Strato-Mesospheric Measurements of Density, Temperature, and Other Meteorological Variables in the Central Tropical Pacific

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ABSTRACT

The structure and state of the stratosphere and the mesosphere have been measured in the central tropical Pacific under a composite program of meteorological measurements. Density and temperature profiles between the altitudes of 30 and 120 km have been obtained, and wind velocities between the altitudes of 30 and 60 km have been derived from the radar track of an inflated sphere ejected from a rocket. The wind data have been supplemented by profiles from conventional meteorological rockets. Water vapor measurements by balloon-borne frost-point hygrometers have provided accurate humidity measurements in the upper troposphere and lower stratosphere.

1. Introduction

To meet environmental requirements placed on the Pacific Missile Range over the central tropical Pacific, a program of composite meteorological measurements was conducted to obtain knowledge of meteorological variables ranging from temperature, density, winds and composition in the mesosphere, to ozone and water vapor in the stratosphere and troposphere. The thesis in pursuing these measurements was that in order to conduct satisfactory experiments and operations in the atmosphere, the structure and state of the atmosphere should be known. Available and proven techniques were adapted to existing instrumentation to accomplish the required atmospheric measurements.

This program was conducted at Kwajalein Atoll, Marshall Islands, and extended from mid 1963 through mid 1964. During this period, density, temperature, and wind data were obtained from 10 inflated sphere soundings, and water vapor measurements were obtained from 5 frost-point hygrometer flights. Beginning in January 1964, these observations were supplemented by wind data from routine firings of 17 conventional meteorological rockets. The resulting data, although sparse by middle-latitude standards, are believed to comprise the most comprehensive measurements of the tropical stratosphere and mesosphere to date.

2. The inflated sphere technique

In selecting a technique for high altitude measurements, the tools available on Kwajalein were considered. There was an excellent NIKE-APACHE rocket launching facility manned by experienced personnel of the Physical Science Laboratory, New Mexico State University. In addition, a precision tracking radar, the TRADEX (*T*racking *R*esolution *A*nd *D*iscrimination *EX*periments) was available. With its 84-ft dish this radar has a tracking accuracy of 0.2 mil and can measure range rate to 0.6 mps as well as range which can be measured to an accuracy of 4.5 m. The radar data could be processed almost immediately by the IBM 7090 computer at the radar site. With these available tools, the inflated sphere technique was selected as the best possible method of obtaining density, temperature, and wind measurements. The High Altitude Engineering Laboratory of the University of Michigan was contracted to engineer and build such a system to obtain the necessary measurements over Kwajalein (Peterson *et al.*, 1965). This Laboratory was responsible for the compatibility of their system with the existing facilities at Kwajalein and for the data reduction program. As shown in Fig. 1, computation of density is derived from the classical drag equation, $D=ma=\rho(C_DAV^2/2)$, where D is the drag force, m is the mass, a is acceleration, C_D is the drag coefficient, ρ is atmospheric density, A is cross section area, and V is velocity.

The sphere, ejected from a NIKE CAJUN rocket, was 66 cm in diameter and weighed 50 gm. It was ejected on the up-leg trajectory between 80 and 85 km and tracked through apogee and down to an altitude of approximately 30 km, where it collapsed. Data were obtained from the up-leg trajectory as well as the down-leg. Temperature was derived from density by using the hydrostatic equation and equation of state after adopting temperature from the 1962 U. S. Standard Atmosphere at the highest altitude on the temperature profile. Data outputs were provided at 1-km intervals.

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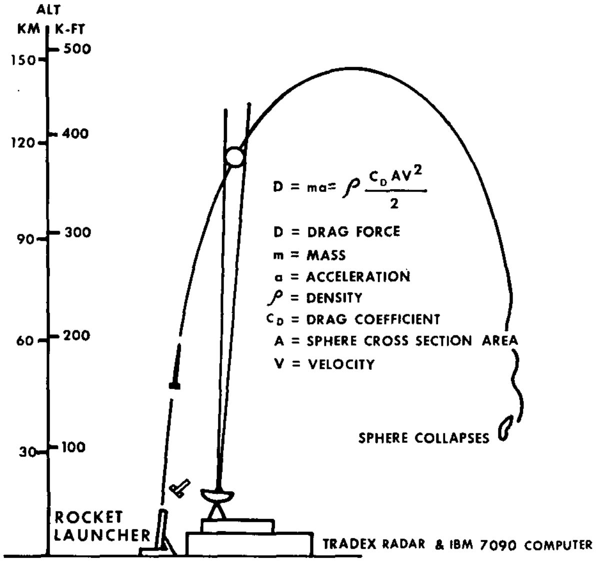

