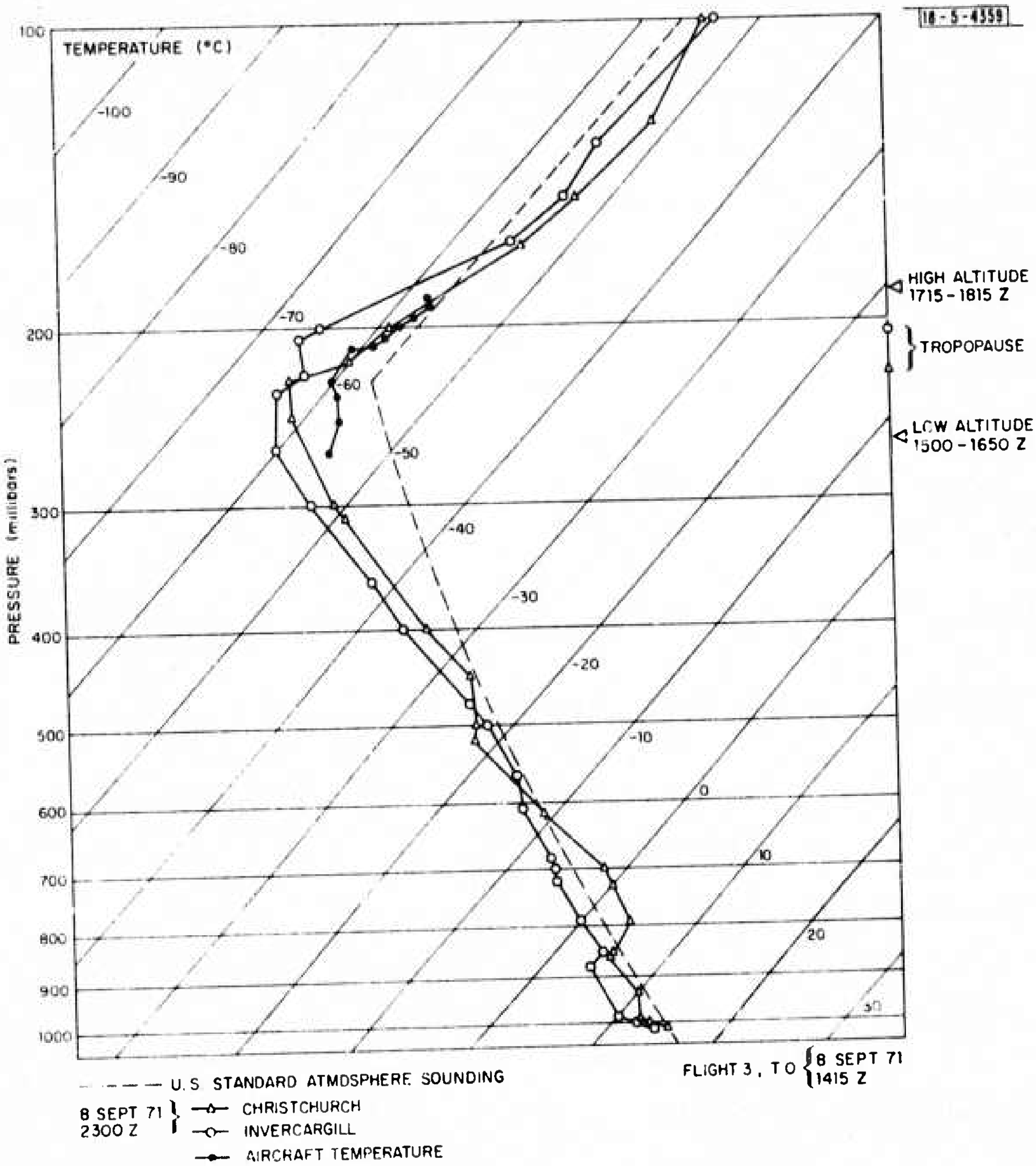

Fig. 4. Atmospheric soundings, 8 September 1971-Flight 3.