Fig. 1. The inflated sphere technique of density measurement utilizes a rocket vehicle, a tracking radar for data acquisition, and a computer for data reduction. The cross-sectional area and drag coefficient are pre-determined. Atmospheric density is derived from the radar track of the rocket ejected sphere.

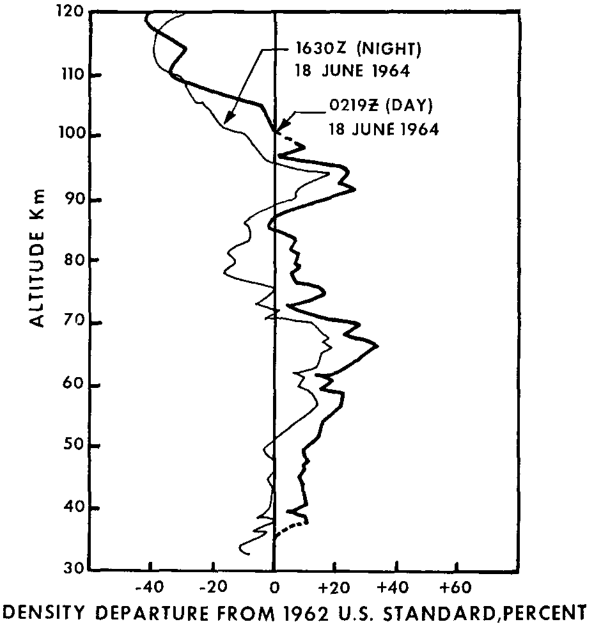

Fig. 2. Two density profiles at Kwajalein taken 14 hours apart. Below 100 km the profiles show the same general features. Broken line at the bottom of the profile indicates possible sphere collapse as determined by TRADEX radar.

A major source of uncertainty in calculating density by the sphere technique is the lack of substantiated drag coefficient data in the altitude interval 73 to 69 km in which the falling sphere passes through the transonic range of Mach numbers while slowing from supersonic to subsonic speeds. Vertical motion was disregarded because the magnitude of the assumed motions as compared to the mass and velocity of the sphere were considered negligible. The sphere was tracked until the TRADEX radar signal indicated that the sphere was commencing to deflate. The AGC record of the radar was examined when abnormal or early deflation was observed.

3. Density data

Density was considered the most important variable to be measured in the high atmosphere from 30 to 90 km. Density profiles for two June soundings are shown in Fig. 2. Density is plotted in terms of per cent departure from the 1962 U. S. Standard Atmosphere rather than in absolute value to avoid ranging the data over several orders of magnitude and to bring out finer detail. These two soundings were taken 14 hours apart, at 1419 and 0430 local time; therefore, differences between the two may be indicative of diurnal variations. Below 100 km the two profiles display the same general features but with daytime densities consistently higher than nighttime.

The envelope surrounding the density profiles for 10 Kwajalein soundings is shown in Fig. 3. For comparison, the proposed Tropical Supplemental Atmosphere (TSA) (Cole and Kantor, 1963) is also entered. The envelope shows three distinct levels of maximum departure from Standard: 1) a positive departure (i.e., Kwajalein density greater than Standard) near 70 km, 2) another positive maximum at 95 km, and 3) a negative maximum in the lower thermosphere at 120 km. It

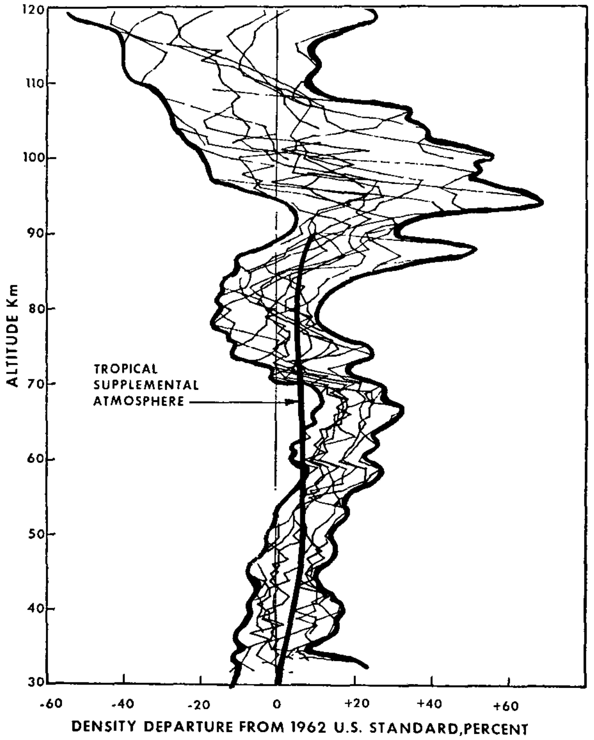

Fig. 3. The envelope encloses ten density profiles taken from mid-1963 to mid-1964 at Kwajalein.

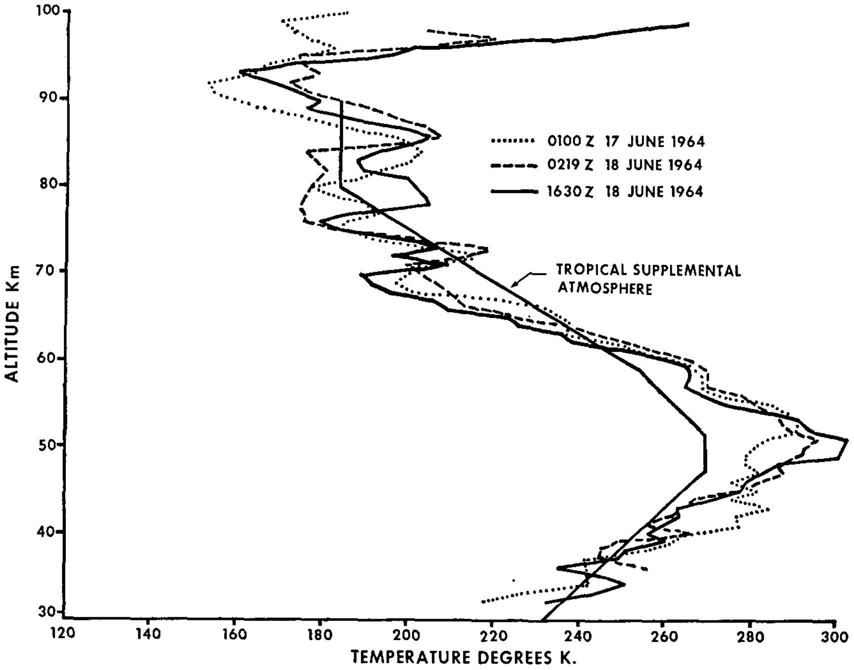

Fig. 4. Three typical strato-mesospheric temperature profiles derived from radar track of inflated sphere, June 1964, Kwajalein.

should be noted that the maximum departure near 70 km coincides with the altitude at which the falling sphere decelerates from supersonic to subsonic speed. In this transonic range the aerodynamics of the falling sphere are not well known. Variability about the mean, as indicated by the spread of the envelope, is about the same at all altitudes below 90 km, approximately ±15 per cent. Above 90 km, indicated variability about the mean is nearer ±30 per cent.

4. Temperature

Three typical temperature soundings taken within a 39-hr period in mid-June 1964 are shown in Fig. 4. The envelope enclosing the temperature limits of all