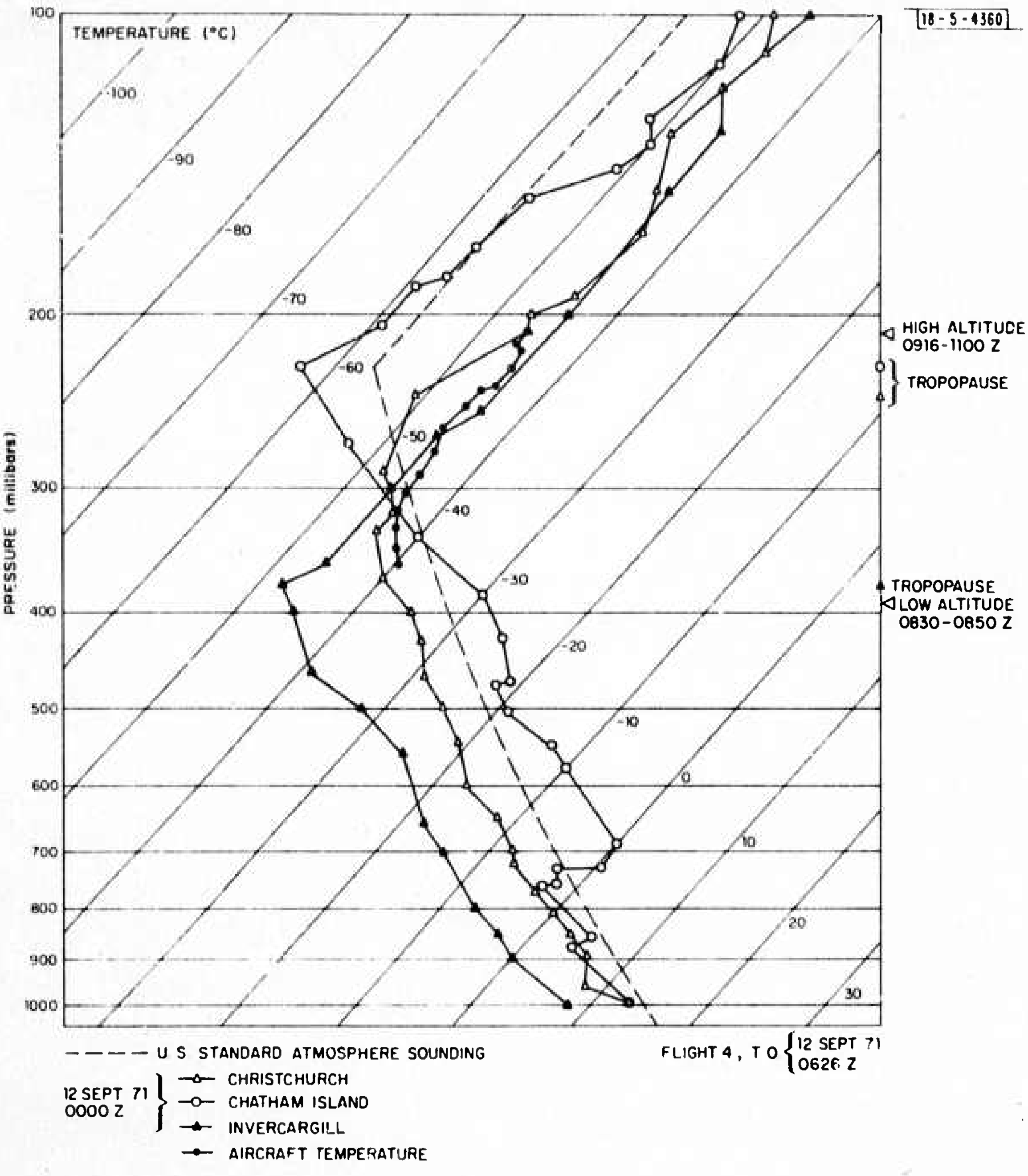

Fig. 5. Atmospheric soundings, 12 September 1971-Flight 4.

to make certain that the altitudes of data collection were known relative to tropopause altitudes. In real-time this information was used to plan the flight conditions, and in retrospect it has been used to verify the assumptions made in interpretation of the optical results. We feel that these assumptions were adequately justified in the case of the four experimental flights carried out during September 1971.

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REFERENCES

1. R. E. Hufnagel, "An Improved Model Turbulent Atmosphere," Woods Hole Summer Study on Restoration of Atmospherically Degraded Images, Vol. 2, pp. 15-18 (1966).

2. J. L. Bufton, P. O. Minott, M. W. Fitzmaurice and P. J. Titterton, "Measurements of Turbulence Profiles in the Troposphere," J. Opt. Soc. Amer. 62, (1972).

3. U. S. Navy, "Marine Climatic Atlas of the World," Vol. VII, Antarctic, NAVWEPS 50-1C-50, 1 September 1965.

4. Climate of the Upper Air, Southern Hemisphere, Vol. I, U. S. Dept. of Commerce, September 1969.

5. R. A. Craig, The Upper Atmosphere, Meteorology and Physics, (Academic Press, New York, 1965).

6. E. Palmen and C. W. Newton, Atmospheric Circulation Systems, (Academic Press, New York, 1969).

7. R. C. Taylor, "Mean Monthly Meridional Cross-Sections of Temperature from the South Pole to the North Pole Near 170°E - A Preliminary Note," Antarctic Meteorology Symposium (1959), (Pergamon Press, 1960), pp. 439-452.

8. "Summaries of Radiosonde Data, 1957-61," Misc. Pub. 119, Air Dept., New Zealand Meteorological Service.