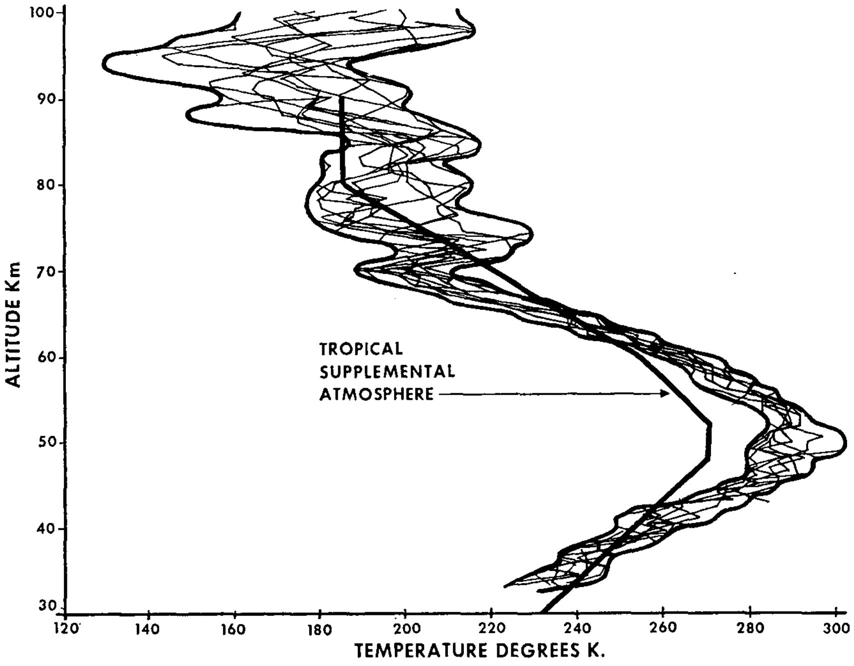

Fig. 5. The envelope encloses ten strato-mesospheric temperature profiles derived from inflated sphere soundings at Kwajalein.

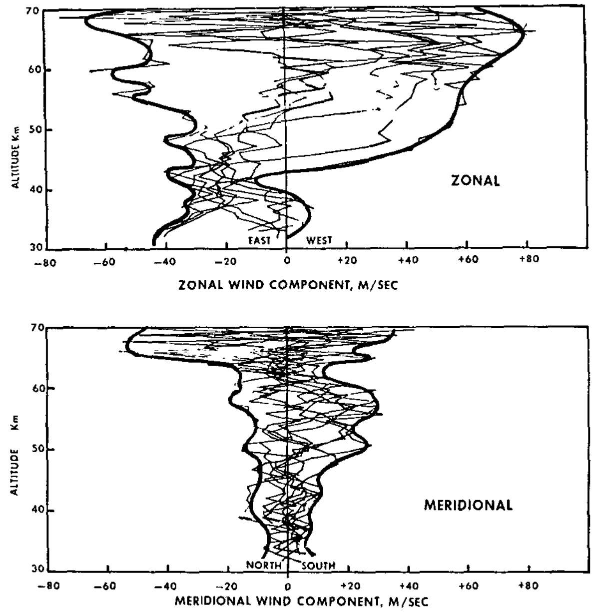

Fig. 6. The envelopes for zonal and meridional wind components for ten soundings at Kwajalein.

ten inflated sphere soundings is shown in Fig. 5. Several significant points are apparent:

a) The temperature at the stratopause averages 24K warmer than the TSA. The warmest temperature shown is 303K.

b) Disregarding the inversion at 70 km where the drag coefficient data are uncertain, multiple inversions above 70 km appear on every sounding.

c) The coldest inversion on every sounding occurs between 91 and 98 km and averages 154K, 30K colder than the TSA mesopause. The coldest temperature is 126K at 94 km on the afternoon of 18 June 1963.

Which of the multiple inversions above 70 km should be considered the mesopause would seem to be a matter of opinion. Arbitrary definitions of "pauses" often allow considerable ambiguity when applied to a specific sounding. Even with detailed quantitative criteria, locating the tropopause level on a given sounding is frequently not straightforward. In the system of nomenclature recommended by the World Meteorological Organization's Executive Committee, the mesopause is broadly defined as the base of the inversion topping the region in which the temperature *generally* decreases with height (Sawyer, 1963). Thus, either the lowest inversion, usually between 75 and 80 km, or the coldest inversion, between 91 and 98 km, might reasonably be interpreted as the mesopause. The former would agree better with present standard atmospheres (Cole and Kantor, 1963) which place the mesopause at 80 km independent of latitude or season, and with early theoretical work (Kellogg and Schilling, 1951) which inferred a latitudinal minimum of mesopause altitude over the equator as low as 70 km. On the other hand, Schilling (1965) has recently suggested a mesopause altitude about 25 km higher over the equator than over the poles, based on observations of the flattening of the earth's shadow during lunar eclipses. The multiple inversions reported here lend credence to Schilling's further inference of a possible double mesopause with the two temperature minimum levels having a height difference of 20–30 km over equatorial regions.

5. Wind

Envelopes of wind components for the ten soundings are shown in Fig. 6. Above 45 km the envelope of the zonal component is roughly symmetric about the zero line, and the range between extremes is quite large, from −55 to +65 mps at 70 km. In the meridional component, the variability increases slightly with height up to 65 km, above which the variability increases sharply. At all altitudes the meridional component envelope is approximately symmetric about the zero line.

Since the soundings in the series were made over a 12-month period, the spread of the zonal envelope presumably reflects the quasi-biennial or 26-month cycle of tropical strato-mesospheric winds (Reed *et al.*, 1961; Angell and Korshover, 1962; Veryard and Ebdon, 1961). An apparent indication of the quasi-biennial effect is shown in Fig. 7, which compares two daytime zonal wind profiles for June 1963 with two corresponding profiles for June 1964. The profiles cross, i.e., the year-to-year difference changes sign between 40 and 50 km, apparently as a result of the downward progres-

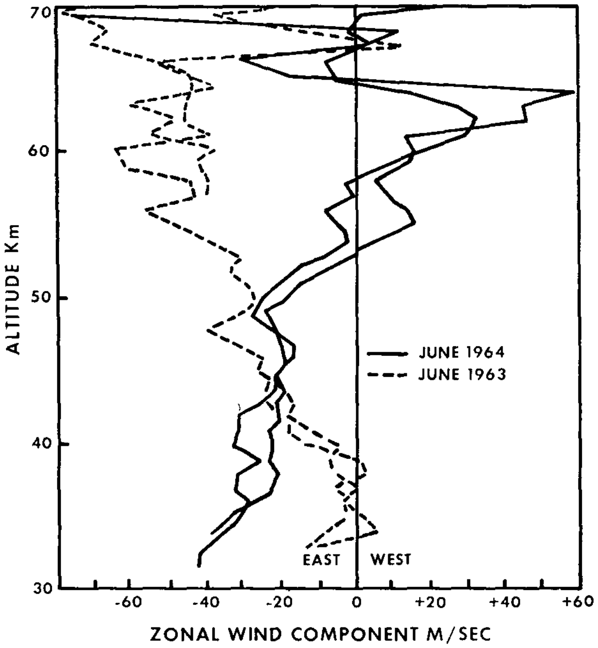

Fig. 7. The comparison of four zonal wind profiles for June 1963 and June 1964 at Kwajalein which support the 26-month cycle theory.

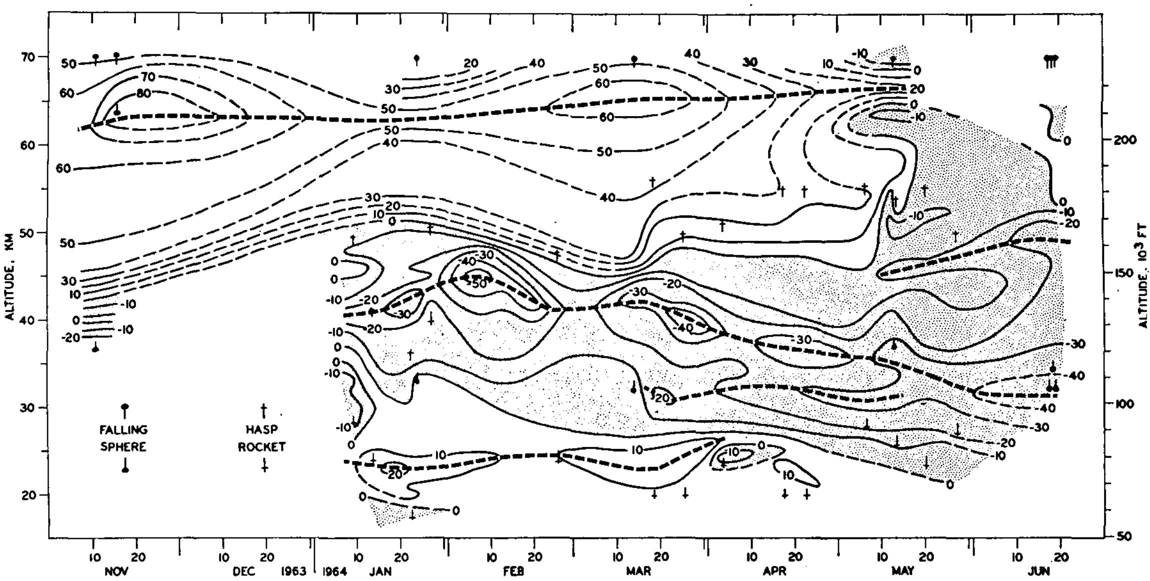

FIG. 8. A time-height analysis of west-wind component (m sec^{-1}) at Kwajalein, November 1963 through June 1964; areas of easterly wind (negative zonal component) are stippled. Heavy broken lines are axes of maximum wind.

sion of the quasi-biennial cycle with time (Reed *et al.*, 1961). Since all four profiles represent afternoon local time (firings between 1301 and 1528 hours), diurnal tidal effects are not reflected.

Eight of the successful inflated sphere firings were made during a 7-month period from mid-November 1963 through mid-June 1964. Wind data from these firings have been combined with wind data from 17 conventional (Hasp-chaff payload) meteorological rockets to produce a vertical time section of zonal wind shown in Fig. 8.

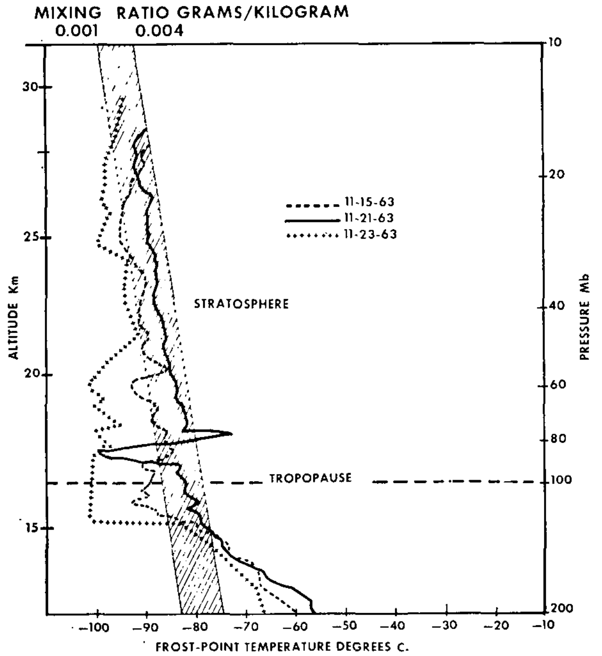

FIG. 9. A plot of frost point versus altitude as obtained from three flights extending into the stratosphere over Kwajalein in November 1963. Shaded area indicates mixing ratios of 0.001 to 0.004 gm kg^{-1}.

The time section shows a belt of easterlies in the upper stratosphere persisting throughout the period, surmounted by westerlies in the lower mesophere. The existence of continuous easterlies through the winter is in sharp contrast to circulation in the winter stratosphere of middle and high latitudes, where general westerlies persist in winter, interrupted only occasionally by short "stormy" periods of easterlies.

Since continuous easterlies are characteristic of the summer stratosphere, this Kwajalein time section suggests that the southern hemisphere summer circulation regime overlaps the equator and extends into the winter northern hemisphere to some latitude beyond Kwajalein (9N).

6. Water vapor

In addition to knowledge of the structure and state of the upper stratosphere and the mesosphere for Pacific Missile Range programs, it was necessary to know the amount of water vapor in the troposphere and lower stratosphere. Previous investigators (Brunt and Kapur, 1938; Dobson and Brewer, 1951) had found the amounts of water vapor in the lower stratosphere over the tropics to be quite small.

Water vapor measurements were made by use of the Naval Research Laboratory frost-point hygrometer on five flights in November 1963. A complete description of the system used with a discussion of the accuracies is provided by Mastenbrook and Dinger (1960). Three of these flights provided data from the stratosphere as shown in Fig. 9. The flight on 23 November is suspect because the balloon burst and the descent rate of the parachute was too fast to produce reliable data; however, it tends to support the other two more reliable soundings. The two flights with reliable data yielded values between 0.001 and 0.004 gm kg^{-1}. A more complete discussion of these water vapor measurements in the stratosphere has been made by Mastenbrook (1964).

All five flights produced good data below the tropopause. A composite relative humidity curve to 100 mb is shown in Fig. 10. The mean air temperature curve is included. Three distinct layers can be distinguished with transition layers between them. A significant feature of these data is a layer of high relative humidity lying just below the tropopause. This entire layer is at a temperature below the cut-off temperature for the evaluation of humidity data from standard radiosonde observations (U. S. Weather Bureau, Air Force, Navy, 1957). It is, therefore, not surprising that this moist layer has not been reported by previous soundings. In terms of the amount of water vapor in the atmosphere, this moist layer below the tropopause represents only a small portion of the total. Using a conservative estimate of 0.005 gm kg^{-1} of water vapor for the mixing ratio above 100 mb, we calculate that 99 per cent of the water vapor or 3.069 cm of precipitable water lies below approximately 500 mb, whereas only 0.046 cm of precipitable water remains above this altitude.

In summary, the lower tropical stratosphere is dry, i.e., less than 0.005 gm kg^{-1} of water vapor. There is a significant moisture layer just beneath the tropical tropopause that is not detectable by the current radiosonde carbon humidity element.

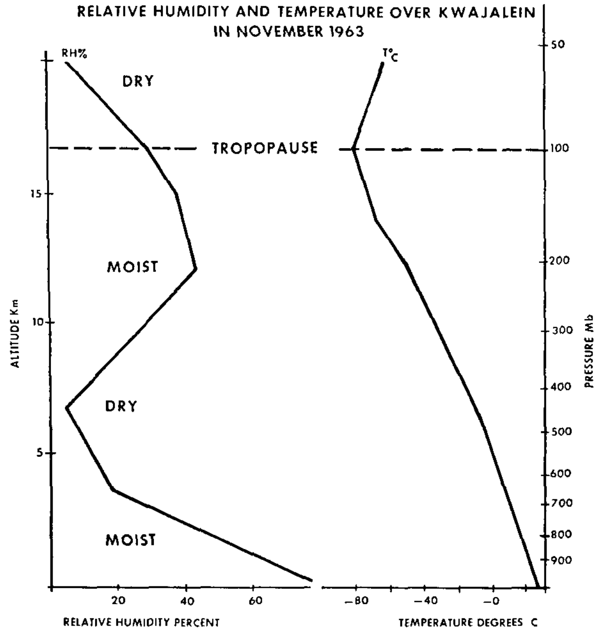

Fig. 10. Composite curves of relative humidity and temperature obtained from five frost point hygrometer flights over Kwajalein in November 1963.

7. Other Variables

Measurement of ozone at Kwajalein was attempted using large balloons to carry the Regener ozone meter as well as temperature and pressure sensors to 40 km. Because of unsuspected damage to ozone calibration equipment during shipping and balloon launching problems, reliable data were not obtained.

A parallel development effort using meteorological rocketsondes and the ultraviolet photo-absorption technique for ozone was pursued, but not without the perils frequently associated with meteorological rockets. This effort was carried out for the PMR by A. Krueger of the Naval Ordnance Test Station, China Lake, Calif. On the last flight at Point Mugu ozone was measured from 48 km to the ground. Although developed too late for application at Kwajalein, the technique and instrumentation was successfully used during the March 1964 cruise of the NASA Mobile Launch Platform, NSTS CROATAN, where six out of nine soundings produced ozone data.

The University of Michigan was also contracted to engineer a system for the measurement of atmospheric composition using the technique of ejecting a mass spectrometer from the NIKE APACHE sounding rocket between 90 and 150 km. Two unsuccessful flights were conducted at Kwajalein. On the first flight there was no payload ejection and on the second flight the sustainer rocket malfunctioned. Two identical PMR atmospheric composition payloads were subsequently flown on 11 March 1965 at 9S from the CROATAN. A night sounding which appeared completely successful and a day sounding which was a partial success because a filament burnout resulted in 40 per cent data loss. The final results and data will be published by the University of Michigan

8. Conclusions

This composite program of meteorological measurements in the central tropical Pacific while providing a partial picture of the structure and state of the tropical atmosphere has produced interesting and significant data. Of special note are:

a) the layer of moisture just beneath the tropopause,
b) the dry stratosphere,
c) the warm stratopause,
d) the multiple inversions above 70 km, and
e) the extremely cold inversion between 91 and 98 km.

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